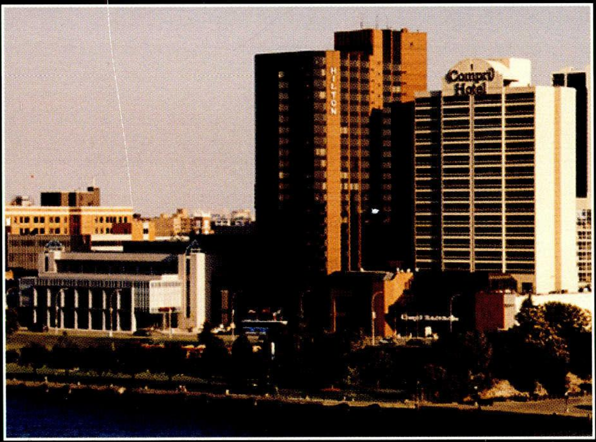
May 31 to June 4 1998

16th International Technical Conference on the **Enhanced Safety of Vehicles**

Volume 2 of 3



The Cleary International Centre
Windsor, Ontario
CANADA

ESV
WINDSOR98

16th International Technical Conference on the **Enhanced Safety of Vehicles**

Proceedings Volume 2 of 3

U.S. Department of Transportation

National Highway Traffic Safety Administration

Transport Canada / Transports Canada

Road Safety / Sécurité routière

DOT HS 808 759

October 1998

May 31 to June 4 1998

16th International
Technical Conference on the
Enhanced Safety of Vehicles

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The first six (6) pages in each of the different sections of the Proceedings are edged in black ink for quick guidance.

Papers in each of the eleven (11) technical sessions have an assigned paper number i.e., 98-S1-O-07, which is representative of the following:

Code		Explanation
98	=	The Year of the Conference
S1	=	The Technical Session Number
O	=	The Type of Paper Presentation (**Oral, Poster, Written**)
07	=	The Assigned Paper Number within each Technical Session

When a break in the sequence of an assigned paper number occurs, it is because the paper was (1) withdrawn, (2) re-arranged within the session, or (3) transferred to another session.

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The 16th ESV Conference Proceedings are published by the United States Government and distributed globally, currently at no cost. These reports, which detail international harmonization and safety research efforts, have been recognized as the definitive work on motor vehicle safety research. If you are interested in obtaining a copy of the Proceedings, please fill in the form below and mail to:

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Introduction

The United States Department of Transportation, National Highway Traffic Safety Administration (NHTSA), Office of Research and Development is the official government agency responsible for the implementation of the International Technical Conferences on the Enhanced Safety of Vehicles (ESV). The Conferences are held approximately every two years and hosted by participating Governments. Delegate and attendee participation includes worldwide governments, automotive industries, motor vehicle research engineers and scientists, medical, insurance, and legal professions, consumers, academia, private corporations, and international media.

The ESV Program originated in 1968 under the North Atlantic Treaty Organization (NATO) Committee on the Challenges of Modern Society, and was implemented through bilateral agreements between the governments of the United States, France, the Federal Republic of Germany, Italy, the United Kingdom, Japan, and Sweden. The participating nations agreed to develop experimental safety vehicles to advance the state-of-the-art technology in automotive engineering and to meet periodically to exchange information on their progress. Since its inception the number of international partners has grown to include the governments of Canada, Australia, the Netherlands, Hungary, Poland, and two international organizations -- the European Enhanced Vehicle-Safety Committee, and the European Commission. A representative from each country and organization serves as a Government Focal Point in support of the Conference.

In 1968 the Conference was known as the International Experimental Safety of Vehicles Conference. Over time, the focus of the Conference shifted from concentration on the development of experimental safety vehicles to broader issues of safety and international cooperation seeking reductions in motor vehicle fatalities and injuries. These issues include program advances such as Pedestrian Safety, Frontal and Side Impact Protection, Biomechanics, Intelligent Transportation Systems, and Vehicle Compatibility. In 1991, the participating governments agreed to change the name of the Conference to "The International Technical Conference on the Enhanced Safety of Vehicles" to reflect the current focus. The 14th ESV Conference, held in Munich, Germany, May, 1994, was the first conference in which the new name was used, and "25 Years of ESV Development" was celebrated.

The 15th ESV Conference, held in Melbourne, Australia, May, 1996, was precedence-setting as well. A new 5-year priority research program known as International Harmonized Research Activities (IHRA) was established under the auspices of the ESV Conference. The program established six international priority research areas; Biomechanics, Advanced Offset Frontal Crash Protection, Vehicle Compatibility, Pedestrian Safety, Intelligent Transportation Systems and recently chosen Side Impact Protection. In May of 1997, NHTSA hosted a Public Workshop to share with its partners the goals and objectives of IHRA. In November of 1997, the ESV Government Focal Points agreed that all participating governments would join in these priority research programs, and that the programs would be governed by an IHRA Steering Committee comprised mainly of the ESV Government Focal Points. Six Working Groups that now exist in each of the priority research areas are led by participating Governments, and are comprised of government and industry experts. The IHRA Steering Committee consisting of Government members meets biannually to review recommendations and research plans being developed by the Working Groups.

This, the 16th ESV Conference hosted by Transport Canada, held in Windsor, Ontario, Canada, May 31-June 4, 1998, was attended by delegates from twenty one (21) different countries. The IHRA Status Reports on the progress of the five priority research areas were presented during this Conference. Well over 300 technical papers were accepted for inclusion in the Conference Proceedings, with international authors representative of sixteen (16) different nations. This Conference also marked the first time scientific poster presentations were given.

The 17th ESV Conference, the first Conference of the 21st Century, will be held in Amsterdam, The Netherlands, in the year 2001. The year was chosen because IHRA will have met the 5-year deadline for reporting their vision, goals, objectives, and achievements under the program.

We thank our international conference participants for their continued interest, dedication and support. It is an outstanding example of the highest regard for automotive safety research we are certain will continue.

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European Enhanced Vehicle-Safety Committee

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Moderator: Gerard J.M. Meekel, Head of Vehicle Standards Development, Ministry of Transport, The Netherlands

Invited Speakers Executive Panel

Human Factors
Moderator: Y. Ian Noy, Chief Ergonomics Division, Transport Canada, Canada

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Chairperson: Cezary Szczepaniak, Vehicle Research Institute, Poland

COLLISION AVOIDANCE THROUGH IMPROVED COMMUNICATION BETWEEN TRACTOR AND TRAILER

C. James Britell
National Highway Traffic Safety Administration
Alan C. Lesesky
Vehicle Enhancement Systems, Inc.
United States
Paper Number 98-S4-O-01

ABSTRACT

On September 2, 1994, NHTSA issued a notice in the Federal Register* to promote a cooperative program which would foster the development, evaluation, and deployment of heavy vehicle intelligent communication and powering enhancement system(s). In response to this solicitation, Delco Electronics Corporation, on behalf of it potential project partners, submitted a proposal ** detailing a collaborative, jointly governed venture between industry and Government to develop and evaluate heavy-duty technology vehicles using two-way communication between the tractor and the trailer.

The object of this cooperative agreement was to foster the development, evaluation, and deployment of intelligent communication and powering, also requiring the installation of several advanced electrical sub-systems on the trailers in order to properly exercise these communication and powering techniques between the tractor and trailer in the real world. Among the devices installed on the vehicles, of particular interest to the government agencies, were the Side Collision Warning System, Brake Stroke Indicator, Head-Up Display, and a Rear View Video Camera as collision avoidance devices.

A unique feature of this program was the in-fleet operational testing of the systems, using real truck drivers, who faced real driver problems and performance pressures. The drivers introduced a recordable "human factors" element into the evaluation system with regard to the safety and productivity value of many of the tested systems. If something bothered them, it got shutoff or broken.

*Federal Register/Vol. 59, No., 170/Fri. Sept 2, 1994/ Notices pp 45750-52

**The application to the Dept. of Transportation - National Highway Traffic Safety Administration (NHTSA) was submitted by NHTSA Truck Technology Demonstration Consortium on November 22, 1994

INTRODUCTION

The medium- and heavy-duty vehicle industry has a significant impact on the U.S. transportation system and plays a vital role in shaping the health of the Nation's economy. An estimated 423,153 firms, comprised of Fortune 500 companies, smaller private firms, and common and contract carriers, operate medium- to heavy-duty trucks. In 1996, these firms:

- employed 9.5 million people, 5.6 million of whom are drivers;
- operated 1.62 million combination-unit and 4.27 million single-units medium- and heavy-duty trucks;
- operated 4.1 million trailers; and
- drove 267 billion vehicle miles. *

The last decade has seen a tremendous growth in truck travel, an increase of 40 percent; however, during that same time period, the fatal crash involvement rate for medium- to heavy-duty trucks decreased by 35 percent. Whether or not truck safety is being adequately addressed has caused conflict between industry and safety advocacy groups. Although there is a general consensus as to the need for expanding and improving overall safety measures regarding truck maintenance, performance, and design, there is strong opposition to certain industry initiatives, such as the utilization of larger, heavier trucks to increase productivity levels.

Other industries, i.e., the defense, aerospace, and computer industries, are beginning to penetrate and target the commercial vehicle market with their own technological initiatives to address the safety and productivity issues currently facing the trucking industry. The interests of both private and public sectors are at stake, dictating the necessity for mutual involvement in addressing pertinent issues, i.e., safety, design, performance, productivity, and maintenance.

* Source, American Trucking Associations (1996 Data)

Heavy-duty truck combination vehicles have two distinct units--the tractor and the trailer. Both units are designed, developed, manufactured, and marketed independent of each other by either the tractor manufacturer (supplying the towing unit) or the trailer manufacturer (supplying the cargo space to move goods). However, both units, the tractor and trailer, when linked together at the fifth wheel of the power unit and the king-pin of the trailer, function as one complete system.

The U.S. trucking industry relies on the widespread application of the SAE J560 plug/receptacle, an electrical connector developed in the 1950s, to provide electrical current and power between the tractor and the trailer. It is atypical for trailers (unlike their tractor counterparts) to have an independent electrical power source, such as a battery. Therefore, power and control are supplied from the tractor, via the seven-pin connector, to the trailer's running lights. This electrical connector provides six electrical circuits and one ground for vehicle powering and communications:

- **pin one** is used as a common ground for the six other positive power pins;
- **pin two** is used to power clearance and side marker lamps;
- **pin three** is used to power the left hand turn signal and hazard signal;
- **pin four** is used to power the stoplamp;
- **pin five** is used to power the right hand turn signal and hazard signal;
- **pin six** is used to power the taillamp, marker lamps, and license plate lamps; and
- **pin seven** is an auxiliary circuit that is available in most vehicle combinations. *

Unfortunately, technological growth and advancement have been hampered by the limitations of the standard six-circuit connection. Any changes to this connector may result in a lack of compatibility between the tractor and trailer units, particularly multi-unit vehicles, which are sensitive to the inherent constraints associated with vehicle powering and communication. New technologies frequently do not provide adequate power to trailer-based systems and do not have the capacity to transmit signals back to the tractor. Consequently, the current application of developing technologies has been limited to single unit trucks and truck tractors.

* TMC and SAE have recently changed the function of Pin Seven - Switched and shared power for ABS.

The multi-unit combination vehicle will likely play an instrumental role in improving the productivity of the trucking industry. The industry must move forward to eliminate constraints that limit the effectiveness of applying and integrating both existing and newly developed technologies for the trailer. Listed below are several technologies which are being envisioned for the application of, and in some cases, have already been installed on trucks and tractor systems.

Technologies which promote Operational Efficiency Benefits:

- vehicle/unit locators
- vehicle/driver trip loggers
- on-board weight measurement and recording systems
- vehicle maintenance status monitor/recorder/transmitters
- administrative credentials transponders

Technologies which promote Operational Safety Performance:

- sideward-looking, rearward-looking, and forward-looking collision avoidance systems
- driver performance monitors
- antilock and electronic braking systems
- brake maintenance status monitors, etc.

Tractor and trailer electrical systems will need to function as a combined unit to fully realize the safety, efficiency, and productivity potentials of these emerging technologies. Data generated by these sensing, processing, and signaling systems will be invaluable to the industry-wide operations of heavy-duty truck trailers.

Government

Rapid advancements in technology and its expansion into the U.S. transportation system have made it imperative for Government and industry to work together. Cooperation between Government and industry is necessary for fostering the developmental efforts of critical technological systems. Although, the industry is ultimately responsible for designing, manufacturing, marketing and implementing technology, it is the Government, i.e., the National Highway Traffic Safety Administration (NHTSA) and Federal Highway Administration (FHWA), through its research and regulatory efforts, which plays an instrumental role in the developmental process.

The Government serves in the following capacities:

- Identifies potential safety problems and opportunities and defines functional and performance targets for system improvements, that, if met by product designers, will maximize safety benefits.

- Develops research tools and databases for use by both industry and Government to provide fundamental driver/vehicle performance data needed by the private sector designers of collision avoidance, crashworthiness, and occupant protection systems.

- Performs tests and evaluations of generic product groups designed for a specific function or purpose.

- Works cooperatively with industry groups (e.g., manufacturers, suppliers, and truck users) to assess performance, reliability, maintainability, failure modes/consequences, and costs. Validation of safety performance specifications under real-world operating conditions will facilitate the deployment of marketable systems.
- Facilitates the early development of effective, cost-beneficial, and user friendly collision avoidance, crashworthiness, and truck occupant protection systems, especially in cases where corporate proprietary interests would normally preclude broad-based research efforts.

NHTSA is responsible for devising strategies that not only prevent, but also reduce, the number and severity of motor vehicle collisions on U.S. highways. More specifically, NHTSA's objective is to minimize the potential for personal injuries and property damage, and ultimately, to save lives.

NHTSA's **Office of Crash Avoidance Research** conducts and manages research intended to analyze driver-vehicle interaction; identify specific vehicle designs, components, or parameters associated with driver performance errors and resulting collisions; and develop and evaluate vehicle-based collision avoidance countermeasure concepts and devices. In order to meet these research objectives, NHTSA uses a variety of experimental techniques and analytical approaches:

- Analytical modeling
- Controlled laboratory experiments
- Controlled tests on test tracks or closed test courses
- Controlled tests conducted in real traffic
- Instrumented-vehicle field studies

FHWA's Office of Motor Carriers (OMC) is moving toward a new era of highway safety: the final destination, a "crash-free" environment. OMC will place emphasis on the fact that highway safety is EVERYONES' responsibility; all actions and reactions make an impact!

The OMC mission is to promote safe commercial vehicle operations through the development, communication, and enforcement of effective and cost-beneficial safety regulations and practices, and to promote technological and operational advances that support an efficient and economical transportation system. The agency's safety programs have been designed to meet the following goals and objectives as it moves into the twenty-first century:

1. Reduce the number of commercial motor vehicles crashes;
2. Build partnerships to improve motor carrier safety and performance; and
3. Identify and promote new technologies and strategies to enhance safety performance and productivity.

COOPERATIVE RESEARCH PROGRAMS

The cooperative research programs enable both the Federal Government and industry to pool their collective resources and work towards the improvement and advancement of the U.S. transportation system. Results from these research studies are used in published research papers and technical reports, and they form the basis for Federal Motor Vehicle Safety Standards (FMVSS)*. NHTSA/FHWA-sponsored research has also been used in the formulation of many industry Standards/Recommended Practices (RPs) through the auspices of the Society of Automotive Engineers (SAE) International and the Maintenance Council (TMC).

In these cooperative agreements, the Government is dependent upon the active participation and cooperation of the industry to provide the necessary vehicles, equipment, and personnel to effectively conduct, evaluate, and meet its

* NHTSA develops and publishes FMVSS as part of its overall highway and motor vehicle safety program. These standards specify safety performance requirements for complete vehicles and vehicle components (e.g., brake systems and occupant restraint systems). They apply to manufacturers of motor vehicles and suppliers of equipment for motor vehicles (e.g., tire, brake hose and lighting equipment manufactures) who offer their products for sale in the U.S. (Heavy Vehicle Safety Research: A New Agenda for the 21st, Page 37).

research objectives. Ultimately, the industry reacts to, debates, or implements the issues, findings, or solutions put forth by the Government's research efforts. NHTSA and FHWA, along with the mutual support of other Government agencies and industry organizations, strive to develop non-overlapping, synergistic research and regulatory efforts. It is the agencies' goal to facilitate industry-wide consensus and the voluntary implementation of performance, design, and safety standards. These measures will ultimately impact both the public and commercial sectors thereby preparing the U.S. transportation system for the twenty-first century.

TECHNOLOGY DEMONSTRATOR PROJECT

On September 2, 1994, NHTSA issued a notice in the Federal Register* to promote a cooperative program which would foster the development, evaluation, and deployment of heavy vehicle intelligent communication and powering enhancement system(s). In response to this solicitation, Delco Electronics Corporation, on behalf of its potential project partners, submitted a proposal** detailing a collaborative, jointly governed venture between industry and Government to develop and evaluate heavy-duty technology vehicles using two-way communication between the tractor and the trailer.

The following connectors were supplied by the industry to test the powering and communication systems between the two tractors and trailers used in this project, testing the following connectors—Cole Hersee (13-Pin/J560); 3731 ISO Modified Connector; Infrared Connector; and three (3) Power Line Carriers.

COLLISION AVOIDANCE DEVICES

The object of this cooperative agreement was to foster the development, evaluation, and deployment of intelligent communication and powering systems on heavy duty vehicles. The ability to effectively demonstrate various communication and powering techniques required the installation of several advanced electrical sub-systems on the trailers in order to properly exercise these communication and powering techniques. Among the 30 devices installed, of particular interest to the government agencies, was the Side Collision Warning System, Brake Stroke Indicator, Head-Up Display, and a Rear View Video Camera as collision avoidance devices.

A unique feature of this program was the in-fleet operational testing of the systems, using real truck drivers, who faced real driver problems and performance pressures. The drivers introduced a recordable "human factors" element into the evaluation system with regard to the safety and productivity value of many of the tested systems. If something bothered them, it got shutoff or broken.

The Side Collision Warning feature worked continuously with a small light in the upper portion of the rear view mirror. An audible buzzer warning sounded if the turn signal was on. The signal transmission was in the form of power-line carrier, meaning the signal was transferred over a power line (in this case, the auxiliary circuit). The drivers' reaction was very positive. They used the device to enhance their driving capability. They still relied on their mirrors before making any final decision. Maintenance records did not indicate any problem. A minor problem did occur when the Side Collision Warning device set-off the police radar detector in Tennessee. We had to arm the drivers with a letter stating this was not a radar detector device.

The Head Up Display was useful to the driver in that information such as vehicle speed, engine RPMS, engine temperature, brake stroke indicator, ABS malfunction indicator, and the rear view video were available to the driver without having to search down on the dash-board. In other words, the driver could keep his eye on the road in front of him. One driver showed a police officer how he kept track of his speed on the Head Up Display and was not given a speeding ticket for which he was stopped.

The Brake Stroke Indicator used a magnetic field to electronically measure the brake stroke travel and notified the driver by means of a red light as the travel approached pre-set conditions. Drivers found this device useful and in a demonstration project, the truck's home office was notified of the brake stroke travel on a particular unit using the Qualcomm communications system in real time. In order to use as many communication systems as possible, the Brake Stroke Indicator feature used the infrared connector and the Side Collision Warning feature used a form of power line carrier to communicate information to the cab.

The Rear View Video Camera displayed a picture to the driver of what was behind him, using the Head-Up Display. This feature was very useful in the Domino's Pizza unit because of the nature of their deliveries. Because of the low

*Federal Register/Vol. 59, No., 170/Fri. Sept 2, 1994/ Notices pp 45750-52

**The application of the Dept. of Transportation NHTSA was submitted by the NHTSA Truck Technology Demonstration Consortium on November 22, 1994.

power range in which the video signal operated, problems with corrosion in the connector were very evident. Also the signal was very susceptible to electro-magnetic interference. Drivers wanted the picture reversed to appear as if they were looking in a rear view mirror.

The following table shows core members, service or product contributions, and product attributes.

This is followed by a brief critique of the cooperative agreement.

NHTSA TECHNOLOGY DEMONSTRATOR CONSORTIUM.....
CORE MEMBERS, SERVICE & PRODUCT CONTRIBUTIONS, AND PRODUCT ATTRIBUTES

COMPANY NAME	SERVICES	PRODUCTS	PRODUCT ATTRIBUTES POSITIVE	PRODUCT ATTRIBUTES NEGATIVE
Delco Electronics Core Member	• Project Coordinator and Management • Liaison between Consortium and Government (i.e. NHTSA)	■ Data Vision HUD (Head-Up-Display). Displays oil pressure; speed; engine RPM; Boost Pressure, etc. [*Refer to Figure 11 & 19 under Photographs*] • Forewarn Collision Warning System for tractor and trailer	• All drivers like to use the Head-Up-Display and the Collision Warning System. • Interface to video camera is also considered a great feature.	• A failure of the collision warning system occurred to the Wabash trailer. The SDS (side detection system) experienced interference from police radar detector.
Freightliner Core Member	■ Tractor paired with Wabash Trailer ■ Leased to Certified Transports, Seattle, WA	• Tractor Model # FLD-120 [*Refer to Figure 2, 10, 11, 12, 13, 18 & 19 under Photographs*]		
Ryder Transportation Services Core Member	• Leasing services to Certified Transports, Seattle, WA • Leasing services to Domino's Pizza • Field Support/Data Collection	• Mileage - Field Operations		
Vehicle Enhancement Systems, Inc. Core Member	• Installation of Technologies on two Tech Demo vehicles. • Technical Support • Field Service Support and Repair • Final Report	• Infrared Gladhand–SAE J1708/1587 data communications between tractor and trailer [*Refer to Figure 4 & 9 under Photographs*]	Connection worked well	• Infrared gladhand on Utility trailer would intermittently contaminate and pull down the SAE J1708/1587 buss on the Volvo Tractor. Has been temporarily removed.

NHTSA TECHNOLOGY DEMONSTRATOR CONSORTIUM.....
CORE MEMBERS, SERVICE & PRODUCT CONTRIBUTIONS, AND PRODUCT ATTRIBUTES

COMPANY NAME	SERVICES	PRODUCTS	PRODUCT ATTRIBUTES POSITIVE	PRODUCT ATTRIBUTES NEGATIVE
Volvo Core Member	• Tractor paired with Utility Trailer equipped with Thermo King Reefer [*Refer to Figure 1 under Photographs*] • Technical support • Leased to Domino's Pizza, Nashville, TN	• Tractor V/N (model) Conventional • Electronic Engine		• Electronic engine problem with software package used for driver management (CADEC System)
NHTSA/FHWA Core Member	• Project Director • Funding • Technical Guidance and support • Coordinated and supported Navy connector testing	• Provided independent evaluation of connectors		
Air Weigh	• Technical assistance	F. Electronic Weigh System [*Refer to Figure 2 under Photographs*]	G. Real time weight of trailer and tractor rear axles. Interfaces with Satellite communications	■ System presently available only on Air Suspension Vehicles.
Allied Signal Truck Brake Systems	G. Technical assistance	■ ABS System (Volvo Tractor) [*Refer to Figure 1 under Photographs*]	■ No problems found during tests (70,000 miles and 150,000 miles)	
American Trucking Association, Inc. (ATA)	10. Technical assistance 11. Project assistance: Powering and communications between tractor and trailer(s)			

NHTSA TECHNOLOGY DEMONSTRATOR CONSORTIUM.....
CORE MEMBERS, SERVICE & PRODUCT CONTRIBUTIONS, AND PRODUCT ATTRIBUTES

COMPANY NAME	SERVICES	PRODUCTS	PRODUCT ATTRIBUTES POSITIVE	PRODUCT ATTRIBUTES NEGATIVE
Certified Transport	8. Fleet Service Application 9. Leased Freightliner/Wabash Unit *[Refer to Figure 2 under Photographs]*	■ 13-Pin Connector ■ ISO 3731 Connector (Freightliner/Wabash) *[Refer to Figure 3.9 & 23 under Photographs]*	■ Allows six (6) extra circuits within the SAE J560 Connector	■ Corrosion problems with the terminals in the plug. Plug has separated once on each vehicle ■ Availability of parts in the field limited. ■ Data communications and low current devices, such as LED lamps appear to work intermittently once corrosion occurs.
Dearborn Group	■ Technical Support	■ Chatter Boxes - broadcast SAE J1708/1587 and J1939	■ Device will only test tractor/trailer communications with SAE J1587 and SAE J1939 ■ Data can be broadcasted to Qualcomm Satellite Communications	■ Trailer (s) may not need SAE J1939
Delco Remy America	■ Technical Support	■ Smart Alternator (Freightliner)	■ Capable of broadcasting alternator status to Head-Up Display/Satellite Communications	
Domino's Pizza	■ Fleet Service Applications ■ Leased Volvo/Utility Unit *[Refer to Figure 1 & 2 under Photographs]*			
Goodyear Tire & Rubber	■ Tire Installations	■ Tires (tractor & trailer) *[Refer to Figure 1 & 2 under Photographs]*		
Graphiclite Systems		■ Lamps for exterior trailer wall illumination (Utility)	■ Better conspicuity of trailer (night driving)	■ Lamps protrusion exceeds 102" width of trailer

NHTSA TECHNOLOGY DEMONSTRATOR CONSORTIUM.....
CORE MEMBERS, SERVICE & PRODUCT CONTRIBUTIONS, AND PRODUCT ATTRIBUTES

COMPANY NAME	SERVICES	PRODUCTS	PRODUCT ATTRIBUTES POSITIVE	PRODUCT ATTRIBUTES NEGATIVE
MGM Brakes	■ Technical support and installations	■ Brake chambers ■ Electric Stroke Alert technology	■ Electronically indicates over stroke and dragging brake problems ■ Information is displayed on Head-Up Display/Satellite Communications ■ Detected dragging brake conditions on Freightliner/Wabash vehicle	■ Several connector problems with wires at brake chamber
Midland-Grau Heavy Duty Systems	■ Technical support	■ Trailer ABS systems	■ Diagnostic codes on ECU helpful	■ Trailer LED (light Emitting Diode) wanting lamp would not function with ABS system. Additional resistive load on the lamp warning circuit had to be added for system to function
Moto-Mirror	■ Technical support	■ Motorized passenger side mirrors which incorporate Collision warning lamps [*Refer to Figure 13 under Photographs*]	■ Driver is forced to look at mirror in order to get collision warning system	■ One driver used warning system without using the mirror
Pressure Systems International	■ Technical support and installation	■ Automatic Tire Inflation Systems	■ Automatically keeps tires inflated to proper pressure levels ■ Several flats were fixed at drivers convenience ■ Very favorable response from drivers	■ No problems found
Purkey's Fleet Electrics	■ Technical support and installation	■ Battery Management Systems	■ Automatically saves batteries for cranking. [e.g. refrigerator left on, (Freightliner) vehicle started right away]	■ No problems found
Qualcomm	■ Technical support	■ Satellite systems	■ Locates vehicles, interfaces tractor and trailer data to home base ■ Very reliable	■ No problems found
Raychem	■ Technical Support	■ SAE J1939 physical layer cable for tractors and trailers	■ Twisted-pair wire with shield required to protect signal from outside electrical interference	■ Twisted-pair wires with shield extremely hard to install on tractor and trailer already built

NHTSA Technology Demonstrator Consortium.....
Core Members, Service & Product Contributions, and Product Attributes

Company Name	Services	Products	Product Attributes Positive	Product Attributes Negative
Sure Power Industries		■ Power Booster Module (Freightliner)	■ Added to ensure proper voltage in trailer	■ Power line carrier data was attenuated in the power booster
Thermo King Corp.	■ Technical consulting services regarding communication capabilities	■ Smart Reefer unit		
Tramec	■ Technical support	■ Delay stop lamp switch (Volvo)	■ Delayed stop lamp power allows trailer ABS system to remain on during pumping of brakes (if constant power not used)	■ Prototype switch failed after six months of use
Truck-Lite	■ Technical support and installations	■ Power Line Carrier (PLC) Spread Spectrum technology for ABS trailer warning ■ Smart-Lite™ Technology ■ Smart-Plex ™ Technology *[Refer to Figure 5,7,10,112,14,15,16,17 & 18 under Photographs]*	■ Appears to be immune to connector terminal corrosion problems ■ Appears to be compatible with other communication systems using power line carrier technologies such as Qualcomm's trailer ID system and Air Weigh. All three (3) systems function together on the Freightliner/Wabash combination	■ Prototype transceiver chips susceptible to attenuation of other electronic modules on trailer
Utiler Trailer Manufacturing Co.	■ Technical support	■ Reefer trailer. Used with Volvo tractor *[Refer to Figure 2,3,4,5,6,7,8,9,15,16,17,20 & 22 under Photographs]*		
Wabash National	■ Technical support	■ Trailer. Used with Freightliner tractor		
Weldon	■ Technical support	■ High energy strobe system (Utility)	■ Solid state, high output strobe energized during backing	■ Several systems were affected by the high-energy strobe system such as video interference on the rear camera ■ The strobe affected the Smart-Plex system, until a better ground was implemented on the strobe

COOPERATIVE AGREEMENTS BETWEEN INDUSTRY & GOVERNMENT...A CRITIQUE:

In critiquing the industry/Government cooperative agreements, several factors have to be considered:

1. In getting (in this case) 30 independent companies/agencies to work together, extremely long delays can be encountered while the lawyers determine if the individual companies can agree to participate.

2. A core group has to be formed to provide the leadership necessary to advance the project.

   A. In this case, a core group of seven companies/ agencies (NHTSA and FHWA) formed the core group.

   B. One company must provide the overall leadership (i.e., handling administration, signing contracts, etc.)

   C. There needs to be rules for accepting other members into the project.

   D. The project grew from 7 to 30 members. Rules established included:

      1. Only core members could vote.

      2. Acceptance of other members was based on what they had to offer the project.

      3. Ability to work with core members.

   E. To be realistic, vehicles should be placed in revenue-producing service.

3. The Group was able to identify strengths and weaknesses of some 30 items.

4. Driver input was limited.

   A. Written reports from drivers were poor.

   B. Oral reports were good.

5. Management reports were good.

6. The project forced industries that do not normally associate with one another to work together for successful completion of the project. Each member got a better understanding of how other industries worked.

7. Data collection from vehicles operating in the field has always been a problem.

   A. Able to collect data in real time using Qualcomm

   B. Because of delays in getting vehicles on the road and not being sure of what each vehicle would have in terms of technology, it was difficult to develop a data collection plan or collect data since information had to be programmed so that the Qualcomm System would understand, what was being sent.

8. New driver indoctrination was poor. The driver was usually given a few minutes briefing before being turned loose.

   A. More time is needed in order to have things properly explained.

   B. Drivers felt that they were special and, therefore, they may have driven differently than normal.

   C. A means must be developed to verify drivers' reactions (driver may not realize what he is doing).

9. The core and supporting members exceeded the demands placed on them. Everybody wanted the project to work, especially the truck fleet management and leasing companies.

10. The ease with which The Qualcomm system provided data, in almost real time, has and will open new methods of data collection for in-fleet operational data collection efforts.

PHOTOGRAPHS

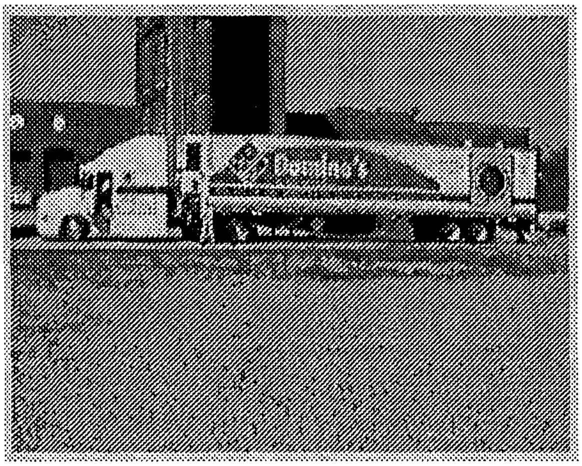

Figure 1. Technology Demonstration Vehicle #2 operated by Domino's Pizza of Nashville, TN.

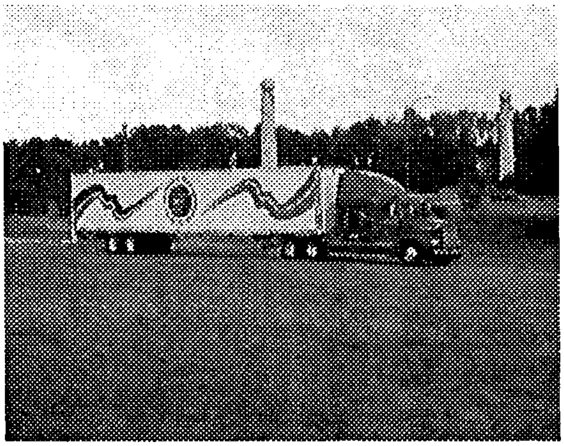

Figure 2. Technology Demonstration Vehicle #1 operated by Certified Transport of Seattle, WA.

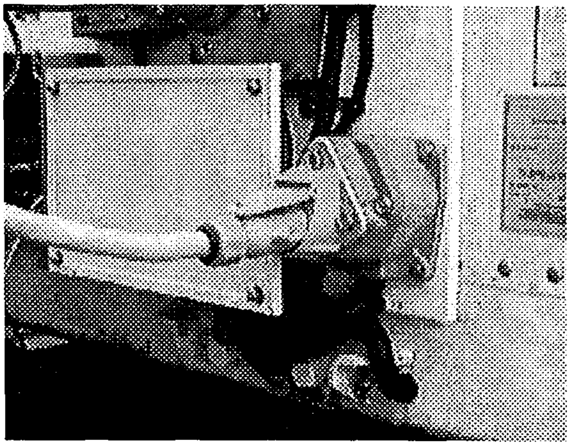

Figure 3. Wabash Trailer: Cole Hersee 13-Pin Connector is used for SAE J1939 (3 pins) and Video RS170 (2 pins) with Power Line Carrier Communications on Aux. Pin 7.

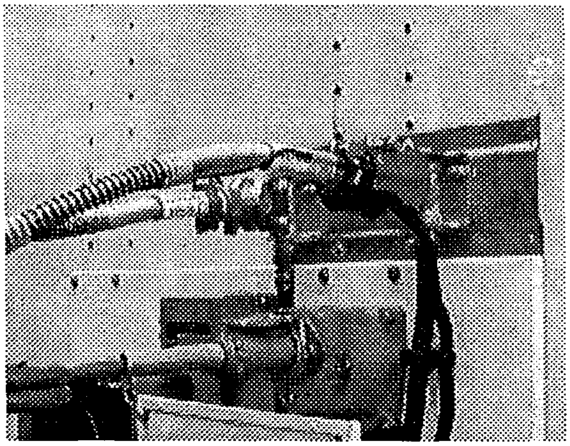

Figure 4. Wabash Trailer: ISO Connector 3731 and SAE J318 Emergency gladhand with SAE J1708/1587 Bridge. The ISO Connector is wire for SAE J1708/1587 and ABS Constant Power.

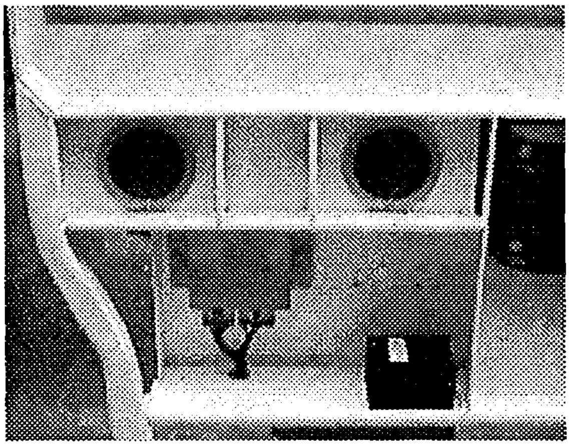

Figure 5. Wabash Trailer: Left Rear–the Truck-Lite Smart Power Line Carrier Technology Box controls the backup lamps, Backup Alarm, Internal Dome Lamps, ABS Warning, Low Air pressure, and Brake Warning.

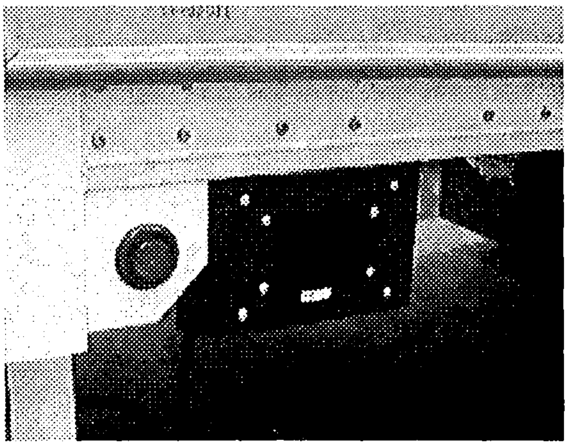

Figure 6. Wabash Trailer: Delco Electronics Radar Collision Warning Side Detection System. Power Line Carrier Communication is the method for tractor/trailer communication.

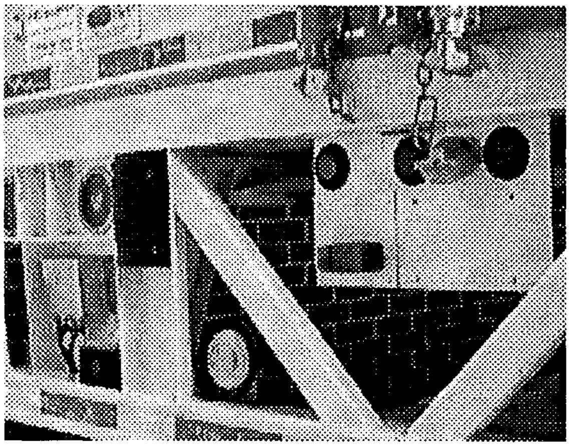

Figure 7. Wabash Trailer: Left Rear–The Truck-Lite Smart Power Line Carrier Technology box controlling the Backup Alarm–Bottom Left Rear. Right Rear–Video/Lamp Camera, Center Rear–Backup Lamps controlled by the Truck-Lite Power Line Carrier box.

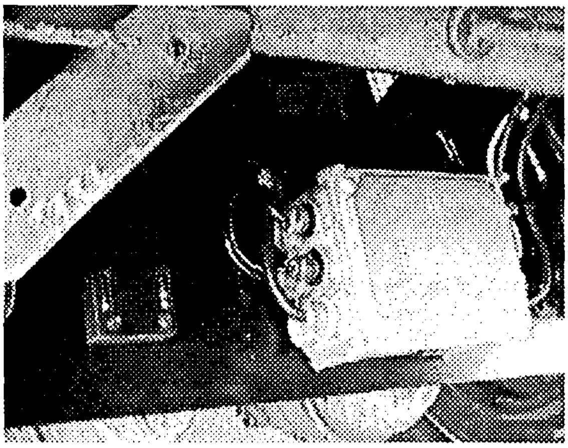

Figure 8. Wabash Trailer: Midland-Grau ABS and Airweight System. Midland-Grau system uses SAE J1708/1587 Communications while the air weigh system uses the Power Line Carrier System over the turn signal circuits of the SAE J560 electrical connector.

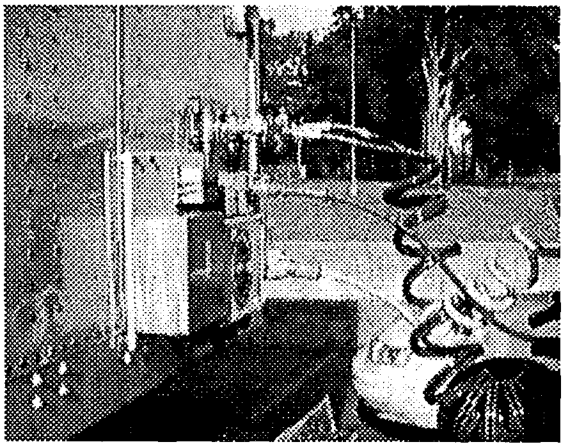

Figure 9. Wabash Trailer: Front nose–Junction Box, Qualcomm Trailer ID Module ISO Connector 3731, SAE J310 Emergency gladhand with infrared SAE J1708/1587 Bridge, Cole Hersee 13-Pin connector.

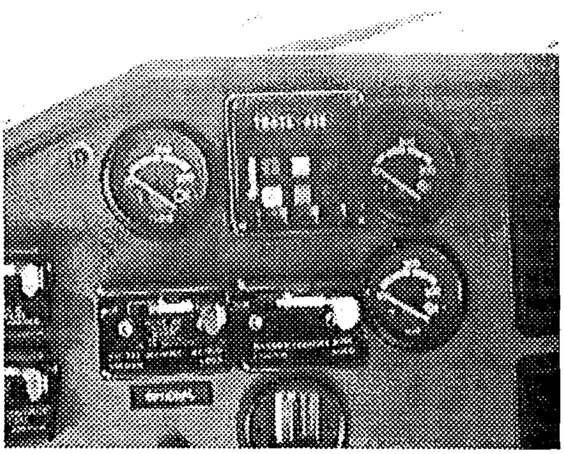

Figure 10. Freightliner Tractor: Truck-Lite Smart Technology display. Display is showing low air brake status from the trailer. The communication technology is Power Line Carrier, which uses existing power lines on the Tractor/Trailer.

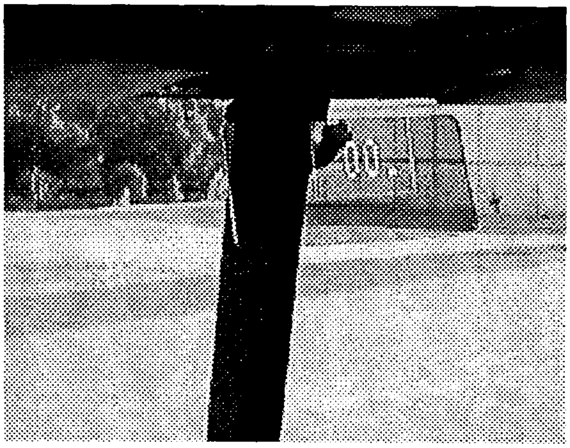

Figure 11. Freightliner Tractor: Head-Up Display Combined with Engine RPM, Vehicle Speed, Engine Oil Pressure, Water Temperature, and Tractor/Trailer Brake Stroke Warning System–All Driven by SAE J1708/1587 Data Bus.

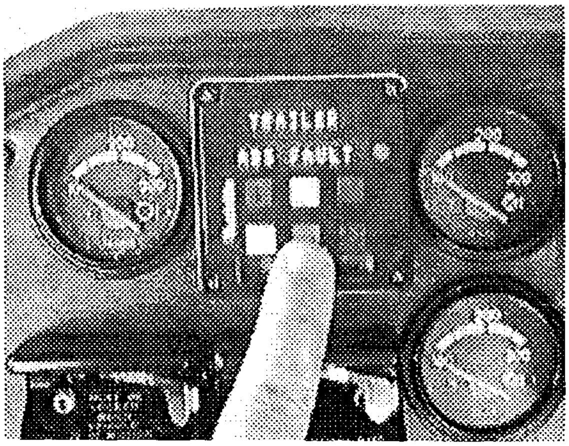

Figure 12. Freightliner Tractor: truck-Lite Smart Technology Display. Display is showing trailer ABS fault warning on the tractor dash. The communication technology is Power Line Carrier, which uses existing power lines.

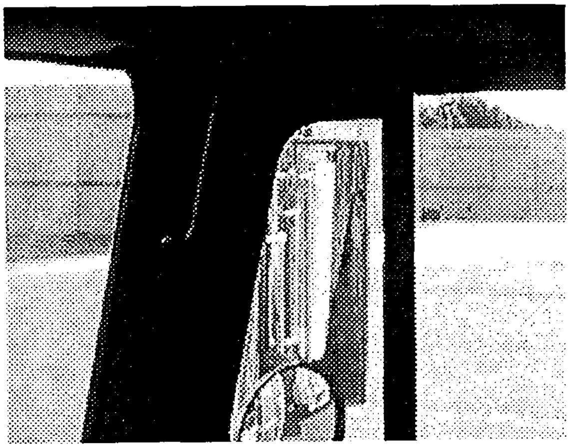

Figure 13. Freightliner Tractor with Delco Electronic Side Detection System Warning mounted in Passenger side mirror system.

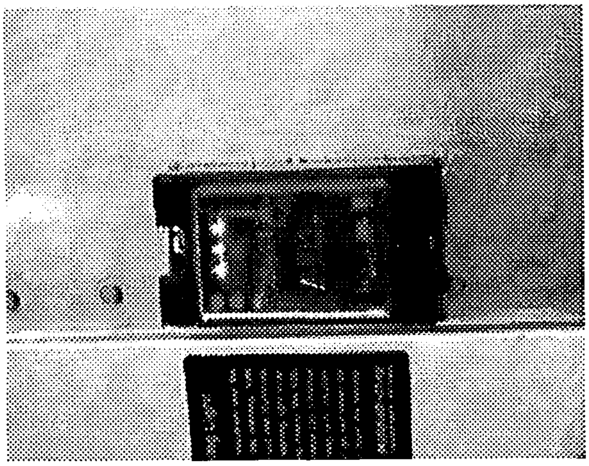

Figure 14. Freightliner Tractor: MGM Electronic Stroke alert module communicating SAEJ1708/1587 with Visible led warning.

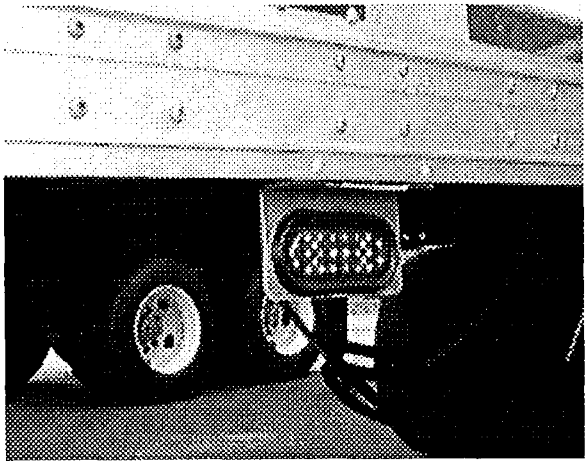

Figure 15. Wabash Trailer: Led (Light Emitting Diode Lamps) installed on the side of the trailer.

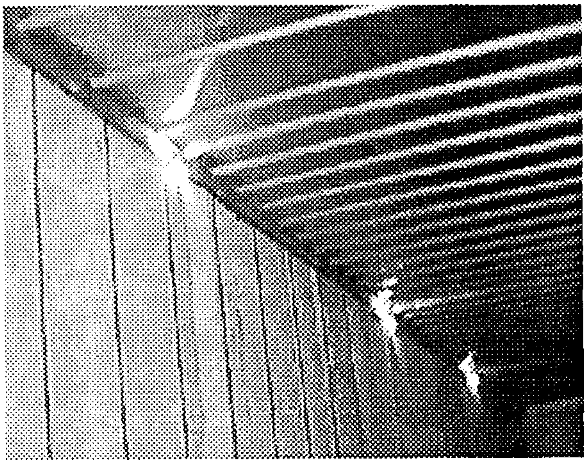

Figure 16. Wabash Trailer: Dome Lamps controlled by the Truck-Lite Smart Technology control box (power-line carrier communication technology).

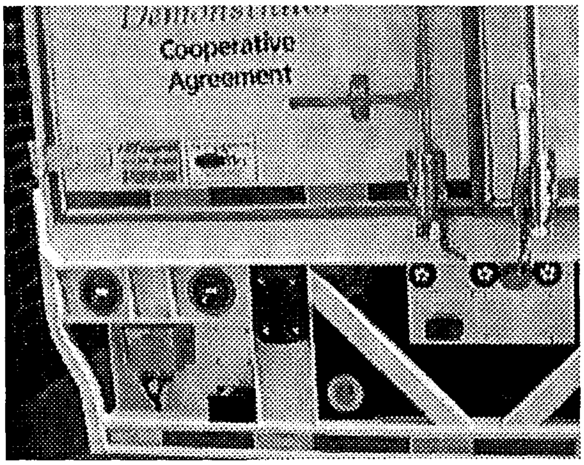

Figure 17. Wabash Trailer: Left Rear–The Truck-Lite Smart Power Line Carrier Technology Box.

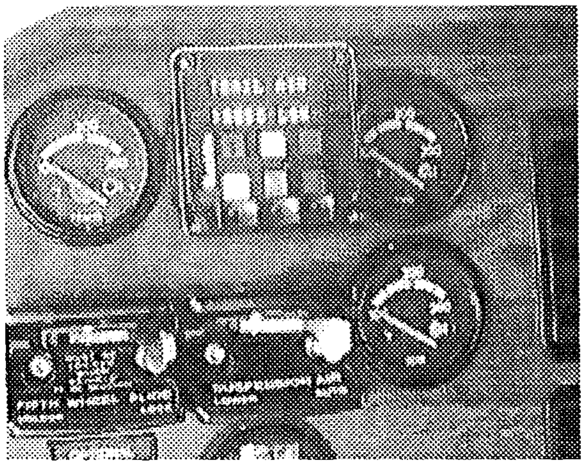

Figure 18. Freightliner Tractor: Truck-Lite Smart Technology Display. Display is showing low air brake status from the trailer the communication technology is Power Line Carrier.

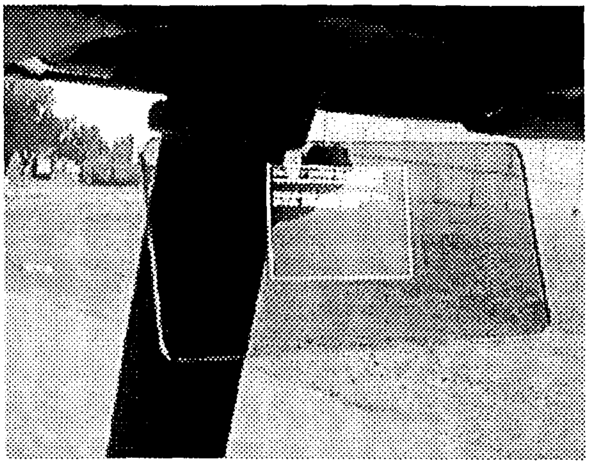

Figure 19. Freightliner Tractor: Head Up Display combined with text messages from SAE J1708/1587 Data Bus. Messages describe brake chamber status.

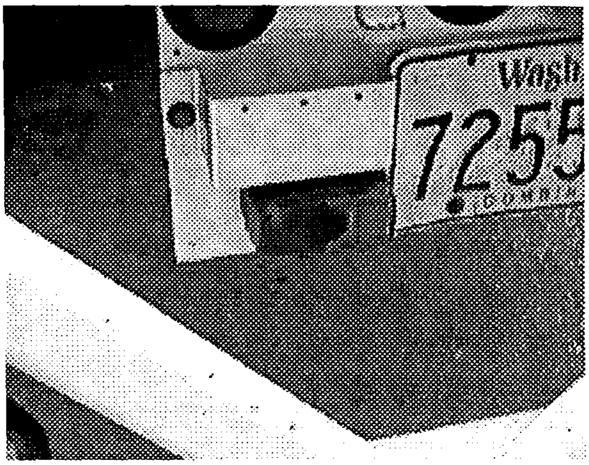

Figure 20. Camera not working (corrosion in J560)

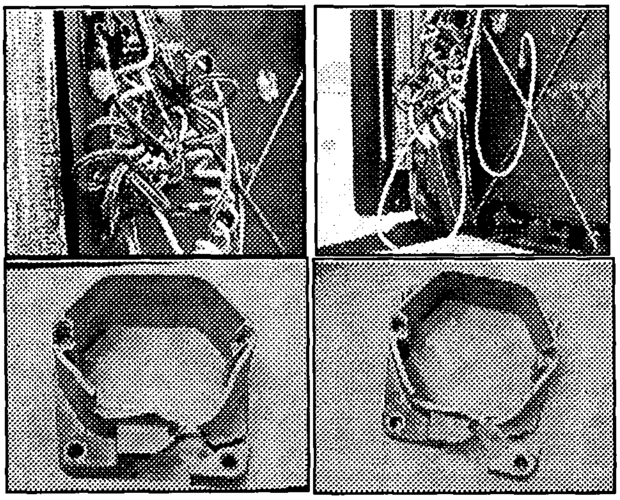

Figure 21. ISO 3731 cable not coiled. Caused receptacle box to break.

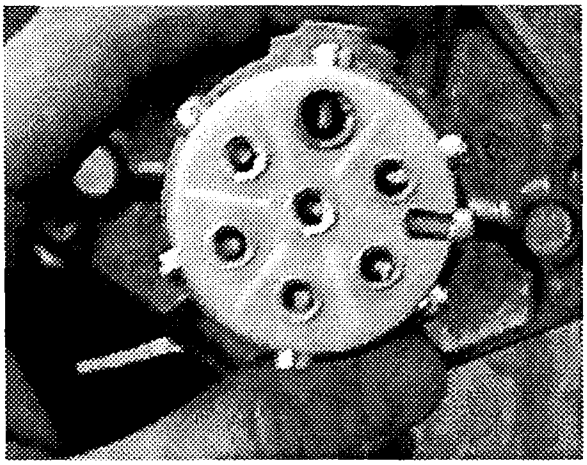

Figure 23. The ISO3731 receptacle suffered a broke wire termination screw during initial installation. A new connector was installed in its place.

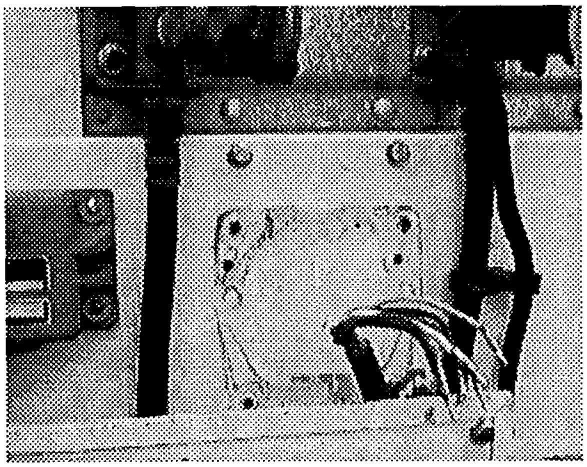

Figure 22. ISO3731 receptacle Broken (cable snagged on Tractor).

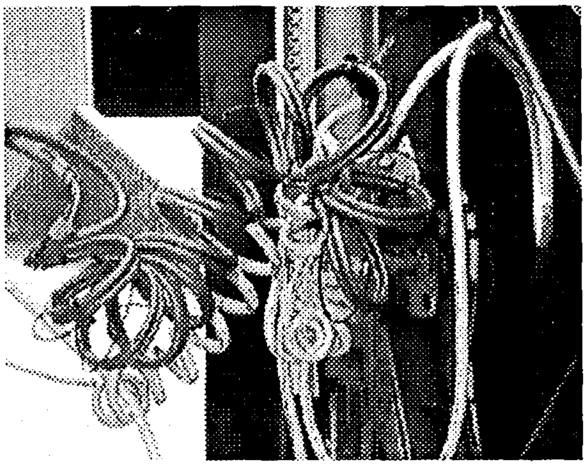

Figure 24. The combination of electrical cords and pneumatic hoses creates a tangle at the back of the Freightliner tractor.

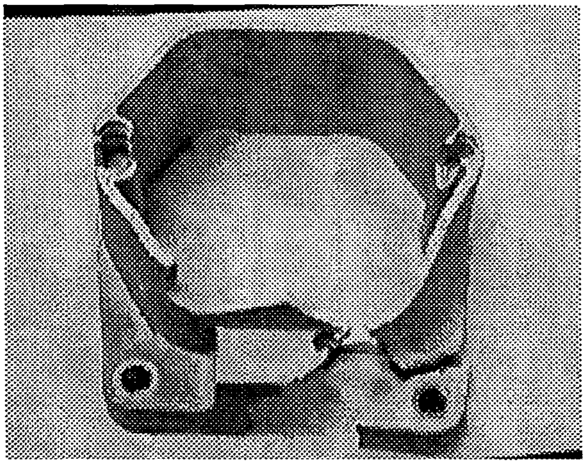

Figure 25. The ISO3731 connector mounting box at the front of the Wabash trailer was broken during a tight turning maneuver. The cable was caught on the deck plate and pulled the receptacle from the trailer.

SAFETY MEASURES FOR THE STRUCTURE OF TRUCKS AND BUSES

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Paper Number 98-S4-O-02

ABSTRACT

There are an increasing number of cases in which the drivers and passengers of trucks and buses that become involved in collisions on expressways are subject to severe injury. For this reason, study committees --- consist of university scholars, fleet operators, vehicle manufacturers, etc. --- have been established, and framed the measures of protecting drivers and passengers with a focus on vehicle structure.

INTRODUCTION

In recent years, the rising volume of traffic and the growing congestion on truck roads have led to a marked increase in the number of accidents involving trucks and buses, particularly on expressways, in which drivers and passengers sustain severe injuries. In view of this situation, two study committees — "The Committee to Study Bus Structure Improvement Measures to Protect Drivers and Passengers" and "The Committee to Study Truck Structure Improvement Measures to Protect Drivers and Passengers — have been established. These committees consist of university scholars; fleet operators, drivers, and vehicle manufacturers; and representatives of the Ministry of Transport (MOT). These committees study vehicle structure and equipment in terms of measures to reduce injuries to drivers and passengers.

FRAMEWORK OF STUDY

These study committees, which operate from the perspective of quickly advancing the spread of safer motor vehicles, do not have the objectives of devising completely new countermeasures or of devising countermeasures aimed at formulating regulations characterized by minimal safety measures. Instead, the objectives of these committees are to select items from among existing safety equipment, equipment that has proven effectiveness and has been adopted in passenger vehicles, or equipment that has high potential for development that are worthy of being spread widely but have failed to spread due to their cost or lack of information, and to formulate measures to promote the spread of these items as early as possible.

These committees commenced activities by conducting questionnaires and holding hearings on bus and truck safety at fleet operators and drivers in order to learn just what actual users consider to be essential to safety in terms of vehicle equipment and structure.

Next, the results of the above questionnaires and hearings formed the basis for the discussions carried out by scholars, motor vehicle manufacturers, and other safety-related parties. During those discussions, certain effective safety measures were selected, and those particular safety measures were examined further in terms of their cost-efficiency.

Lastly, the study committees proposed the necessary action plans to be carried out by fleet operators, motor vehicle manufacturers, and government administrative agencies in order to ensure the spread and regular application of the various safety measures.

The presence of a limited number of concerned parties who shared common perceptions of the necessity and effectiveness of the various countermeasures was a key factor that enabled such a framework to be applied.

SAFETY MEASURES FOR PASSENGERS etc.

Among the various safety measures aimed at passengers, the expenses and effectiveness of equipment were made as clear as possible, in addition to the specific content of the safety measures.

Safety measures to protect bus drivers and passengers were divided into short-term safety measures targeted at being put into practice as soon as possible, and medium- and long-term safety measures that will require substantial time in order to be put into practice.

Safety measures to protect truck passengers were handled in the same way as measures for buses.

Table 1
Specific short-term safety measures for large size buses

a	Strengthening of front chassis structure
b	Three-point safety belts for driver's seat
c	Crash-absorbent steering wheel
d	Strengthening of roof and window pillars
e	Review of the location of seat for the tour guide
f	Elimination of protrusion set on seat backs
g	Adoption of crash-absorbent interior decorations
h	Device that warns when distance between vehicles is inadequate
i	Easy-fastening safety belts
j	Improvement of safety-belt use rate among drivers
k	Thorough notification to passengers on need to fasten safety belts
l	Thorough guidance by bus tour guide who is seated
m	Review of desirable methods of operation management
n	Improvement of method of displaying location of emergency exits, clarification of way of opening exits
o	Installation of Automatic Mayday System

Table 2
Medium- and long-term safety measures for large size buses

a	Improvement of safety in frontal impacts
b	Three-point safety belts for guide seats
c	Crash-absorbent seat backs
d	Installation of safety belts on seat attached to emergency exit
e	Installation of safety belts on spare seats
f	Shift to high-back seats for all passenger seats
g	Uniformity of switch location and method of operation
h	Improvement of emergency exits

EXAMPLES OF SPECIFIC SAFETY MEASURES

Following are outlines of the content of two specific safety measures: improvement of safety in frontal impacts and three-point safety belts for driver's seat.

1) Improvement of Safety in Frontal Impacts

(1) Content of Safety Measure

Motor vehicle manufacturers carry out frontal impact tests based on "Guidelines for Frontal Impact Tests of Large Tourist Buses and Long-Distance Highway Buses," which are the guidelines on frontal impact tests for buses formulated voluntarily by the manufacturers, and implement safety measures to comply with the guidelines. The general content of the safety measures is as follows; however, their specific content differs depending on the manufacturer.

a. Preservation of survival space for the driver's seat during impacts and prevention of secondary impacts
b. Strengthening of the floor and sides of the driver's seat section and establishment of a crushable zone in part of the chassis as needed
c. More secure attachment of the enclosure and floor of the driver's seat
d. More secure attachment of the service box and floor
e. Installation of a three-point safety belt on the guide seat located within the driver's seat enclosure
f. Improvement of the safety of general passenger seats
g. Installation of safety belts on seat attached the emergency exit and spare seats

Table 3
Outline of the Guidelines on Frontal Impact Tests for Large Tourist Buses and Long-distance Highway Buses

Scope of application : GVW of 12 tons or more
Type of impact : Frontal impact collision against fixed barrier
Dummy : Hybrid II or III
Speed at impact : 35 km/h
Parts observed : HIC, chest acceleration, upper leg compressive force
Determination standards : HIC value: 1,000
Chest acceleration : 60 G
Upper leg compressive force : 10 kN
Others: Recognition of calculation methods

2) Three-point safety belt for driver's seat

(1) Aim of measure

To restrain the driver's upper body from pitching forward in impacts, to reduce injury, and to keep the vehicle from going out of control due to external disturbance.

(2) Content of measure

The use of three-point safety belt for driver's seat

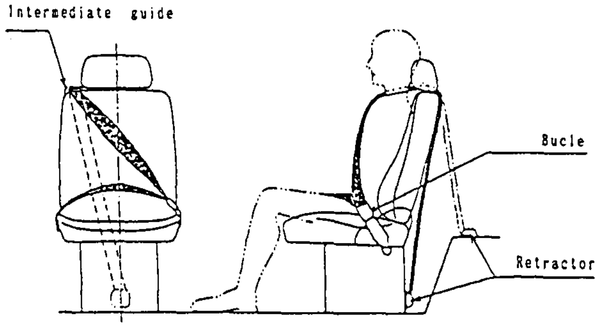

Figure 1 Three-point safety belt for driver's seat

(3) Increase in weight due to the measure: approximately 5 kg.

(4) Increase in vehicle price due to the measure: ¥90,000-¥100,000

CONCLUSION

These study committees consist of university scholars, fleet operators, vehicle manufacturers, and other parties have succeeded in formulating a recommended list of various measures to protect drivers and passengers. Motor vehicle manufacturers will from now on take steps to establish a systematic framework for providing the individual measures. In addition, the government and other authorities will actively supply information concerning the measures to transport businesses and drivers. In turn, fleet operators and drivers will review these information supplied and then work to introduce motor vehicles that have installed whatever safety measures they have deemed necessary.

Some of these measures will require further development, and there is a possibility that some will fail to spread and gain widespread acceptance. For this reason, The status of implementation of the individual measures will be checked periodically..

POINTERS TOWARD THE IMPROVEMENT OF SAFETY IN BUSES, DERIVED FROM AN ANALYSIS OF 371 ACCIDENTS INVOLVING BUSES IN GERMANY AND FROM CRASH TEST RESULTS

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Paper Number 98-S4-O-03

ABSTRACT

DEKRA accident research division has carried out in-depth analyses of 371 accidents involving 395 buses which occurred from 1985 to 1997 in Germany. From these, pointers were derived toward possible improvements in the active safety and, in conjunction with crash test results, in the passive safety of buses.

With regard to the pre-crash phase of the accidents, findings emerge on, among other things, the relative significance and frequency of the following characteristics: speed being driven before collision, critical situation triggering the accident (accident type), consequences of bus occupants and opposites. From these findings, potential benefits of technical aids and bus equipment can be assessed.

A main focus of actual accident occurrences involving buses concerns in which buses topple over their side. On this point, relevant characteristics resulting from the accident assessments are also described. The results of actual accident simulations carried out at the DEKRA crash centre involving the overturning of a moving bus onto its side complete this topic.

From the collision parameters (kind of opposite, driving and collision velocity etc.) pointers emerge regarding the performance of appropriate crash tests for the analysis of internal bus safety. In this context there is also a discussion of the results of bus crash tests carried out at the DEKRA crash centre (vehicle damage, seat- and passenger-stresses).

Lastly, using actual accident occurrences, there is a discussion of external bus safety. A description of the relevant characteristics of collisions with other traffic participants (trucks, buses, cars, two-wheeled vehicles, pedestrians) provides pointers to potential improvements.

INTRODUCTION

The current official categories of road users in Germany contains five types of buses:

- **Kraftomnibus** (Motor coach or bus) seating more than 9 persons including the driver (this category covers all buses which can be separated to „Reisebus" (coach), „Linienbus" (public service bus) or „Schulbus" (school bus).

- **Reisebus** (coach)

- **Linienbus** (public service bus)

- **Schulbus** (school bus)

- **Oberleitungsomnibus** (trolley bus)

These details have only recently come to light, as part of an endeavour to be able to show the incidence of accidents involving buses separately within the official traffic accident statistics. It has been possible to obtain separate accident figures for coaches, public service buses and school buses from official statistics since 1995.

For long-term statistical overviews of total figures covering accidents involving coaches and buses, the figures shown separately for the former German countries are still the most suitable (STATISTICAL OFFICE, 1997). **Figure 1** shows the trend in the number of drivers and passengers involved in accidents who were either seriously injured or killed during the period 1957 to 1996. **Figure 2** shows the reference figures coaches and buses shown in the official statistics for the former countries for the same period.

The number of bus passengers who have been either killed or injured either inside or outside urban areas is declining over the long-term. However, the number of bus passengers killed outside their urban areas has in particular been subject to considerable fluctuations in certain years. As can be seen from Figure 1 in the former countries the number of bus passengers killed outside of their local area per year since the late 60's, with the exception of 1985 and 1992 has been consistently less than 30. In 1985, 38 bus passengers were killed, in 1992, the figure was 35. During the following year, in 1993, three bus passengers were killed outside of urban areas. The reasons behind such fluctuations are isolated tragic incidents during which many victims were either injured or killed in a bus involved in an accident. In both 1985 and

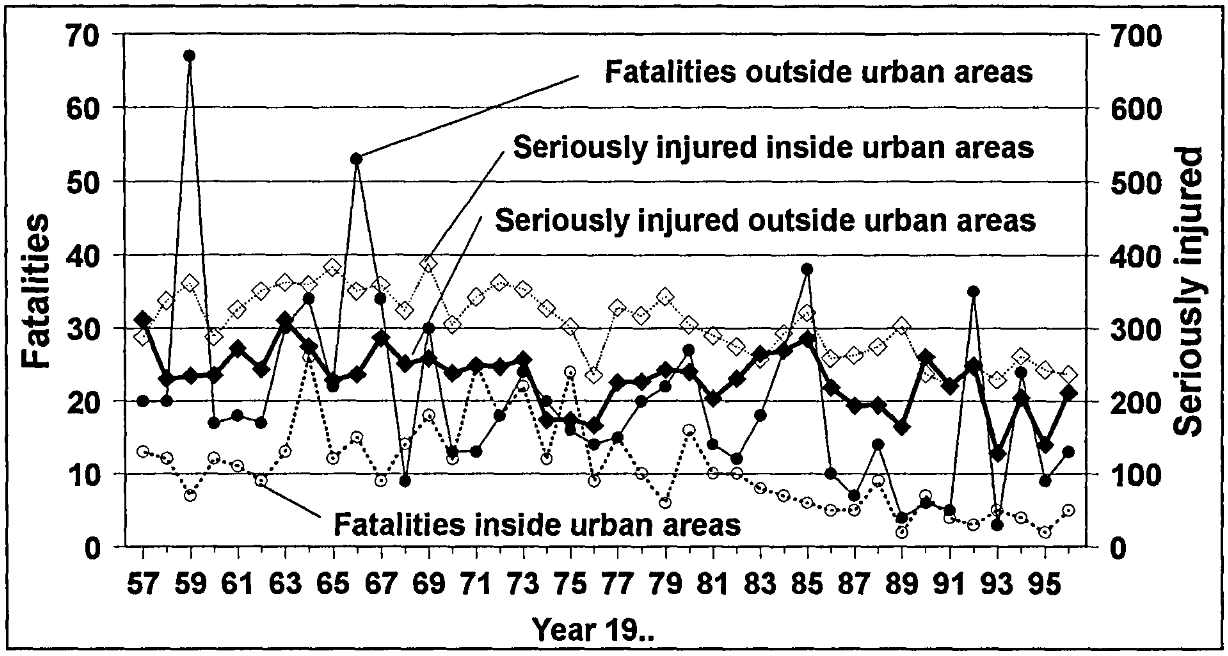

Figure 1. Absolute Frequency of fatal injured or severely injured occupants in buses in the former German countries within the period 1957 to 1996 (Source: German Federal Ministry of Statistics)

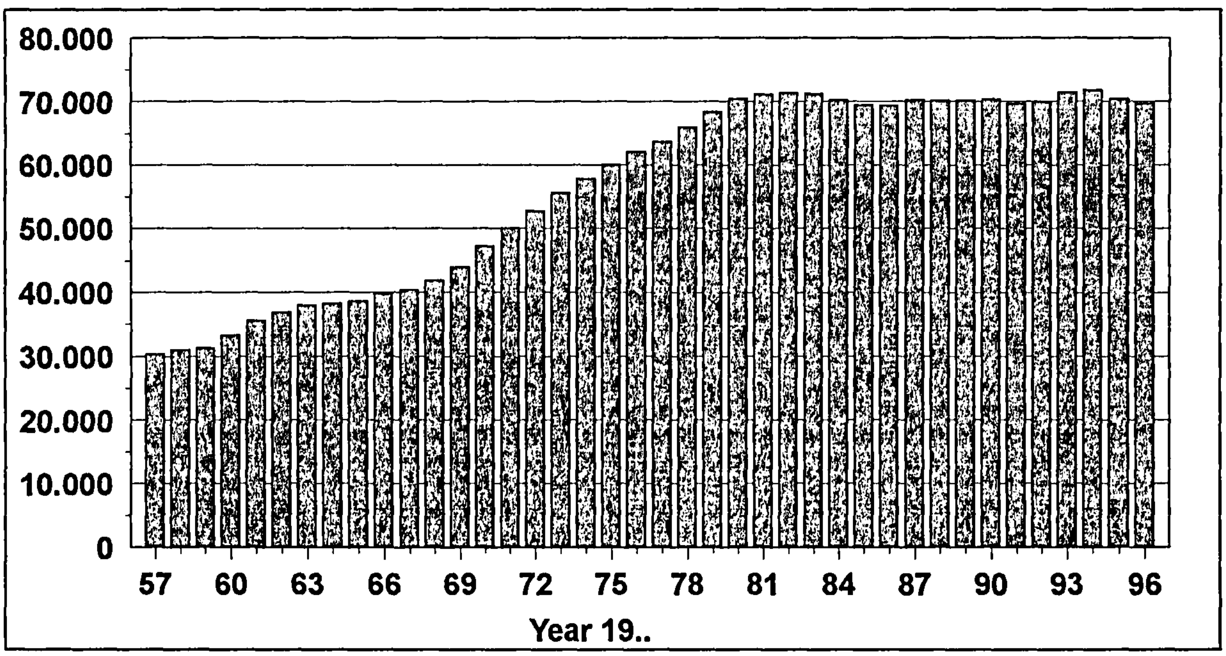

Figure 2. Absolute Frequency of registered buses in the former German countries within the period 1957 to 1996 (Source: German Federal Ministry of Statistics)

1992, 20 people were killed in one single accident. If these two accidents are excluded, the figures for the two years do not stand out from the general trend. Such accidents are reported repeatedly and in detail by the media. There is also enormous and lasting public interest in such incidents.

The number of buses registered in the former countries increased rather steadily from around 30,000 in 1957 to approximately 40,000 in 1967. This was followed by an almost linear, significant increase to around 70,000 registered buses in 1979. Since that time, the number has remained fairly constant. Transport performance in kilo-

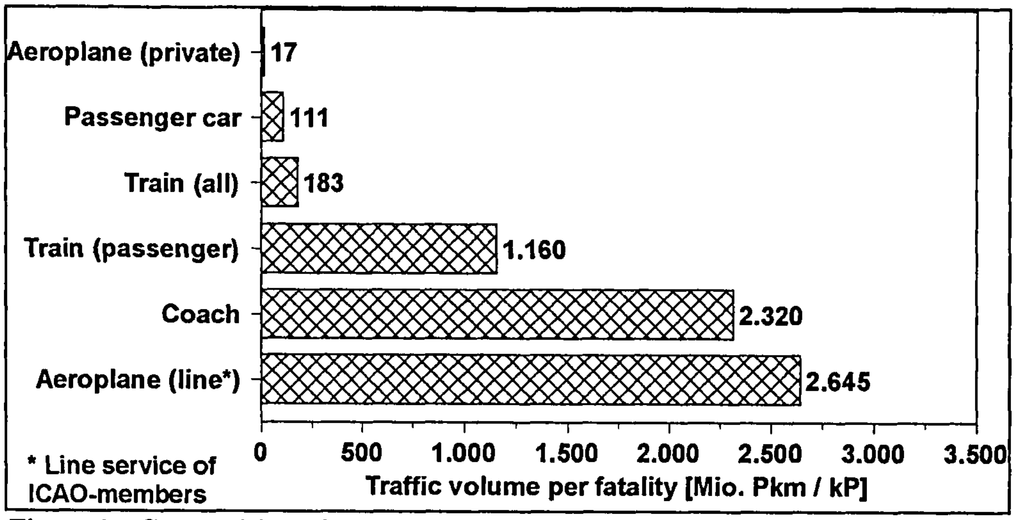

Figure 3. Comparision of the safety of means of transportation (Source: Schesky and Zernick, 1997)

metres per person per fatality shows the coach as one of the safest forms of transport, equal to an aircraft flying scheduled routes, **Figure 3.** (SCHESKY and ZERNICK, 1997). Correspondingly, the risk of a car passenger being killed is approximately 21 times greater than the equivalent risk to a coach passenger.

Nevertheless, improvements to the safety of coaches and buses is an important subject, on the one hand to further limit the potential consequences of isolated coach accidents and on the other, as part of a comprehensive accident research, to take into account the consequences for the other accident vehicle. Hence, DEKRA Automobil AG has carried out an in-depth analysis of 371 accidents involving buses which occurred in Germany between 1985 and 1997. The results obtained from real simulated, instrumented bus crash tests and overturn tests with buses supplement the knowledge derived from the accident analysis.

DEKRA DATABASE

The data sources for the real accident tests are accident analysis reports produced by DEKRA experts in Germany. These reports are being evaluated for scientific purposes in compliance with the Data Protection Act. **Figure 4** shows the relative frequency of individual accidents and in the case of accidents involving a second party, the other vehicle concerned, as represented by the official statistics for road traffic accidents where physical injury has occurred (these are accidents whereby people have been either killed or injured) and for accidents with serious damage to vehicles in Germany during 1996. As a comparison, the same diagram shows the corresponding frequency distribution for 371 bus accidents in the DEKRA database. The vehicle most often colliding with the bus is the car (57.1 % in official statistics, 53 % in DEKRA statistics). Individual bus accidents, bus/bus accidents and bus/heavy goods vehicle accidents occur more frequently within DEKRA than in official statistics. Bus/bicycle and bus/pedestrian accidents occur less frequently in the DEKRA database than in official statistics. Accidents which are relatively safe for bus passengers seldom occur in the DEKRA database.

The distribution of accidents over months shown in **Figure 5** shows a slightly higher number of bus accidents during the months before and after the main holiday period (July and August). This trend which is recognized in the official statistics is given even stronger recognition in the DEKRA data. The number of accidents during the months of May, September, October is significantly different from the figure for other months. **Figure 6** shows a balanced distribution of the road characteristics for bus accidents. A deeper examination of accidents on bends showed that the number of accidents occurring on left-hand bends is almost double that occurring on right-hand bends. This issue which is discussed in the Report by GRANDEL and NIEWÖHNER (1995) is to be clarified by a corresponding number of car/bus collisions. A car travelling too fast around a right-hand bend moves onto the wrong side of the road and collides with an oncoming bus which from it's own point of view, is travelling a left-hand bend.

PRE-CRASH PHASES

Cases of collisions with other road-users or with fixed objects, or if the bus overturns autonomously are all gen-

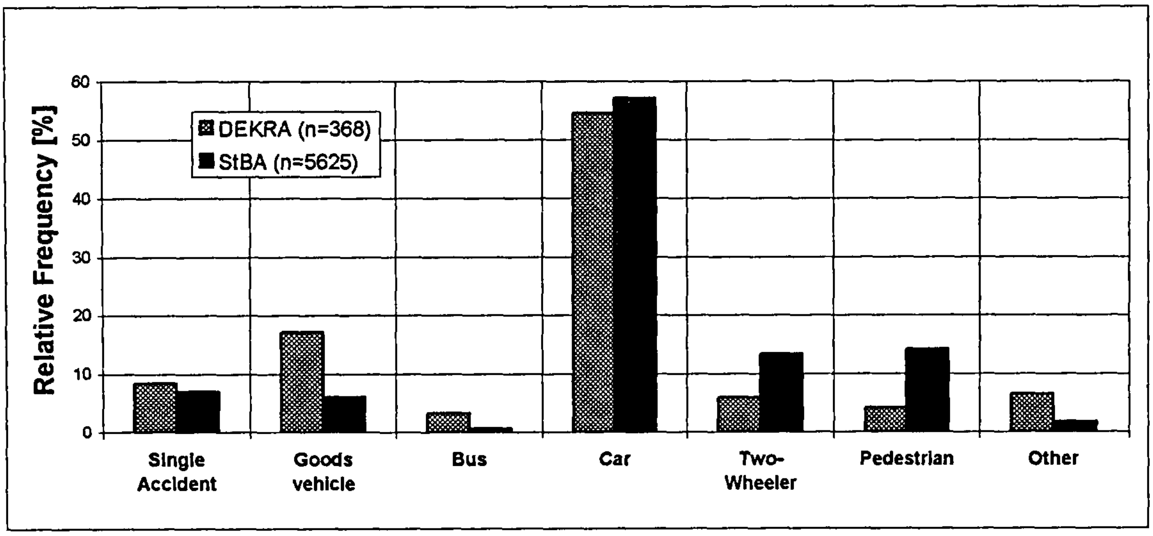

Figure 4. Single accidents of buses and bus opponents in accidents with two involved parties, comparison between German federal statistics (1996) and DEKRA database

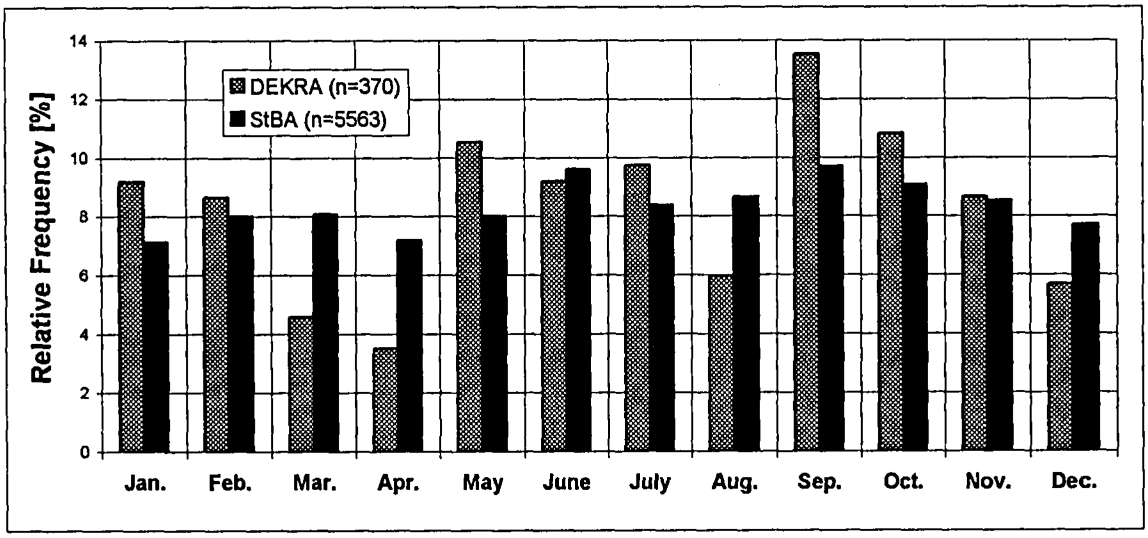

Figure 5. Relative frequency of monthly happened bus accidents, comparison between German federal statistics (1996) and DEKRA database

erally preceded by the pre-crash phase. If it is possible to take corrective action during this phase, the great potential for active safety to avoid the accident and therefore all its consequences is exploited.

Figure 7 provides information on the speed travelled by the bus during the pre-crash phase in the DEKRA examination material. This shows that the majority of buses are travelling at speeds of 91 to 105 km/h preceding accidents on motorways. The corresponding speed on secondary roads is between 61 and 75 km/h. On local roads, the speed is 31 to 45 km/h.

The distribution of accident types in **Figure 8** provides information on the critical situation preceding bus accidents. Within the sense of the official road traffic accident statistics, the type of accident is described, "the conflict situation which resulted in the accident, i.e. a phase in the traffic situation where the further course of events could no longer be controlled because of improper action or some other cause". The most frequent type of bus accident occur within the group of accidents in lateral traffic. This group describes those accidents in which the vehicles involved are travelling in either the same or an opposing direction.

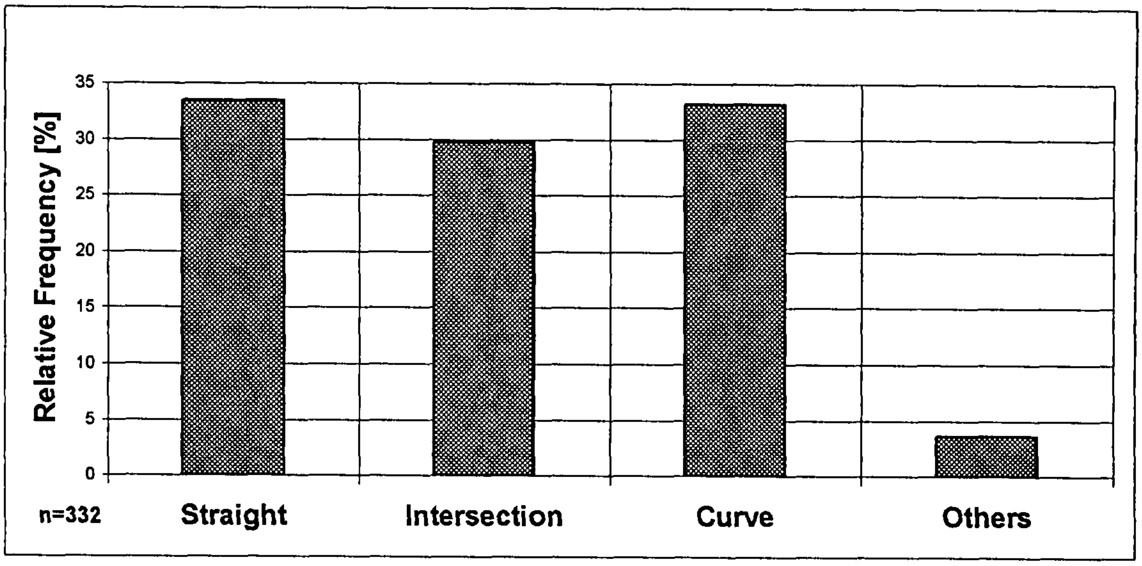

Figure 6. Relative frequency of road characteristics

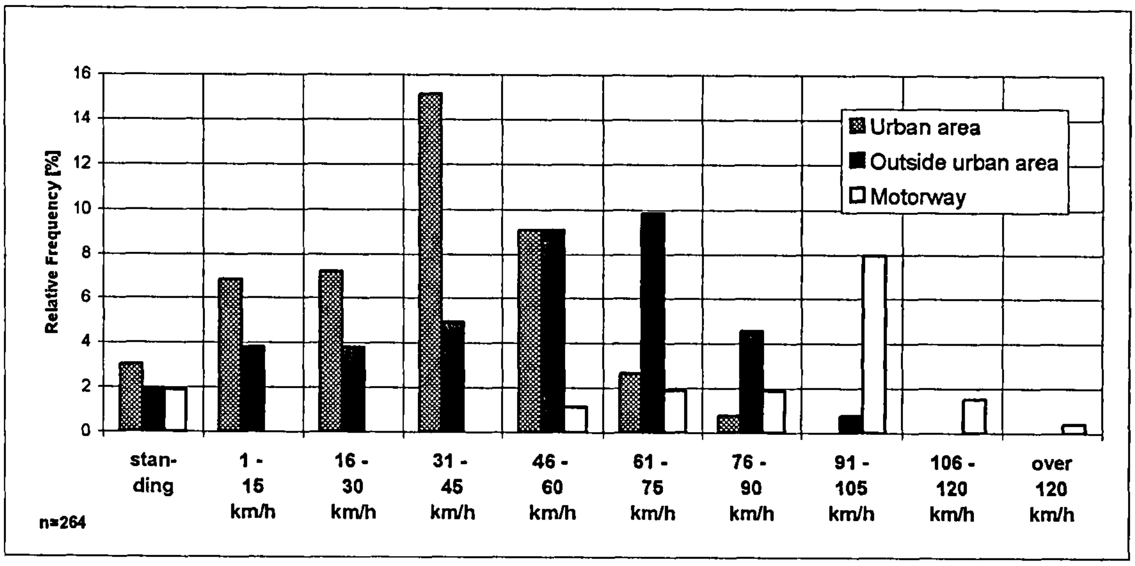

Figure 7: Relative frequency of driving speed separated to (urban area, outside urban area, motorway)

The majority of bus drivers involved in accidents (78 %) took no evasive action before the collision, **Figure 9.** Almost one of five bus drivers (18 %) was able to initiate at least one evasive manoeuvre before the collision occurred. In contrast to the evasive manoeuvre, three of five bus drivers (61 %) applied the brakes, **Figure 10.** In the majority of these cases, the brakes were fully applied.

FINDINGS FROM THE PRE-CRASH PHASES

The behaviour of the driver of a bus has an important influence on the safety of its passengers. He should possess appropriate qualifications, start the journey in a rested condition and always carry out his functions as a driver in a responsible manner. In addition to driving safety, active safety criteria include condition safety, awareness safety and operating safety. Bus drivers are subject to the same regulations as truck drivers in respect of rest times.

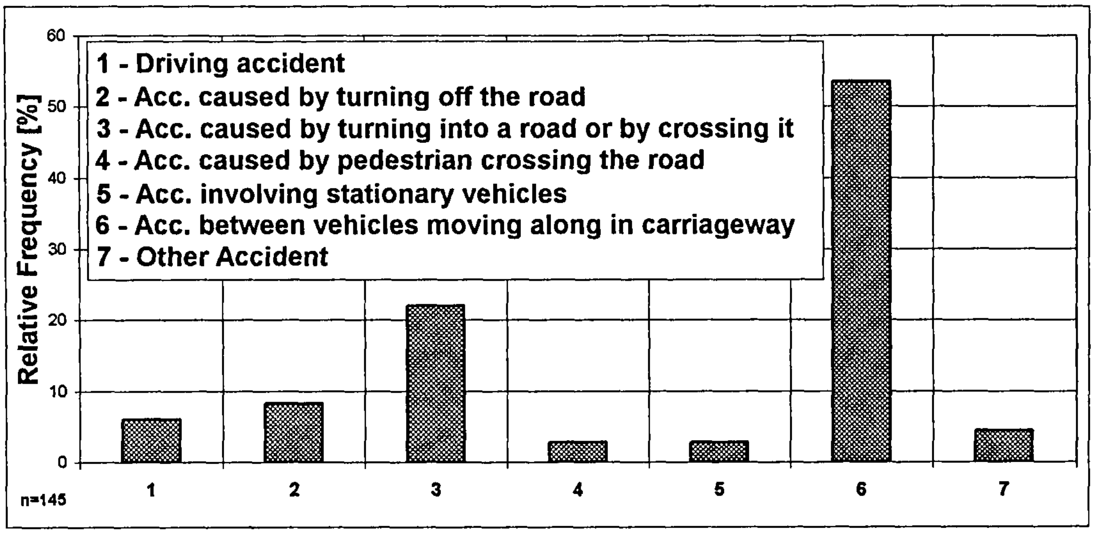

Figure 8. Relative frequency of accident types

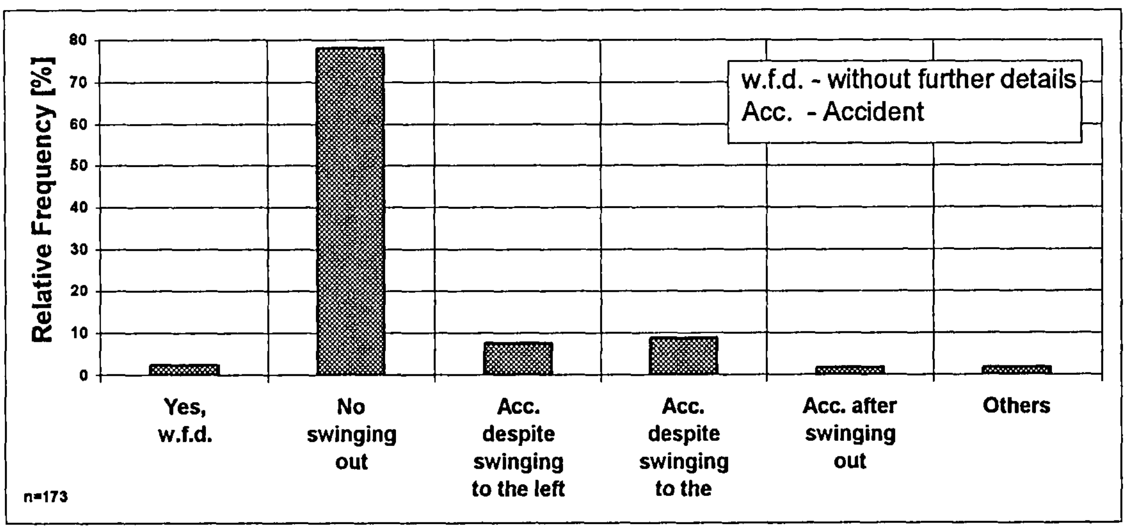

Figure 9. Relative frequency of swinging out manoeuvres

Increasing use is being made of technical equipment to support the driver in critical situations and/or in order to prevent such situations from occurring at all. Some of this equipment was initially developed for use on cars and subsequently adapted to the particular requirements of commercial vehicles, hence it is also suitable for buses. A classic example is the anti-lock braking system ABS. The technical equipment currently being fitted mainly into new cars (e.g. the vehicle dynamics control described by MÜLLER et al., 1994, or the brake assistant, KIESEWETTER et al., 1997) can therefore provide pointers for other technical improvements to active safety, the potential of which can be used to further increase active bus safety using information on accident occurrence.

Features of the active safety of modern buses include efficient chassis with lateral acceleration of more than 0.6 g to the top limit and brake systems, e.g. with pressure operated disc brakes on the front axle, which on a 16 t loaded bus from 100 km/h, facilitate full brake deceleration of 0.7 g, RIECK, 1994). Modern commercial vehicle brake systems with high deceleration values also have a corresponding user potential in the bus which is shown by the high number of buses (58 %) which brake before accidents. Every meter of distance braked can therefore minimize the consequences of accidents. Currently, several technical devices are officially specified for all buses in Germany, the most important of which are listed below:

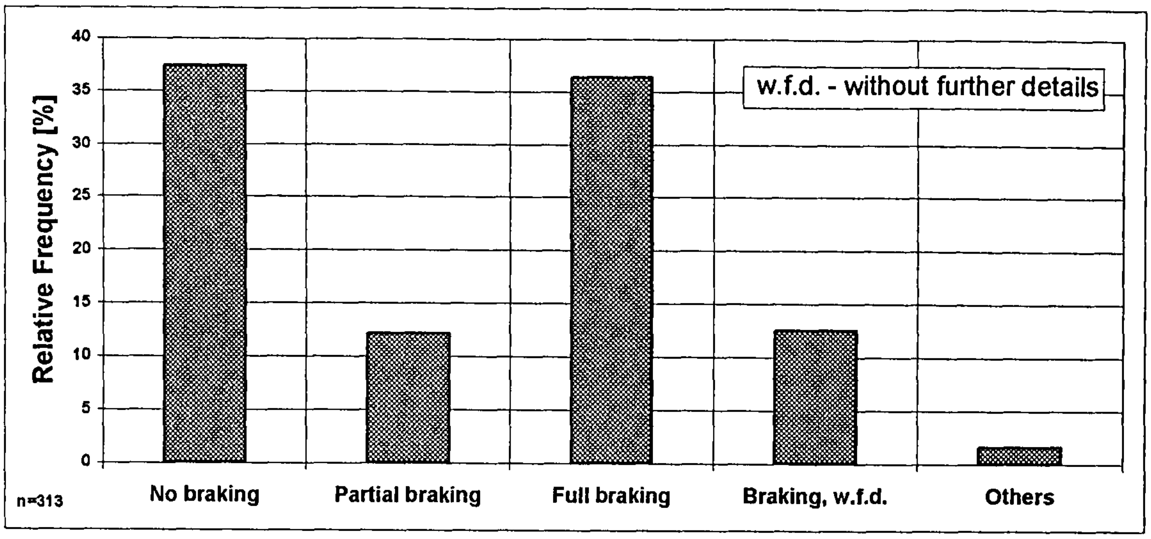

Figure 10. Relative frequency of braking

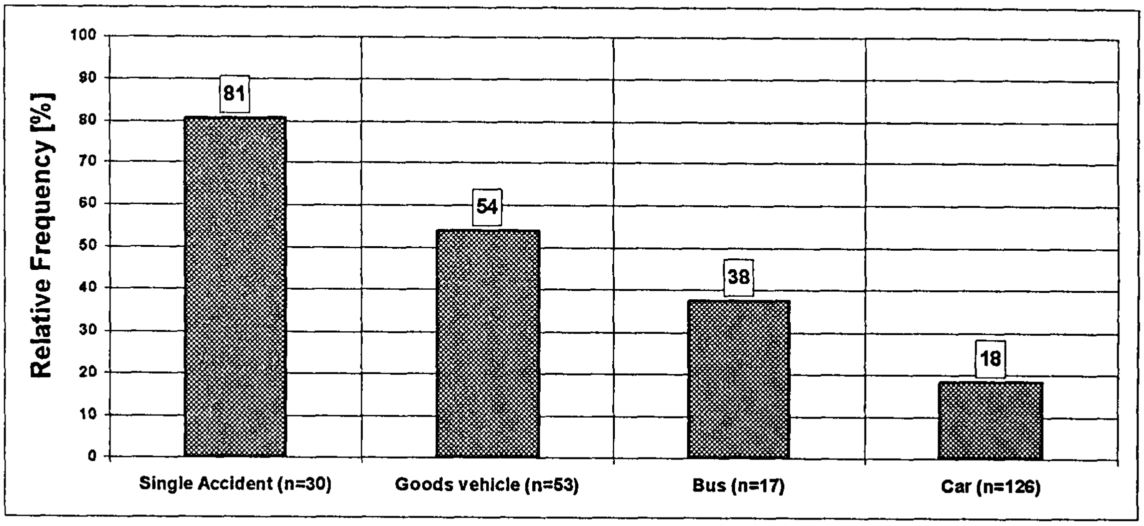

Figure 11. Share of accidents with severe injured or killed bus occupants separated to bus opponents

- ABVs (automatic anti-lock systems) are specified for all buses and coaches with a permissible total weight of over 12 t which were registered after 1991-09-30 (71/320/EWG, § 41 b StVZO).

- Since January 1994, all new buses with a total weight in excess of 10 t, the designed maximum speed of which is over 100 km/h, must be fitted with automatic speed limiters. From 1996, even older buses (first registration 1988-01-01) have had to be retrofitted with automatic speed limiters. The speed is regulated at 100 km/h (EC Directive 92/6, StVZO § 57c, 50. Ausn. Vo. 19 StVR-ÄVo).

- Increased permanent brake effect for passenger-carrying vehicles with more than eight passenger seats and a total weight in excess of 10 t (71/320/EWG/G. App. II).

In 3.2 % of the cases analysed, it was possible to prove that the maximum permissible vehicle speed of 100 km/h had been exceeded. Therefore, the level of potential usage of speed limiters in buses should be categorized as rather low. Nevertheless, speed limiters can be justified as a preventative measure to avoid serious accidents which could occur when the bus is travelling at a significantly increased speed.

OVERTURN/ROLLOVER - ACCIDENTS

From the point of view of passenger safety, individual accidents involving overturn and/or rollover, have a significant meaning. Given the size of the vehicle and the higher seat position, the bus provides a high degree of protection for its passengers in the event of a collision with most other vehicles (motorcycles, cars, vans). By contrast, the risk to passengers is twice as great if the bus overturns. If the bus overturns or rolls over, the passengers not wearing seat belts will usually fall from the rows of seats turned upwards into the danger zone below. Passengers sitting in this danger zone will then collide with the falling persons and objects which for example escape from luggage racks, and are forced into the impacted side of the bus. On this side, the rails, upper and lower window runs and also the side panes are under extreme pressure. Should external components from the road and objects located on the road edge (e.g. protective plank posts) project inside the bus, fatal consequences can ensue for the passengers directly behind this area.

From the bus accidents investigated by DEKRA, bus passengers were seriously injured or killed in 81 % of individual accidents (see **Figure 11**). At 54 %, the risk of being killed or seriously injured in bus/truck accidents and at 38 % in bus/bus accidents, is essentially lower than in individual bus accidents. Only in 18 % of bus/car accidents the bus passengers were serious injured or killed. This figure of 18 % may initially appear high, given the type of the other vehicle involved. It must be understood however, that after colliding with a car, the bus can become unstable and the passengers will sustain serious injuries as a result of the subsequent crash.

In order to investigate the dynamics of the passengers and also the impact to the seats and the supporting structures when a bus overturns, DEKRA performed dynamic tests in the crash centre at Neumünster. In contrast to the static tests carried out in accordance with ECE-R 66, in the tests carried out by DEKRA in the crash centre, the buses overturned dynamically on its side. As an example **Figure 12** shows a test carried out using a Neoplan N 216 coach.

The vehicle was accelerated by means of a cable drive from the DEKRA crash centre to a speed of 40 km/h and run with a constant transverse control of the movement over the vehicle's own steering system along an optically tracked guide mark with the right front wheel on a ramp. After the vehicle was also run with the right rear axle on the ramp, the traction cable was unhooked. Due to its inertia, the bus continued to run without drive and by means of the transverse control, with the right wheels further up on the ramp up to the tilt limit, which it reached at a sustained speed of 30 km/h. The bus then tilted to the left and skid into the final position, **Figure 13**.

Five dummies (D1 to D5, **Figure 14**.) were placed inside the bus. Two of the dummies (D2 and D3, both hybrid III, 50 % male, instrumented) were restrained in aisle seats by means of two-point belts. An unbelted dummy D1 (also hybrid III, 50 % male, instrumented) sat behind dummy D2. As with ECE-R 80, this arrangement was used to examine the potential risk of a belted passenger through a passenger sat behind without a seat belt. In this area, between the two right doors of the bus, the vehicle manufacturer retrofitted the seats (shown in Figure 14) and the support structures so that they conformed to state of the art in accordance with ECE-R 80.

The remaining seats and respective support structures were left in their older original condition (year of manufacture 1981). The unbelted dummy D4 (Hybrid III, 50 % male, instrumented) was placed in an aisle seat in the second row behind the right door. Dummy D5 which was also unbelted (Hybrid III, 50 % male, not instrumented) sat on the right side of the vehicle in the fifth row, in a window seat behind the driver.

Figure 12. Bus tip over on a ramp

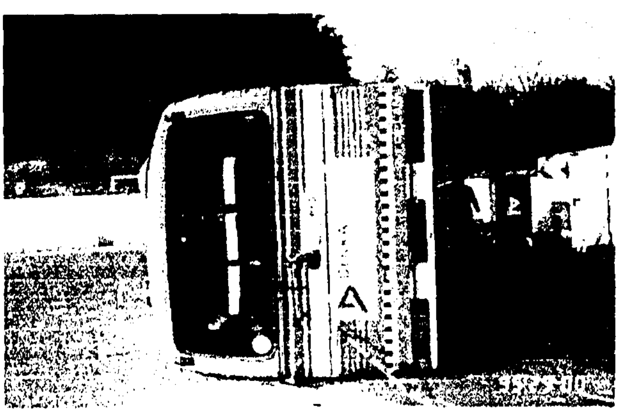

Figure 13. Bus in final position after tip over

In order to obtain more information on facial loadings caused by direct contact with the seat or bus structures using the standard options of the instrumented dummies (Dl to D4) (according to GRÖSCH et al., 1990), pressure-sensitive film (known as Fuji film) was used, **Figure 15.**

Also, several acceleration sensors were fitted to some of the relevant seat fittings in the bus. To record the acceleration on the level of the centre of gravity at the front of the vehicle, at the vehicle's centre of gravity and at relevant points on the frame, a total of ten triaxle acceleration sensor units were installed.

The measured values of the instrumented dummies Dl to D4 are summarized in **Table 1.**

The measured values of the belted dummies are significantly lower than those of the unbelted dummies and would therefore indicate that the belt reduces passenger injury.

The injury reducing effect of the belt is recorded on high speed film inside the bus whilst it is overturning. As the bus starts to tilt, the unbelted dummies Dl and D4 turn to the left towards the centre aisle. They are temporarily restrained by the arm rests on the seats. As the side of the bus hits the road, the arm rest on the seat of dummy D4 breaks and the dummy is thrown head-first over the opposite seat downwards towards the side window at the point of impact. For any reason, the head remains unaffected from the hard impact, as the head decelerates, no increased values are given. As the bus is overturning, dummy Dl slides against the bending arm rest on its seat, over the centre aisle and its knees take the impact of the frame of the seat opposite where it eventually lands. This collision is characterized by increased thigh forces. When the side of the bus hits the road, dummy Dl is thrown downwards and the back of its head hits the luggage rack (increased head deceleration). Also, dummy Dl is thrown against the non-instrumented dummy D5. The consequence being that the head and torso of Dummy D5 is pushed against the side window.

	Dummy D1 (not belted)	**Dummy D2** (belted)
Head injury criterion HIC-36	476	76
Resultant head deceleration (3 ms peak)	90 g	45 g
Resultant chest deceleration (3 ms peak)	7 g	6 g
Resultant pelvis deceleration (3 ms peak)	7 g	6 g
Femur force Left/right (max.value)	1.43 kN / 2.14 kN	0.37 kN/ 0.28 kN
Belt force (max. value)		2.15 kN
	Dummy D4 (not belted)	**Dummy D3** (belted)
Head injury criterion HIC-36	20	5
Resultant head deceleration (3 ms peak)	25 g	7 g
Resultant chest deceleration (3 ms peak)	11g	7 g
Resultant pelvis deceleration (3 ms peak)	14 g	8 g
Belt force (max. value)		1.90 kN

Table 1. Loadings of the dummies Dl to D4, seating positions see Figure 14, in a dynamic overturn test

Dummy D5 is exposed to an extreme risk of injury from projecting external parts.

As the bus is overturning, Dummies D2 and D3 also tip towards the centre of the vehicle, their heads, torsos, arms and legs project into the centre aisle. They are how-

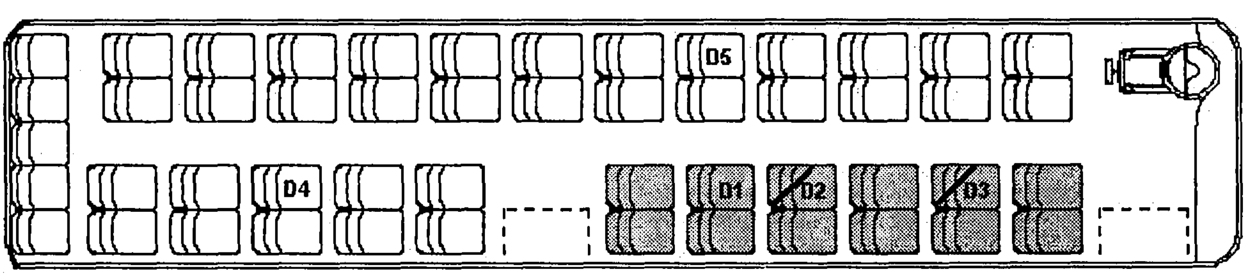

Figure 14. Seating positions of the dummies in the bus

ever held in their seats by the seat belts. This prevents the dummies falling into the highly dangerous areas on the side of the bus taking the impact.

In terms of the results of the film evaluation and the dummy measured values, the evaluations correspond to the pressure film. No increased impact loadings can be ascertained on belted dummy D3. The unbelted dummy D4 sustains contact loadings on the chin, noise and forehead, which is not however categorized as potentially injurious. The damage sustained as a result of the back of the unbelted dummy's head (D1) colliding with the luggage rack is categorized as potentially injurious in view of the possible skull fracture.

Figure 16 shows the bus interior with the dummies in the end position after the bus has overturned.

FINDINGS FROM OVERTURN TESTS

The tests carried out confirm the known risks to passengers arising from real accidents where the bus overturns. Here, two-point seat belts (lap straps) for the rows of seats which turn upwards when the bus overturns, have a significant far-reaching protective effect. Static overturn tests in accordance with ECE-R 66 (RIEBECK and BREITLING, 1997) and numerical simulations (APPEL et al, 1996) also provide similar results. Given the current status of knowledge, two-point seat belts offer advantages over the three-point belt (shoulder/lap belt). The particular dynamics with side overturns and rollovers can lead to the torso of the belted passenger becoming free from the shoulder strap. This causes the entire belt to become loose and there is also the risk of the passenger becoming released by the belt around the hips.

The belts must be integrated into the existing restraint system. This type of seat belt system is already available. Obviously, it is hoped that passengers travelling in buses with existing seat belts will fasten them, as currently is the case with air travel.

In the case of the seats located on the side of the bus which impacts the road as it overturns, a two-point belt cannot prevent the heads, torsos, arms and hands of passengers colliding with rails or side windows. On the one hand, the effect of this can be minimized by flexible design and padding. On the other hand, if the side structures fail, e.g. a window breaks, the risk is greater when the bus impacts the road. Three-point belts on the outside seats, could, if the seat belts are tightened with a simulated rollover and if certain threshold values are exceeded (GRÖSCH et al, 1996) hold the passengers in their seats. Therefore the possibility is given to hold the passengers

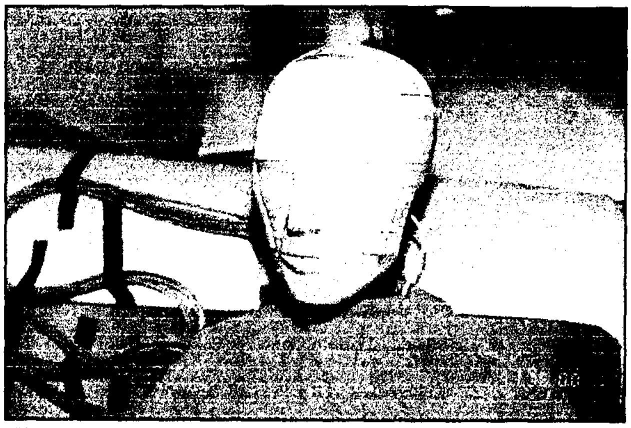

Figure 15. Dummy head with applicated pressure detection foil

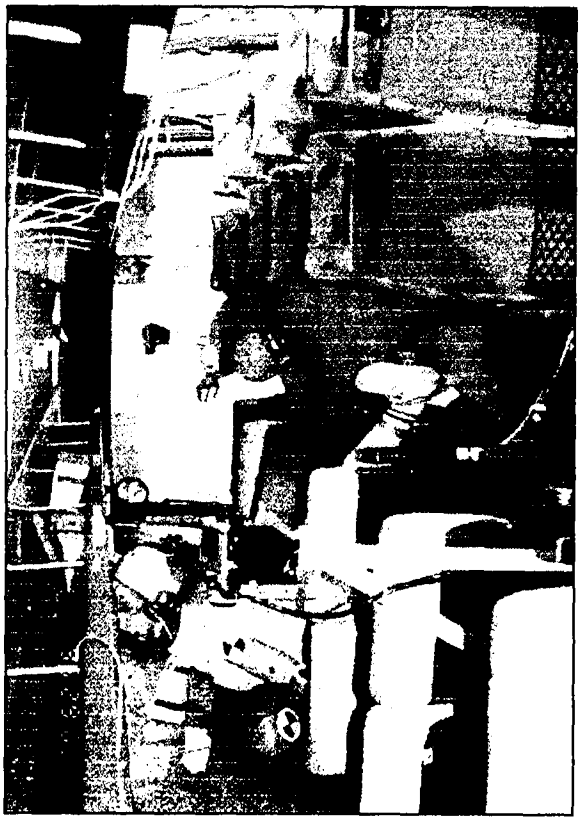

Figure 16. Final positions of the dummies in the bus after tip over

away from the side bus structures and the road. This means that the risk of injury to the majority of the exposed passengers is further reduced, provided that no external parts penetrate the bus when it overturns.

With the dynamic overturn tests so far carried out in the DEKRA crash centre on the ramp, the damage to the bus structure in the area of the side wall columns and also the upper and lower window runs is less than that found from the static test according to ECE-R 66 and from many real accidents. In order to increase the structural damage during the dynamic test with lateral movement components during overturn, thereby better adapting to the "worst case" of the real accident, the ramp should be elevated. Furthermore, in this type of test, various obstacles could be placed on the road. Currently, interest is being shown in confirming whether protective devices (crash barriers) from steel or concrete walls, can be differentiated in terms of their aggressive nature, in respect of the overturning bus.

FRONTAL CRASHES

Essential parameters for describing the seriousness of an accident-related collision and/or simulation of same as part of a test, are the location of the main damage, the accident geometry and the collision speeds. The frequency distributions illustrated in **Figure 17.**, **18.** and **19.** provide further information on internal bus safety.

The distribution of major damage areas on the potential other vehicle (Figure 17.), shows that in the case of the individual accident, the major damage is predominantly sustained in the side areas of the vehicle. In the case of individual accidents, the explanation lies in the frequent number of overturns. In the case of a collision with a truck, most of the damage is sustained at the front. With this accident group (bus/truck), the causes lie in frontal collisions (front bus/front truck) and rear end collisions (front bus/rear truck). Primary collisions between buses and cars cause the most serious deformation, virtually equally distributed between front and side areas. Some of this damage is caused by secondary collisions (also see Figure 11.). In the case of motorcycles and pedestrians, most of the damage is sustained at the front and is caused almost exclusively as a result of direct contact with the other vehicle.

85.6 % of buses collide at a max. speed of 60 km/h (Figure 18.). Collision speeds above this level occur only seldom.

The overturn speeds of the examined buses are distributed over the full speed range. There are more overturn speeds in the 31 to 75 km/h speed range (Figure 19.).

A typical accident geometry is the rear of the bus on the rear of a moving or stationary utility vehicle. In these cases, there is a considerable risk of death or injury for the bus driver and persons seated near to him.

In the DEKRA crash centre, two tests involving front collisions with buses have been carried out. In one of the tests, the bus (Büssing, year of manufacture 1975, weight 10 t) travelling at 40 km/h and 70 % frontal overlap, collided into the rear of a stationary 16 t truck with its brakes on, **Figure 20.** In the other test, the bus (Neoplan N216, year of manufacture 1981) travelling at 31 km/h at 30% frontal overlap, colliding with the fixed concrete barrier at the crash centre, **Figure 21.**

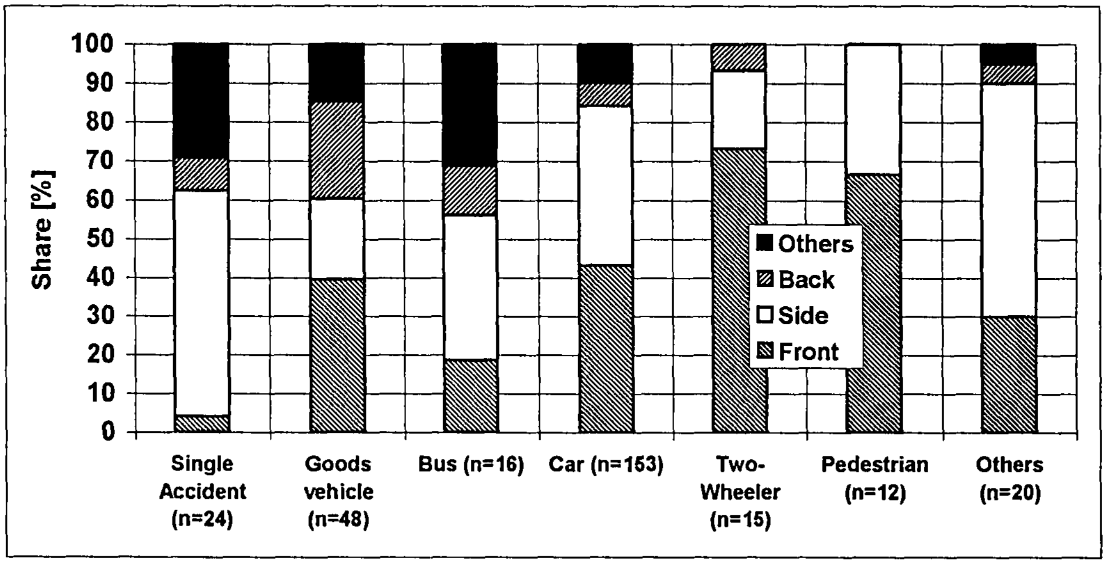

Figure 17. Relative frequency of main damaged bus areas separated to the different opponents

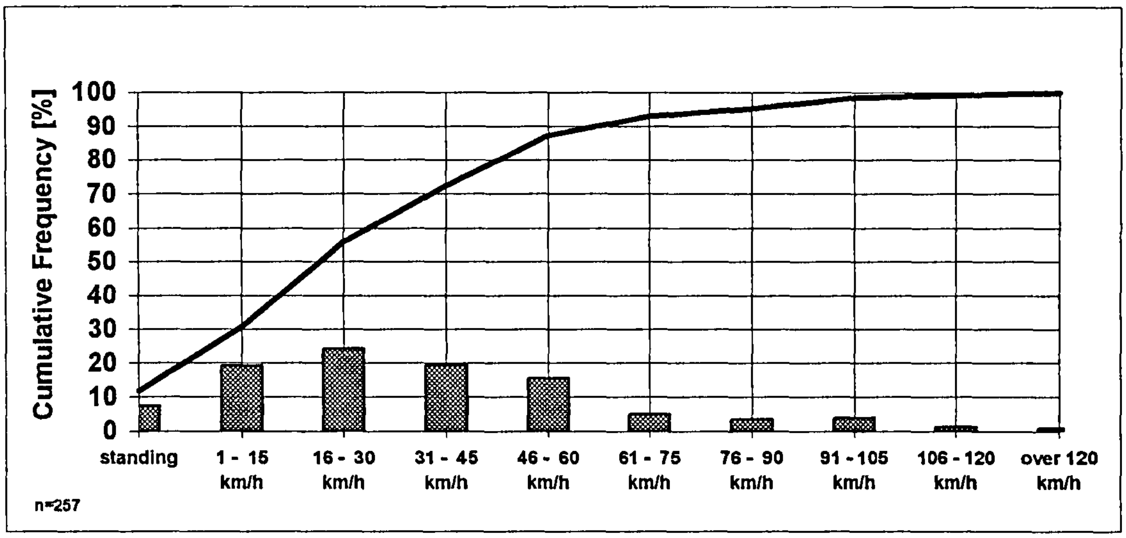

Figure 18. Cumulative frequency of bus collision speeds (containing all accident configurations)

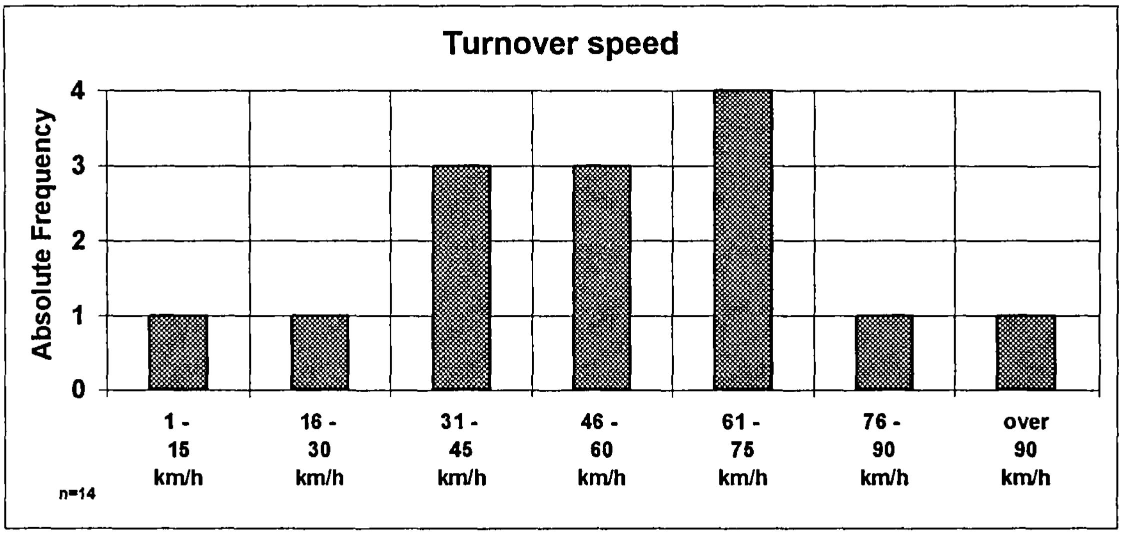

Figure 19. Absolut frequency of the speed when the bus turned over

The lateral deceleration measured at the total centre of gravity in the buses is illustrated in **Figure 22.**, together with the deceleration channel specified for checking seats and restraint systems in accordance with ECE-R 80 for skid tests. Due to the very flexible front structure of the buses (Deformation path Büssing: approx. 0.8 m, deformation path Neoplan: approx. 1.2 m), the deceleration of the centre of gravity is significantly less than the maximum decelerations specified in ECE-R 80 and lasts correspondingly longer.

Two hybrid III dummies (50 % male, instrumented) were placed inside the Büssing bus. One of these dummies (DI) was restrained in a seat by a two-point belt (lap belt) and no seat was located in front. The other dummy (DII) sat unbelted in a seat in front of which was located another seat. This arrangement produced a restraining effect of the back rest of the seat in front.

The damage measured on the two dummies is shown in **Table 2.**

All measured loadings of the unbelted dummies DII are greater than the corresponding damage values of the belted dummy DI. Since there is no seat in front of dummy DI, its head and torso can move forwards freely

	Dummy DI (belted)	Dummy DII (not belted)
Head injury criterion HIC-36	14	88
Resultant head deceleration (3 ms peak)	11 g	46 g
Resultant chest deceleration (3 ms peak)	6 g	12 g
Resultant pelvis deceleration (3 ms peak)	10 g	17 g
Femur force Left/right (max. value)	0.68 kN / 0.76 kN	2.16 kN/ 3.12 kN
Belt force (max. value)	2.5 kN	

Table 2. Loadings of the dummies D1 and D2, in a bus/truck crash test (Büssing bus frontal to rear end of truck, see Figure 20.).

	Dummy D1 (not belted)	Dummy D2 (belted)
Head injury criterion HIC-36	281	62
Resultant head deceleration (3 ms peak)	23 g	57 g
Resultant chest deceleration (3 ms peak)	8 g	10 g
Resultant pelvis deceleration (3 ms peak)	15 g	7 g
Femur force Left (max. value)	0.97 kN	0.93 kN
	Dummy D4 (not belted)	**Dummy D3** (belted)
Head injury criterion HIC-36	31	66
Resultant head deceleration (3 ms peak)	31 g	41 g
Resultant chest deceleration (3 ms peak)	8 g	10 g
Resultant pelvis deceleration (3 ms peak)	8 g	10 g

Table 3. Loadings of the dummies D1 to D4, seating positions see Figure 14., in a frontal bus impact (Neoplan) with a rigid barrier.

without impact. The increased forces in the thighs of the unbelted dummies are typical, these occur on impact with the back rest of the seat in front. This causes slippage in the pelvis of dummy DI which is greater than that of dummy DII restrained by the seat belt. Due to the relatively low vehicle deceleration, there is no measured value in the area of the corresponding protection criterion.

On collision with the barrier, the Neoplan bus occupied by the instrumented dummy D1 (not belted), D2 and D3 (belted) and D4 (not belted) and also the non-instrumented dummy D5 (not belted) as in the dynamic overturn test, Figure 12. **Table 3.** shows an overview of the damage measured on the instrumented dummies. The level of damage is generally low and a long way from injury criteria threshold values.

The higher damage values are sustained by the dummies' heads and chests. This correlates with the impact on the back rests of the seats in front of the dummies. As the high-speed film shows, the heads of the belted dummies collide with the holding bar and ashtray as they are restrained at the hips by the seat belts.

The unbelted dummies propel forward with hip and torso and then the knees, followed by the torsos collide with the backrest of the seat in front. In one of the old rows of seats, on collision with dummy D4, the seat breaks away. On the new, retrofitted seat, which is damaged as a result dummy D2 being restrained by the lap strap and the impact of the unbelted dummy D1 sat behind, only slight deformation to the base of the seat. There are clearly further loading reserves here. The seat can therefore effectively restrain the passenger sat in it and there is no additional risk from the passenger sat behind.

The evaluations of the pressure film applied to the dummy heads agree with the collision observed in the film. Especially for those passengers wearing seat belts, there is a risk of injury from the awkwardly fitted holding bars and ashtrays, **Figure** 24. On the right forehead of dummy D3, a pressure of approx. 6.5 N/mm^2 occurs on collision with the hard plastic components of the ashtray and the holding bar. As with the contact damage on the right cheeks, such type of damage is not criteria for injury. In contrast, collision damage with the nose at a pressure of around 13 N/mm^2 would suggest a potential nose fracture.

FINDINGS FROM FRONTAL CRASH TESTS

The frontal crash tests carried out confirm that the particularly exposed seats occupied by the bus driver and the persons sitting next to him are at increased risk as a result of intrusions in the front area of the bus. The flexibility of the front structures of the bus lead to a relatively low level of deceleration in the passenger area behind. This means that belted as well as unbelted passengers are at a relatively low risk of injury.

Especially when there is sufficient room in front of the seat for the head and torso to move, lap belts can offer passengers protection in the event of front collision with the bus. If the back rests of other seats are positioned in front of the passengers, it must be ensured that no awkwardly positioned and designed components present an unnecessary risk of injury. If the seat is positioned correctly and with the correct shape and padding, the back rest can be designed as part of the restraining system for the passengers sitting behind and so effectively support the restraining effect of the lap belt (KRÜGER, 1986). The double loading when the passenger is restrained and simultaneous collision with the passenger sitting behind can clearly be withstood by the state of the art seats and seat restraints.

Another technical option for integrating the back rests into the restraining system of the passenger seated behind is offered by the airbag. There is however a considerable cost involved with development and fitting into the relevant seats of the bus. Therefore, fundamental cost/benefit - analyses are necessary before any of the measures described here are converted.

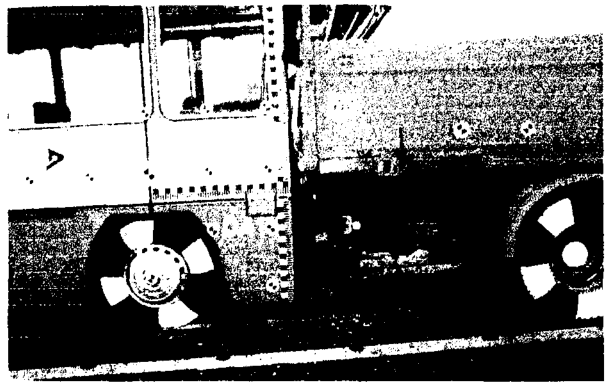

Figure 20. Bus in final position after impact to rear end of a truck

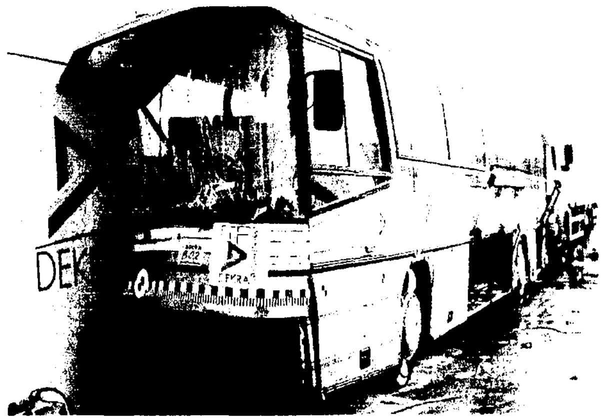

Figure 21. Bus in final position after an offset impact to a rigid barrier

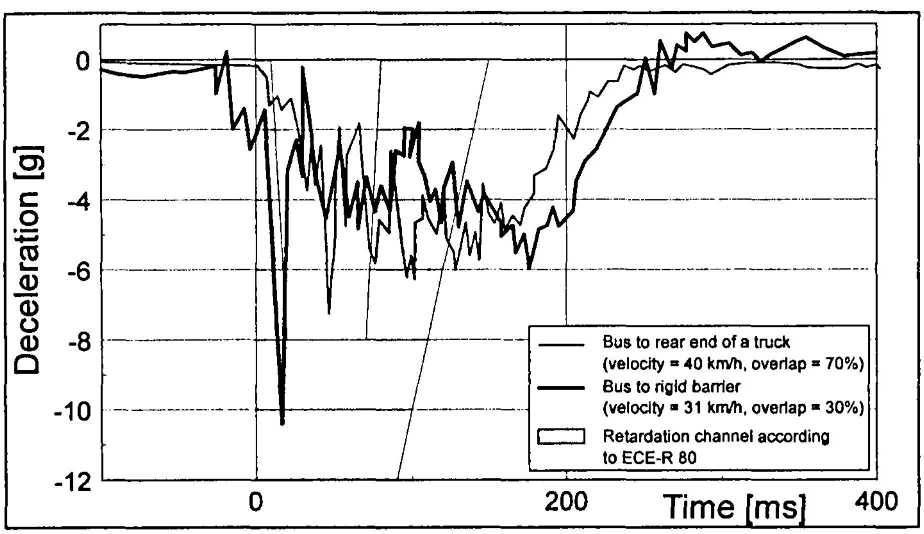

Figure 22. Retardation of buses in crash tests in comparison to the retardation channel according to ECE-R 80

EXTERNAL BUS SAFETY

The number of people injured and killed in individual accidents and accidents with two participants can be taken from the official road traffic accident statistics. These figures are separated into accidents within the urban areas, outside urban areas, and on motorways. For 1996, the figures shown in Figure 22 for accidents in Germany, show the number people in the other vehicle who were either killed or injured.

With the exception of cars and trucks, with all other vehicles involved in accidents with buses, the highest number of people are either killed or injured within urban areas. The motorcyclist and the pedestrian are of particular importance. It is not yet possible to use official statistics to differentiate between bus and coach. One can however correctly assume, that the other vehicle involved the motorcycle or pedestrian accidents shown in Figure 4 was usually a bus travelling within urban areas. By the very nature of their intended purpose, buses travel almost exclusively within the inner city area. These buses travel in close proximity to cyclists and pedestrians when at bus stops and also on the road. Therefore, the probability of a collision with these un-motorized road users is relatively high. In addition, only public transport has access to traffic free zones in town and city centres and the un-motorized road user moves around carelessly and without paying attention.

Given these facts, measures for the bus for minimizing the consequences of collisions with pedestrians and cyclists appear to have little future. Since the body of the front of the bus, at the rear and the sides all project onto the road, thereby rendering rear and side protectors useless, not many options exist for avoiding the opponent in a collision.

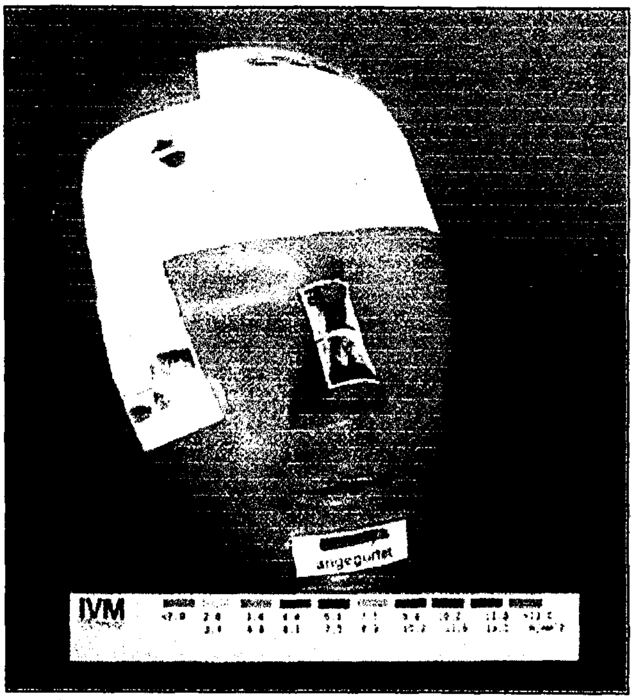

Fig 24. Pressure imprints to head of dummy D3

As a matter of priority, particular attention must be paid to avoiding collisions between buses and pedestrians and/or cyclists. In this regard, the direct and indirect fields of vision for the bus driver through the windows

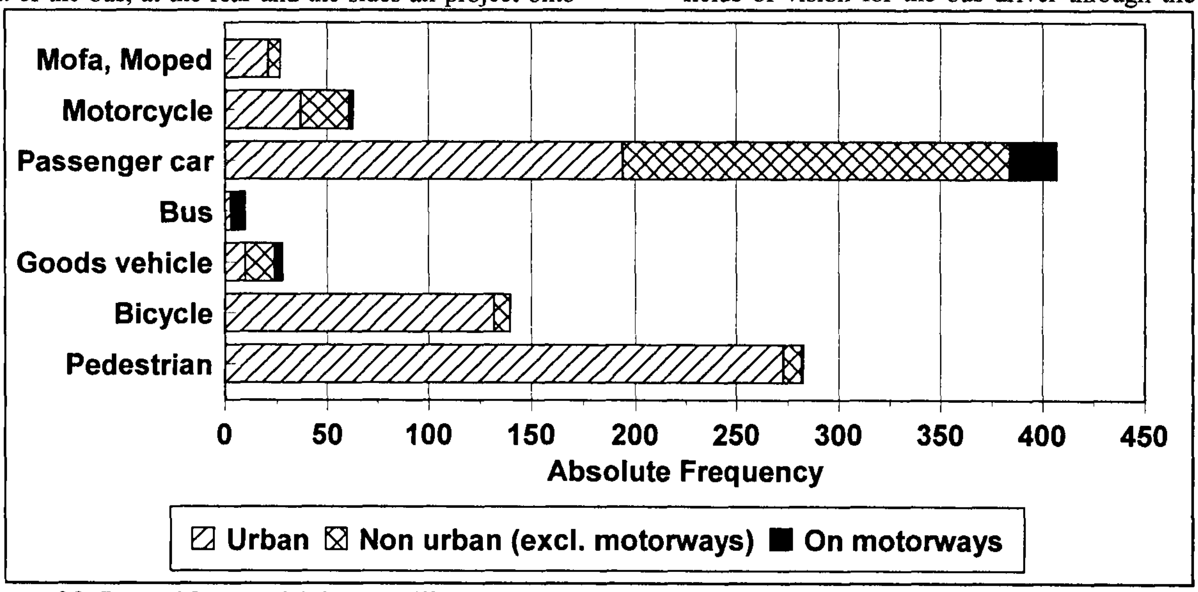

Figure 23. In accidents with buses killed and severe injured opponents

and the mirror is of particular significance. However, further measures can also be considered such as additional mirrors at bus stops, additional cameras or sensors for detecting persons and objects which are likely to collide with the bus, and also audible warning devices which signal that the bus is about to pull out.

The car is the most common accident opponent of the bus. The number of people either killed or seriously injured in accidents with buses is roughly halved between inside and outside urban areas, **Figure 23.** In those accidents occurring outside urban areas, it is assumed that the coach and not a public service bus is the most common vehicle colliding with the car.

In modern buses, measures are being implemented to protect the front of on-coming vehicles. It is therefore possible, to effectively restrain a car on colliding at 50 km/h and 50 % frontal overlap by using the deformation structure on the car, so that the car passengers can survive without serious injury, RIECK (1994).

CONCLUSIONS

1. The long-term trend in the number of passengers killed in bus accidents is falling.

2. Most bus drivers can perform a braking manoeuvre before a collision. Improved braking systems therefore have a high level of potential. Evasive action seldom occurs.

3. Accidents involving overturns have a greater risk of death and serious injury to passengers.

4. Accidents between buses and cars can cause injury to passengers, which then occur through a secondary collision of the bus.

5. Seat belts are advisable. In the event of an overturn, they prevent passengers being thrown into the centre of the bus. Seat belts can reduce the high number of those killed and injured in serious accidents.

6. In the case of public service buses, it is important to avoid collisions inside urban areas with unprotected road users such as pedestrians and cyclists.

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DEVELOPMENT POSSIBILITIES IN RELATION TO ECE REGULATION 66 (BUS ROLLOVER PROTECTION)

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Paper Number 98-S4-O-04

ABSTRACT

This paper gives an analysis about the rollover process of buses in case of a standard accident simulation. International regulation requires certain strength and energy absorbing capacity of the superstructure to ensure survival space for the passengers. The kinetic energy of a rolling bus is transformed into deformation work and involving the energy losses too, an energy balance can be set up, and studied.

1. INTRODUCTION

International requirements for the roof strength of buses are formulated in UN-ECE Regulation 66., which is specifying a simple, reproducible „standard accident" as a test method and the requirements are related to this rollover test. Fig. 1. shows the general layout of this test: the empty bus, having no longitudinal speed rolls down into a ditch having a depth of 800 mm. The side rollover process starts from the unstable position of the bus with zero angular velocity. During this rollover, the deformation of the bus superstructure must be limited to provide a required survival space for the passengers. For the historical faith, it is interesting to mention that Reg. 66 - after some serious and tragic accident shocking the international public opinion - was born as the result of a long, ten years discussion in Geneva. (Between 1975-85). In spite of this long discussion the regulation contains a lot of contradictions, undetermined details. The ten years practice (1986-96) being the regulation in force and in use, gives the basis to the revision of Reg. 66. This study also tries to give technical arguments to this work.

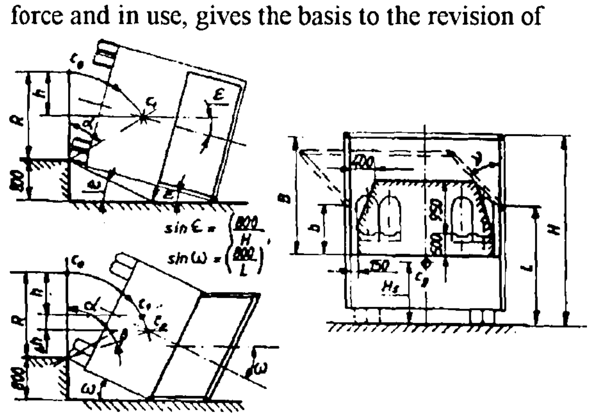

Fig. 1. Scheme of rollover test

2. THE ENERGY BALANCE

In the standard rollover accident (test) the kinetic (rotational) energy of the bus (E_k) is transformed partly into deformation work (W_d) which is absorbed by the load bearing elements of the superstructure and into a „residual" work (W_r) which does not influence directly the strength and deformation of the load bearing frame. The deformation work is absorbed by plastic hinges, in which the plastic deformation is concentrated. These hinges and their energy absorbing capacity [1] are the tools, the help of which the body is designed to meet the requirements of Reg.66. The kinetic energy of the bus can be given by the mass (M) and height drop (h) of CG as follows:

$$E_k = M\, g\, h = W_d + W_r \qquad (1)$$

This energy balance can be used for defining the condition of the required roof strength. The roof will not collapse, or in other words the deformation will be limited, if:

- starting the process when the cant-rail touches the ground, the kinetic energy is defined in Equ.1. by „h",
- having a certain deformation in the frame, which results further, additional height drop (Δh) of CG
- which produces further increase in the kinetic energy (ΔE_k)
- and the increase of the kinetic energy is less, than the increase of absorbed deformation work (ΔW_d) and residual work (ΔW_r)

$$\Delta E_k = M^*\, g\, \Delta h \le \Delta W_d + \Delta W_r \qquad (2)$$

In the light of this energy balance it is interesting to study in details the followings:

- the kinetic energy as the function of the geometry of the standard rollover accident and the bus to be tested.

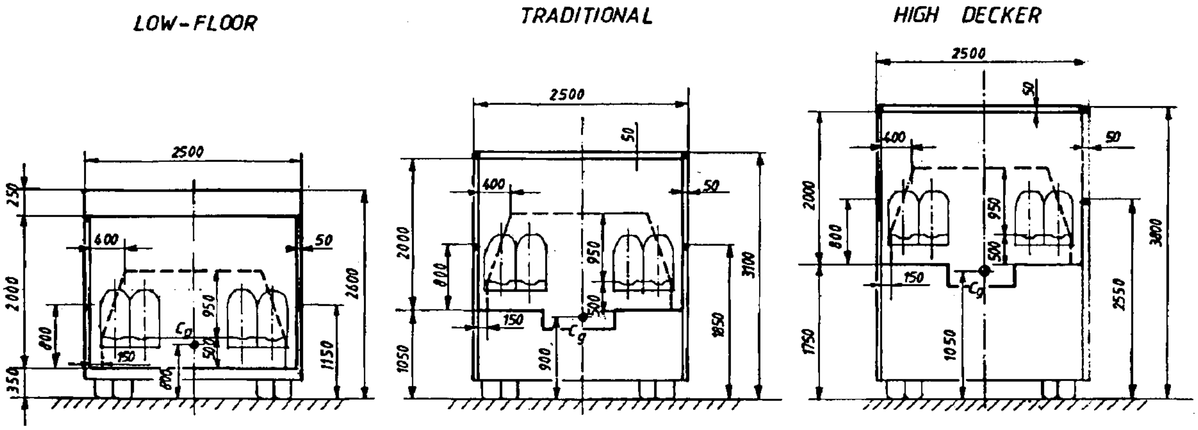

Fig.3 Different bus categories

- determination of the total kinetic energy

$$E_T = E_k + \Delta E_k$$

- components and built up of the residual work.

3. ENERGY DEFINED BY REG. 66

3.1. Energy equations

The kinetic energy, when the bus cant-rail touches the ground can be derived by using some simplifications:

- the bus has a rectangular cross section
- the axis of rotation (determined by the tyres) is in the corner of the cross sections
- the tyres do not leave the ground (the axis of rotation) during the rollover
- the cant-rail of the body is rigid, there is no local deformation

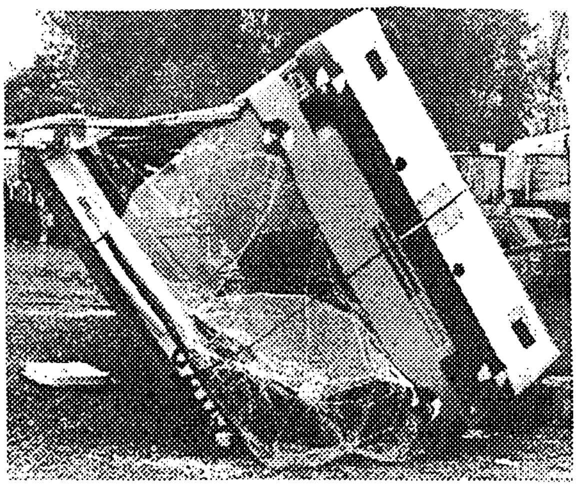

Fig.2. Real deformations after rollover

On the basis of Equ.1. and Fig.1, the kinetic energy may be formulated as follows:

$$E_k = Mg\left[\sqrt{\left(\frac{W}{2}\right)^2 + H_s^2} + \left(\frac{A}{H}\right)H_s - \frac{W}{2H}\sqrt{H^2 - A^2}\right] \quad (3)$$

Assuming a simplified deformation mechanism - which is realistic as Fig.2. shows - in which the deformation is characterised by four plastic hinges on one ring [2] (two hinges at the waistrail and two on the cant-rails) the deformation process can be easily described. When the cant-rail contacts the ground, the plastic hinges start to work, the rigid part of the bus body (below the waistrail) roles further and if the rings of the body (window and door pillars) are not strong enough the waistrail will also contact the ground (See Fig.1.) During this deformation process the height of the bus CG is decreasing by Δh, or in other words the kinetic energy is increasing:

$$\Delta E_k = M^* g\left[\frac{W}{2H}\sqrt{H^2 - A^2} - \left(\frac{A}{H}\right)H_s - (\cos\gamma)\sqrt{\left(\frac{H}{2}\right)^2 + H_s^2}\right]$$

It should be emphasised that $M^* < M$ while the roof is stopped by the ground, it does not moves, it does not represent kinetic energy. ($M^* = 0{,}95M$ seems to be a good first approximation)

3.2. Bus categories, the main technical parameters

Regulation 66. in its scope relates to the large simple deck buses (The articulated buses should be considered as two independent part of the vehicle) Let us study the existing bus categories covered by the scope of Reg.66.

3.2.1. Different floor heights.

Let us assume that the passenger compartment has constant dimension in height and width, independently from the floor height and the service circumstances (e.g. the inside height of the passenger compartment is 2000 mm and its width 2400 mm, and the cross section is rectangular, not shaped) The survival space is connected to the passenger compartment (see dotted lines in Fig.3.) These mean that the higher floor needs larger total height, increasing the floor height means: lifting upwards the passenger compartment. Fig.3. shows this phenomenon with low-floor, traditional and high decker buses. If we assume that all of these three buses have a total length of 12 m and empty mass of 10 tons, we can compare their rollover process and energy figures only on a geometrical base. In the first three lines of Table I. these three buses are compared.

3.2.2. Ranges in length, width and mass.

The length of the buses covered by Reg.66. can change between 7 m and 15 m, the width between 2000 mm and 2550 mm. In consequence of these the empty mass range is 4,5 - 13,5 tons. The two extreme configurations are the „Midi" and „Highdecker" buses. Table I. also contains the data of these two vehicles.

3.2.3. Mini and double-decker buses.

The question has been raised whether these categories could be involved into the scope of Reg.66? What are the conditions of this extension? In this case the ranges of the main parameters of the buses are further widened. Table I. contains the main figures of these categories, too.

3.2.4. The shape effect

The rectangular bus model is a rather simplified one. To get some feeling about the shape effect, Fig.7. shows a real cross section (type IKARUS 250) comparing it to the rectangular approach. Table II. compares the main geometrical parameters, showing that the kinetic energy of the real bus is less (only 86%) than in the case of a rectangular cross section approach. Also the additional kinetic energy (ΔE_k) is less (only 50%) in the case of shaped cross section. The figures (ω and ν) in Table II. show that the superstructure will pass the rollover test in both cases. (But taking into consideration the uncertainties in the measurement of the angles ε, ω and ν in case of curved cross section, and the real dimensions of plastic hinges can cause negative test result in a real rollover test)

3.3. Deformation limits created by the test method.

The rollover test - standard accident - has an essential, hidden problem: if the bus is high enough and the height of its waistrail (above the ground) is exceeding a certain value, the possible deformation of the window and door columns (ω) is limited - see Fig.1. - while the waistrail hits the ground and this stops the further rotation. Having a week superstructure, this rollover test will prove it as a strong one. The survival space will be untouched because of the limited window column deformations. The problem occurs, if:

$$\omega < \nu \qquad (5)$$

The highdecker bus shown on Fig.3. has the following values: ω = 18,3° and ν = 31,6° and that means that the rollover test (or its simulation by computer) will prove the superstructure practically independently from its real strength.

3.4.Comparing the kinetic energies

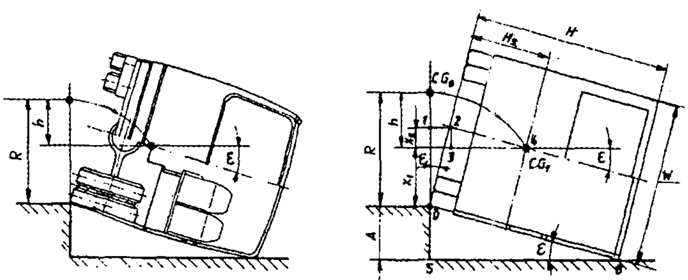

Fig.4. Real cross section compaired

It is interesting to compare and analyse the energy values of the buses covered by the scope of Reg.66. To make it easier rectangular cross sections are used as first approximation. Table I. contains these data. The question is whether the rollover test provides the same conditions for the different bus categories? Some general statement can be fixed on the basis of the data:

- The kinetic energy (E_k) of the different buses when the cant-rail hits the ground is not the same, it has a wide-range scatter. The maximum value is more than 4 times higher than the minimum. (See high decker and midi buses) The scatter is influenced mainly by three parameters: the mass (M), the total height (H) and the height of CG.
- The relative kinetic energy - when the energy is related to the mass - is proportional to the droop of CG (h). In this case the scatter is smaller, the ratio between the maximum and minimum values is 1,4. In the case of real buses (real shape) it can be 2. So it can be stated that the relative energy is also different for different buses.
- the additional kinetic energy (ΔE_k) which is the result of the superstructure deformation until the waistrail touches the ground, has also the same wide-range scatter as the energy (E_k) itself, as well as its relative value (Δh) both of them having a ratio 4 of the max. /min. values.
- in the case of lower buses (e.g. low-floor bus) the additional kinetic energy (ΔE_k) can be equal

to the original kinetic energy (E_k) while in the case of high deckers it is 20-25%

3.5 What is the basis of the standard rollover test?

The following question can be raised: which parameter is the same (constant, equivalent) when using the standard rollover accident specified in Reg. 66. for different bus categories. As -the result of the former analysis, it can be said:

a) the direction and the value of the impact force (on the contrail) is different
b) the kinetic energy is not the same
c) the relative kinetic energy is also different
d) the geometrical limitation of the superstructure is different that means: limited for some buses and not limited for others, depending on the strength of the main load bearing elements, rings.

The only one parameter, which is constant in the standard test is the depth of the ditch (800 mm). But this value is not related to the construction of the buses and it is not representative for the road constructions, as well. There are different real ditches along the roads, but not similar, not the same as specified in Reg.66. This is an artificial shape and artificial value. The new standard accident - which could be the basis of the rollover test must be simple as the recent test, but one or two problems listed above should be solved (should be equal for every kind of bus)

4. POSSIBLE NEW STANDARD ACCIDENTS, ROLLOVER TESTS.

Defining a new standard accident the followings should be maintained from the existing one:

- it should be a simple, reproducible rolling down by side from a standing position (without travelling speed)
- it should be a quasi static rollover: the rolling down should not have an angular velocity in the starting position (This is the equilibrium position of the bus tilting on side)

Considering the four problems listed in chapter 3.5. (a, - d,), the following standard accidents can be defined (See Fig.5.)

A) **Constant direction of reaction force** (ε) on the cant-rail. Having different bus heights (H) the depth of the ditch (A) should be adjusted. The required value of the force angle (ε) should be based on the criteria of avoiding the limited roof deformation, avoiding the waistrail to hit the ground before rings (pillars, columns) can introduce into the survival space if the superstructure is week.

B) **Constant kinetic energy level** (E_k) The depth of the ditch (A) can be adjusted to „h" (see Equ.1.) considering the mass (M) of the bus. This is not a realistic method: using this criteria a small midibus superstructure should absorb the same kinetic energy as a big high decker coach.

C) **Constant relative kinetic energy level.** (When the energy is related to the mass of the vehicle) This means constant drop of CG (h) until the contrail hits the ground. The required value of „h" has to also ensure the unlimited deformation of the superstructure.

D) **Ensuring unlimited superstructure deformation.** The depth of the ditch can remain 800 mm as it now exist in Reg.66. but the ground level is shaped, deepened to avoid the too early contact of the waistrail. The value of ΔA do not effect the value „h" but it can influence the value „Δh" when limiting the structural deformation.

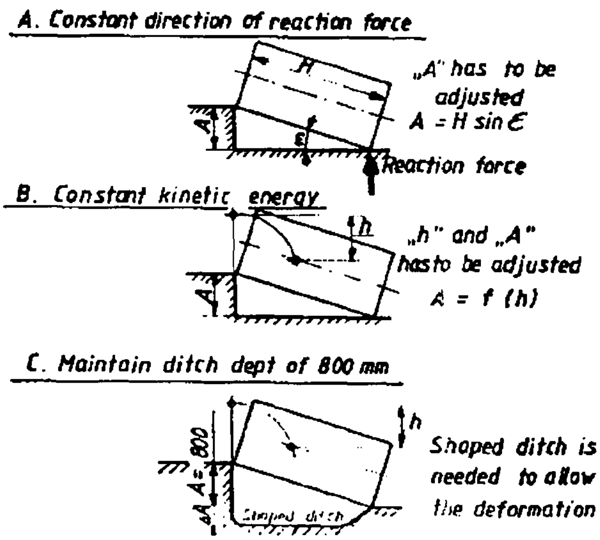

Fig.5. Different types of rollover test

Theoretically the best solution is the combination of „A", „C" and „D", where the deformation is not limited, the relative kinetic energy (h) and the direction of the impact force on the contrail (ε) is fixed. Fig.6. shows that the technical solution of the proposed new rollover tests in rather tests is rather simply, the principle and the tilting platform, developed to the existing test, can be used. That means: the modification of the test is simple and not cost sensitive.

5. RESIDUAL WORK, ENERGY WASTE

A certain part of the kinetic energy - see Equ.1. - is not absorbed by the structural deformations (more exactly that deformations which are dangerous related to the survival space) and it is gone on different paths, ways. Sometime this energy is called „energy waste", but this term is not appropriate because the higher energy waste the better for the survival space. In the followings the components of the residual work (energy waste) is analysed.

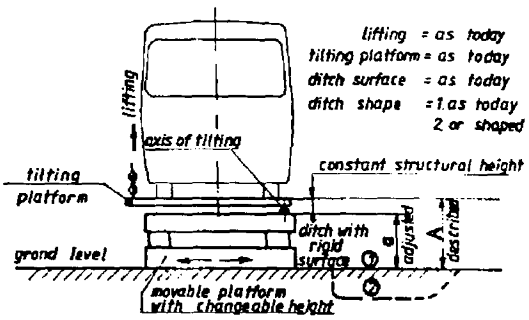

Fig.6. Technical solution to new rollover test.

5.1. Local wastes when cant-rail hits the ground

Along the cant-rail, when it hits the ground a reaction force is built up which - beyond causing ring (column) deformations - results local energy absorbtions, too:

- by the soil deformation an oscillation
- by the cant-rail local buckling local deformation
- friction work, while the cant-rail slips on the ground

5.2. Kinetic energy of moving further

During the rollover process the centre of rotation is determined by the wheels (by their plumb points, see Fig.1.) The reaction forces at these standing plumb points are continuously decreasing during the free rotation of the bus. The situation is changed when the contrail hits the ground. The contrail is stopped in its motion, another reaction force is built up along it and the further motion (rotation) is determined by two centres of rotation (wheels and contrail) The plastic hinges start to work, the two parts of the body have a contra rotating motion. This period of the rotation is still energy producer while the CG-s are going downward. The condition of this further motion is expressed by Equ.2. Another essential change occurs in the motion when the waistrail touches the ground:

- the whole upper part of the body (above the waistrail) stops, it does not have further motion
- the lower part of the body (below the waistrail) rotates further but its centre of rotation is changed, it is relocated to the waistrail, because the wheels leaves off, there is no more supporting force at the wheels.

This is an energy consuming motion, while the CG is moving upwards and also kinetic energy is absorbed by the working of plastic hinges. When the whole kinetic energy is consumed by the lifting of CG, a certain potential energy has been stored which starts a rotation backwards again, so a certain oscillation of the body can be observed. This oscillation is strongly damped by local deformations and slips, but this energy waste also does not influence the survival space.

5.3. Energy relations of big suspended units

The main aggregates of the bus (e.g. engine, radiator, axles) represent big concentrated masses in the body which are suspended elastically to the body through some definite points. It means:

- during the rollover (when the body hits the ground) big dynamic mass forces are created on the suspension points by the big masses, the results of which is plastic deformations around these suspension points. This means energy absorbtions without effecting the survival space
- the elastic suspension results independent oscillation of the big masses which also consumes energy
- the axles (the mass of which is 22-25% of the total mass of the empty vehicle) have long spring way (80 mm) therefor when the body hits the ground and the motion of the body is stopped in a very short time (0,1s), the axle masses can move further and their deceleration takes 0,5 s, that means their mass force effect is delayed, retarded, their kinetic energy is not absorbed by the plastic hinges but by oscillation (e.g. shockabsorbers)

All of these energy components, which are not effecting the plastic hinges have to be analysed and measured in the future, because it is very important to know the ratio of W_r/W_d when making a rollover simulation by calculation. The existing Reg.66 gives a ratio $W_r/W_d = 0,333$

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Table I

Bus and coach				Kinetic energy		Geometrical values			Angular values (°)			
Category	M (t)	H (m)	W (m)	E_k	ΔE_k	R (m)	h (m)	Δh (m)	ω	ε	β	α
Low floor	10	2,6	2,5	$5,39 \times 10^4$	$5,67 \times 10^4$	1,48	0,55	0,61	44,0	17,9	26,1	51,1
Traditional	10	3,1	2,5	$5,69 \times 10^4$	$2,33 \times 10^4$	1,54	0,58	0,25	25,6	14,9	10,7	51,5
High decker	10	3,8	2,5	$6,18 \times 10^4$	$1,39 \times 10^4$	1,63	0,63	0,15	18,3	12,1	6,2	52,2
Midi	4,5	2,55	2,3	$2,07 \times 10^4$	$2,00 \times 10^4$	1,34	0,47	0,48	41,8	18,3	23,5	49,5
High decker	13,5	3,8	2,55	$8,60 \times 10^4$	$1,76 \times 10^4$	1,65	0,65	0,14	18,3	12,1	6,2	52,2
Mini	3	2	2,0	$1,32 \times 10^4$	$1,73 \times 10^4$	1,14	0,45	0,62	57,3	23,6	23,7	52,7
Double decker	15	4	2,55	$12,8 \times 10^4$	$1,82 \times 10^4$	1,85	0,87	0,13	16,0	11,5	4,5	58,1

Table II

Cross section	**R**	**h**	**Δh**	**ω**	**ε**	**β**	**ν**
Regtangular	1540	580	250	25,6°	15,2°	10,2°	31,6°
Real IK 250	1500	500	125	24,2°	15,9°	63°	28°

EVALUATION OF MOTOR VEHICLE INITIATION AND PROPOGATION, VEHICLE CRASH AND FIRE PROPOGATION TEST PROGRAM

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Paper Number 98-S4-O-05

ABSTRACT

As part of the vehicle safety research outlined in the March 7, 1995 Settlement Agreement between General Motors and the U.S. Department of Transportation, General Motors is conducting a series of vehicle crash and fire propagation tests. The vehicles used for these tests include a passenger van, a rear wheel drive passenger car, a front wheel drive passenger car and a sport utility vehicle. Crash tests will be conducted to characterize potential ignition sources resulting from collision events. Standard ignition protocols will be developed to simulate gasoline spill fires, electrical fires, and hot-manifold ignition of non-gasoline combustible fluids. Fire propagation tests will be conducted to characterize fire propagation in crashed vehicles. The crash tested vehicles will be burned using the ignition protocols.

INTRODUCTION

On March 7, 1995, General Motors and the US Department of Transportation entered into an agreement (hereafter referred to as the Agreement) to settle a dispute regarding the safety of 1970-1991 full-sized GM pickup trucks equipped with fuel tanks mounted outboard of the frame rails. Part of this Agreement involves the establishment of a 5 year, $10 million motor vehicle fire safety research program. The overall objectives of this research program are to better understand how vehicle fires start and spread and to determine what can be done to prevent, contain and extinguish such fires. To this end, GM and the National Highway Traffic Safety Administration (NHTSA) have jointly developed 14 separate vehicle fire safety research projects. One of these projects, entitled "B.3 Fire Initiation and Propagation Tests", is the subject of this technical report.

This report does not present results of any tests; these will be documented in subsequent technical reports. The following statement describing Project B.3 was developed by GM and the National Highway Traffic Safety Administration:

"Vehicle crash tests, including for example frontal and rear impacts, will be conducted. The crash test results, particularly the fluid plumes that result from component failures during the collision events, will be analyzed for fire initiation potential. These data will be used to develop a standard initiation protocol. Crash tested vehicles will be burned, using this standard initiation protocol; and fire propagation characteristics, such as component temperatures, flame spread and combustion off-gases will be studied, particularly in their effects in the passenger compartment."

The project statement of work delineated three major objectives:

1. Design and conduct vehicle crash tests to identify fire initiation potential. Specific objectives include:

   - Determine potential heat sources such as electrical shorts or hot surfaces during or after the impact;
   - Identify potential fuel sources including: gasoline leaks, other fluid leaks, presence of hydrocarbon vapors resulting from fluid leaks, and solid fuel sources;
   - Measure standard vehicle crashworthiness and occupant injury parameters.

   As necessary, the crash test protocol developed for this work will utilize specialized instrumentation and test conditions not normally used for vehicle certification or engineering development.

2. Develop standard initiation protocols for the vehicle fire propagation tests. The objective of this task is to develop controlled, reproducible, and realistic procedures for igniting fires for use in the vehicle fire tests. Ignition protocols will be developed to simulate both engine compartment fires and gasoline-pool fires.

3. Design and conduct vehicle fire propagation tests using the vehicles crash-tested in Task 1 and the initiation protocols developed in Task 2.

The objectives of the fire propagation tests include:

- Determine the major paths and time-lines for fire propagation, especially entry of fire into the passenger compartment;
- Identify what components burn and measure the thermal environments around these components during the fire;
- Measure air temperature, heat fluxes, and toxic gas concentrations in the passenger compartment.

Two research laboratories with expertise in fire science are participating in this research program. The Building and Fire Research Laboratory of the National Institute of Standards and Technology (NIST) is participating through a cooperative research and development agreement (CRADA). Factory Mutual Research Corporation (FMRC) is involved in this research program through a research contract. Technical personnel from GM and from the NHTSA selected the vehicles and developed the crash test conditions to be used in this program. Technical personnel from GM, NHTSA, NIST, and FMRC worked jointly to develop the protocols for fire initiation and for the fire propagation tests.

TEST VEHICLES

In order to represent the current United States vehicle fleet, several different vehicle types will be used for these crash tests. The purpose of the crash testing is not to compare the performance of different vehicle models or vehicle types but rather to increase the understanding of post-collision fires and how they start. As it will not be feasible to test all vehicle types currently available in the market, the following four vehicle types were selected: 1) passenger van, 2) rear wheel drive mid-sized passenger car, 3) sport utility vehicle, and 4) front wheel drive mid-sized passenger car. Both a front- and a rear-wheel drive passenger car will be tested because these vehicle types have significantly different power-train configurations. As shown in Table 1, the market segments represented by midsize cars, vans, and sport utility vehicles, cumulatively account for greater than 50% of 1995 United States passenger vehicle sales [1].

Table 1.
Year-To-Date Sales of Passenger Cars and Light Trucks in the United States for 1995 By Market Segment [1] (As Of October 15, 1995)

MARKET SEGMENT	MARKET SHARE
Small car	15.7
mid-size car	28.8
Large car	6.5
Luxury car	8.0
sport-utility vehicle	11.6
van	11.6
pickup truck	18.3

DESIGN AND CONDUCT VEHICLE CRASH TESTS

Research Objectives

The objective of these crash tests is to develop a better understanding of events that occur during a vehicle collision which could result in a post-collision fire. Fire requires three components: a source of heat, a source of fuel, and oxygen. Here, fuel refers to any flammable or combustible material that can ignite when exposed to heat. Combustion is a self-sustaining gas-phase chemical reaction in which the heat released by oxidation of the fuel is sufficient to maintain the oxidation process. Ignition of the fuel can occur by one of two mechanisms [2,3]. Piloted ignition occurs when a flame or spark ignites a fuel/air mixture, where the concentration of the fuel in air is within the lower- and upper-limits of flammability. Ignition can occur in the absence of a pilot source if the temperature of the igniting object is greater than the autoignition temperature of one of its constituent materials.

Potential fuels for a post-collision fire could be any of the flammable or combustible liquids, or combustible solids in the vehicle. Most automotive fluids are flammable or combustible, or contain combustible constituents. Gasoline, motor oil, and power steering fluid are mixtures of hydrocarbons. Brake fluids conforming to DOT3 or DOT4 specifications [4] are composed of end-capped poly(glycol ethers). Although engine coolant and washer fluid are water-based, both fluids contain combustible components: ethylene or propylene glycol and methanol, respectively. Damage caused by the vehicle crush may produce leaks in some of the fluid systems, releasing these fuels into or around the vehicle. The plastics and elastomers used in vehicles also are combustible. The amount of thermal energy required to increase the temperature of a combustible solid to above its flash-point or fire-point is generally greater than that required for any of the automotive fluids. One exception can be foamed solid materials which, because of their lower density, are often more easily ignited than liquids.

A number of ignition sources could be present during a crash, some of which are not present in an undeformed vehicle. Hot surfaces such as those of the exhaust system, which includes the exhaust manifold, exhaust pipes, and catalytic converter, can act as an ignition source by transferring thermal energy (heat) to a contacting combustible material raising its temperature above the autoignition temperature for that material. Short circuits in the electrical system caused by the vehicle crush can ignite combustible materials by the same mechanism. Electrical arcing, metal-to-metal and metal-to-ground (road surface) friction-sparks can be piloted ignition sources for a flammable vapor only if the concentration of the vapor is within its limits of flammability when and where the arc or spark occurs.

It is the goal of these tests to characterize both fuel sources and ignition sources in the vehicle crash tests described below.

Crash Tests

To better represent the wide variety of crash conditions which may occur in the field, the four vehicle types will be tested in different crash conditions. The criteria used to develop these crash tests include the following:

- The crash tests are intended to be severe and do not represent current Federal Motor Vehicle Safety Standards. Crashes of low severity which do not result in substantial damage to the vehicle structure, the electrical system, or the fluid systems would provide little information about how post-collision fires start.
- The intent of the crash test matrix is not to compare the performance of vehicles or vehicle types.
- The test matrix will include both frontal and rear impacts per the terms of the Agreement.
- The crash tests should represent conditions which are field relevant.

An analysis of FARS (Fatal Accident Reporting System) data from 1979 through 1992 by the NHTSA [5] was reviewed to identify those conditions which are field relevant. This analysis suggested that frontal and rear impacts should be included in this testing.

Frontal impacts will be included because there were more frontal impacts than rear impacts, side impacts, or rollovers which resulted in a fire and a fatality. This was simply because frontal impacts in general were more common than rear or side impacts. See Table 2, which combines the reported incidents for cars, trucks and vans from the NHTSA analysis.

Table 2.
A 1994 NHTSA analysis of 1979 - 1992 FARS data [5]
Car, Trucks, and Vans

Damaged Area	Number of Fatal Crashes	Number of Fires	Percent Fires	Number MHEF	Percent MHEF
Rollover	70189	2127	3.03	679	0.97
Front	212009	**4750**	2.24	**1319**	0.62
Rear	15608	717	**4.59**	294	**1.88**
Side	75697	1472	1.94	376	0.50
Other	14892	427	2.87	167	1.12

Also included in Table 2 are those incidents in which fire was judged to be the most harmful event (MHEF). Not only did frontal impacts result in the greatest number of fires, they also resulted in the greatest number of MHEF. As described in reference [5] the classification of fire as the most harmful event is based on the personal judgment of the FARS data analyst in each state. The fact that a fire was identified as the most harmful event does not necessarily mean that there was a fatality in the particular vehicle due to fire. Conversely, the fact that fire was not classified as most harmful event does not preclude a fire fatality for a particular crash analysis.

Even though there were fewer incidents of rear impact fatalities with a fire than frontal impact fatalities with a fire, the probability of a fire given a rear impact was about twice that for frontal impacts. Moreover, the probability of fire being the most harmful event given a rear impact was approximately three times greater than for frontal impacts. This supported including at least one rear impact in the test matrix.

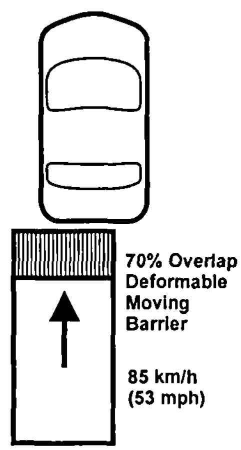
The NHTSA study [5] of incidents resulting in a fire and fatality suggested that the most common object struck is another vehicle, as indicated in Table 3. However, the likelihood of fire was greatest for impacts to narrow objects (*e.g.*, trees).

The three crash conditions used for this project, include two frontal impacts and one rear impact. These crash conditions simulate either a vehicle-to-vehicle or vehicle-to-narrow object impact. The speeds were selected using engineering judgment rather than an analysis of field data, and are intended to produce significant damage to the vehicle's structure, electrical or fluid systems. All vehicle crash tests will be conducted at the General Motors Proving Ground in Milford, Michigan.

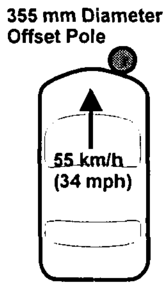
Table 3.
A 1994 NHTSA analysis of 1979 - 1992 FARS data [5]
Car, Trucks, and Vans

Object Struck	Number Fatal Crashes	Number Fires	Percent Fires	Number MHEF	Percent MHEF
Vehicle	224560	**5098**	2.27	**1217**	0.54
Narrow	35899	1766	**4.92**	678	**1.89**
Fixed	45168	1938	4.29	737	1.63
Other	56925	332	0.58	95	0.17
Overturn	25784	355	1.38	108	0.42

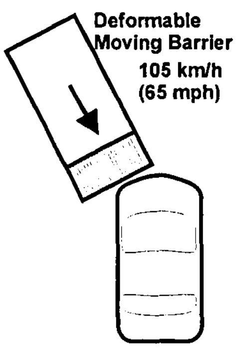
<u>**Deformable Rear Moving Barrier at 85 km/h.**</u> A moving barrier similar to the FMVSS 214 [6] vehicle impactor will be used to impact the stationary test vehicle in the rear with a 70% overlap of the filler neck side of the vehicle. The direction of impact will be parallel with the center line of the vehicle. And, unlike FMVSS 214, the wheels of the barrier will be aligned with the longitudinal axis of the barrier. The barrier will have an impact velocity of 85 km/h (53 mph). The offset will be set so that 70% of the vehicle will be engaged (measuring the width of the vehicle as the widest part of the body vertically in line with the center of the rear wheels.) The standard FMVSS 214 deformable face will be used and will be positioned at its standard height (bumper centerline 17" above grade.) The mass of the moving barrier will be 1367 kg (3015 lb).



Frontal Offset Pole Impact at 55 km/h. The test vehicle will be towed into a fixed, rigid 355 mm (14") diameter steel pole at 55 km/h (34 mph). The impacted side will be vehicle specific and the offset will be 305 mm (12 in.), measured from the center of the pole to the centerline of the vehicle.



Oblique Moving Barrier Impact at 105 km/h. The test vehicle will be stationary and impacted with a moving barrier similar to the FMVSS 214 [6] vehicle impactor with a deformable face. The wheels on the barrier will aligned with its longitudinal axis, however its approach will be at a 20 - 30 degree angle (vehicle specific) relative to the test vehicle. The barrier will impact the front fender. To maximize the test severity, the vehicle will be positioned so that the trajectory of the center of gravity (CG) of the barrier passes through the CG of the test vehicle. The mass of the moving barrier will be 1600 kg (3600 lb.), which is greater than what is used for FMVSS 214 tests (1367 kg (3015 lb.)). The deformable face will be the standard FMVSS 214 face at the standard height (bumper centerline 17" above grade). The impact side will be vehicle specific, but will likely be opposite of the side impacted with the offset pole test.



Crash Test Instrumentation and Vehicle Set-up

The main objective of the crash tests is to identify potential fire ignition sources during a vehicle collision. Instrumentation to detect these events is not usually included on vehicle certification or engineering development crash tests. Following is a description of the instrumentation and test set-up, much of which is experimental and has been developed specifically for these tests.

Vehicle Condition. New vehicles will be purchased for these tests. The test mass will be the mass of the vehicle as delivered (with full fluids) plus the mass of the anthropomorphic test devices (ATDs) and the crash-test instrumentation. More instrumentation than typically included in a crash test may be required and thus the test mass of the vehicle may be higher than what is specified for FMVSS 208 [7] testing. To retain the integrity of the vehicle for the fire propagation tests, no parts will be destroyed or cut prior to the test. Any electrical circuits which are being monitored will be activated during the impact. As an example, electric cooling fans frequently cycle on and off, and if these circuits will be monitored, then the vehicle impact will be timed such that the cooling fans are on at impact. Also, if the headlight circuits are being monitored, they will be on for the test. The front driver and passenger windows will be down for all tests.

The hood may be removed for some of the frontal tests to improve photographic coverage of the engine compartment. The presence of a vehicle hood may have little influence on the deceleration time history because it does not carry significant loads during an impact. However, the hood may play a more significant role in terms of vapor retention should fluid leaks develop during the crash. Flammable vapors from fluid leaks will disperse more quickly with the hood removed, thus resulting in an unrealistic high rate of vapor loss from the engine compartment. The absence of a hood also alters the dispersion patterns of fluid sprays in the engine compartment. This tradeoff will be judged on a test by test basis and it is likely that some tests may be conducted with the hood in place, while others will be conducted with the hood removed.

Engine. The test vehicle's engine will be allowed to run during all of the frontal crash tests with complete vehicle fluids (including battery electrolyte). Preliminary temperature measurements will be conducted to determine operating engine temperatures at various road speeds and loading conditions. It is unlikely that actual road-load temperatures throughout the engine will be matched because it is impractical to drive or somehow provide loading to the vehicle immediately before the crash. However, the engine will be allowed to run at higher than idle speeds to obtain higher than idle temperatures for the crash test. This warm up procedure may result in engine temperatures either hotter or cooler than actual road loads. Following a warm up time of approximately 20 to 30 minutes, the engine will be shut down for instrumentation calibration and set-up (approximately 5 minutes). The engine will be restarted and engine speed will again be increased to above idle speed. Gasoline will be supplied to the engine from an auxiliary fuel tank mounted inside the passenger compartment and connected to the gasoline supply line away from any anticipated vehicle crush. A production fuel pump system will be installed in this auxiliary tank and electrically connnected in place of the existing pump. The production gas tank will be filled to 95% of its usable capacity with Stoddard Solvent.

For the rear impact tests, the fuel tank will be filled to 95% of its usable capacity with Stoddard Solvent. The engine will not be running during the crash test, nor will it have been run prior to the test to minimize the probability of igniting spilled Stoddard Solvent if a fuel system-rupture should occur. However, the ignition will be on and the fuel lines charged. A plastic bag will be sealed around the filler cap to retain and detect the presence of Stoddard Solvent that has escaped from the cap during the impact. Normal collection procedures used for FMVSS 301 [8] testing will be used to quantify fuel system leaks after the impact.

Electrical Current and Voltage. Some, but not all, of the vehicle's electrical systems will be measured during the crash test to help identify potential electrical shorts which may result in ignition sources. These measurements may include both voltages and currents. The currents will be monitored using clamp-on non-intrusive current transducers, while voltages will be measured directly. It will be impractical to measure the condition of every engine compartment circuit, and so prudent engineering judgment will be used to help identify those circuits which are most likely to be damaged by the impact and possibly result in an ignition source. Electrical circuits to be monitored during the frontal tests may include the starter wire, the alternator wire, main battery feeds, the electric cooling fans, the headlights and other circuits specific to the vehicle. Circuits to be monitored for the rear impacts may include the rear taillights, the center high mounted stop light, the rear window defroster and other vehicle specific circuits.

Fluid Pressure. Pressure transducers (Model 8510B and 8510C Pressure Transducers, Endevco, San Jaun Capistrano, CA) will be installed to measure the dynamic pressures of key vehicle fluids during the frontal impacts. This will help identify the times at which a fluid leaks so they may be correlated to structural damage during the crash. For the frontal tests, fluid pressures will be measured in the gasoline supply and return lines, the front brake lines, the engine coolant system, the power steering system, engine crankcase, and transmission. For the rear crash tests, fluid pressures will be measured only in the gasoline supply and return lines.

Fuel Pump. For the frontal crash tests, the fuel pump locating in the auxiliary fuel tank will be operating (as well as the engine.) The electrical power to the fuel pump will be measured to determine when the fuel pump stops. In addition, the rotation of the engine will be measured either by monitoring the on-board engine-speed sending unit and/or by mounting a magnetic speed sensor (Model MP1A High Sensitivity Magnetic Pickup, Philips Technologies, Airpax Instruments, Chesire, CT) adjacent to the flywheel. Some vehicle fuel pumps are designed to shut down when the engine rotation stops, which typically occurs with severe frontal impacts. These two measurements allow the correlation of engine speed to fuel pump status.

Flammable Vapors. Two types of chemical analyses will be performed during the crash test to determine the contribution of fluid leaks to the development of a potentially flammable fuel/air mixture. The concentrations of flammable vapors will be measured with tin oxide semiconductor gas sensors (TGS 813, FIGARO USA, Inc, Wilmette, IL). These sensors are crashworthy, have a fast response, require minimal electronic circuitry, but require careful calibration for accurate measurements.

In addition to the measurements of flammable vapor concentration, samples from each sensor-location will be collected on sorbent cartridges for analysis. The gases retained on the sorbent material in these cartridges will be identified by thermal desorption/gas chromatography or by thermal desorption/gas chromato-graphy/mass spectrometry. Elucidation of the chemical composition of the gases at each location will help to identify the source of the flammable vapor.

Instrumentation to perform these measurements will be included in all the frontal crash tests. For the frontal crash tests, gas sensors and sampling tubes will be located near potential ignition sources (*e.g.*, hot surfaces and likely points of electrical arcing). Since the fuel tank will contain Stoddard Solvent, which has a significantly lower vapor pressure than gasoline, flammable vapor measurements will not be performed during the rear impact tests.

Vehicle Brakes. The dynamic brake fluid pressure will be monitored in the frontal tests in order to identify the times of potential brake fluid leaks.

For the offset pole tests, the brake lines to the front wheels may be isolated from the brake calipers allowing the brake lines to be charged but still allowing the wheel to turn during the vehicle tow. This will be done so a steady state brake pressure can be measured and any drop in brake pressure during the impact will be easily identifiable. For typical crash tests, an auxiliary brake machine is sometimes used to apply the brakes remotely at or shortly after impact. During the initial application of the brakes, however, there is a time delay in the rise of brake pressure and a steady state pressure may not be realized during the time of any leaks. It is desirable to have the brake lines pre-charged during the vehicle tow to identify more clearly a drop in brake pressure. Also for the pole test, an auxiliary brake machine will be connected to the rear brakes and used only to abort the test, if necessary, during tow. For the oblique moving barrier test, the rear brakes will be disconnected from the brake lines and charged by an auxiliary brake machine. The front brakes will be pressurized by loading the brake pedal and mechanically locking it down.

For the rear impacts, the front brakes will be activated with the auxiliary brake machine within 200 msec following the impact to help control the post-impact vehicle motion. The brake line pressure will not be monitored during these tests.

Crashworthiness of Experimental Fire Detection and Suppression Devices. Project "B.4 Evaluation of Potential Fire Intervention Materials and Technologies" involves evaluation of fire detection and suppression systems for automotive applications. The crash tests described here provide an excellent opportunity to evaluate the crashworthiness of several proposed detection or suppression technologies. Therefore, some experimental fire detection devices will be included on some of the crash tests. Examples of technologies to be evaluated include, thermal wire fire detectors, pneumatic fire detectors, and optical fire detection systems. The purpose of including some of these on the crash tests is to identify whether or not these devices would survive the crash and remain functional after the impact. This will be strongly dependent on the placement of the device in the engine compartment, and therefore, various locations will be evaluated.

Anthropomorphic Test Devices. Instrumented 50^{th} percentile male Hybrid III crash dummies will be placed in both outboard front seating positions and will be restrained by the vehicle's production seat belt and air bag restraint systems. Seat and dummy positioning will be done per FMVSS 208 [7] procedures. Instrumented ATDs will be included to represent the dynamic inertial loading of the occupant on the vehicle and also to assess the survivability of these selected crash conditions from an occupant trauma standpoint. For the frontal tests, full dummy instrumentation will be recorded which includes: the measurement of head accelerations, neck loads, chest accelerations, chest compression, pelvic acceleration, femur loads, and several lower leg load measurements. For the rear impacts only the head, neck and chest measurements will be recorded. Most of the injury assessment reference values for the Hybrid III ATD accepted by the automobile industry were developed for frontal loading, therefore, injury measurements recorded during the rear impacts will be interpreted accordingly and generally with less confidence in predicting injury risk than for frontal impacts.

Crash Test Instrumentation. These tests will use standard vehicle crash-testing instrumentation in addition to the specialized instrumentation developed to identify ignition sources. These standard measurements of the vehicle include accelerations at various locations on the vehicle, linear displacements, and contacts. All vehicle and ATD channels will be recorded remotely (off-board) using drag-cables which connect the transducers to the signal conditioning and data acquisition equipment.

All transducer signals will be recorded using a digital data acquisition system (DSP Technology, Fremont, CA) at 10,000 samples per second with 12 bit resolution. These channels will use remote shunt emulation for instrumentation set-up and will be recorded for 28 seconds. Signal conditioning, filtering, and recording techniques will comply to SAE J211 [9].

Some channels, including the time-zero contact, the vapor measurements, and electrical measurements will also be recorded using a remote, PC-based digital data acquisition system for approximately 10 minutes after the impact. From the start of tow to the time of impact, the data acquisition rate will be 1,000 samples per second. The data acquisition rate will be switched to 10 samples per second after the impact.

Photo Coverage. Standard high speed movie coverage will be used to record the crash tests. Typically 15 - 30 high speed (500 or 1000 frames per second) cameras will be used depending on the test configuration. Coverage under the vehicle will be included for the rear and pole impact tests. Numeric film analysis will be done to measure vehicle motion. As an example, the dynamic pole penetration during the pole impact test will be measured using film analysis. In addition to high speed film, real time documentary video cameras will be used to record the vehicle condition for at least 10 minutes following the test.

Post-test Inspections. Following each crash test, the test vehicles will be partially disassembled to allow for a thorough inspection and documentation of possible ignition sources or fire paths into the passenger compartment. Fluid leaks, electrical shorts and structural damage to the vehicles will be photographed and documented.

Post-test Static Rollover. Static rollovers, similar to an FMVSS 301 [8] rollover will be conducted only after selected tests. A rollover will be completed for each of the rear impacts, but not for all of the frontal impacts. This will be decided on a test by test basis. The drawbacks to conducting a static rollover, especially for those vehicles which will be burned, is that the roll may distribute the engine compartment fluids into the passenger compartment. (For example, the vehicle used in the first frontal crash test of this program was rolled and the cracked windshield, the carpet, and the headliner were contaminated by a significant amount of leaking engine compartment fluids.) This contamination could serve as an accelerant, significantly altering fire propagation during the vehicle fire tests. For this reason, most of the frontal test vehicles will not be rolled.

DEVELOPMENT OF STANDARD IGNITION PROTOCOLS

Potential ignition events observed during the crash tests will be the basis for the Standard Initiation Protocols. Simply stated, a Standard Initiation Protocol is a repeatable method for starting a fire for a vehicle fire test. To be useful for the vehicle fire tests, a standard initiation protocol should meet three requirements. First, it must result in an ignition. Second, the ignition must lead to a propagating fire; that is, a fire that does not self-extinguish before spreading from the site of ignition. Lastly, it must be a repeatable and controllable procedure. Thus, factors such as 1) the locations of potential fuel and energy sources in the vehicle, 2) the type, amount, and flammability properties of the fuel, 3) the type, intensity, and duration of the energy source, and 4) the flammability properties of combustible materials in close proximity to the site of ignition must be considered when examining the data from the crash tests and when developing the standard initiation protocols. Some of these parameters may be studied in small-scale test before developing the initiation protocols for the full-scale vehicle fire tests. When appropriate, information about post-collision vehicle fires obtained from other sources (e.g., field incident data, crash data bases) will be considered when developing these initiation protocols.

Technical personnel from GM, NHTSA, NIST, and FMRC will work jointly to develop standard initiation protocols for ignition of combustible materials in the engine compartment and for ignition of a gasoline pool under the vehicle. These initiation protocols will be described in detail in future reports.

Ignition in the Engine Compartment

Possible ignition scenarios for engine compartment fires to be examined in small scale tests include:

- Ignition of combustible solids in the engine compartment by heat generated from an electrical short, which could include an internal short in the battery;
- Ignition of a combustible liquid sprayed onto a hot surface; or
- Ignition of gasoline leaking from a ruptured fuel line by an electrical arc.

These scenarios will be examined for possible development into a standard initiation protocol.

Ignition of a Gasoline Spill

The initiation protocol for vehicles struck in the rear will focus on ignition of gasoline leaking from a ruptured fuel system. There are two possible outcomes of the crash test with regards to fuel system integrity:

- The fuel system ruptures and leaking fluid is detected during the crash test or the vehicle roll, or
- The fuel system does not rupture and leaking fluid is not detected during the crash test or the vehicle roll.

When the crash test results in fluid leaking from a ruptured fuel system, the initiation protocol will recreate as accurately as possible the location of the leak, the leak-rate, and the size and location of the liquid pool relative to the stationary vehicle.

When the fuel system does not rupture and does not leak during the crash test, the ignition protocol will simulate a rupture of the fuel-system at the connection of the filler-neck to the fuel tank. Different procedures will be used for vehicles with steel and plastic fuel tanks. For vehicles equipped with plastic fuel tanks, a 3 mm diameter hole will be drilled at the base of the filler neck and the fuel tank will be partially filled with gasoline. For vehicles equipped with steel fuel tanks, gasoline will be pumped from an external reservoir through a grounded stainless steel tube with the outlet affixed to the base of the filler neck. For simplicity, the gasoline pool will be ignited with a pilot flame in these tests.

DESIGN AND CONDUCT VEHICLE FIRE PROPAGATION TESTS

Objectives

Understanding fire propagation in vehicles with the structure damaged in a crash is a first step in developing effective measures to reduce injuries and fatalities associated with post-collision vehicle fires. Both the probability of a post-collision vehicle fire and the probability of sustaining an incapacitating trauma injury or of being trapped in the vehicle after the crash increase as the severity of the crash increases [5]. In cases where a collision results in both a fire and surviving occupants being trapped in the vehicle, entry of the fire into the passenger compartment is the greatest, immediate threat to the occupants. The crash-tested vehicles will be burned in controlled tests to study propagation of a post-collision fire.

The literature contains several reports documenting investigations of motor vehicle fires. These reports generally fall into two categories: case studies of forensic investigations of motor vehicle fires [10-12], or technical reports describing the results of vehicle fire experiments using uncrashed vehicles [13-16]. The forensic investigations [10-12] were generally concerned with determining the cause and origin of a motor vehicle fire after a crash or when arson is suspected. Forensic investigations focus on the ignition event and usually do not provide detailed information about how the fire propagated for two reasons. First, fire investigations occur after-the-fact; the investigators are not present to observe the fire. Second, much of the evidence needed to determine the fire paths was usually destroyed in the fires.

Most controlled vehicle fire tests have been concerned with determining the effect of a burning vehicle on surrounding structures [13-15], which involves measuring heat-transfer to surrounding objects. One study investigated propagation of an engine compartment fire through the forward bulkhead, using a series of front-half sections of uncrashed vehicles [17]. Neither the results of the fire investigations nor the controlled studies cited above can be generalized to propagation of post-collision vehicle fires.

The vehicle fire tests described below will focus on understanding how fire propagates in crashed vehicles. Data recorded during these tests will be used to (1) determine the paths for the spread of flame from the site of ignition to other locations in the vehicle, (2) measure the rate of flame-spread along each of these paths, (3) determine what components and materials burn, and (4) assess occupant survivability during the fire.

<u>Fire Paths.</u> Two of the objectives of these tests are to determine how the fire moves from the exterior of the vehicle into the passenger compartment, and to determine the time-line for this process. Possible fire paths into the passenger compartment include:

- polymer grommets used as seals in electrical, fluid, and mechanical feed-throughs in the sheet metal bulkheads around the passenger compartment;
- openings in the sheet metal structure of the vehicle created by the crush;
- the windshield, which can be shattered in the crash or by heat from the fire;
- windows, which may be open, or shattered in the crash or by heat from the fire;
- heat transfer through the sheet metal structures (e.g., the forward bulkhead and the floor pan) to combustible materials in contact with these structures (*e.g.*, the carpet pad).

A distinction is made here between the windshield and other windows in the vehicle. The windshield is a laminated structure consisting of a polymer sheet sandwiched by two outer-layers of tempered glass. Although the glass layers may shatter during the crash, the polymer sheet is less brittle and can hold the shattered windshield in place. In contrast, other windows in the vehicle typically consist of a single layer of tempered glass, and may not remain in place when shattered.

<u>Temperatures and Thermal Environments.</u> Another objective of these tests is to identify what components burn. In addition to flammable or combustible fluids, vehicles contain a number of components composed of organic polymers (plastics and elastomers). In general, all of these polymeric materials are combustible, and can be a fuel source in a post-collision fire.

Thus, the flammability of the constituent materials of the various components in the vehicle will affect both where and how fast the fire propagates. These fire tests will yield detailed information about what components burn, the sequence in which they ignite, the thermal environments around these components before and when they are burning, and the rate of growth and heat output of the fire.

Threat to Occupants. Another goal of these tests is to determine the threat to occupants posed by a post-collision fire. Fire can injure or kill by one or a combination of three basic mechanisms:

- Burns to the skin caused by hot gases and thermal radiation to the body or by flame directly contacting the skin;
- Burns to the lungs caused by inhalation of hot gases; or
- Acute toxicity caused by inhalation of toxic combustion products.

Instrumentation will be included in the vehicles to assess the threat from each of these mechanisms.

Fire Propagation Test Procedures

Eight fire propagation tests will be conducted at the Factory Mutual Test Center in West Glocester, Rhode Island. Two crash-tested vehicles per model will be selected for the fire propagation tests. The selection of the vehicles for fire propagation tests will be done by technical personnel from GM and NHTSA with input from technical personnel from the NIST and FMRC. The NIST will be responsible for all aspects of obtaining a detailed video record of each fire propagation test and analysis of these video records to determine the important events in the propagation of the fire from the site of ignition into the passenger compartment. FMRC will be responsible for preparing the fluid containment pan, weight-modules, and simulated road surface before each test, and for operation of the Fire Products Collector during each test. GM will be responsible for all other aspects of the preparation and conduct of the fire tests described below.

One of the vehicles used in the frontal crash tests (offset pole test or deformable oblique moving barrier) will be selected for the engine compartment fire test. If one of the frontal crash tests results in a fire, then this vehicle will be selected for the fire test and the method of ignition will recreate as accurately as possible the cause of the fire observed in the crash test. If none of the frontal crash tests results in a fire for a given vehicle type, then the method of ignition for the fire test will recreate possible ignition scenarios determined after examination of the data from the crash test, disassembly and thorough inspection of the vehicle selected for the fire test. The vehicle used in the rear crash test will be used for the gasoline pool fire test.

Vehicle Condition. The condition of the vehicle for the fire test will approximate the condition of the vehicle after the crash test. For fire tests involving vehicles in which the hood was removed for the crash test, the hood will be crushed dynamically to simulate the crush that would have occurred in during the crash test and remounted on the vehicle. For maximum retention of heat and combustion gases in the passenger compartment, all intact windows will be raised to their fully closed or maximally closed positions. Windows broken during the crash test will not be replaced for the fire tests. Components which separate from the vehicle during the crash tests will be collected and placed in the same positions relative to the vehicle. The entire vehicle, including the engine compartment will be at ambient temperature at the start of the fire test. Automotive fluids will be spilled in the engine compartment and under the vehicle before the fire test to simulate fluid leaks that occurred during the crash test.

Fire Test Facility. The vehicles will be centered under a Fire Products Collector [18,19]. The Fire Products Collector is a large-scale calorimeter which will be used to obtain the release-rates of chemical, convective, and radiative heat, and of carbon dioxide, carbon monoxide, total hydrocarbons, and smoke during a fire test.

To prevent personal injury, fire damage to the test facility, and environmental contamination, the vehicle will be placed in a containment pan to prevent leaking automotive fluids from spreading in the test facility during and after the fire tests.

The bottom of the fluid containment pan will be lined with a simulated road surface consisting a layer of concrete construction board on top of a bed of sand. The purpose of the simulated road surface is to accurately recreate the effect of a semi-porous medium on fluid pool fires which may develop during these tests. The seams between boards will be sealed with latex construction caulk and the grade of the surface measured from the center to the edges along the major and minor axes will be no greater than 1% in all directions. This last specification is to minimize the effect of flaming fluid pools accumulating at low points in the surface.

Mass loss from the burning vehicle and any burning fluids retained by the containment pan will be measured with load cells. The fluid containment pan will be placed on top of an I-beam frame supported by weight-modules (KIS Series, BLH Electronics, Inc.) at each of its four corners. These weight-modules contain cylindrical, double cantilever strain gauge transducers that will not be affected by changes in the mass distribution in the containment pan.

Vehicle Instrumentation

Temperature. Thermocouples will be attached to metal bulkheads, and various components in the vehicles along anticipated fire paths or near combustible components in those paths. Temperature measurements obtained with these thermocouples will be used to track the spread of the fire and to define the thermal environments in the vehicle during the fire. The locations for thermocouple placement will be determined after disassembly and thorough inspection of the crashed vehicles.

Type-N thermocouples (Nicrosil/Nisil) will be used for these measurements. These thermocouples will have ungrounded junctions enclosed in an Inconel 600 sheath and insulated with magnesium oxide (Medtherm Corporation, Huntsville Alabama). The higher thermoelectric stability of Type-N thermocouple compared to the standard base-metal thermocouples [20] will yield more reliable temperature measurements in the extreme environment of the fire tests.

Each thermocouple will be connected to the data acquisition system with thermocouple duplex extension cable with a Teflon®-jacketed stainless steel over-braid. To minimize electromagnetic interference and to prevent ground-loops, the electronics chassis ground, the thermocouple shields, and the vehicle chassis will be connected to a common ground-bus at the data acquisition system. The ground-bus will be connected to earth-ground by a large gage cable.

Air Temperature. Two aspirated thermocouple probe assemblies (Medtherm Corporation) will be used to measure vertical air-temperature gradients at the front occupant positions. Each assembly will contain six Type-N thermocouples with bead-type junctions. The thermocouples will be housed in radiation shields with a vertical spacing of 75 mm (3 in.). The probes will be mounted to the roof of the passenger compartment so that the upper-most shielded thermocouple is approximately 12 mm (0.5 in.) below the lower surface of the head liner. Both probe assemblies will be connected to a vacuum pump to draw air into the radiation shields. The internal diameters of the interconnecting sections of the vacuum manifold will be sized to approximately balance the gas flow rate into each radiation shield, yielding a linear velocity of air flowing over the thermocouple junctions of 10 to 15 m/s. These conditions were chosen to minimize both the response-time of the thermocouples and error in the air temperature measurement due to radiative heat-transfer to the thermocouple bead [21].

Heat Flux. Dual heat-flux transducer/radiometer assemblies will be mounted to selected components and metal bulkheads in the vehicle to measure convection and radiation to objects in the anticipated fire paths. These assemblies will contain two Schmidt-Boelter thermopiles in a water cooled copper body (Medtherm Corporation). The faces of the heat flux transducers will be coated with high-temperature optical black paint. The radiometers will have sapphire windows (view-angle = 150°; optical transmittance range 0.4 to 4.2 μm). Both types of transducers will be calibrated to 10 W/cm^2 at a reference temperature of 80°C.

Dual heat-flux transducer/radiometer assemblies also will be located in the passenger compartment to measure convection and radiation to the occupant positions. These assemblies will contain two Schmidt-Boelter thermopiles in a water cooled copper body (Medtherm Corporation). The faces of the heat flux transducers will be coated with high-temperature optical black paint. The radiometers will have zinc selenide (ZnSe) windows (view-angle = 150°, optical transmitance range of 0.7 to 17 μm). Both types of transducer will be calibrated to 2 W/cm^2 at a reference temperature of 80°C.

Static Pressure. The static air pressures at several locations in the vehicle will be measured using bi-directional low differential pressure gages (Model C-264, Setra Systems, Acton, MA). The pressure gauges will be located outside of the fluid containment pan to protect them from the fire, and will be connected to stainless steel tubes terminating in the vehicle. For measurement of the static pressures, one port of the pressure gauges will be left open to the atmosphere so that these measurements will have a common, unchanging reference. For measurement of pressure differences across structural bulkheads, both ports of the pressure gauges will be connected to the stainless steel tubes terminating on opposite sides of the bulkhead. Pressure data will be recorded by the data acquisition system as analog inputs.

Bi-directional Flow. Directional gas flow velocity will be measured using a bi-directional flow probe connected to one of the low differential pressure gages described above. The differential pressure is related to the flow velocity by the relationship:

$$V = 0.070\sqrt{T\Delta p}$$

where V is the linear flow rate (m/s), T is the absolute temperature (K), and Δp is the pressure difference between the two openings in the probe (Pa). The probe will be placed near the top of an opening in the vehicle to measure the velocity of gas flow into or out-of the vehicle during the fire test [22,23].

Data Acquisition System. The data acquisition system to be used in the fire tests consists of a PC (ACER Inc., Taiwan R. O. C.) and a 100 kHz I/O board with 16 analog input channels (DaqBoard 200A, IOTech, Inc., Cleveland, OH). Four multiplexed analog-input expansion cards (DBK-12, IOTech) will be used for a maximum of 64 variable gain analog input channels for the heat flux transducers, radiometers, and pressure transducers. Twelve multiplexed thermocouple expansion cards (DBK-19, IOTech) will be used for a maximum of 168 thermocouple input channels. The expansion cards will be housed in a shielded metal cabinet with panel-mounted connectors.

The data acquisition software (DASYLab, Daten System Technik GmbH, Mönchengladbach, Germany) will be configured to sample each channel at a rate of 10 samples per second and store the data in 10-point block averages. Thus, data will be recorded at a rate of 1 sample per second per channel. To facilitate the decision to end the test, air temperature and heat fluxes at the occupant positions will be displayed in real-time during each test.

Video Camera Coverage. Hi-8 color camcorders will be positioned outside the vehicle to document each fire test. The cameras will be arranged around the vehicle to give partially overlapping views of the fire, with emphasis on anticipated fire propagation paths into the passenger compartment. The location of each camera relative to the vehicle will be mapped on a 3-dimensional coordinate system to facilitate the determination of the location of the flame on the vehicle and the rate of flame spread. One or more inexpensive CCD cameras mounted in fire-resistant housings may be located inside the passenger compartment to give views of the anticipated fire propagation paths.

Infrared Thermography. Infrared imaging equipment will be used to obtain estimates of flame and surface temperatures during the fire tests. Thermal imaging radiometers will be positioned outside the vehicle to give views similar to those of some of the video cameras. In addition, one camera protected by a fire-resistant housing will be mounted inside the vehicle to give a clear view of one of the anticipated fire paths into the passenger compartment.

The infrared imaging equipment to be used for these tests will include thermal imaging radiometers with spectral windows in the range of 3 to 5 micron (short-wave), 8 to 12 microns (long-wave), and 3 to 12 micron (broad-band). Flame filters with a cut-off wavelength of 3.9 microns may be used to eliminate radiation from the flame. An older, short-wave camera with a spectral range of 3 to 5 microns will be mounted inside the vehicles during the fire tests.

FTIR Spectrometry. Combustion gases accumulating in the passenger compartment during the fire test will be measured by Fourier transform infrared (FTIR) spectrometry. These gases include: ammonia (NH_3), benzene (C_6H_6), carbon dioxide (CO_2), carbon monoxide (CO), hydrogen chloride (HCl), hydrogen cyanide (HCN), methane (CH_4), nitric oxide (NO), nitrogen dioxide (NO_2), and styrene (C_7H_8). The spectrometer to be used for these measurements (Model I1000, MIDAC Corporation, Irvine, CA) will be equipped with a heated, stainless steel gas cell (path length = 10 m) with gold-surfaced mirrors and ZnSe windows, a liquid-nitrogen-cooled Mercury-Cadmium-Telluride detector, and a Michelson-Type interferometer with a Potassium Bromide beam splitter. The optical range of this instrument will be 5,555 to 645 cm^{-1}. The optical bench will be hermetically sealed and desiccated, isolating the internal optics and electronics from the harsh environment in the fire test facility and eliminating the need for continuous purge during the test.

During the fire tests, air from the passenger compartment will be drawn continuously into the gas cell through a stainless steel tube inserted into the breathing zone of the front occupants. Single-scan spectra with a resolution of 0.5 cm^{-1} will be acquired every 10 seconds. Gas concentrations will be determined using a Classical Least Squares algorithm. To facilitate the decision to end the test, the carbon monoxide concentration in the passenger compartment will be displayed in real-time during each test.

Gas Chromatography/Mass Spectrometry. Organic gases in the passenger compartment will be collected on sorbent cartridges packed with Graphitized Tenax® and analyzed by gas chromatography/mass spectrometry. Air from the passenger compartment will be sampled through a stainless steel tube inserted into the breathing zone of the front occupants. A series of five pairs of sequential samples will be acquired during the fire tests; one sample will be collected at a flow rate of 250 cm^3/min (corrected to standard temperature and pressure) and the other sample will be collected at a flow rate of 2.5 L/min (corrected to standard temperature and pressure).

The sorbent cartridges will be analyzed by TD/GC/MS. The instrument to be used for these analyses consists of a purge and trap concentrator (Model 6000 Purge and Trap Concentrator, CDS Analytical, Inc., Oxford, PA) connected to a GC/MS system (Model 5890 Series II Plus Gas Chromatograph and Model 5989B Quadrupole Mass Spectrometer, Hewlet Packard Corporation, Palo Alto, CA). Deuterated standards will be added to the sorbent cartridges before the analyses for quantitation by isotope dilution analysis.

Oxygen. The concentration of oxygen (O_2) in the passenger compartment will be measured using a galvanic-cell type sensor (GS Oxygen Sensor KE-25, Figaro U.S.A.). The oxygen sensor will be attached to the sample-line for the sorbent cartridges. The signal output from the sensor will be recorded by one of the analog input channels of the data acquisition system. The sensor will be calibrated for the effect of gas temperature and pressure on its response.

Particulate. Particulate from the passenger compartment will be collected on pre-weighed quartz fiber filters (o.d. = 47 mm). Stainless steel filter holders will be mounted on the roof of the vehicle, with stainless steel inlet tubes extending through the roof into the breathing zone of the front occupants. Five particulate samples will be acquired over the same time intervals as the sorbent tube samples. After the test, each filter will be weighed, then cut into four equal sections.

Cyanide anion (CN^-) in the particulate will be measured by ion exchange chromatography. One quarter section of each filter will be extracted with aqueous lithium hydroxide. The extracts will be analyzed by High Performance Liquid Chromatography (HPLC) using a DEAE Sephadex ion exchange column (Waters Chromatography, Milford, MA), an isocratic mobile phase (50 mM LiOH containing 0.25 mM Na_2EDTA) at a flow rate of 2 mL/min, and a pulsed electrochemical detector (Model 464, Waters Chromatography).

The anionic composition of the particulate will be measured by ion chromatography. One quarter section of each filter will be extracted with deionized water. The extracts will be analyzed by HPLC using an anion exchange column (IC-PAK Anion HC, Waters Chromatography), an isocratic mobile phase (a borate/gluconate buffer adjusted to pH 8.5 and modified with acetonitrile and n-butanol) at a flow rate of 2 mL/min, and a conductivity detector (Model 431, Waters Chromatography).

Semi-volatile organic compounds absorbed on the particulate will be identified by TD/GC/MS analysis of one quarter section of each filter. Non-volatile organic compounds in the particulate will be identified by GC/MS analysis of the methanol extracts of one quarter section of each filter. The insoluble residue remaining after extraction with methanol will be dissolved in *AquaRegia* and analyzed by inductively coupled plasma-atomic emission spectrometry to determine the metal content of the particulate.

Criteria for Ending the Test

To preserve evidence of fire paths, these tests will be stopped before all of the combustible material on the vehicle is consumed by the fire. These tests will be stopped and the fire will be extinguished when the environment in the passenger compartment is judged to be non-survivable by one of the following criteria:

- The air temperature in the passenger compartment at the breathing zone exceeds 200°C and is rising rapidly,
- The concentration of carbon monoxide in the passenger compartment exceeds 1% and is rising rapidly,
- Flames visibly impinge on one or both front seats,
- The head-liner is in flames over the forward occupant positions,
- Flash-over in the passenger compartment is evident.

As mentioned above, air temperature and carbon monoxide concentration will be monitored continuously to facilitate the decision to end each fire test. However, these decisions most likely will be based on a somewhat subjective evaluation of rapidly changing conditions inside the passenger compartment.

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STABILITY AUGUMENTATION SYSTEM FOR THE HEAVY DUTY COMMERCIAL VEHICLES - ESTIMATION OF THE GRAVITY POSITION WITH AR METHOD AND APPLICATION FOR ANTI-ROLLOVER

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ABSTRACT

The increasing requirement for vehicle safety enforces us to do further investigation research for the stability control system of commercial heavy duty vehicles. About 50% of the these accidents are caused by vehicle spin-out and rollover. Hence, advanced stability control for heavy duty vehicle needs to be implemented. In this paper, the vehicle gravity position is estimated in using Auto-Regressive (AR) method since the commercial vehicle dynamic characteristics is changeable due to its unspecified load. And the rollover behavior is predicted by both the gravity position and the rolling condition such as rolling behavior. Thus rollover preventing system is proposed.

1. INTRODUCTION

Based on the investigation, vehicle spin-out and rollover take up the 50% of the serious heavy duty vehicle accidents. When the spin control technique is developing for passenger cars, accordding to Advanced Safety Vehicle, it is necessary to develop stability control techniques for commercial vehicle in these conditions. One of the important problem is to capture the gravity position for which is affected by loading goods status. Hereafter, based on the vehicle transfer function measurement, the gravity height is estimated by AR method. Then according to the gravity estimation information, the wheel brake force is controlled in order to prevent rollover behavior.

2. PHENOMENAL CONFIRMATION

Vehicle gravity position and height are changeable with the unloaded or loading status. Therefore, it is very important to understand the kinetic characteristics such as the gravity position and height, and so forth. Rolling feature is changed with the variance of gravity height during lane change, as shown in Fig. 1. If the gravity is higher, the vehicle roll rate is larger and phase delay happens. Generally, truck driver can feel the roll motion according to different loading status and can take measure to guarantee the safe driving.

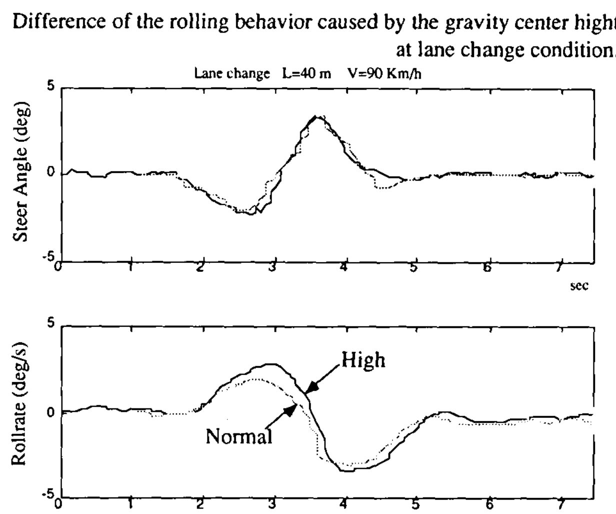


Fig.1 Responce of rollrate

3. GRAVITY POSITION ESTIMATION

3.1 Estimation Consideration

In consideration of the gravity position, the estimation method is investigated for gravity height. In this paper, based on kinetics model with roll motion freedom, the transfer function from steering input to roll output can be estimated. Through the coefficients comparison with experimental transfer function data by AR method, we can get the gravity height.

3.2 Theoretical Equations

In order to obtain the transfer function from steering input to roll output, the kinetics model is described by the coordinate system fixed on vehicle (Fig.2). The 3 DOF model with roll, lateral slip angle and yaw is concerned.

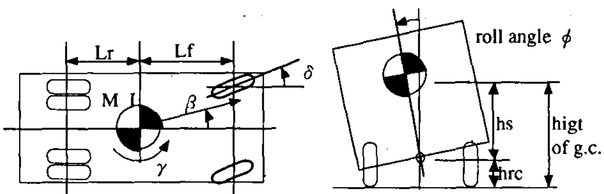


Fig.2 Vehicle model.

The all equations are written as the followings.

$$sx = A'x + Bu$$

$$A' = M^{-1}A''$$

$$M = \begin{pmatrix} MV & 0 & -Mhs & 0 \\ 0 & I & 0 & 0 \\ -MhsV & 0 & I_\phi & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$A'' = \begin{pmatrix} 2(K_f+K_r) & \frac{2(K_fL_f-K_rL_r)}{V}-MV & 0 & -2(K_f\alpha_f+K_r\alpha_r) \\ 2(K_fL_f-K_rL_r) & \frac{2(K_fL_f^2+K_rL_r^2)}{V} & 0 & -2(K_fL_f\alpha_f-K_rL_r\alpha_r) \\ 0 & MhsV & -C_\phi & -K_\phi \\ 0 & 0 & 1 & 0 \end{pmatrix}$$

$$B = M^{-1}B'$$

$$B' = \begin{pmatrix} -2K_f & -2K_fL_f & 0 & 0 \end{pmatrix}^T$$

$$x = \begin{pmatrix} \beta & \gamma & \dot{\phi} & \phi \end{pmatrix}^T$$

$$\phi(s) = Cx \cdot \delta(s)$$

Concerning roll motion, expanding the transfer function of steering angle-roll:

$$\frac{\phi(s)}{\delta(s)} = Cx = CA^{-1}B \qquad \text{---------} [1]$$

$\because \quad A = sE - A'$

E: Identify

$\det(A)$: determinant of A

$$C = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

as followings[1]

$$\frac{\phi(s)}{\delta(s)} = \frac{e_2s^2 + e_1s + e_0}{\det(A)} \qquad \text{---------} [2]$$

3.3 Transfer Function Extracted by AR method

Based on the input and output experimental data of the test vehicle, AR model is expressed as:

$$a(q)y(t) = b(q)u(t-nk) + e(t)$$

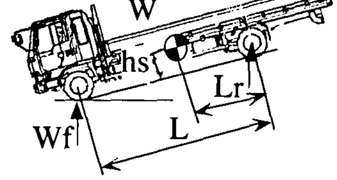
This description is transformed to continuous system. As described above, the obtained transfer function order is same as that of Eq. [2]. Therefore, the power item of the polynomial of transfer function is corresponding to the correlative item. If taking the coefficient of s^2 item as e_2, gravity hs is the function of e_2 and other vehicle element. In other words, if we have the coefficient of transfer function and other vehicle element, the gravity height can be calculated as:

$$hs = F(e_2)$$

$$= \frac{K}{MsV} \frac{\frac{2}{V}K_fK_rl^2 - VM(K_fl_f - K_rl_r)}{\frac{K_f}{e_2} - 2K_r\{2K_rl_r\alpha_r - K_fl_f(\alpha_f + \alpha_r)\}}$$

3.4 Experimental Gravity Estimation and Test vehicle

Based on Security Guarantee Standard, the static gravity measurement method is shown in Fig. 8.



$$hs = \frac{W \cdot Lr - Wf \cdot L}{W \tan\alpha}$$

Fig.3 Hight of gravity center

Here the middle-sized truck is loaded with two conditions. One is lower flat concrete load and the other is the higher load status, and both the gravity height measurement, as well as the gravity height measurement of unloaded condition are taken as the true values.
According to these conditions, the steering angle, roll rate and vehicle velocity are measured on a common road conditions.

3.5 Data Processing

In vehicle riding, comparing with yaw rate, roll rate is easily to be affected by the cant road surface or rugged road surface when the input is steering angle. As seen in Fig. 4, roll angel has a low coherence with the steering angle input.

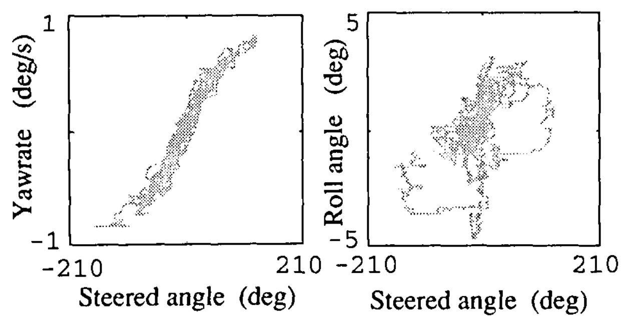


Fig.4 Responce of Yawrate and Roll angle

This is why the acquainted data can not be used directly in estimation. Therefore, the roll response is appropriately extracted in using the continuous algorithm for data pre-processing (Fig. 5), and taking the filtered data to input to the gravity calculation system.

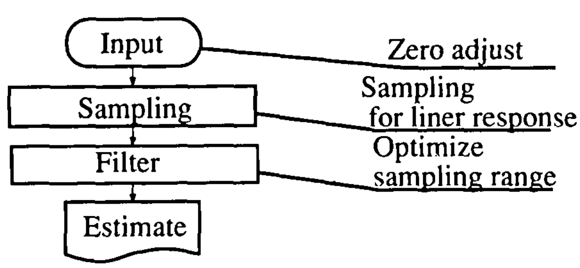


Fig.5 Data processing

All accumulated mean values are started from zero in order to prevent the zero-drifting measurement signals. Moreover, reliable roll response is pursued by taking a certain value of steering input as the trigger signal then recording the sample signals.

Roll rate is sensitive to lateral motion caused by uneven road surface in high frequency range. However, in low frequency range, when roll is integrated as the road cant and vehicle roll rate, integral error exists. In order to prevent roll angle calculation from these influences, band-pass filter is applied for ordinary frequency range. And this is helpful in enhancing measurement sensitivity.

After these process, according to AR method, single-input and single-output transfer function is determined then gravity height can be calculated as described in above section 3.2.

4. ESTIMATION RESULTS

4.1 Premise Condition of Gravity Estimation

The following is the analysis results. Data are collected from the test-course (Fig. 1) and from town road (Fig. 6). The estimation results in using these data are shown in Fig. 7.

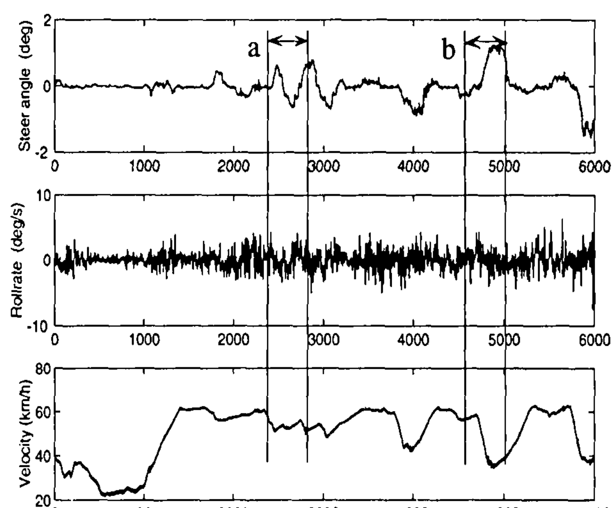


Fig.6 Valid data range

The areas indicated by the arrows in Fig. 6 are used to construct the transfer function. It is very possible to perform the estimation as the coherence between steering input and roll rate located in a higher s/n ratio area.

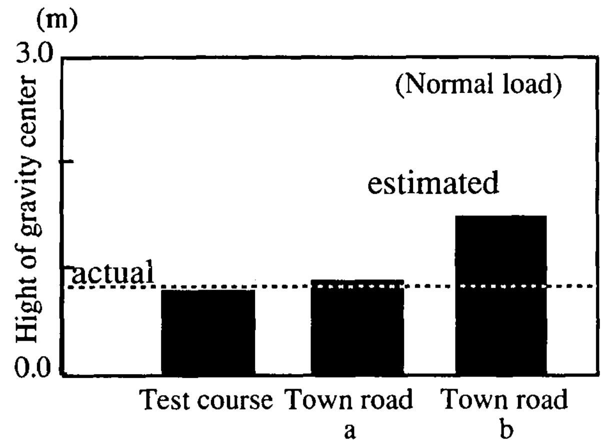


Fig.7 Estimated value

On the other hand, when the input-output are not sufficient or the speed change rate is large, the estimation is different from the true value. Therefore, higher S/N ratio and lower speed change rate is the necessary premise for the estimation.

4.2 Loading Condition and Gravity Height Estimation

With the premise condition of 5.1, when the loading condition is changed and the gravity height is calculated (Fig. 8). The gravity height is in accordant to the trend of the loading status.

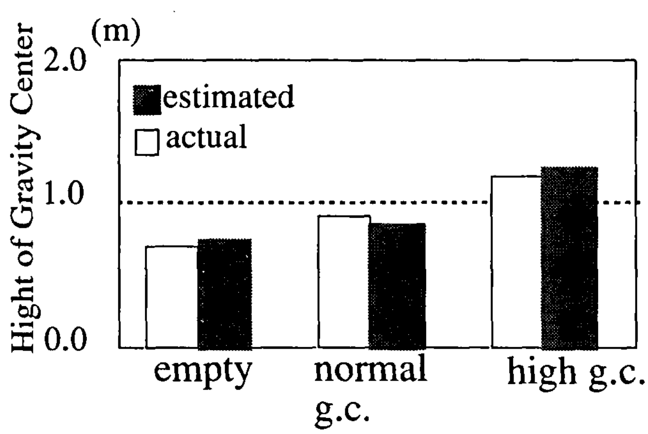


Fig.8 Estimated value

5. APPLICATION TO LATERAL SPIN CONSTRAINT CONTROL

The compensation control for course-out is shown in Fig. 9. The basic theory is founded on the observer estimation for side slip angle, whose inputs are steering angle, yaw rate and garavity speed; and the observer is composed of vehicle specifications and tire characteristics. The systematic characteristics of tire are arranged by Takahasi, et al. According to the side slip states, wheel brake force is controlled to decrease the rollover and this is well known for side slip control of passenger cars. In addition to this control strategy, rollover prevention control should be applied in commercial vehicle control and the consideration is demonstrated as follows.

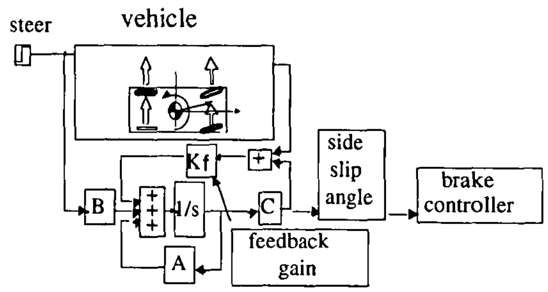


Fig9 Observer

5.1 Rollover Detection

Same as the side slip state estimation, rolling state can be sketched as the quadrant plane (Fig. 10) according to roll and its angle speed. The rolling behavior located in the 1st and 3rd quadrant tends to be divergent and it is possible to estimate the stability in using gravity height information. The result of stability estimation makes wheel brake act appropriately and prevent rollover behavior.

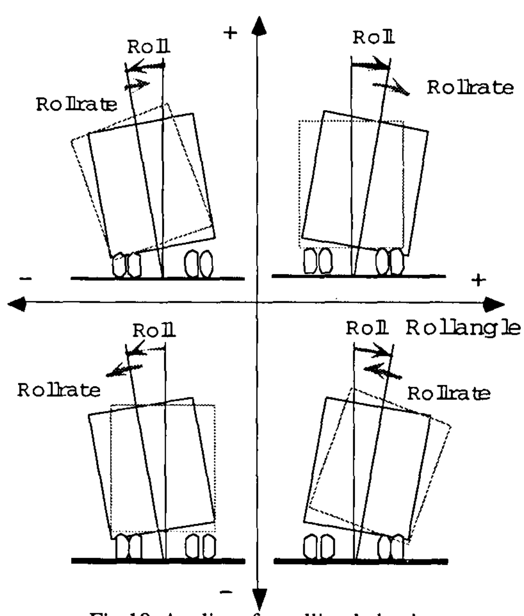


Fig.10 Analisys for rolling behavior

5.2 Application of Rollover Prevention

An experimental result for rollover prevention is shown in Fig. 11. This is the measurement when the test vehicle is passing a J-turn.

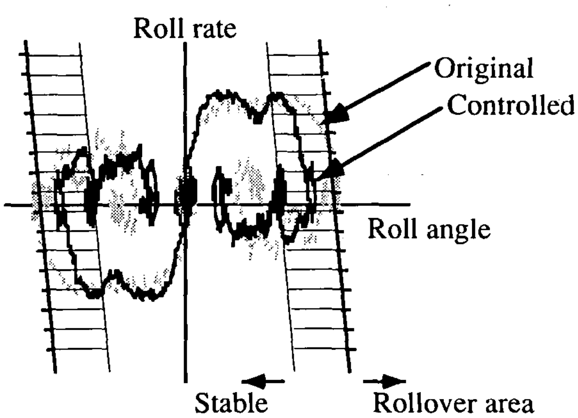


Fig11 Experimental result for anti-rollover protection

When the rollover behavior is over a certain threshold by inspecting the gravity height, the system makes each wheel brake work then reduce the rolling motion quickly. When the maximum roll angle is compared, the roll angle of the controlled vehicle is 2 degree smaller than that of uncontrolled vehicle, and the vehicle can safely pass the curve without getting over the lateral spin criteria(Fig.12).

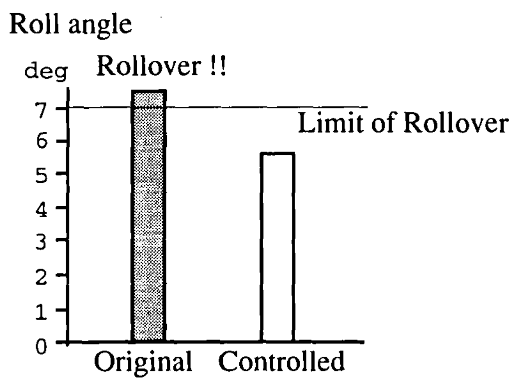


Fig12 Maxmum roll angle at J turn testing

6. CONCLUSIONS AND FUTURE WORK

Through the comparison of transfer function coefficients between the kinetic model and AR estimation model coming from experiment data, the gravity height estimation is performed. As the results of our study, (1) vehicle gravity height can be precisely estimated; and (2) the gravity height can be decided according to the loading status, e.g., flat loading or higher loading status. As the application, the lateral spin prevention control in using the information of vehicle roll and roll rate is testified and good result is achieved.

As the future work, we need to guarantee the system reliability for practical application.

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IMPROVED CRASHWORTHY DESIGNS FOR TRUCK UNDERRIDE GUARDS

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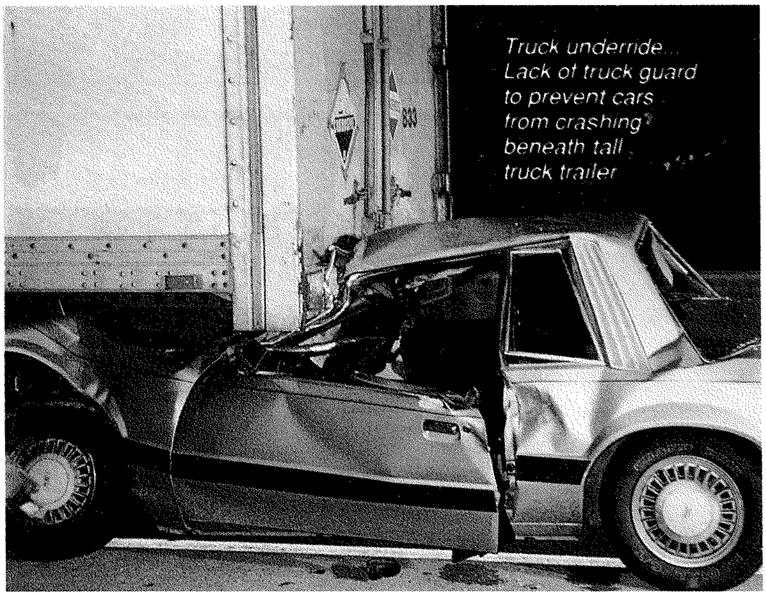


ABSTRACT

When a passenger vehicle collides with a large truck or trailer rig, this mismatch is further aggravated when the passenger vehicle continues beneath the rear or side of the taller truck. These are called ***truck underride*** crashes ... and often decapitate the upper half of the passenger vehicle and its occupants.

In the United States, there is a new federal motor vehicle safety standard requiring a rear underride prevention guard for newly manufactured truck trailers beginning in January 1998. The 22-inch maximum permitted height was based on 30 mph crash tests, yet contradicts prior NHTSA 35-to-40 mph crash test research that recommended an 18-to-20 inch height as necessary to protect smaller vehicles in 40 mph crashes. The guard strength is minimal, and the test is only a slow-push on an exemplar guard.

The new regulation also totally ignores the side underride hazard, which accounts for almost half of the U.S. fatalities in underride accidents each year.

Using existing technology, there are many feasible designs for rear underride guards and side underride guards that are effective, light-weight, and economical. Such guards can be utilized on new trucks and trailers, as well as being capable of being retrofit to existing in-use trucks and trailers. Among the explored designs are (A) the use of Belleville spring-washer stacked pistons, (B) the use of rigid foam-filled convoluted tube structures, (C) the use of recycled non-metallic synthetics, and (D) cable entrapment platforms.

And what of the requirement for ***harmonization*** of vehicle safety standards, so that all member nations utilize the same underride guard requirements, and thereby impose a reduced burden for variety among the vehicle manufacturers?

Can there be a singular international safety standard for truck underride guards, and if so, it should be based on the most effective requirements, rather than compromised to meet the least-challenging requirements?

INTRODUCTION:
The Truck Underride Decapitation Epidemic

When a passenger vehicle crashes into and continues beneath.. or *underrides*... the rear or side of a large truck or trailer, the consequences to the vehicle's driver and passengers are often the extreme ripping into and crushing of the passenger compartment *"survival space"*, and severe or fatal head injuries or even decapitation. The prevention of passenger compartment intrusion (PCI) is clearly the primary purpose of having an underride prevention guard. Though estimates have varied over the years, there are likely about 200-to-300 fatalities in underride accidents each year in the U.S.

There is also the parallel issue of the front of a large truck crashing over... or *overriding*... the lower structures of a passenger vehicle. Thus, there is a need for energy-absorbing and lower-to the-road frontal bumpers and overall design considerations to try to reduce the often lethal consequences of a massive truck colliding head-on with a smaller passenger vehicle. (The front override issue has been addressed in prior ESV papers, and continues as a major focus for needed safety improvements. This paper will focus on the truck rear underride and side underride issues and designs.)

In the United States, there has recently been a new requirement for an improved rear underride prevention guard for all newly-manufactured trailers and semi-trailers, as of January 26th, 1998. The new Federal Motor Vehicle Safety Standards are "Rear Impact Guards", FMVSS No. 223, and "Rear Impact Protection", FMVSS No. 224. The need for such underride prevention guards for trucks and trailers was initially proposed in 1967, some thirty years ago, as one of the initial standards promulgated by the then-newly- created National Highway Safety Bureau (NHSB).

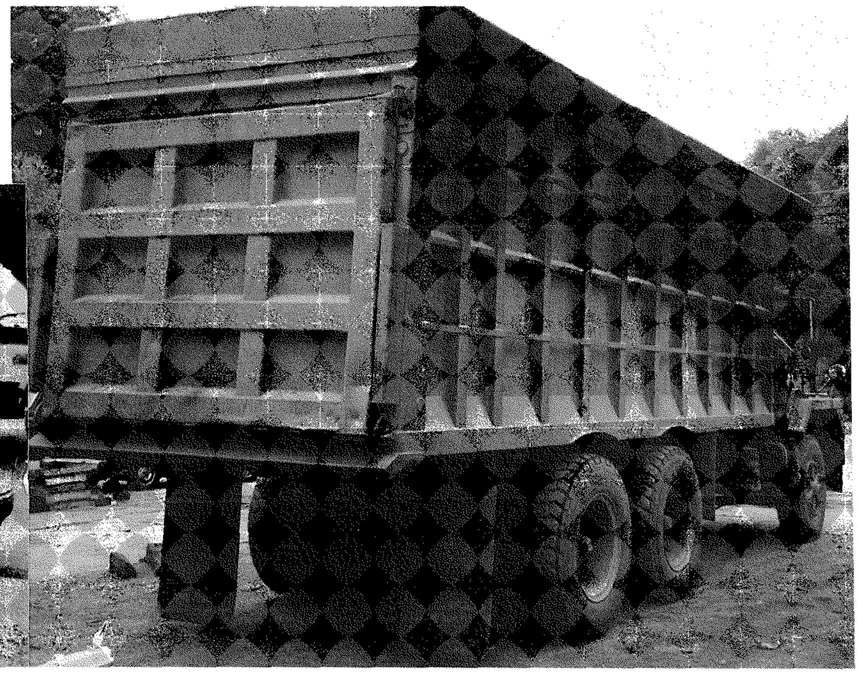
After a laborious and often-delayed thirty-year process from its inception as a proclaimed safety need, until its enactment in 1995 and its implementation in 1998, there is concern that the long gestation period did not give birth to an optimal safety standard. Admittedly, the process was on-again, off-again, on-again, off-again to such a perplexing extent, that merely having "some standard at last" seems better than continuing that thirty-year delay even more. **Yet, the new NHTSA regulation has many shortcomings:**

- The regulation applies only to new trailers, and does not also include single-unit trucks, dump trucks, or other trucks with lethal designs.
- The permissible guard height above the ground can be up to 22 inches, but should be 16 to 18 inches to protect smaller vehicles.
- The guard's strength requirements are too weak, and were derived from 30 mph crash tests, but should have been based on 40-plus mph requirements.
- Does not address the side underride hazard, which accounts for almost 50-percent of all underride fatalities.

The NHTSA fixation on fatalities does not take into account the merits of underride guards in reducing the severity of injuries, or preventing them completely. Severe brain trauma, extensive facial fractures, and the loss of eyes, are notable injuries that can be prevented with underride guards.

In many years of investigating car-into-truck collision accidents and evaluating the crashworthiness of the involved vehicles, the authors have noted many truck underride accidents in which the ICC rear bumper was grossly ineffective in its failure to prevent the intrusion into and crushing of the passenger compartment of the car, pickup, or van. In some cases, there was no rear or side guard or bumper at all.

In the United States, coal dump trucks and trash-hauling trucks typically do not have any rear underride guards or bumpers at all. In Brazil, and in many other nations as well, virtually all trucks are without underride guards,



or there is the pretense of a makeshift rear bumper that is totally ineffective. With or without governmental regulations, there is also neglect by truck and trailer manufacturers and operators to voluntarily and compassionately correct the underride hazard by designing and implementing safer trucks and trailers with effective underride prevention guards.

The truck industry in many nations, including the United States, has well known of the underride hazard and its toll of death and injury, but has delayed and argued and been indifferent to moving ahead constructively to help solve the underride hazard problems.

Many European nations, beginning with Sweden in the mid-1970's, have adopted rear underride guards. The European Economic Community (EEC) Commission Directive 79/490/EEC concerns rear underrun (underride) protection, and was enacted in 1979.

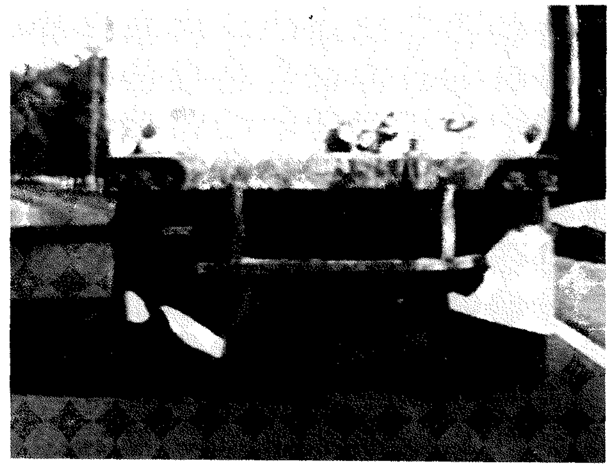
With regard to side underrun protection, ECE/TRANS/505 Regulation No. 73 was enacted in January 1988. While initially intended primarily to prevent pedestrians, cyclists, and motorcyclists from getting trapped beneath the long open sides of large trucks and trailers, the side underride guards have also been beneficial to help prevent cars from underriding, especially with angular crashes.

THE ICC REAR BUMPER IS OBSOLETE AND INEFFECTIVE

The 1953 ICC regulation for "Rear End Protection" has been demonstrated to be grossly ineffective. The vast majority of the ICC bumpers at the rear of trucks and trailers are too high off the ground (typically in the 24 to 28 inch range), are too narrow across the rear of the truck, and are too weak. These deficiencies of the ICC rear bumper have been shown in actual car-into-truck accidents and crash tests to fail to prevent a passenger car, minivan, compact pickup truck, sport utility vehicle, or van from penetrating deeply beneath the truck… resulting in passenger compartment intrusion (PCI) that causes severe to fatal injuries.

Nothing has prevented a truck or trailer manufacturer from designing rear bumpers that were safer, and were less than the "shall not exceed" maximums. Many years ago, they could have designed and installed rear bumpers that were **18 inches above the ground** (notably below the 30-inch maximum), and **full-width** across the truck's rear, and that had **strength and energy-absorbing features** that optimized the prevention of the underride hazard for vehicles that might crash into the rear of the truck or trailer.

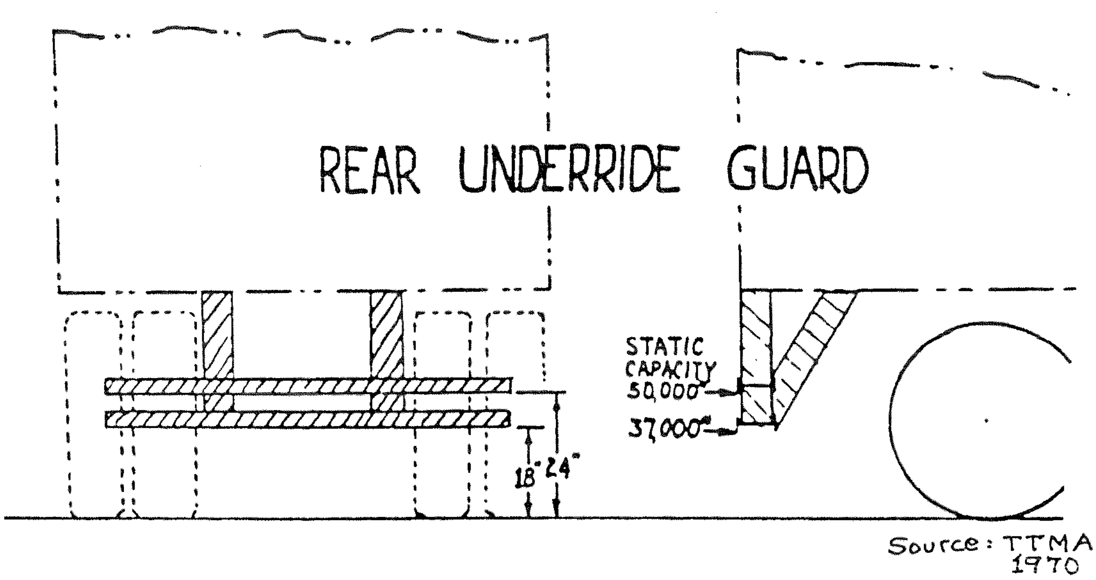
Over the past thirty years, safer rear underride guard designs have been discussed and described, but they have been largely ignored.

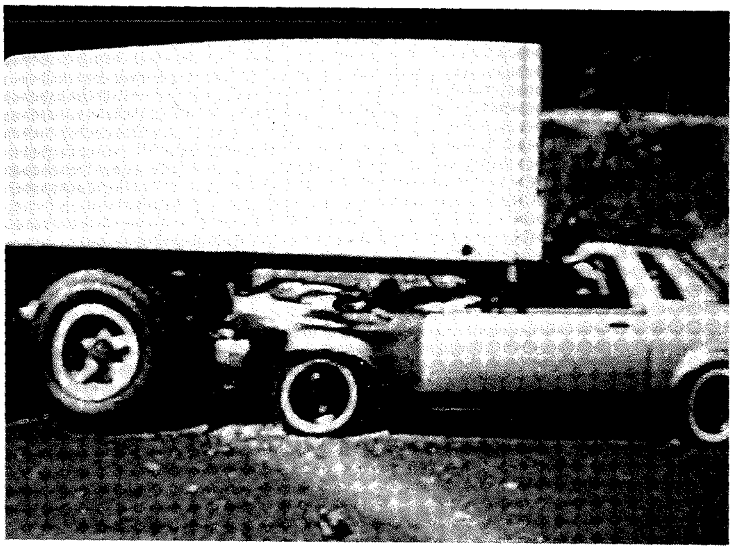


For example, the Truck Trailer Manufacturers Association (TTMA) back in 1970 noted that:

> ***"…it is within our competency to design and and mount on new trailers an underride guard capable of withstanding the test loads described in the DOT proposal and at a height of 18 inches above the road." "It is possible to provide the dual capability of 50,000 (pounds) at the 24-inch height and 37,000 (pounds) at the 18-inch height using the same structure. (See enclosed sketch)."***

Yet, in the subsequent 25 years since that 1970 proclamation, the TTMA did not recommended nor require that its trailer-manufacturer members actually implement such safer rear underride guards.





NHTSA STANDARD SHOULD ALSO APPLY TO TRUCKS

The new rear underride prevention guard requirement applies only to trailers and semi-trailers with a gross vehicle weight rating (GVWR) of 10,000 pounds or more. The standard does not apply to single-unit trucks, dump trucks, truck tractors, pole trailers, low chassis trailers, special purpose vehicles, or wheels back vehicles. A "special purpose vehicle" is defined as a trailer or semi-trailer that has work-performing equipment at the lower rear and whose function would be significantly impaired by a rear impact guard. The arbitrary weight requirement for excluding trucks and trailers below 10,000 pounds contradicts the fact that many light-duty and medium-duty and cab-chassis trucks are equipped with truck bodies that present the same lethal underride hazard as do the larger, heavier trailers and semi-trailers.

In its Final Regulatory Analysis of December 1995, NHTSA noted that over the past 13 years, total car-into-truck rear-end fatalities have averaged 421 per year, with 73-percent (308) due to collisions with combination truck-trailers, and the remaining 27-percent (113) due to collisions with straight trucks (GVWR greater than 10,000 lbs.). NHTSA noted that about 1.5 times more straight body trucks are manufactured each year compared to trailers (250,000 straight body trucks versus 162,000 trailers).

The fixation on fatalities does not take into account the merits of underride guards in reducing the severity of injuries, or preventing them completely. Severe brain trauma, extensive facial fractures, and the loss of eyes, are notable injuries that can be prevented with underride guards.

Because of NHTSA's abdication of setting a safer standard for straight trucks, it is important for the manufacturers and/or their trade association to voluntarily adopt a requirement similar to or preferably superior to FMVSS 223 and 224. Such a "Recommended Practice" should be issued by the Truck Trailer Manufacturers Association (TTMA), the American Trucking Associations (ATA), and the Truck Body Equipment Association (TBEA), and urged upon its members for immediate implementation.

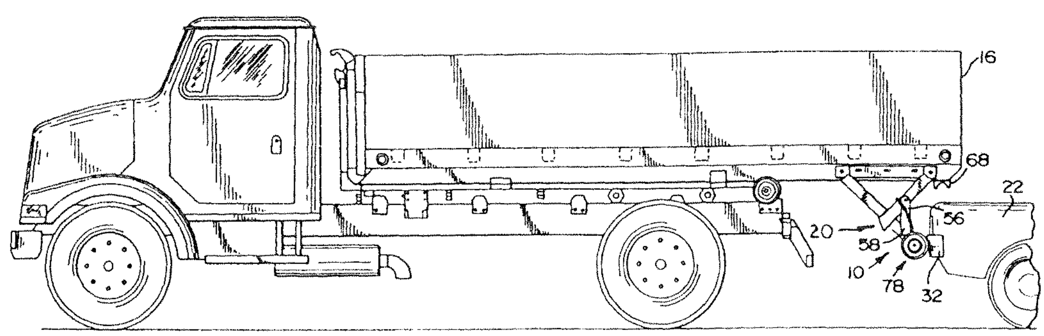
Thus, the U.S. now has two different sets of regulations. For new trailers only, effective in 1998, there are FMVSS 223 and 224. But for all other new trucks, the old 1953 ICC regulation is applicable. And for all existing trucks and trailers, they are also still regulated by the old ICC regulation, since there is no retrofit requirement. Thus, there is truly a "double-standard" conflict for new trucks versus new trailers. Yet, the underride hazard is the same.

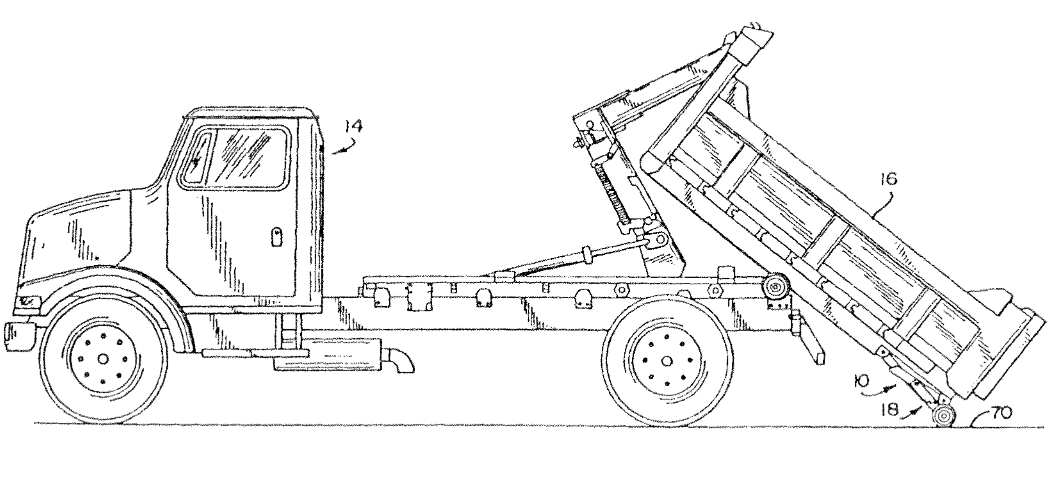
If you're a truck manufacturer, here's your dilemma... Let's assume you manufacture straight van trucks with a load floor or bed height at 36 inches, and city delivery van trucks with a bed height of 44 inches. Do you continue to use an ICC rear bumper that's permissibly (albeit unsafely) up to 30 inches above the ground, and is inboard about 18 inches from each side ? Or instead, do you incorporate a design that complies with the newer requirements as specified in FMVSS 223 and 224 which are specifically applicable to trailers. The decision should clearly be to adopt a lower, wider, stronger rear underride guard for all trucks.

Trucks come in all sizes, shapes, and weights... and they all should be designed to minimize the underride hazard if at all possible. There are coal dump trucks with extensive rear overhangs of about 6 feet, and they clearly present a lethal underride hazard.

Coal dump trucks and tilt-bed tow trucks and others can be feasibly equipped with rear underride guards that automatically pivot and fold rearward beneath the truck body as it tilts in performing its work function. Shown below is an example of a United States patent for a rear underride guard that can be retracted upward when the truck dump function is utilized, and then is returned down to an effective height to serve as an underride prevention guard when the dump truck is traveling on the road.

There are tow trucks with tiltable car-carrying platforms that project rearward like an ax blade. There are straight body trucks which have frame rails or bed heights in the 36-to-48 inch range, presenting an underride hazard virtually identical to that of a trailer. There are large trucks with tuck-under lift gates that are sloped beneath the rear of the truck and can thus accentuate the underride hazard by "funneling" the car even lower as it continues beneath the rear of the truck.





These drawings are from a United States patent that shows a rear underride guard for dump trucks. The guard is normally in a down position when the truck is traveling on the roads, but can be retracted pivotally upward when the truck is performing its dump functions at a work site.

DESIGN FOR CRASHES ABOVE 30 MPH AND LOWER GUARD HEIGHT

NHTSA's most recent crash test program to evaluate the underride situation involved the use of the subcompact GM Saturn and Honda Civic, and the compact-size Ford Tempo and Chevrolet Corsica sedan and Beretta coupe. The car crashed into either a rigid guard or a moderate-strength guard, which were mounted to either a 1988 Fruehauf 48-foot-long trailer, or a specially-constructed Rigid Test Fixture that had a ground-to-floor-bottom height of about 49 inches. (Refer to "Heavy Truck Rear Underride Protection," VRTC-82-0267, Vehicle Research and Test Center, East Liberty, Ohio, June 1993, Final Report, DOT HS 808-081.)

The 30 mph crash level for the new NHTSA regulation is grossly inadequate, since the technical capability exists to exceed at least a 40-plus mph level. Accident data and case evaluations indicate that the vast majority of truck underrides occur in the 30-to-50 mph range. And prior crash tests programs, such as Cornell in 1971 and Dynamic Science in 1980, demonstrated that a 40-plus mph rear underride guard was feasible, it seems short-sighted of NHTSA to settle for the unrealistically low level of 30 mph. Truck and trailer manufacturers should recognize that the new NHTSA regulation #223 and #224 are only "minimums" that should be significantly exceeded by the installation of production guards with a notably higher capability.

In contrast to this most-recent 30-to-35 mph crash test series conducted at VRTC in 1993-94, previous NHTSA crash test programs (e.g., 1979-80 at Dynamic Science) for developing and evaluating rear underride prevention guards have included crash tests in the realistic 35-to-40 mph range... [Note that a 40 mph crash test is about 1.8 times more severe than a 30 mph crash test. The energy varies as the square of the velocity... the ratio is $(40)^2$ over $(30)^2$, or 1600/900 = 1.8]

The application of a slowly-applied force to the underride guard exemplar may not adequately test impact strength. Some underride guard designs that may be capable of withstanding gradually applied loads may fail when the same amount of force is applied abruptly. Similarly, the attachment of the guard to the frame structure of the truck or trailer may transfer the applied loads in an actual crash accident to what may be a weaker frame rail. The applied load requirement of 22,480 lbs. is also notably below the previously-recommended 50,000 lbs. that was derived from crash tests in the 35-40 mph range, including larger passenger vehicles than the Saturn-Civic-Tempo-Corsica range.

The slowly-applied loads also do not necessarily account for offest and angular impacts that occur in real-world accidents, and which may tend to overwhelm a vertical support and cause it to catastrophically fail or break-away... thereby allowing the car to continue to dangerously underride beneath the taller truck or trailer..

The 1971 Cornell crash test program for NHTSA, in its report titled "A Study of Heavy-Vehicle Underride Guards" (SAE 710121), described the twelve car-into-truck crash tests with guard heights of 18 inches and 24 inches. Their conclusion was that an 18 inch guard height provides protection for the smaller cars. Small VW Beetles and full-size Fords were used in most tests.

The 1980 Dynamic Science crash test program for NHTSA, in its report titled "Development of Compliance Test for Truck Rear Underride Protection" (DOT HS-805-564), noted among its Recommendations:

> ***"To prevent excessive underride, it is recommended that the guard height***

not exceed 20 inches at the impact speeds from 30-40 mph and 22 inches below 30 mph to ensure adequate structural engagement of the car (engine) with the guard."

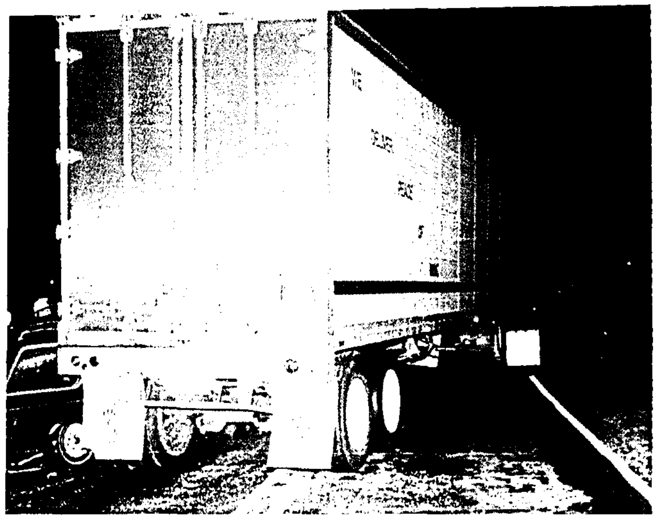
However, when the new FMVSS 223 and 224 requirements were issued in the mid-1990's, the prior recommendations for the 18-inch maximum height and the 20-inch maximum height were both ignored. The new requirement is for a 22-inch maximum height, which is too high in view of the 16-to-20 height of many vehicle bumpers and supporting structures.

THE CRITICAL NEED FOR *SIDE* UNDERRIDE PROTECTION

The new NHTSA regulation totally ignores the need to require side underride prevention guards.

Back in 1968, the National Highway Safety Bureau (which became NHTSA in 1971), funded a study entitled "Development of Standards for a Heavy Vehicle Underride Guard". The research was conducted by Aerospace Research Associates (ARA) of California. Various side underride guard designs were discussed, including those with energy-absorbing features. The report noted that *"If a heavy vehicle is struck from the rear or side by a light vehicle, serious injury can be incurred by the occupants of the smaller vehicle. It would appear that equipping such heavy vehicles with rear and side underride guards would result in a reduction of a number of fatalities and the severity of injuries."*

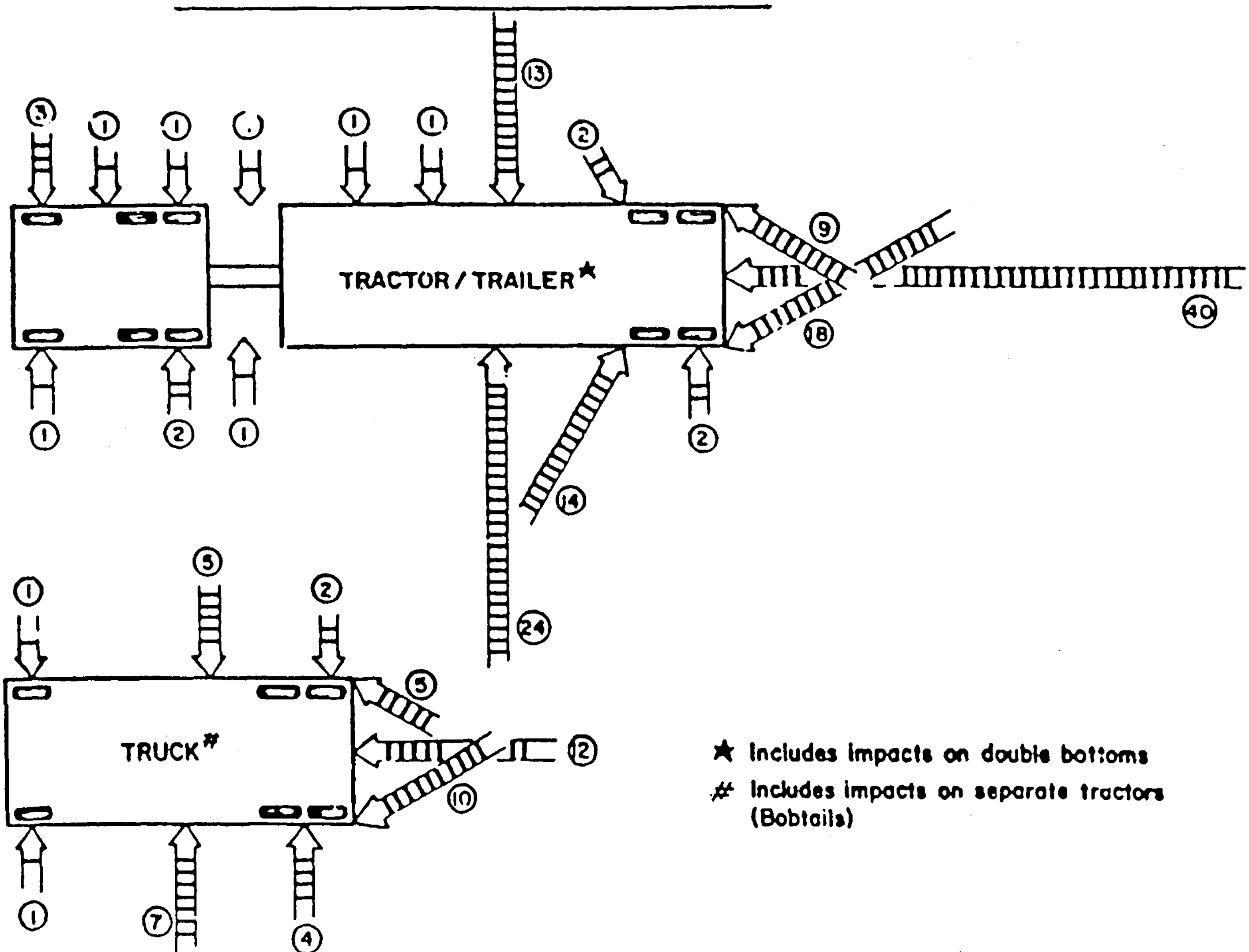
Then in 1970, as the NHSB proceeded further with rule-making efforts for rear underride guards, they noted that further consideration would be given, after ompleteion of technical studies, to underride protection for the sides of large vehicles. Despite those good intentions, the side underride efforts were essentially put in llimbo following the 1971 White House directive to cancel or shelve various then-pending vehicle safety regulations.



In the 1977 research report "Car-Truck Fatal Accidents in Michigan and Texas", by the Highway Safety Research Institute (HSRI), at the University of Michigan, U.S. Dept. of Commerce PB-274-111, a study was conducted of car-into-truck and car-into-trailer accidents. As a rough **estimate, the researchers noted that there would be 261 rear-end underride car-into-truck fatal collisions per year, and 195 side underrides per year.**

The distribution of points of impact for 181 car-truck/trailer fatal crashes were illustrated as shown in this excerpt drawing from the HSRI report. The report notes not only the large quantity and percentage (almost half) that are side and side-angular crashes, and also notes the majority (65 out of 87) were in the 30-to-50 mph range

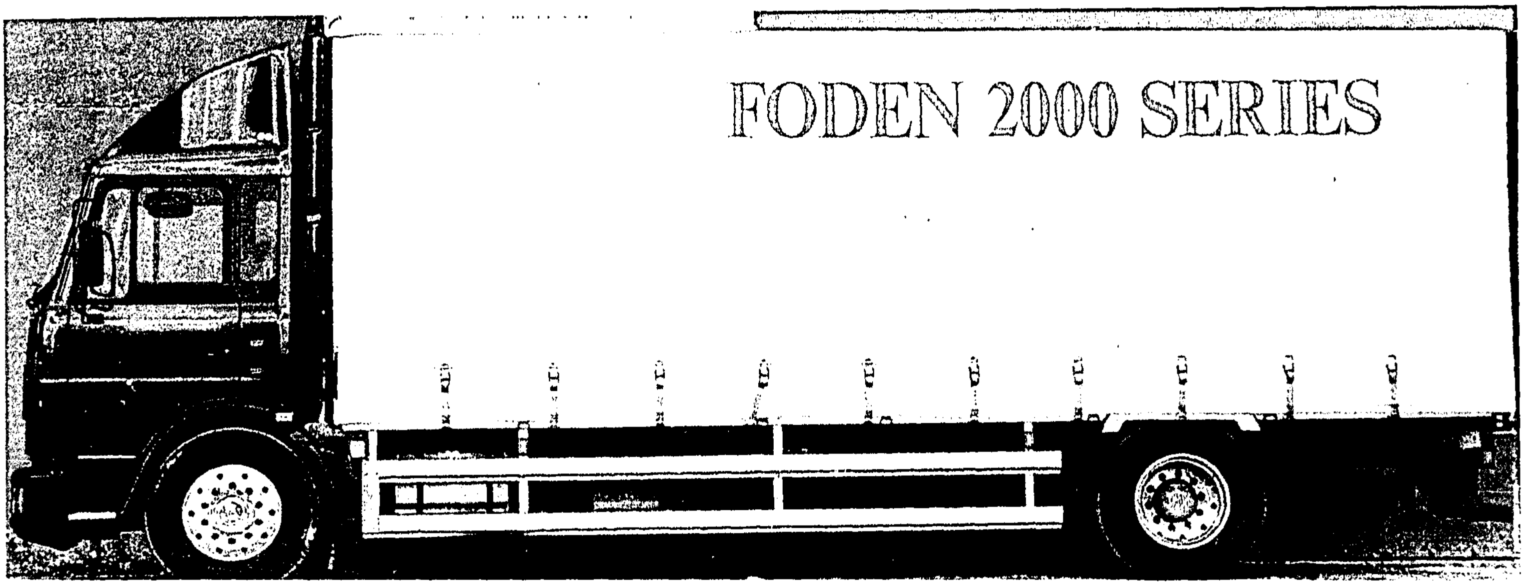
Figure I. DISTRIBUTION OF POINTS OF IMPACT
181 CAR-TRUCK/TRAILER FATAL CRASHES



★ Includes impacts on double bottoms

Includes impacts on separate tractors (Bobtails)

Source: H.S.R.I.-19



In England and other European nations, side underride guards were implemented beginning in the early to mid 1980's to protect motorcyclists, bicyclists, and pedestrians from becoming entrapped in the open space along the sides of the trucks and trailers. Discussions with European colleagues indicate that such side underride (or "underrun") guards have also demonstrated effectiveness in helping prevent cars from underriding.

Similar to a guard rail along the highway, such side underride guards also can be effective in helping deflect cars from unsafely underriding into and beneath the tall sides of trucks and especially long trailers. When a large tractor-trailer rig makes a lane change on the highway, an adjacent car may not be readily perceived by the truck driver… and the car gets trapped in the long-open side of the trailer and crushed by the trailer's rear wheels, as well as having the trailer's side structures crush into the car's roof.

Other side underride accidents have occurred when a tractor-trailer makes a turn at an intersection or pulls out onto the highway in front of oncoming traffic. Others occur at night, for example, when the Headlights of the tractor create glare to an oncoming driver and thereby camouflages the visual perception that the tractor's long trailer is still diagonally straddling the road ahead.

The use of retro-reflective tape along the sides and rear of trucks and trailers is exteremely beneficial in enhancing their ***"conspicuity"*** or perception and identification at night and in inclement weather, so that motorists can see and understand the nature of the large truck danger ahead, and thereby hopefully avoid the accident from occurring in the first place, or at least reduce the severity of any collision that might occur.

It is imperative for NHTSA to immediately focus on rulemaking for a side underride prevention safety standard. This would be a logical companion standard to FMVSS 223 and 224.

It is interesting to note that NHTSA, back in 1970, noted they soon would be giving consideration to the subject of underride protection for the sides of large trucks and trailers. Virtually nothing has been done since then. There is also a need for a federal safety standard to address heavy truck frontal aggressivity and front underride prevention.

IMPROVED CRASHWORTHY DESIGNS

Most rear underride guards have been of a simple design, with two vertical struts and a single horizontal bar. As guard designs have become stronger and full-width across the rear of the truck or trailer, additional vertical struts and diagonal braces and gussets have been added to help prevent the guard from bending forward too easily, or even breaking a strut completely away from its anchorage.

While the use of energy-absorbing mechanisms has been attempted, few current designs utilize any such features. Therefore, the typical guard will begin to yield and bend forward under the load from a rear-ending car... which can cause the adverse effect of "funneling" the car downward, compressing the front suspension downward, and aggravating the underride hazard.

It is also preferable to utilize rear underride guard designs that engage the passenger vehicle at a lower height, preferably in the 16-to-18 inch height above the road surface, so as to more effectively engage the front bumper structures, front suspension, and tires. This lower engagement will help reduce the adverse effect of the rear structures of the truck loading essentially downward on the car's sloping hood.

THE BRAZILIAN PLYER GUARD

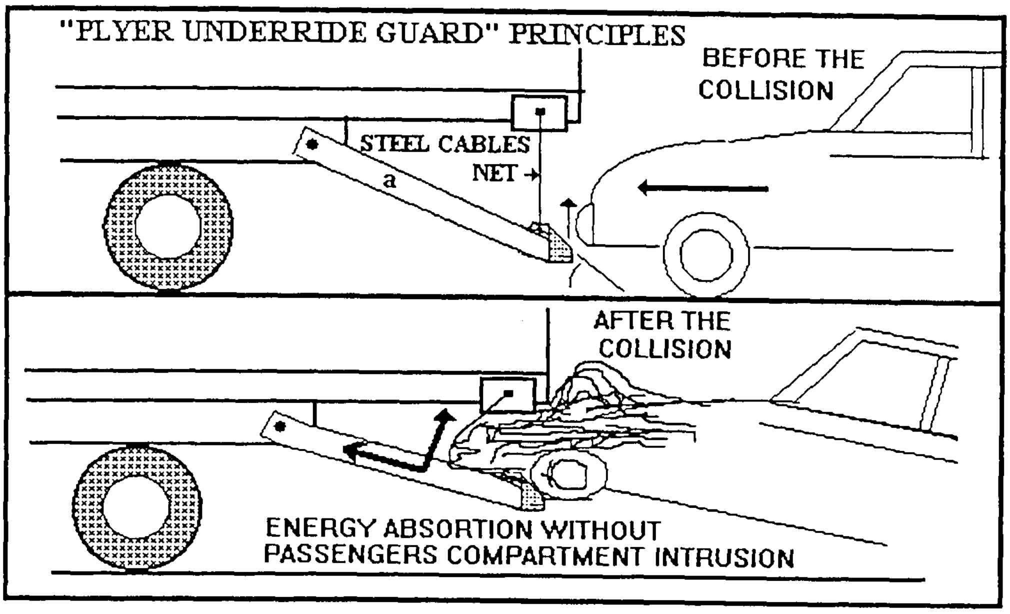
A novel design for an underride prevention guard was conceived at the Biomechanics Engineering Laboratory, at Unicamp State University, in Campinas, Brazil. The particular design is referred to as the "Plyer Underride Guard", denoting its relationship to the mechanical principles of a simple pliers tool.

As the passenger vehicle or car engages the low-mounted crossbar, the car becomes entrapped. As the car continues forward, it progressively deforms the "net" of steel cables. As this engagement takes place, it also allows the vehicle's designed-in frontal "crush zone" to deform and absorb the collision forces as well. Thus, the passengers are receiving the dual safety benefits of the car's frontal crush zone doing its work, and also the elimination of the unsafe underride penetration into the passenger compartment.

The Brazilian Plyer Guard was successfully crash-tested on April 14, 1998, at the General Motors crash laboratory facilities near the city of Indaiatuba, Sao Paulo State. The car was a GM Vectra that crashed into the rear of the target truck at 40 mph in a 50% offset collision.

The Vectra's front bumper was the first part of the car to impact the Plyer Guard's steel cables, which assured that the Vectra's designed-in energy-absorption capabilities, its frontal "crush zone", was fully employed. The Vectra's windshield was not touched by any part of the truck. The front doors could be easily opened, which would thus facilitate the exiting or rescue of the passengers.

In this initial crash test of the Plyer Guard, the main goal of preventing intrusion into the passenger compartment was fully achieved. An initial review of this demonstration crash test of the prototype Plyer Guard indicates that it would likely perform well with regard to higher



impact speeds or forces. The project staff will continue to optimize the design.

For further details of the Brazilian Plyer Guard Project, including the crash test results, please refer to the internet website as follows:

http://www.cte.unicamp.br./impact

There are other energy absorbing techniques that can be readily applied to underride guards.

Belleville Spring Washer Concept:
Belleville spring washers are like thin-metal "pie plates" of varying strengths and concave/convex contours. These "pie plates" can be strategically stacked within a chamber, so that a movable piston will react into the stack. By selecting the strength and contour of these "pie plates", they can absorb energy progressively so that smaller cars of lighter weight can be allowed a progressive "ride down" as it crashes into the guard at 30 mph or at 50 mph... since the higher-speed crash will also engage the stiffer, stronger pie plates. Heavier cars will similarly be accommodated by the varying energy-absorbing deformability of the differing pie plates that have been stacked within the piston chamber.

Rigid Foam Filled Structures Concept:
The use of high-density rigid polyurethane foam inside of tubular or compartmented structures has been shown to triple the bending strength and compressive strength of that structure. Thus, the foam-filled design concept enables a light-weight, economical, and efficient technique to be applied to the design of rear and side underride guards. For example, the foam-filled strengthening can be applied within the diagonal struts that are typically used to brace the vertical members of a rear underride guard.

Recycled Non-Metallic Synthetics
The rubber from used tires is often recycled. The rubber tires are initially shredded and powdered, and can be mixed with bonding agents to create a moldable basic material. The molding of underride guard members or

rails can be accomplished in large molds, with inserts of reinforcements such as wires, cables, or interwoven fibreglas-type sheets.

The freedom to explore many different and novel design for rear underride guards and side underride guards should be encouraged. An early concept of a dual-level and dual-strength rear underride guard was shown by the Truck Trailer Manufacturers Association (TTMA) back in 1970. Quinton-Hazell of England demonstrated an energy-absorbing rear underride guard that utilized hydraulics and pistons. Tube Industries of England demonstrated a novel concept of inverted tubes to absorb energy (the larger tube inverted over the smaller tube in a manner somewhat akin to peeling a stocking off of a leg).

CONCLUSION

The truck underride issue will continue to be of vital concern. The truck underride regulation must be made applicable to all trucks and trailers that may present an underride risk, primarily due to their extended rear overhang profile and side underride dangers as well.

We can encourage progress in developing and implementing side underride guards, and in improving the rear underride guards that will be installed in conformance with the new NHTSA regulation. We can also encourage progress in developing and implementing safety measures to alleviate the hazards of heavy truck frontal aggressivity and underrun.

Manufacturers and operators of trucks and trailers should maximize their efforts and implement the safest available designs, and not settle for the minimum levels of compliance. Thus, the continuing epidemic of underride accidents will be reduced, many of the underride fatalities and severe injuries will be prevented, and the industry will reduce its risks and costs of litigation and liability.

Many nations, such as Brazil, must move ahead expeditiously and adopt regulations to require that all large trucks and any other vehicles that present an underride hazard, be equipped with effective underride prevention guards.

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A CASE STUDY OF 214 FATAL CRASHES INVOLVING FIRE

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ABSTRACT

A detailed case study of 214 fatal fire related crashes was conducted to determine whether the death was caused by the fire or blunt trauma. The cases were also examined to determine the specific crash conditions which caused the fire. This analysis was necessary because none of the existing fatal crash databases contained sufficient details to determine the impact configuration or the cause of death. Two hundred and ninety three (293) fatalities occurred in these crashes. Sixty-five (65) of these fatalities resulted from fire, with 30 of these fatalities from 16 rear impacts. The speed of impact was determined in eight of the 16 cases which caused these 30 burn fatalities. In these eight cases, the average rear impact speed was 54 mph with speeds ranging from 50 - 60 mph, at 71% overlap (71 % of the rear vehicle width engaged), and collinear at 6:00 O'clock. By projecting these cases to the national sample, the number of rear impact fire related fatalities may be estimated between 94 and 191.

INTRODUCTION

A case study of 214 fatal fire related crashes was conducted. FARS (Fatal Analysis Reporting System) data were queried for 1990, 1991, 1992 and 1993 to obtain a listing of cases in which fire was coded. Cases were obtained by soliciting seven states for crash records in which case history information was available. The crash records may have included all or part of the following: (1) photographs which documented the crash site and the vehicle damage, (2) "police accident reports" (PARs) which described the crash according to the opinion and findings of the investigating officer, (3) witness statements sometimes indicating the intensity, location, and timing of the fire, (4) medical records which stated whether an autopsy was performed and what the findings of the autopsy were related to the cause of death, typically differentiating between conflagration and blunt trauma. The states solicited were Illinois, Florida, Colorado, Arizona, Ohio, Delaware, and West Virginia. Approximately 303 cases were received from which 89 were eliminated for one or more of the following: (1) The case Information was insufficient to determine impact mode, (2) the cause of occupant's death could not be determined, (3) there was a multiple vehicle collision with no fatality in the vehicle which burned, (4) the fatally injured was a motorcycle rider (two cases). While this sample is not claimed to represent a statistically valid sample, it does represent a large randomly selected sample of fatal crashes in which a fire was involved.

FARS data for 1990-1993 were used to compare the trend of fatalities in these seven states to the national FARS data for the four years used in this study. In 1990-1993 FARS there are 4,090 vehicles involved in a crash with a fire, known principal impact point, and at least one occupant fatality. Likewise, for the seven states there are 698 vehicles coded for the four year study. Table 1 shows the number and distribution of these vehicles by principal impact point.

METHODOLOGY

The study consisted of reviewing the available hard copy case files and determining from the available data the likely crash scenario which caused the fire. Note that this is different from FARS coding which does not attempt to identify the event that caused the fire. The only similar parameter available from FARS is the principal impact point (see Table 1) which may or may not be the cause of the fire. To determine the impact speed and crash configuration, the police accident report and the scene photos were used. If data were sufficient, the specific impact condition which caused the fire was compared to available crash test data to estimate the crash severity and crash conditions likely to cause similar damage.

Additionally, the cause of death was determined by judgemental decisions based on the crash severity, likely occupant kinematics, crash type, and autopsy or coroner's report. Priority was given to death certificates by a medical examiner, unless there were confounding findings in the case analysis. Witness statements were also used in a few cases to determine the immediate post crash state of the burn victim.

Table 1.
Number and Percent of Vehicles with at Least One Occupant Fatality and a Fire

Crash Configuration	National Sample FARS	Seven State FARS
Front	2797 (68.4%)	483 (69.2%)
Rear	286 (7.0%)	43 (6.2%)
Side	844 (20.6%)	145 (20.8)
Top	87 (2.1%)	21 (3.0%)
Other	6 (0.9%)	76 (1.9%)

To project the number of fatalities expected from fire on an annual basis, the 1995 FARS automated files were queried. Assuming these cases were representative, an annual projection was made and statistical variance calculated.

FINDINGS

From the 214 fire related crash cases, 45 cases (21%) resulted in one or more fatalities due to the fire (burn related trauma). There were 293 total fatalities in 251 vehicles which burned, consisting of impact related trauma to 228 occupants (78%) and burn related trauma to 65 occupants (22%).

The distribution of all 214 cases by crash mode is shown in Figure 1. To compare the selected seven state cases to all fatalities as reported in FARS, see Table 1. This comparison indicates that the seven states are almost identical to the overall national FARS data. However, as might be expected due to inconsistencies as previously discussed, the data in Figure 1 and Table 1 are not entirely consistent. This may be explainable by differences in FARS coding and the detailed case study which only focused on the impact which caused the fire. Additionally, Figure 1 is sorted by crash case whereas the FARS data are sorted by vehicle. Therefore a vehicle reported in FARS as involved

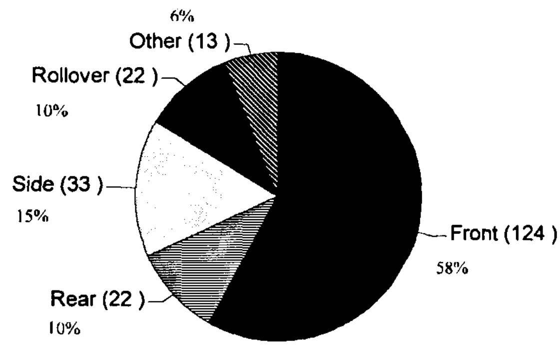

Figure 1. Distribution of all occupant fatal crashes in which a vehicle caught fire (total cases 214).

in a fire crash with principal frontal damage, may have run in to the back of a vehicle which caught fire from fuel leakage and caused both vehicles to burn. Therefore FARS analysis would have double counted this case under front and rear impacts, whereas the case study would have only counted the source of the fire (rear struck).

The distribution of all fire related fatal crashes (Figure 1) does not establish the most probable impact to cause a burn fatality, but does show the majority of fires occur in frontal impacts. The subset consisting of 45 cases in which the fire was judged to have caused the fatality is shown in Figure 2 as a distribution of fatalities. For the 45 cases and 65 fatalities in which the occupant was judged to have died because of the fire (burn trauma), a distribution was calculated for percent of fire trauma fatalities by impact type. This distribution shows that 46% of the fatalities occur from rear impacts, 23% from front impacts,

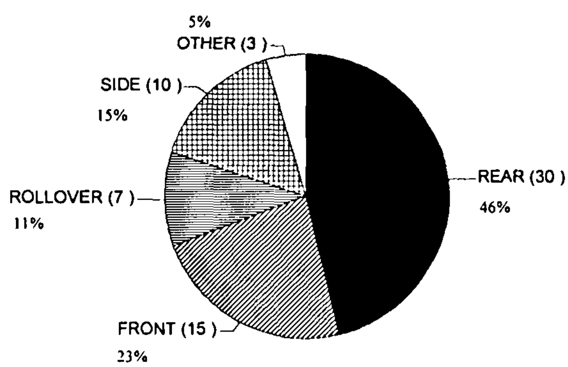

Figure 2. Distribution of occupant fatalities due to fires in vehicle crashes (total fire fatalities 65).

15% from side impacts and 11% from rollover crashes. In addition, four percent of the fatalities were classified as "other". The appendix summarizes the crash cases in which the fire caused the fatality. If the percentage of fatally burned victims and the distribution of crash type determined by these cases is assumed to represent the entire population of fatal fires, a prediction of annual fire related fatalities by impact mode may be estimated. FARS data from 1995 shows there were 1392 car and light truck fire related fatalities (approximately 5 times the study sample). By assuming the cases in this study are representative of 1995 fatalities, we may estimate that 22% (65 burn victims out of 293 fatalities in the study) of these fatalities would have resulted in burn trauma for a total of 309 fatalities/year. Of these, the number of projected fatalities based on Figure 2 are 143 rear impact fatalities, 71 front impact fatalities, 33 rollover fatalities, 48 side impact fatalities and 14 others. The 95% upper and lower confidence limits (1) for the projected fatalities are calculated as shown in Table 2.

Table 2.
Projected Upper and Lower Confidence Limits of 1995 Fatalities Based on the Sample of FARS Cases Analyzed for Impact Condition and Fatality Cause

Crash Configuration	Lower Limit of Fatalities	Projected '95 Fire Fatalities	Upper limit of Fatalities
Front	36	71	106
Rear	94	143	191
Side	19	48	76
Rollover	9	33	58
Other	0	14	30

Past studies have attempted to distinguish burn trauma from impact trauma injuries associated with fire. Since FARS currently has no means of distinguishing cause of death in crash-related fires, some researchers have attempted to use the variable called "Most Harmful Event or MHE". A search was done on FARS data to check the correlation of the coding of this variable as "fire/explosion" for the cases in this study for which we determined death resulted from burn trauma. It was found that MHE was coded for the vehicle as fire/explosion in only 29% of the cases. This finding points out the need for a better indicator to determine the cause of harm to the occupant in a fire-related crash.

The case narratives are included in the appendix for the 45 cases discussed above for which fire was judged as the cause of the fatalities. Of all crash configurations, only rear impacts have consistent crash and fire scenarios. In all 16 rear impact cases the vehicle is struck in the rear causing loss of fuel from the tank area which ignites during impact and results in a rapidly spreading fire and resulting fatalities.

At the end of each crash description for the rear impacts, the crash test simulation based on the available information which best replicates this scenario is summarized. For this summary the impact speed is normalized to a 3000 pound moving deformable barrier (MDB) , striking the rear of the stationary subject car. Listed in this summary are: the speed of impact, the percentage of overlap, and the angle from collinear (0 degrees representing collinear). This level of detail was available for eight of the 16 rear impact cases. The average of these eight is a 54 mph MDB impact at 71% overlap. Seven of the eight cases were collinear. Therefore it appears that a 70% overlap 3000 lb. rear moving deformable barrier at 50-55 mph may provide a reasonable crash simulation of real world rear impact fatal burn cases (2).

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APPENDIX

Rear-End Crashes

CASE NO. 220 V1, a 1979 Pontiac 2 dr Sunbird while traveling westbound at high rate of speed (approx. 80 mph) in the middle lane of a 6 lane divided highway, impacted the right rear end of V2, a 1984 2 dr Mustang, which had just pulled into the middle lane out of a driveway 180 feet before the impact. V2 exploded upon impact in the vicinity of the rear mounted tank. Attempt to extricate the driver were unsuccessful as the car was quickly consumed by fire. At impact The Mustang speed was estimated at 30 mph and the Pontiac speed at 80 mph (no pre impact braking). The damage severity and pattern were compared to a NHTSA research crash test using a moving deformable barrier into the right rear of a 1993 Ford Mustang at 52 mph at 80% overlap. The results were almost identical. The crash test resulted in a ruptured fuel tank and excessive spillage of stoddard solvent (Used in place of gasoline). Fuel tank rupture must be assumed as the cause of fire. The gas tank was also reported in the PAR to be damaged, spilling gasoline and causing fire. It also was reported to have been pushed up and into passenger compartment. The autopsy concluded the cause of death as "Thermal burns". (52 mph, 80%, 0 degree)

CASE NO. 9 This was principally a two vehicle front to rear impact with minor involvement with third vehicle. V1, an 1988 Chevy Beretta, 2 dr was traveling in a 45 mph speed zone and failed to stop for V2, a 1979 Chevrolet (Nova?) 2 dr sedan which was stopped for traffic congestion due to construction. V2 was pushed forward into the rear of V3, resulting in minor bumper damage to V3. D1 was coded as 'possible injury' and D2 a 25 year old male was fatally injured. Autopsy findings stated that the cause of death was "Conflagration injuries". Autopsy also found "blunt posterior thoracic trauma with hyper extension injury through T-2 vertebra and fracture of left 6-9 ribs in the subscapular line". I would estimate the speed of impact to be approximately 50 mph with a 50% overlap on left side and collinear. There was some underride of bumper due to braking. (50 mph, 50%, 0 degree)

CASE NO. 129 A 1981 Plymouth Champ sideswiped two vehicles and was directed into the path of a tractor/trailer which impacted the rear end of the Champ. According to the PAR, the sole occupant, a 27 year old male driver was trapped inside the vehicle and died from fire burns. (Since no photos were available specific crash conditions were unknown)

CASE NO. 142 A 1987 Jeep Cherokee was stopped at a light and struck in the rear by a 1972 Mercedes 230. The Cherokee was pushed in the intersection into the side of a third vehicle. The Cherokee burned and the Coroner's report listed fire burns as cause of fatal injuries for the 33 year old male driver. Also 8.6% CO was noted in the blood. (Since no photos were available specific crash conditions were unknown)

CASE NO. 165 A 1982 Ford Mustang, 2 door, was stalled in traffic and struck in the rear by a 1986 Chrysler Lebaron. There were three occupants in the Mustang. Two occupants were able to exit the vehicle before it became engulfed in flames. The driver did not escape the fire and died. No Coroner's report was provided, but it must be assumed that the incident was survivable based on the safe exit of the other two occupants. From sketches this appears to be a right offset/oblique impact to the rear of the Mustang. (Since no photos were available specific crash conditions were unknown)

CASE NO. 144 A 1984 Mercury Marquis was stopped in traffic when struck in the rear by a 1985 International 175 straight truck. The Marquis was pushed into another vehicle which in turn was pushed into yet another. Neither of the secondary collisions resulted in fatalities or serious injuries and the damage severity was relatively low. There were four occupants in the Marquis, two in front and two in the rear. Their ages ranged from 59 to 82 years old. According to the coroner report three positively died from the fire as evidenced from CO found in lungs (ranging from 10-53%) and one left rear seated 82 year old female was so severely burned that the lab was unable to perform TOX test. The autopsy found fracture of third and fourth ribs causing laceration of aorta and contusion of the heart. It may be reasonably assumed that fire would have caused the death of a younger and stronger individual. Therefore this will also be consider for this analysis as a burn related fatality. This was a major fire in which the entire vehicle was consumed, by fuel tank to fuel filler separation. Ignition was likely a result of bumper dragging pavement. Photocopy photos were available but of little use because of poor quality. The crash was approximately 60 - 70 % overlap at 6:00 on the right side of the Marquis. The speed of the truck was reported to be 60 mph but had to have slowed considerably by time of impact, probably to approximately 30-40 mph at impact due to evasive maneuver to right and pre-impact braking. Subject car was spotted just 15 feet prior to impact according to truck driver's statement but this would not have allowed sufficient time for documented evasive maneuvers. (Est. 55 mph MDB, 65 % overlap, 0 degrees)

CASE NO. 175 A 1977 White tractor/trailer was making a lane change and impacted the left rear corner of a 1992 Honda Accord. There was a major fire from fuel tank rupture of the Accord. The sole occupant (driver) of the Honda, a 27 year old male died from fourth degree burns and smoke inhalation according to the death certificate. (Since no photos were available detailed crash conditions were unknown)

CASE NO. 223 A 1986 Chevrolet Nova, four door sedan drifted into the emergency lane and impacted the rear of a parked unoccupied 1976 Dodge Van. A major fire consumed both vehicles and the sole occupant/driver of the Nova, a 31 year old male, died two days after the incident from thermal burns over 80% of his body. This finding is summarized from a very detailed and thorough autopsy report which was provided. According to sketch in PAR appeared to be a left offset rear impact to van which caused the fuel spillage and fire. (Since no photos were available exact crash conditions were unknown)

CASE NO. 224 V1, a '88 Pontiac with T top turned left into path of V2, an '85 Ford PU. V2 STRUCK V1 at the right front wheel at approximately 2:00 O'clock position. V1 then spun counter-clockwise and turned over. Both vehicles came to rest with the rear of V1 against the right side of V2. The filler cap on V1 was missing and the filler and tank was intact on V2 (left side filler and tank). It was therefore concluded that only gasoline spillage resulting from rupture of the fuel tank could produce such an intense fire as seen in photos. Therefore cause was attributed to the secondary impact between the rear of the Pontiac and the right side of the PU. The secondary collision between the rear of V1 and the side of V2 caused significant distortion in the rear of V1 and likewise caused the breech of the fuel system. There were three occupants in V1. In V1, D1 and P1 were extricated before being consumed by fire while P2 was able to extricate himself. All were teenagers. The two occupants of V2 however, were trapped inside the overturned vehicle and died from asphyxiation. The autopsy listed 12% Carbon Monoxide in D2 and P2. The closing speed of the first impact was approximately 50 mph with the secondary impact speed unknown as part of the damage and buckling may have been due to the side impact. Impact could best be simulated by hitting the rear of the Pontiac at an oblique angle with MDB. (Specific simulation of this crash is difficult due to its complexity)

CASE NO. 219 This was a rear impact between a 1986 Pontiac Sunbird (V1) and a 1981 Chevy Citation 4 dr (V2). V1 was traveling at a speed estimated at 60 mph when striking V2 at 5 mph (stopping for red light). The impact was approx. 70% overlap to the left side. Even though PAR indicated collinear impact, estimate angle of impact appears to be approximately 200 degrees. Closing speed approx. 55 mph. The Citation, V2, immediately caught fire and the sole two front seated occupants of the vehicle burned. Fire was determined to be the cause of death from the evidence pictures. (55 mph, 70%, 20 degrees)

CASE NO. 201 Five Vehicle collision. V1 - '92 International Cabover Tractor/trailer; V2 - '91 Honda Accord 4 dr.; V3 - '92 Dodge Dynasty 4 dr.; V4 - '86 Chevrolet Caprice Classic 4 dr.; V5 - '92 Dodge Dynasty 4 dr. V1 failed to stop for a changing light (yellow/red) and ran into the back of V2, pushing it through the intersection. V1/V2 combination also struck right side of V4 and left side of V3 as driver of truck attempted to find an opening. V2 was pushed across intersection into V5 who was waiting to make a left turn from the opposing direction of travel. V2 was wedged under V1 and caught fire from rupture of the fuel tank. V1, V2 and V5 were all engulfed in flames. There were drivers in all vehicle and all but the driver of V2 escaped without injury. It is unknown if the driver of V2 died from the fire or from the impact, but fire would have been fatal if he had survived the impact and the photos show survivable space for the driver. Therefore this is assumed to be a burn related fatality. It appears that the impact was offset to the right side and would be equivalent to hitting with a 3000 pound moving deformable at 55-60 mph. (58 mph, 70%, 0 degrees)

CASE NO. 198 Two vehicle collision where V2, a westbound '76 Chev Monte Carlo went out of control, spun out and entered the eastbound lanes backwards and struck V1, a '90 Ford F-150 who was towing a car trailer with a '67 Chevy Nova SS. The Trailer apparently under-rode the Ford and caused puncture to the fuel tank which resulted in immediate fire. Both drivers were killed. Autopsy was performed on the driver of vehicle #2 showing blunt trauma injuries as cause of death. This was confirmed by photographs. No mention was made in the report of cause of death of V1 driver, nor were photos available. Due to the nature of the fire and vehicle damage it was assumed that fire was the cause of the death. The Ford was equipped with dual fuel tanks with one of the tanks behind the rear axle. The fire was extensive and burnt both tanks as seen from the photos where the filler cap was blown outward. Though this was not a fire from the initial rear impact, the resulting impact of the trailer to the rear of the pickup truck is very similar to a rear impact with a narrow object. (Specific simulation of this crash is difficult due to its complexity)

CASE NO. 75 A 1991 Dodge Dynasty stopped in traffic was impacted in the right rear by a tractor trailer in a collinear direction. The Dynasty was pushed into another vehicle which in turn was pushed into a stopped tractor/trailer. These secondary impacts did not result in fatalities. There was a major fire in the Dynasty and tractor/trailer and the sole occupant of the Dynasty, a 38 year old male was killed. There was no coroner's or autopsy report, but from the photos the crash appeared survivable for the driver. There was however significant intrusion on the passenger side. From the damage the speed of impact is estimated at 45 mph. (60 mph MDB, right 50% overlap, 0 degree)

CASE NO. 86 This was a vehicle-to-vehicle rear impact into a 1982 Ford Mustang, V1. All three occupants died in the Mustang including driver, right front passenger and rear center passenger (all were in teens). The driver of V2, an '88 Chev Camaro, was charged with 3 counts of homicide and was driving under influence of alcohol. Photos were compared to a crash test conducted at similar conditions and the crash was judged to be a 70% right overlap at approximately 60 mph. No autopsy or witness reports were furnished. Determination of conflagration fatalities was based on examination of damage from photos, age of occupants and apparently rapid fire spread. (55 mph MDB, right 70% overlap, 15 degree from right)

CASE NO. 218 V1, a '90 Ford Econoline impacted the rear of a slow moving '84 Nissan Sentra 4 door sedan. On impact, V2 burst into flames according to eye witness accounts. V2 was traveling on a four lane divided highway with flashers on, apparently due to some vehicle defect. V1 failed to see V2 and impacted the rear end of V2 at full highway speed (55 mph limit), probably around 65 mph with V2 traveling around 15 mph for a closing vel. of 50 mph. There was severe damage to the rear of V2 with moderate damage to the front of V1. Though it was difficult to determine from photos, appears to be sightly offset to left of V2 (70-90% overlap). The sole occupant/driver in V2, a 26 yr. old female was consumed by the fire and burned beyond recognition (dental records were used for ID). There was no coroner's report included, but the crash appeared survivable in the absence of fire. (50 mph MDB, 80% left overlap, 0 degrees)

CASE NO. 24 This was a five vehicle collision which resulted in four vehicle fires and eight fatalities. Incident occurred when V1, a 1979 Dodge Aspen, stopped in traffic, was struck in rear by a Tractor/Trailer hauling cars which failed to stop due to defective brakes. The Dodge Aspen which immediately caught on fire from a ruptured fuel tank then hit the rear of an '88 Plymouth Colt. Subsequently the Tractor hit the Colt and pushed it into a parked construction vehicle. Also the Colt was damaged from a car which became dislodged from the car carrier. The death certificate listed conflagration as the cause of death for all 3 occupants of the Aspen and all 5 occupants from the Colt. All vehicles except the construction vehicle burned. This was a very catastrophic crash and although conflagration was listed as cause of death, there would certainly have been serious injuries without fires.

Frontal Crashes

CASE NO. 173 Single vehicle crash occurred on a state highway. The vehicle, a 1988 Toyota pickup, traveling at a high rate of speed ran off the roadway. It hit an earth embankment, became air borne, and nosed-down into the ground. Then went through an end-to-end rotation, crushing the roof and came to rest on its wheels and caught fire. The lone driver, a 21-year old male, was found lying face up across the seat with his head partially outside, pinned between the door and roof. Certificate of death, based on autopsy stated he died of acute carbon monoxide poisoning and generalized (100%) body burns. There was evidence at the scene that the driver had been drinking.

CASE NO. 87 Two-vehicle frontal collision occurred on a U.S. highway. Vehicle #1, a 1988 Ford pickup, crossed the center dividing line and collided head-on with vehicle #2, a 1989 tractor-trailer traveling in the opposite direction. Vehicle #1 sustained heavy damage to the left front end and was totally consumed by the ensuing fire. The lone driver, a 19-year old male, died at the scene. Medical examiner report listed soot in bronchi and trachea and blood alcohol concentration (BAC) of 0.18 and carboxyhemoglobin. Cause of death was listed as incineration and smoke inhalation. Medical examination was performed without autopsy. Prior to the fatal crash, vehicle #1 was allegedly involved in an crash earlier in the day resulting in damage to its left front end and left front wheel assembly. The collision forced vehicle #2 off the roadway into the dirt shoulder, causing the trailer to overturn onto its right side. Vehicle #2 sustained heavy front end damage and damage to the right side of the trailer. The lone driver suffered minor bruises and blunt chest trauma.

CASE NO. 95 Single vehicle crash occurred on a state highway. The vehicle, a 1986 Ford pickup, ran off the right side of roadway and hit a concrete culvert. It sustained heavy crush damage to its front and the entire cab. After the impact the vehicle flipped onto its roof and caught fire. A medical examiner's's report for the 32 year old male stated he died of "severe flame burns" inside the vehicle. There was no autopsy or detailed medical examination. The 19-year old male passenger received broken ankles and leg, minor cuts, bruises and burns. Based on statement given by this passenger, both he and the driver had been consuming alcohol since 5 PM in the day.

CASE NO. 189 Two-vehicle side collision occurred at an intersection of a state highway. Vehicle #2, a 1983 tractor-trailer, failed to stop at stop sign and was struck at the left side by vehicle #1, a 1984 Chevrolet van towing a house trailer. After the impact vehicle #2 partially jack-knifed and came to rest inside the intersection. Vehicle #1, severely damaged by the impact, caught fire and was completely destroyed. There was also fire damage to the front of the house trailer. Medical report stated that the lone driver of vehicle #1, a 58-year old male, died of partial incineration, extensive pharynx and hypopharynx, and was found to have tracheal soot deposition. An autopsy was performed. The driver and two passengers in vehicle #2 suffered no injury.

CASE NO. 188 Single vehicle crash occurred on a state highway. The vehicle, a 1986 Ford pickup, ran off the right side of the roadway and struck a large tree with its left front. Upon impact the vehicle rotated counter-clockwise and burst into flames. The 22-year old male driver, ejected upon impact, fell under the rear of vehicle and suffered serious injury. The medical report stated that the 16-year old male passenger was partially ejected out left door and died of asphyxia and conflagration. An autopsy and toxicology test was performed. Tests showed that the driver and the passenger each had a BAC of 0.14 and 0.18, respectively.

CASE NO. 180 Two-vehicle frontal collision occurred on a state highway. Vehicle #1, a 1991 Toyota Celica, crossed the center line into the path of vehicle #2, a 1987 Ford pickup. Vehicle #2, struck by the front of vehicle #1 at left front, went off the roadway, overturned and caught fire. It came to final rest laying on its right side and was completely destroyed by the fire. The center seat passenger, a 70-year old female, died of carbon monoxide asphyxia at the scene. This finding was stated in a certificate of death, but no autopsy was performed to support findings. The driver and the right seat passenger suffered serious injuries. Vehicle #1 came to final rest on the roadway after the collision. The lone driver, a 20-year old male, died the following day in a hospital of central nervous system trauma and basilar skull fractures. Tests showed he had a BAC of 0.20.

CASE NO. 182 Two-car frontal collision occurred on a state highway. Vehicle #1, a 1986 BMW, traveling wrong way collided head-on with vehicle #2, a 1989 Cadillac. Upon impact vehicle #1 burst into flames and came to rest against a utility pole in the median with its right side. According to medical examiners report, the 38-year old female driver and the 37-year old male passenger both died of fire burns inside vehicle. An autopsy was performed. The lone driver of vehicle #2, a 52-year old male, suffered serious injuries.

CASE NO. 168 Single-car crash occurred on a state highway. The vehicle, a 1986 Ford Taurus, traveling at a very high rate of speed ran off the roadway and struck a concrete median. It then burst into flames, flipped down an embankment and landed on its top. The lone driver, a 23-year old male, was trapped in the car and died of total body burns according to the coroner's report. Tests showed that he had a BAC of 0.301 and a CO of 10%.

CASE NO. 120 Two-vehicle front to side collision occurred on a state highway. Vehicle #1, a 1988 Chevrolet S-10 pickup, crossed the centerline in a right curve and struck the driver side of vehicle #2, a 1979 Mercury Zephyr. After the impact, vehicle #1 rolled to its right, landed on its top and caught fire, trapping the driver inside. The lone driver, a 21-year old male, died at the scene. Coroners report stated he had a 12% CO in his blood and a BAC of 0.150. No autopsy report was provided and it is unknown whether one was conducted. The lone driver of vehicle #2, a 54-year old male, was ejected from the vehicle and died of injuries at the scene.

CASE NO. 138 Two-car frontal collision occurred on a U.S. highway. Vehicle #1, a 1984 Honda Accord, crossed the center dividing line into the path of vehicle #2, a 1986 Toyota Celica, and struck vehicle #2 head-on. After the impact vehicle #1 went off the roadway into a ditch, overturned and caught fire. The lone driver, a 24-year old male, was burned to death beyond recognition. The coroners report stated that he had a BAC of 0.291 and a 4% CO in blood. The driver of vehicle #2 was seriously injured and the right front seat passenger suffered minor injury.

CASE NO. 172 Single-car crash occurred on an interstate highway. The lone 36-year old female driver of a 1990 Cadillac Seville had a seizure causing her to loss control of the vehicle. The vehicle ran off the right side of the roadway and struck several trees before coming to rest. It then caught fire trapping the driver inside. The driver died 27 days after the crash in a hospital of sepsis due to major thermal burns.

CASE NO. 174 Single-car crash occurred on a U.S. highway. The vehicle, a 1985 Oldsmobile Delta 88 Royale, failed to stop at stop sign at an intersection. It ran off the roadway and struck an earth embankment before crashing into a building. Upon impact, both the vehicle and the building caught fire. The lone driver of the vehicle, a 84-year old male, died of smoke inhalation at the scene. An autopsy was performed.

CASE NO. 171 Single-car crash occurred on a U.S. highway. The vehicle, a 1983 Chevrolet Citation, traveling at a high rate of speed went out of control after passing a vehicle in a no-passing zone. It swerved to the left, crossed the centerline, ran off the roadway and struck a drain culvert. The vehicle then went airborne, flipped in the air, and exploded upon landing upright in a ditch. According to the certificate of Death, the lone driver, a 38-year old male, was trapped in the vehicle and died of asphyxiation due to smoke inhalation at the scene. No autopsy was performed. One witness who had seen the driver at a restaurant just prior to the crash stated that the victim appeared to be intoxicated then.

CASE NO. 79 Single-car crash occurred on a city street. The vehicle, a 1984 Chevrolet Citation, traveling at a high rate of speed struck the right curb. It then hit a steel utility pole and caught fire. The impact resulted in crush to the center hood area. The 17-year old male driver was partially ejected and died of blunt impact to trunk with skeletal, visceral and vascular injuries. One 18-year old male passenger was found dead on the right front seat with fourth degree thermal burns of head, neck, trunk and extremities. A detailed autopsy report was included from the coroner's office. The three rear seat passengers, found outside the vehicle, were transported to hospitals. Among them a 19-year old male, died of blunt impact to head, trunk and extremities with visceral and vascular injuries upon the arrival at the hospital. The other two passengers suffered serious injuries and burns.

Other Crashes

CASE NO. 183 Single-car crash occurred on a state highway. The vehicle, a 1984 Lincoln Town Car, struck a large metal object on the roadway and caught fire due to severed fuel lines. The two rear seat passengers, a 35-year old female and a one-year old girl, died of fire burns at the scene. Autopsies were performed on both occupants to confirm cause of death from fire. Another rear seat passenger, a 5-year old boy, died of asphyxia and third degree burns at a burns institute the following day (no autopsy). The front center seat passenger and the rear center seat passenger suffered serious injuries. The driver, the right front seat passenger, and the right rear seat passenger suffered no injury in the crash.

Rollover Crashes

CASE NO. 161 Single-car crash occurred on a state highway. The vehicle, a 1981 Mercury Cougar, failed to stop at an intersection, struck the median curbing and became airborne. After striking a guard rail the vehicle landed on its top and burst into flames. The lone driver, a 27-year old male, was trapped in the vehicle and died of fire burns according to coroner's report (no autopsy). Tests showed that he had a 39.2% CO in blood and a BAC of 0.220.

CASE NO. 163 Single-car crash occurred on an interstate highway. The vehicle, a 1992 Toyota Tercel, traveling on the left outside lane ran into several construction barricades on the left and fell into a pit, landing on its right side. The lone driver, a 54-year old male, was trapped inside the vehicle when it exploded into flames. The victim died of fire burns at the scene according to PAR (no autopsy or coroner's report).

CASE NO.19 Single-car crash occurred on an interstate highway. The vehicle, a 1989 Mitsubishi, traveling at a high rate of speed went out of control during a passing maneuver when approaching a bridge. It struck the centerline dividing concrete barrier, hit the guardrail on the right, then climbed up the superstructure of the bridge. After striking the cross beam of the bridge, the vehicle fell back onto the bridge surface on its top and caught fire. Three rear seat passengers, all females ranging in age from 17 to 22, died of "body burns", according to medical examiner's report. Autopsies were performed on these three passengers. The male driver was able to climb out of the vehicle and moved around. The right front seat male passenger who was pulled out of the vehicle suffered serious injuries.

CASE NO. 85 Single-car crash occurred on an interstate highway. The vehicle, a 1990 Dodge Daytona, traveling at an estimated speed of 78 mph, ran off the right side of roadway and struck a concrete culvert with its right front. The vehicle then overturned into a stream, caught fire and burned. The lone driver, a 65-year old male, was found dead inside the vehicle and died of burns according to the PAR (no autopsy or medical report).

CASE NO. 60 Single-car crash occurred on a suburban road. The vehicle, a 1981 Oldsmobile Omega, failing to negotiate a left curve, ran off the right side of the roadway and struck a wooden utility pole head-on. The vehicle then rolled over onto its top and caught fire. The lone driver, a 31-year old male, was trapped in the vehicle and died of fire burns at the scene. He was found to have a 32% CO in his blood (a coroner's report was provided and an autopsy was performed).

Side Impact Crashes

CASE NO. 1 Two-vehicle side collision occurred on a U.S.

highway. Vehicle #1, a 1981 Chevrolet pickup, was struck on the passenger side by the front of vehicle #2, a 1975 Mazda pickup, at an intersection. The collision forced vehicle #1 into the dirt median, struck a delineator and caught fire before coming to rest in a ditch. The damage to the vehicle indicated that it had overturned. A large puncture was found in the vehicle's gas tank on the passenger side. The lone driver, a 61-year old male, died inside the vehicle of "thermal burns", according to medical examiner. No autopsy was performed, but the trachea was opened to examine for soot and none was found. Therefore cause of death is somewhat questionable. The front end of vehicle #2 also caught fire after the impact. The female driver of vehicle #2 and three children ranging from 1 to 6 in age sustained different degrees of injuries and burns.

CASE NO. 6 Two-vehicle side collision occurred on an interstate highway. Vehicle #1, a stolen 1986 Chevrolet C-10 pickup, was traveling at a high rate of speed when it went out of control. The vehicle left the southbound lane, crossed the grass median, struck a concrete drainage ditch, and entered into the path of vehicle #2, a 1990 Ford F-350 U-Haul panel truck traveling in the northbound lane. Vehicle #1 was struck by the front of vehicle #2 on the driver's side and caught fire. The collision forced vehicle #2 into the right lanes where it was struck in the right side and right rear corner by two passenger cars traveling behind in the northbound lanes. The lone driver of vehicle #1, a 27-year old male, was burned beyond recognition at the scene. The certificate of death stated cause of the death as inhalation of combustion products (CO 17.7%), thermal burns, and multiple blunt force injuries. An autopsy was performed. The driver and passenger in vehicle #2, as well as, the driver and two passengers in one of the other two passenger cars sustained various degrees of injuries.

CASE NO. 178 Single-car crash occurred on a state highway. The vehicle, a stolen 1987 Chevrolet Monte Carlo, went out of control, crossed the centerline into opposite traffic lane and then struck a tree at the roadside with the passenger side. Upon impact the vehicle rolled over onto its right side and caught fire. The 37-year old lone driver was trapped in the burning vehicle and died of conflagration, according to certificate of death. An autopsy was performed.

CASE NO. 190 Single-car crash occurred on a state highway. The vehicle, a 1987 BMW, traveling at a high rate of speed failed to negotiate a right curve. It went out of control and crossed over to the grass shoulder of opposite traffic lane. After striking three trees with its right side it rolled over onto the passenger side and caught fire. The vehicle was completely destroyed by the impact and the fire. The driver and the right front seat passenger, both 28-year old male, died of "subtotal incineration, auto crash followed by fire", according to certificate of death. An autopsy was performed.

CASE NO. 159 Two-vehicle collision occurred at the intersection of an exit ramp from an interstate highway. Vehicle #1, a 1986 Chevrolet Camaro, clipped the front end of vehicle #2, a 1979 semi-trailer truck. After bouncing off the truck vehicle #1 struck a curb and became airborne before landing astride a guard rail and burst into flames. The right rear seat passenger, a 16-year old male, was pinned in the wreckage and died of fire burns, according to PAR. No medical report was provided. The driver and the right front seat passenger both suffered serious injuries.

CASE NO. 148 Single-car crash occurred on an interstate highway. The vehicle, a 1990 Volvo 740, ran off the roadway on a left curve when the driver fell asleep at the wheel. The vehicle struck a guard rail with the left front, went down an embankment and struck a tree with its driver side. A fire started under the front of the car quickly spread to the entire vehicle. The driver was able to crawl out of the vehicle and pull the right front seat passenger from the burning car. The two rear seat passengers, a 7-year old boy and a 3-year old girl, died of fire burns in the vehicle, according to PAR. No medical examiner's report was provided.

CASE NO. 116 Two-car side collision occurred on a state highway. Vehicle #1, a 1990 Ford Escort, went out of control and crossed center line into the path of vehicle #2, a 1988 Chevrolet Celebrity. It was struck by the front of vehicle #2 on the passenger side and knocked into a ditch where it was destroyed by the ensuing fire. The lone driver of vehicle #1, a 60-year old male, died of fire burns according to coroner's report. Test showed he had a BAC of 0.165 and 10% or less CO in his blood. The lone driver of vehicle #1 suffered serious injuries.

CASE NO. 102 Two-car frontal collision occurred on an intersection of a city road. Vehicle #1, a 1991 Volkswagen Caravelle van, was struck on the left front by vehicle #2, a 1989 Plymouth Sundance, which was speeding and ran the red light. The lone driver of vehicle #1, a 21-year old female, died of over 80% charring burns, according to medical examiner's report. Test showed the victim has soot in her trachea by a vertical incision. No autopsy was performed. The lone driver of vehicle #2 was seriously injured.

A LOOK AT THE NHTSA MINIMALLY COMPLIANT UNDERRIDE GUARD AT IMPACT SPEEDS ABOVE 30 MPH

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ABSTRACT

The NHTSA has promulgated a new underride regulation (Ref 1) which became effective for heavy commercial trailers manufactured after January 26, 1998. Heavy trucks are excluded. Although this new rule is considered by many to be deficient in some respects (not as good as it could be), it certainly represents a safety improvement over the old FMCSR 393.86, which has been in effect since January 1953 and will continue to be so for heavy trucks. The new rule is also compatible with the European and Japanese rear underride standards.

A series of eight rear underride crash tests (Ref 2), used as a basis for this new rule, demonstrated the effectiveness of an underride guard that minimally complied with the new rule at impact speeds of 30 mile per hour (mph). But in some of the tests the underride magnitude was such that passenger compartment intrusion (PCI) occurred. It has generally been considered that for effective underride performance PCI should not be allowed. This raises the question: how would this minimally compliant guard (MCG) perform at impact speeds greater than 30 mph which occurs quite frequently in the real world?

This paper addresses this issue based on the previous eight NHTSA underride crash test results. The primary purpose is to illustrate the potential performance of the MCG at impact speeds above 30 mph, and also to demonstrate the effect of guard strength on underride magnitude.

BACKGROUND - NHTSA CRASH TESTS

Much research has been done on the underride problem involving crash testing and accident analysis. See Refs 2-10 which contain test results for a variety of underride guards and impact conditions. The NHTSA files contain a total of 67 rear underride crash test cases. But the new NHTSA rule was primarily based on the recent eight crash tests which were conducted at 30 mph. Concern for the 30+ mph impact speed is real because many underride accidents do occur above 30 mph (See Ref 11 & 12), and specifically because PCI did occur in some of the NHTSA tests which were centric, in-line impacts. Although tests with the MCG for offset and angle impacts have not been conducted, it is expected that greater PCI would occur for these conditions with potential for serious injury or death to the front seat occupants.

In order to evaluate the performance of the MCG at impact speeds above 30 mph it will be necessary to initially review the available 30 mph crash test conditions and results.

A) DESCRIPTION OF THE NHTSA TESTS

The eight NHTSA rear underride crash tests were conducted in the early 1990s with four different passenger cars. These were: 1991 Chevrolet Corsica, 1993 Ford Tempo, 1992 Honda Civic CX, and 1993 Saturn SL. All tests were conducted at 30 mph with the passenger cars centrically impacting the guard at zero angle. The guard height above the ground was 22 inches in all of the tests. The cars were also set at a nose down attitude representing a braking condition. Only the guard was involved with stopping the car (no trailer rear wheels or other barriers). Summary data are listed in Table 1, and additional details of the tests can be obtained from Ref 2. Seven of the eight tests used a guard which was designed to minimally comply with the requirements of the new rule in strength and geometry. This guard was mounted to a laboratory test fixture in five tests. Two of the tests were conducted with the MCG mounted to a Fruehauf van trailer. A rigid guard was used in one test. In all of the eight tests the occupant response measurements (HIC and chest G) were within the FMVSS No 208 allowables except for the rigid guard case. The driver chest G in this one case (rigid guard mounted to the laboratory fixture) exceeded the allowable but by only one count (61 G - See Table 1, TESTNO 921229). It should be noted, however, that in six of the tests (this one included), the driver belts were not used.

In the two trailer tests the guard was mounted directly to the trailer frame rails, which proved to be the weak link in the structural system. PCI magnitude of 10.5 inches occurred in the first of these tests. The addition of a reinforcing strap to each vertical strut at the frame attachment point substantially improved the trailer frame strength for the second test. The underride was greatly reduced in this test with no PCI.

TABLE 1. CRASH TEST RESULTS

YR	MAKE	MODEL	SPD	TESTNO	TWT	HICD	CGD	HICP	CGP	CMAX	CDYN	ANG	SG	PEAK F	NOTES
89	FORD	TEMPO	29.3	7715-04	3210	435	45	390	41	13.7	18.5				COMPLIANCE TEST
94	FORD	TEMPO	29.3	8145-06	3200	914	45	383	45	14.7	19.9				COMPLIANCE TEST
92	HONDA	CIVIC CX	29.6	7979-05	2470	382	44	169	35	16.3	22.1				COMPLIANCE TEST
93	SATURN	SL	29.8	8056-08	2754	317	35	311	35	19.0					COMPLIANCE TEST
91	CHEV	CORSICA	34.8	7893-05	3300	493	41	956	44	25.1	32.0			66300	NCAP TEST
93	FORD	TEMPO	35.0	MP0205	3099	655	51	772	43	19.2	28.1			83700	NCAP TEST
93	HONDA	CIVIC DX	35.3	8058-04	2769	744	54	902	43	21.7	26.0				NCAP TEST
92	SATURN	SL	35.0	920427	2922	705	51	1063	47	21.3	31.5			81800	NCAP TEST
91	CHEV	CORSICA	30	921207	3208	24	33	37	20		71.9	60	2.0	44900	LAB GUARD
91	CHEV	CORSICA	30	921229	3218	188	61	788	37		33.0	0		74000	LAB GUARD RIGID, CAR FRAME BUCKLED
91	CHEV	CORSICA	30	930420	3186	37	16	77	20		88.1	60	2.6	38600	TRAILER - FRAME FAILED
93	FORD	TEMPO	30	921203	3087	139	19	117	25		51.0	70		32700	LAB GUARD **
92	HONDA	CIVIC CX	30	921130	2462	127	24	119	31		51.6	30	5.6	51700	LAB GUARD
92	HONDA	CIVIC CX	30	930428	2654	129	28	118	36		41.2	20	7.6	50800	TRAILER - W STRAP
93 *	SATURN	SL	30	921106	2738	360	19	858	24		97.1	90	0.5	26000	LAB GUARD ** - BOLTS FAILED
93 *	SATURN	SL	30	921228	2748	100	27	117	27		62.6	45	2.7	37600	LAB GUARD **

SPD -- Impact speed - mph
TWT -- Vehicle test weight - pound
HICD -- Driver Head Injury Criteria
CGD -- Driver chest G
HICP -- Passenger Head Injury Criteria
CGP -- Passenger chest G
CMAX -- Post impact static crush - inch
CDYN -- Maximum crush or underride during impact - inch
ANG -- Guard bend angle - degree
SG -- Scrape-over G
PEAK F -- Peak force during impact - pound, based on equivalent filtered peak compartment G

- Driver Airbags were used in all of the above tests.
- In the underride tests, driver belts were used in only the two vehicles flagged with *.
- Right strut on the guard bent 1st in cases noted under the NOTES column with **.

It should also be noted that the low edge of the laboratory test fixture and trailer frames were set at 48 inches above the ground. This is a significant factor because this is the level of the rear structure that is most critical to PCI. But most of the current on-the-road trailers have the PCI critical frame level at approximately 42 inches above the ground. Some are as low as 38 inches, and drop-frame trailers are even lower. 42 inches is the height just above the outside rear view mirror of the typical passenger car. If the frame height had been set at the typical trailer level in the tests, the results would have been different with greater potential for PCI.

B) SALIENT FEATURES OF THE TEST RESULTS

Acceleration, velocity and displacement time histories (taken directly from Ref 2) are shown in Figures 1-8 for each of the eight NHTSA underride crash tests. Force vs displacement is also included. It should be noted that the force traces were derived by simply multiplying the acceleration trace by the vehicle test weight (GxW) which is a common procedure. The figures are presented in the order of those numbers used in Figure 11 for identification convenience only. The test numbers in this underride series are established based on the date on which the test was conducted. For example, TESTNO 921108 is derived from - 19<u>92</u> in the <u>11</u>th month on the <u>08</u>th day of that month.

Some salient features of these data are as follows:

- o Initial car-to-guard contact is with the grill just above the bumper.
- o Peak compartment G occurs at or near the guard engagement of the engine block. This is compatible with observations from the crash test movies.
- o Minimum load usually occurs at a displacement (underride) of 35-50 inches.
- o Frontal stiffness of the vehicles is generally in the order of 2,000 pounds/inch. This is for that portion of the front structure (above the bumper) that engages the guard which extends from the grill to the engine block.
- o The presence of high frequencies in the acceleration response makes the determination of the absolute force using the product of GxW somewhat questionable. Since the acceleration trace is a filtered output, different levels of filtering will produce different force magnitudes per the GxW process. It is very likely that the actual force would be more closely associated with an acceleration trace in which the high frequencies are ignored.
- o Although the MCG was designed to withstand a loading of 45,000 pounds for the centric hit, the peak loads varied from 26,000 pounds (TESTNO 921108 in which the 3/4 inch attachment bolts failed) to 51,700 pounds.
- o Low peak loads are associated with the test cases in which the right vertical strut deformed first.
- o Strong similarities exist between traces from same vehicle tests particularly in the initial region of the pulse. This is the case regardless of the structure on which the guard was attached (laboratory fixture or trailer).
- o The loads that result at the end of the pulse (maximum underride) are generally in the order of 15,000 pounds. This occurs after the guard was well beyond its yield and fully displaced forward.
- o The energy associated with the force vs displacement trace closely matches the car's initial kinetic energy as it should.

<u>COMMENTARY REGARDING THE NHTSA TEST RESULTS</u>

Based on the measured occupant responses (driver and front seat passenger, see Table 1), and remaining distance (clearance) between the intruding laboratory fixture or trailer frame and the windshield of the underriding car, the test results generally indicated acceptable guard performance. This served as technical support for the new rule. But some questions remain regarding the overall efficacy of the 'minimally' compliant guard. These have to do with the following:

1) The rule allows that the guard itself can be certified by test as an equipment item using a laboratory fixture. The guard does not have to be mounted to the actual trailer frame. See Ref 1 for specifics.

<u>Comment</u>: This may not be an appropriate requirement because the trailer frame proved to be the weak link in one of the NHTSA tests (No 930420). The resulting peak load was considerably less than the 45,000 pounds required by the rule (the sum of both vertical struts) because of the frame structure. In this test the magnitude of underride was greater than it would have been with an appropriately structured frame (10.5 inches of intrusion) as evidenced by the results of a subsequent test (No 930428) where the strength of each frame member was significantly increased and underride was reduced by more than 1/2. In each case, however, the occupant responses were still well within the FMVSS 208 allowables. Prudent trailer manufacturers will most likely assure guard compliance by physically testing the guard as mounted to the trailer. However, manufacturers that produce a small number of trailers may have a problem with this approach because of costs involved.

The trailer frame also proved to be the weak link in a previous underride test program. See Ref 7.

2) The rule requires that the guard structure must absorb a minimum amount of energy within a specified displacement in the process of compliance test loading. See Ref 1 for specifics.

Comment: This energy requirement, although desireable, will very likely prevent a trailer manufacturer from installing a very strong (non-yielding) guard which can be beneficial in both offset impacts and at centric impact speeds above 30 mph. A very strong guard can be made to meet the energy requirement of Ref 1, but in an underride impact it will not absorb energy (which is the intent of the requirement) as long as its strength exceeds the impacting vehicle crush strength. A test (No 921229) demonstrated that a non-yielding guard (which would likely not comply with the new rule because of the energy requirement) resulted in acceptable occupant response levels with the exception of the driver chest G which was high by one count. In this case the driver was restrained with an air bag but no belts. It is likely that had the driver belts been used he would have experienced a lower chest G as evidenced by an NCAP test of the same vehicle (conducted at 35 mph into a full flat rigid barrier, 36% more kinetic energy) which produced occupant responses below the allowables. Compare TESTNO 7893-05 with 921229 (Table 1). In the NCAP test the full front structure of the vehicle engaged the barrier whereas only the structure above the bumper engaged the guard in the underride test. The stiffness of the upper front structure engaged in the underride test is considerably less than the total front structure stiffness. See Ref 13 for related data.

The NCAP test is a clear indication that a very strong guard would provide acceptable injury performance even though it would not meet the new rule's energy requirement. On the other hand, the energy requirement for the MCG assures that the guard will not fail catastrophically immediately after peak force is reached.

3) All of the tests were conducted at 30 mph with the vehicle contacting the guard centrically and in-line.

Comment: Rear underride accidents do occur at speeds well above 30 mph, and in offsets and angles to the guard as well. Page 21 of Ref 11 states that closing speed estimates for rear underride accidents exceed 30 mph approximately 67% of the time, and 40 mph 32% of the time. This represents a significant number of incidents. It is also well known that real world offset impacts into the rear of heavy vehicles are common. Refs 14 and 15 present data on this. The performance of the MCG has not yet been demonstrated by test at speeds above 30 mph.

4) If the guard performs acceptably at 30 mph centrically, how will it perform in offset impacts?

Comment: It is clear that offset impacts will result in greater underride magnitudes than in centric impacts, all else being the same. Underride is also expected to increase with increasing offset. But impacting vehicle rotation will also occur in offset impacts. This will, of course, depend upon the amount of offset and the interacting structural properties. It is very likely that the occupant responses will be less than with centric impacts, but this will be only if the occupant head and torso are not contacted by the intruding structure. Injury measures, however, will be greater for the occupant on the impacted side. It is possible that vehicle rotation can be either clockwise or counterclockwise depending upon the strengths of the interacting vehicle front structure and the guard. If the guard offset strength is less than the engaged portion of the car crush strength, then the guard will deform and may cause the car to rotate with its front deflecting somewhat away from the centerline. On the other hand, if the guard offset strength is greater than the car crush strength, then car rotation will be in the opposite direction where its rear end will displace away from the centerline. See offset impact data contained in Refs 5, 6 and 8 which indicate that a guard total strength of greater than 45,000 pounds is needed for adequate offset impact protection. It is expected that certain offset conditions could result in car rotation such that the passenger compartment may beneficially avoid intrusion entirely. The performance of the MCG has not yet been demonstrated by test for offset or angle impacts.

The minimum offset load requirement specified in Ref 1 is only 11,240 pounds. The MCG actually provided a load of nearly 14,000 pounds in one static test (Ref 2), but this will not provide sufficient underride protection for reasonable offset impacts at 30 mph.

5) The test frame height was set at 48 inches for both the laboratory fixture and trailer.

Comment: The trailer rear structure that is critical to PCI is the lower edge of the rear frame which for some trailer designs is as low as 36 inches. This is about the height of the hood at its intersection with the windshield which for most passenger cars is in the range of 35-39 inches. The rear lower edge on most trailers is about 42 inches. The NHTSA test results would certainly have been different with a lower frame height which would have caused greater PCI. But other effects will also be present such as guard higher bend angle and change in scrape-over force including potential penetration by the folded hood into the windshield.

WHY DOESN'T A 45,000 POUND GUARD EXPERIENCE 45,000 POUNDS?

The MCG was designed such that it would support a peak load of approximately 45,000 pounds with simultaneous strut loading. This was confirmed by static test in accordance with the procedure described in the new rule (Ref 1). See test results in Ref 2. Because of this, it would be expected that in the crash test cases where the MCG was deformed, the peak load should have been in the vicinity of 45,000 pounds. A review of Table 1 data shows that the peak loads generated in the crash tests varied significantly for the MCG from 32,700 pounds to 51,700 pounds. The bolt failure and rigid guard cases are not considered in this group. Possible explanations for the occurrance of this variation follows.

A) STRUCTURAL DISSYMMETRY

Some of the NHTSA tests show that with a centric impact the guard does not deform symmetrically as would have been expected. Study of the high speed test films indicated that the right vertical strut began to bend forward before the left one in some cases. This results in a total peak load that is somewhat less than the expected 45,000 pounds for both struts even though the struts individually met the rule's minimum static strength requirement. A comparison of the symmetric and unsymmetric strut bending is presented in Table 2. These data show that on average, the unsymmetric peak loads are approximately 2/3 of the symmetric.

TABLE 2

SYMMETRIC LOADING				RIGHT STRUT BENT 1st			
VEHICLE	TESTNO	PK F	CLR	VEHICLE	TESTNO	PK F	CLR
Corsica	921207	44900	0.2	Saturn	921106	26000	-17.1
Civic CX	921130	51700	19.7	Tempo	921203	32700	12.4
Civic CX	930428	50800	23.8	Saturn	921228	37600	10.1
	Average =	49133			Average =	32100	
Corsica	921229	74000	32.2				
Non-yield guard							
Corsica	930420	38600	-10.5				
Trailer frame failed							

Note: Negative CLR means PCI occurred

The unsymmetric deformation may be attributed to the alternator being located on the right side and several inches forward of the engine block which for these vehicles served as a hard point before guard contact with the engine block.

B) METHOD FOR DETERMINING THE PEAK LOAD

As stated above, centric impact of the vehicle with an MCG was expected to produce peak forces in the crash tests of approximately 45,000 pounds, because this was the peak load the MCG was designed to support. But in the crash tests the peak loads actually varied significantly between tests as shown in Table 2. It should be noted that these peak load values are different from (less than) those reported in the NHTSA test report (Ref 2) because the procedure used to determine the NHTSA results was simply to multiply the maximum value of the acceleration response (measured at the vehicle center of gravity) by the vehicle test weight (GxW). This procedure, which is commonly used, is not necessarily valid because the G output is obtained from a method of data processing involving specific electronic filtering. It is clear that different filtering would produce different peak G values (because of the high frequency amplitude) which in the GxW approach would in turn produce different values of peak load which is not possible. In fact, acceleration responses at different locations on the vehicle produce different peak G values which, in some cases, vary by as much as 25%.

It is quite logical that the high frequencies contained in the acceleration pulse (100-150 Hz, which would contribute to the peak G) are more likely to be associated with local resonance of the structure on which the accelerometer is attached and not associated with the total vehicle activity at the structural crushing interface.

To avoid this problem and to obtain a more appropriate value of peak force, the procedure used to determine the peak loads listed in Tables 1 and 2 was to use the slope of the velocity trace in Figures 1-8 to obtain an 'equivalent' filtered peak G to combine with vehicle weight. This is believed to be more acceptable for use in the GxW procedure although it deserves more study.

C) EFFECT OF STRAIN RATE

Strain rate is a phenomenon that results from a force that is dynamically applied to a structure. It causes the structure to increase resistance to a dynamically applied force over that which would exist for a force that is statically applied. Generally, the higher the rate of force application, the higher the effect of strain rate with some type of limitation. See Ref 18 for a study of strain rate effects in crushing structures. In the symmetric load application to the MCG (see Table 2), the peak load for the Corsica was nearly 45,000 pounds and for the Civic CX the peak force was above 45,000 pounds. Because of these data it appears that a strain rate effect may be present. But for test evaluation it would be best to disregard any potential effect of strain rate since a great variety of variables are present in the interaction of an underride guard with the crushing car front structure.

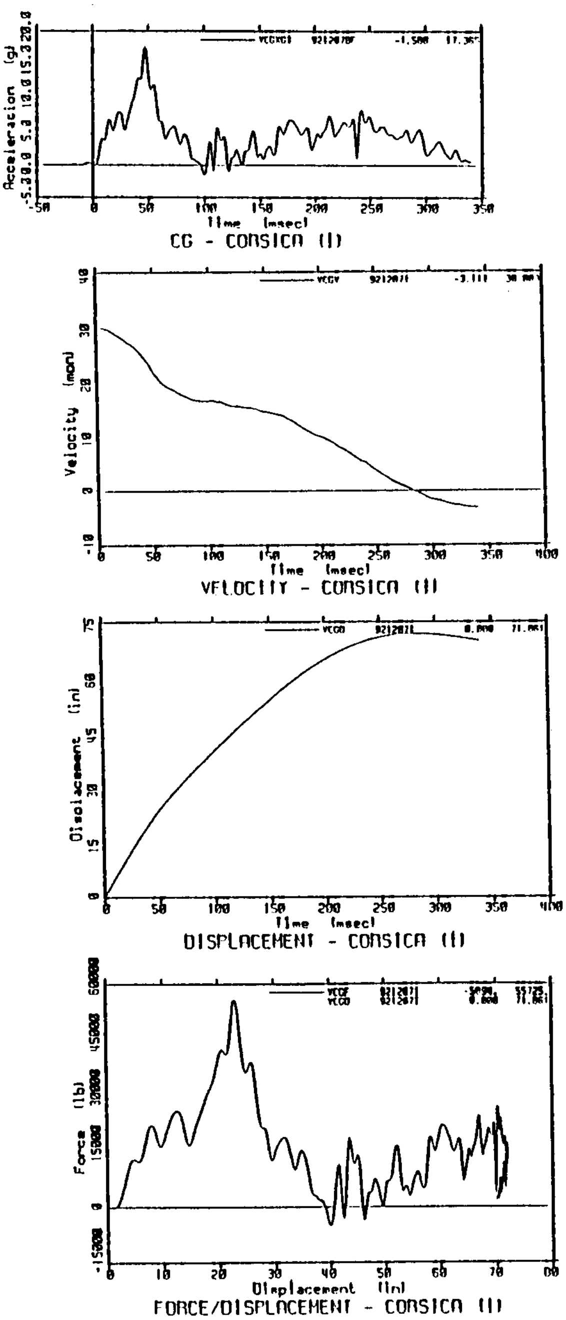


FIGURE 1: CRASH TEST RESPONSE
- CORSICA
- LAB FIXTURE

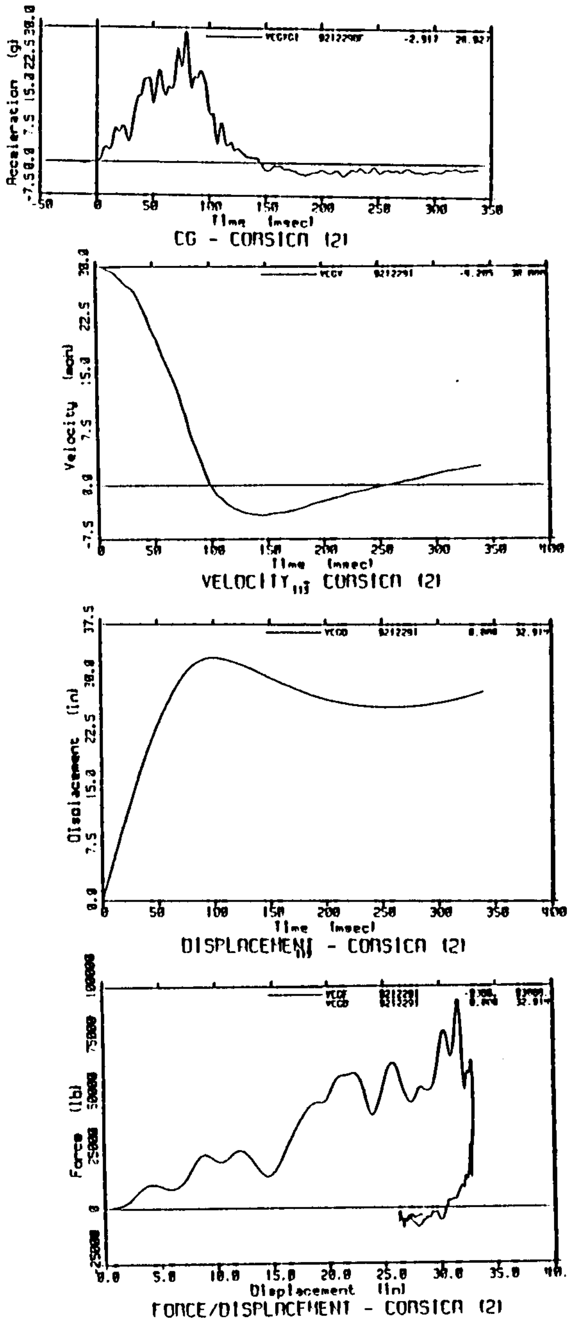


FIGURE 2: CRASH TEST RESPONSE
- CORSICA
- LAB FIXTURE - RIGID GUARD

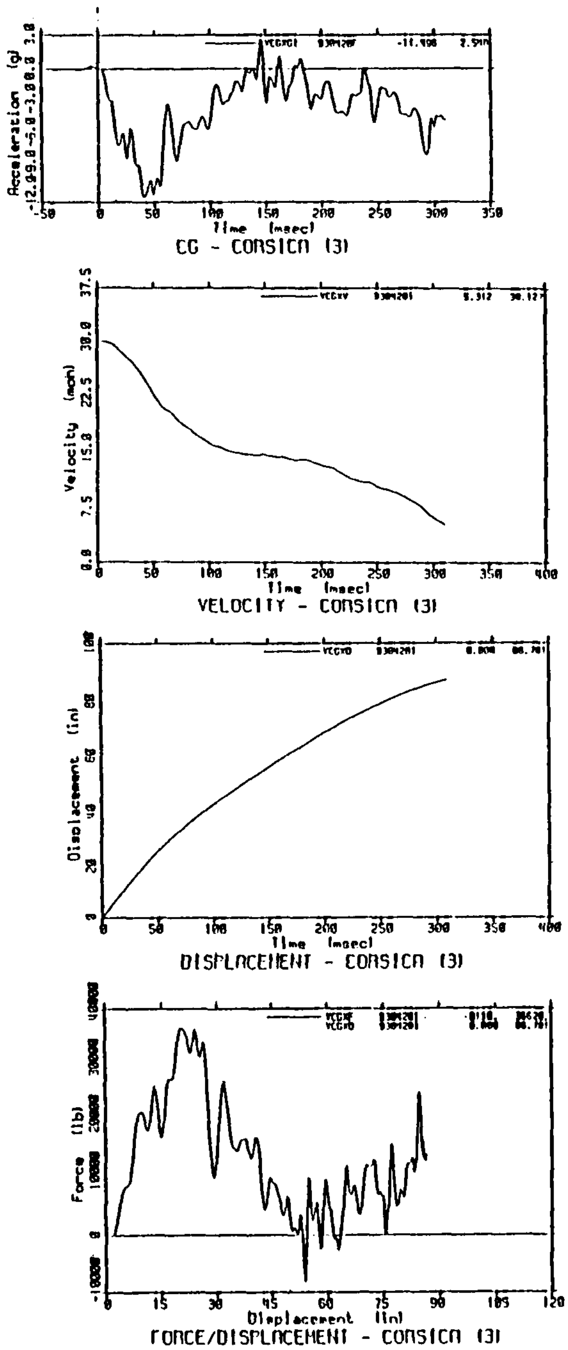


FIGURE 3: CRASH TEST RESPONSE
- CORSICA
- TRAILER, FRAME FAILED

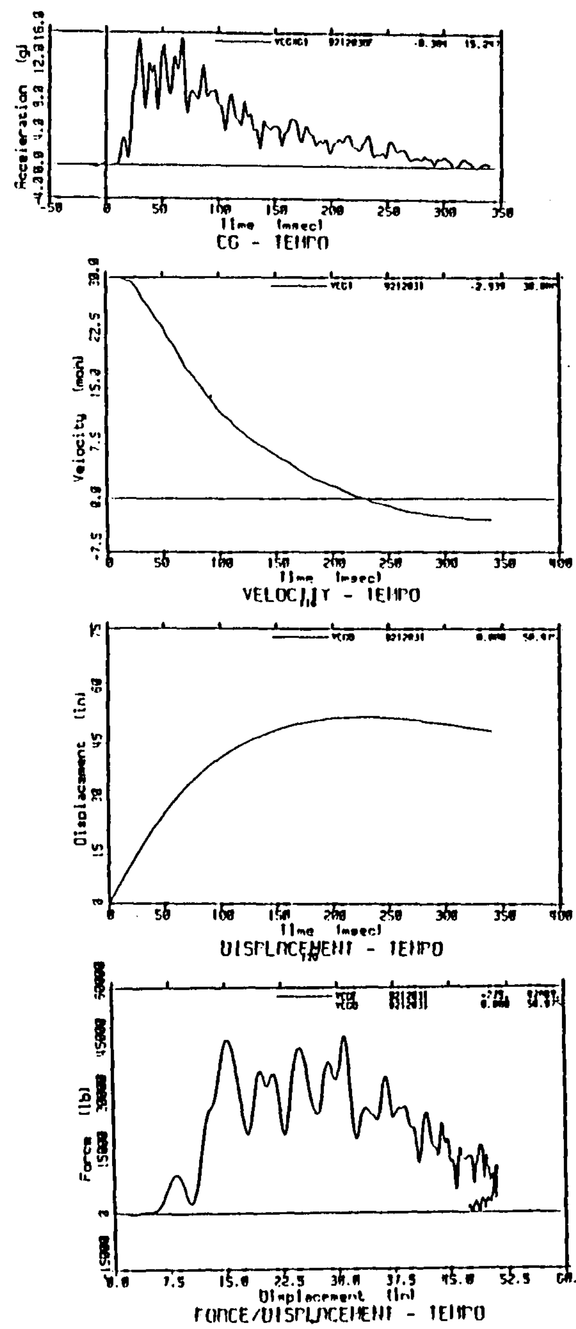


FIGURE 4: CRASH TEST RESPONSE
- TEMPO
- LAB FIXTURE

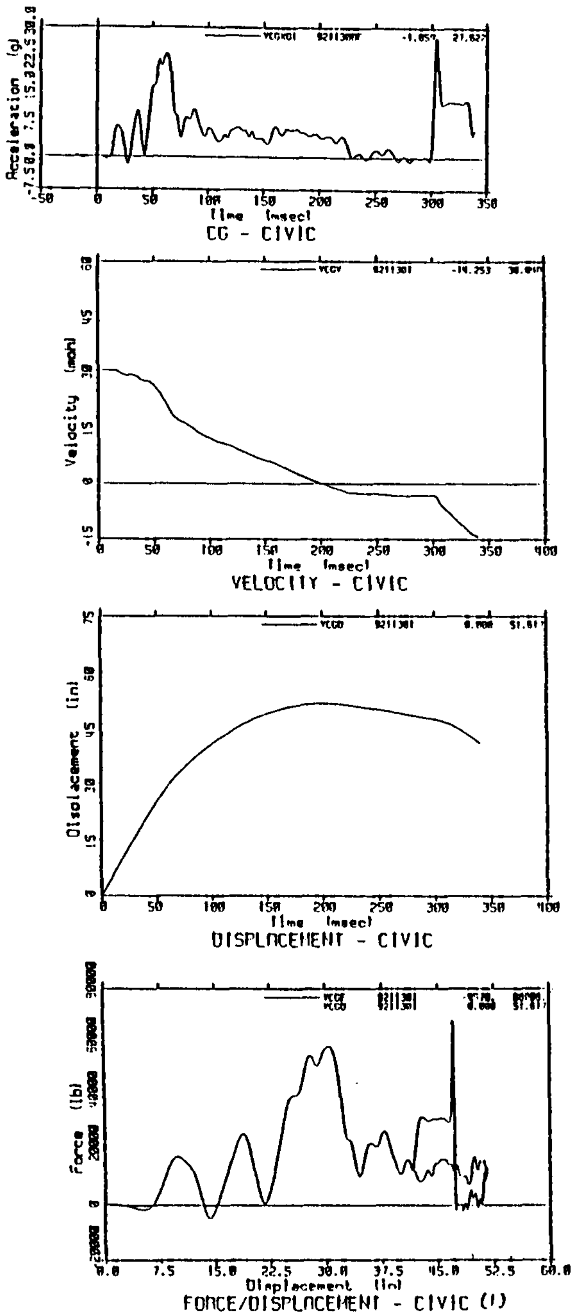


FIGURE 5: CRASH TEST RESPONSE
- CIVIC CX
- LAB FIXTURE

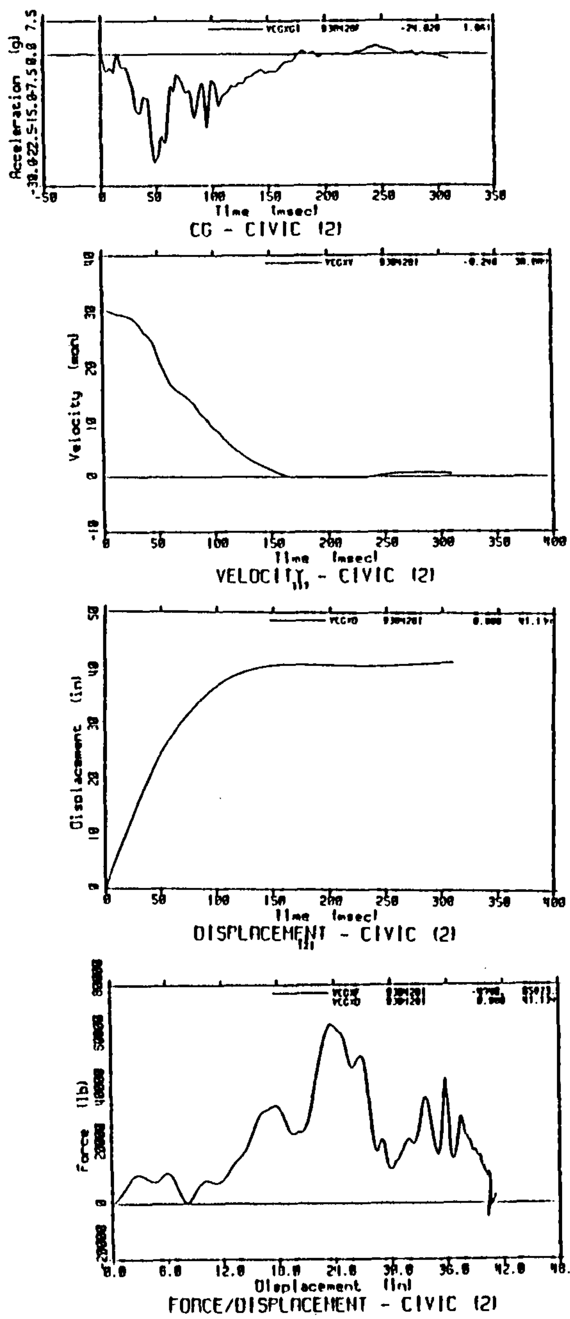


FIGURE 6: CRASH TEST RESPONSE
- CIVIC CX
- TRAILER w STRAP

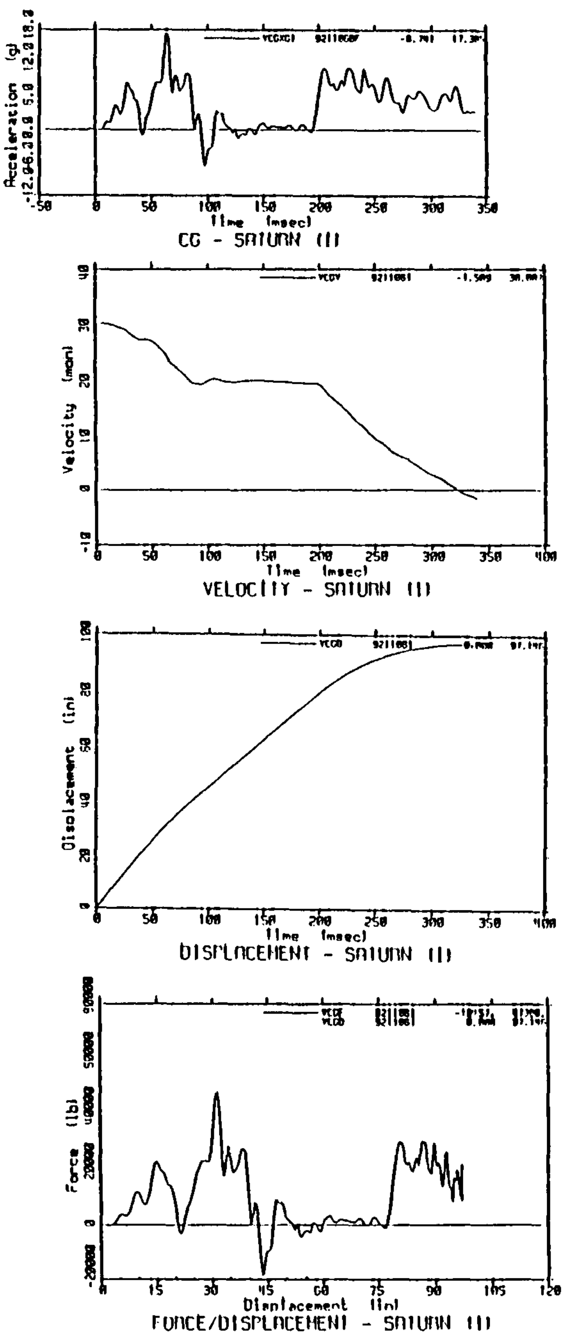


FIGURE 7: CRASH TEST RESPONSE
- SATURN SL
- LAB FIXTURE BOLT FAILURE

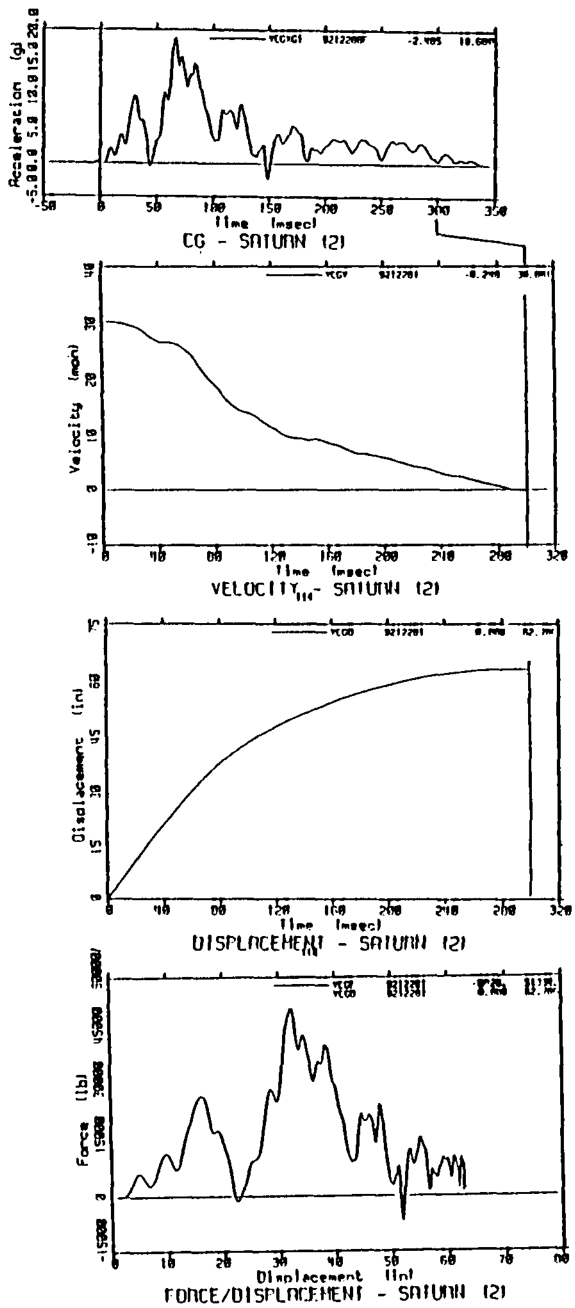


FIGURE 8: CRASH TEST RESPONSE
- SATURN SL
- LAB FIXTURE

GENERAL PERFORMANCE OF THE DEFORMING UNDERRIDE GUARD (MCG)

Figures 1-8 show the performance of each of the NHTSA underride crash tests. Taken directly from Ref 2 they show the acceleration, velocity, and displacement traces for each of the vehicles tested. The force vs displacement trace is also included.

A review of these crash pulses reveal that there are several distinct regions of energy dissipation. These are:

Region 1: Initial crush phase - involves the car upper front structure crush only, which extends generally to the engine block. The guard remains undeformed in this crush region.

Region 2: This region involves guard deformation only. The horizontal member of the guard is being displaced forward and upward until it is at the height of the top of the engine block at which point it begins to override and scrape over the engine and engine compartment.

Region 3: In this region the guard does not deform any further but it begins the process of scraping over the engine compartment and continues to do so until all of the car's kinetic energy is finally consumed (dissipated). This region may extend to the point of initial PCI.

Region 4: This region exists only if PCI occurs.

Figure 9 shows the force vs displacement traces reproduced directly from Ref 2 for three different tests of the Corsica vehicle, namely laboratory fixture test, trailer test, and rigid (non-yielding) guard test. Note that the force build-up during the initial portion of the traces are very similar and nearly identical. Note also that they are essentially linear when the oscillatory content is ignored. The vehicle stiffness in this region is approximately 2,000 pounds per inch. This is Region 1 which extends from zero displacement to approximately 22 inches for this vehicle. The next portion of the traces (Region 2) is due mainly to the guard deformation after peak force is reached. The force then decreases with increasing displacement. This is because the guard is being displaced forward and upward losing strength and direct contact with the car structure in the process. For this vehicle, Region 2 covers a displacement range of approximately 22-37 inches. The force for the rigid guard test, however, continues to increase as expected. Region 3 extends from the end of Region 2 to maximum displacement (underride) in which the guard scrapes over the engine and engine compartment or to the start of PCI.

To illustrate these regions more clearly a simplified picture is presented in Figure 10 which represents the response of the Corsica into the MCG mounted to the laboratory fixture. The energy associated with this chart matches that of the test. The peak force in this case is approximately 45,000 pounds and the force at maximum displacement is approximately 15,000 pounds. The energies associated with each of these regions are independently signficant as shown below:

- Region 1: 43% - Car front upper structure
- Region 2: 29% - Guard deformation
- Region 3: 28% - Guard scrape-over engine compartment

Total: 100%

Note that the greatest individual batch of energy is consumed during the crush of the car front upper structure.

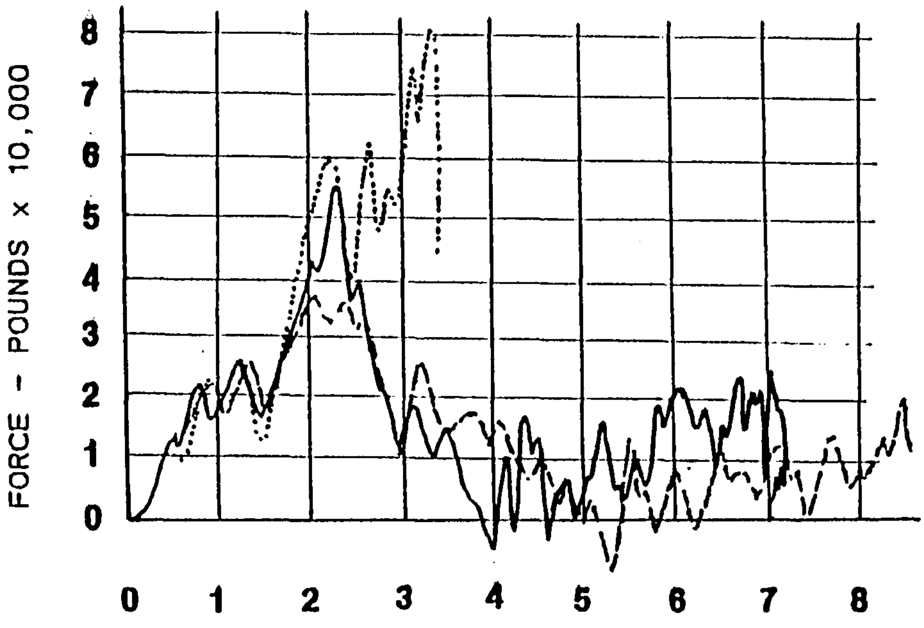
IMPACT SPEEDS ABOVE 30 MPH

A clear understanding of the underride crash test results is needed in order to project or estimate the guard performance at impact speeds above 30 mph. Tests at higher impact speeds would, of course, be more appropriate for this purpose. Critical to the determination of underride performance of the vehicles used in the NHTSA tests for impact speeds above 30 mph is the force level that occurs during the end of the crash pulse, which is the point of maximum underride. The remaining distance between the trailer or laboratory fixture frame and windshield is referred to as clearance. A negative clearance value indicates PCI.

The test results for those cases involving a deforming guard show that the force level at the tail end of the crash pulse is approximately 15,000 pounds. The exact value would certainly be somewhat different for each vehicle, and it would also be affected by the height of the intruding frame. This value, however, is supported as being reasonable by other underride test results where the upper compartment was severely penetrated by the intruding heavy vehicle body. See Ref 6 for the Ford Fiesta underride test in which the guard failed in a 40 mph impact, and Ref 17 where a series of underride crash tests were conducted with passenger cars into the side of a van trailer.

To estimate the MCG performance at impact speeds above 30 mph it was assumed that the 15,000 pound force would continue to extend as a constant value with increasing displacement until the additional energy for speeds above 30 mph would be consumed (35% for 35 mph, and 78% for 40 mph).

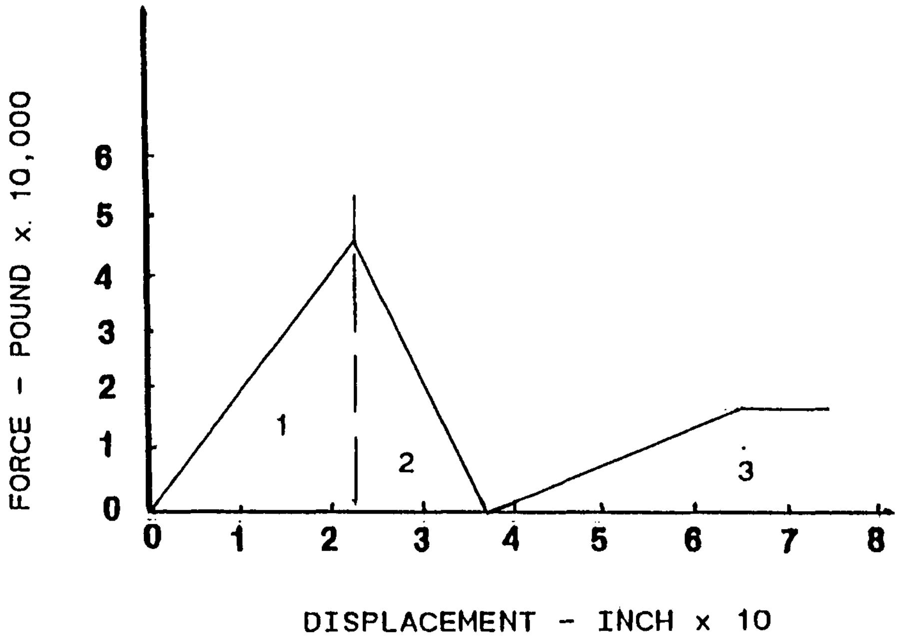
The clearance which resulted from the eight NHTSA underride tests is presented as a function of peak force in the upper chart in Figure 11. Note from this chart that a specific trend exists where clearance logically becomes more beneficial (less total underride) with increasing peak



TEST DESCRIPTION	TEST NO
—— LAB FIXTURE *	921207
---- TRAILER - FRAME FAILED *	930420
······ LAB FIXTURE - RIGID GUARD	921229

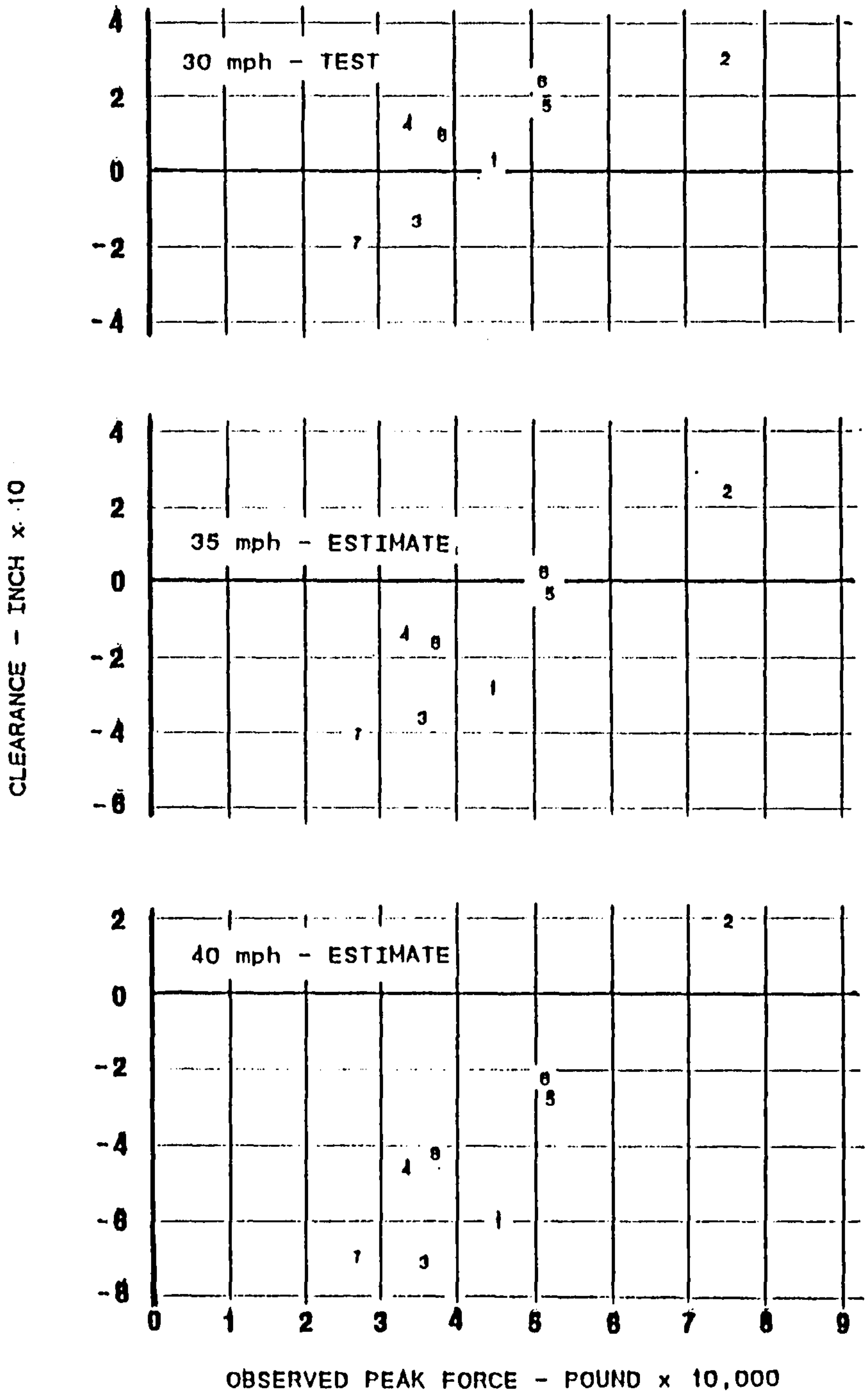
* MINIMUM COMPLIANT GUARD

FIGURE 9: UNDERRIDE CRASH TEST RESPONSE - CORSICA
FORCE v DISPLACEMENT



REGIONS OF ENERGY DISSIPATION
1 - Grill-to-Engine
2 - Guard Deformation
3 - Engine Compartment Scrape-Over

FIGURE 10: GENERALIZED UNDERRIDE FORCE v DISPLACEMENT
- o BASED ON CORSICA LAB FIXTURE TEST
- o TEST NO 921207 - SEE FIGURE 9



1 - 921207 CORSICA LAB
2 - 921229 CORSICA LAB - RIGID GUARD
3 - 930420 CORSICA TRAILER - FRAME FAILED
4 - 921203 TEMPO LAB
5 - 921130 CIVIC CX LAB
6 - 930428 CIVIC CX TRAILER - w STRAP
7 - 921106 SATURN SL LAB - BOLT FAILURE
8 - 921228 SATURN SL LAB

FIGURE 11: VEHICLE CLEARANCE AS A FUNCTION OF GUARD OBSERVED PEAK FORCE

force. The primary trends would be specific to the individual vehicles, such as points 1, 2, and 3 which are for the Corsica. It is expected, however, that a different set of data would exist for groups of larger or smaller size vehicles.

The estimated clearance values based on the procedure described above are shown in Figure 11 for the 35 mph and 40 mph impact speeds. Note that the clearance decreases significantly with the increase in impact speed. Note also that although the clearance for the rigid guard case decreases with increasing impact speed, PCI does not occur, even at 40 mph. These data charts are presented to essentially quantify the guard minimum peak force capacity that would be required to prevent PCI for this group of vehicles in a centric type impact.

Figure 12 is presented to illustrate the average minimum force that would be required to prevent PCI as a function of impact velocity for the NHTSA test series. Note that on average, a 45,000 pound force would be adequate to an impact speed of 33 mph. But based on the unsymmetrical MCG loadings as listed in Table 2 (presumably because of the car's unsymmetrical front crushing structure) the sum of the independent strut load capacity must be greater than 45,000 pounds in order for the guard to generate an impact resistance equivalent to 45,000 pounds. Also, it must be recalled that these test data were obtained with a 48 inch frame height, and since the critical height of most current trailers is considerably lower, the associated impact speed at which PCI will occur will decrease somewhat as shown by the dashed curve in this figure. Note also that the minimum required load varies as a function of the square of the impact velocity.

The data in Figures 11 and 12 indicate that a guard load capacity of greater than 45,000 pounds is needed in the 30-40 mph impact speed range based on PCI concerns. Noteworthy is the fact that occupant injury measures were, in general, quite low for the NHTSA 30 mph tests with the MCG. Although injury measures would certainly increase with increasing impact speeds for a given guard load capacity, more studies are needed to determine the impact speed at which they will exceed injury allowables in combination with the guard strength needed to prevent PCI. This should be done for a variety of vehicle sizes and types. But it is very likely that large magnitudes of PCI that will occur for the MCG at impact speeds above 30 mph will cause serious injury or death to the front seat occupants.

Vehicle size is expected to have an effect on clearance depending upon vehicle weight, hood length and height, and windshield slope. For a given impact speed, the higher kinetic energy of higher weight vehicles will be consumed through larger overall crush distance (underride). Less overall distance will be associated with lower weight vehicles. The peak force will be limited by the guard load capacity regardless of the vehicle size unless the guard is very rigid. Tests with different sized vehicles are needed to evaluate the MCG overall effectiveness for vehicle size and weight. Pickups, vans and sport utility vehicles which have been increasing in popularity since the NHTSA tests were conducted should also be examined for underride protection against the MCG.

SHOULD PCI BE A CRITERION FOR UNDERRIDE SAFETY?

When rear underride was initially treated as a safety problem (in the 1950s), the windshields of the early car models were moderately sloped and occupants were not restrained. The combination of these two factors indicated that any level of PCI from underride would likely cause very serious injury or death to the front seat occupants. It was clear, therefore, that the safety objective of an underride guard was primarily to prevent PCI. But current car highly sloped windshield designs in combination with the use of airbag and belt restraints have shown through the recent NHTSA underride crash tests that some level of PCI will not neccessarily be injurious. All injury levels with the MCG in these tests were relatively low.

The height of the intruding frame in combination with the slope of the windshield and its distance forward of the steering wheel are also significant parameters affecting underride distance to PCI or zero clearance as exemplified in Figure 13 below:

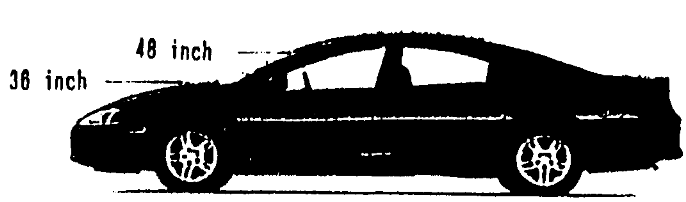


FIGURE 13: EFFECT OF FRAME HEIGHT ON POINT OF PCI

Consideration should also be given to PCI being associated with hood penetration as well. In all impact cases involving an underride guard, accident or test, the hood folds and is displaced rearward. In many cases the hood will penetrate the windshield before the trailer frame does. This is more likely to occur with lower trailer frames which will decrease clearance for a given underride magnitude, and

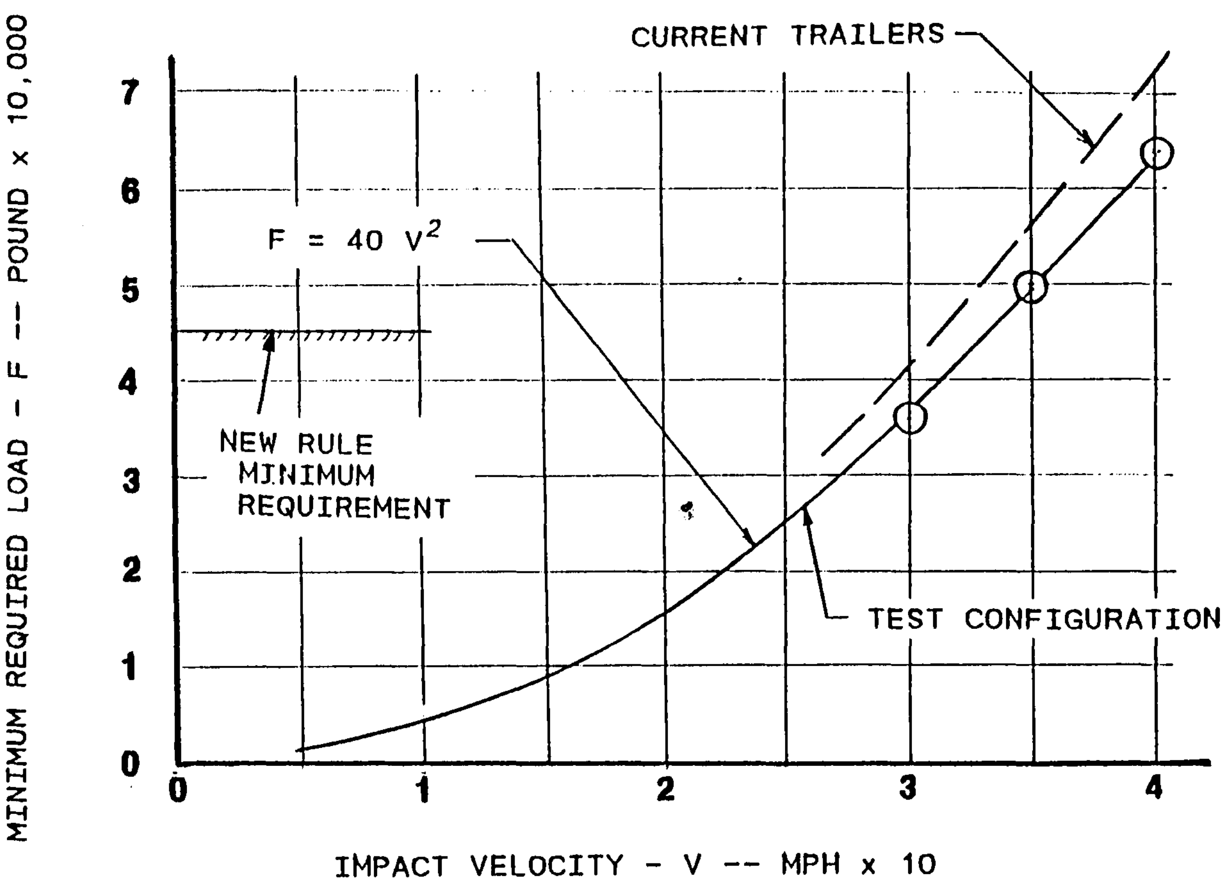


FIGURE 12: MINIMUM REQUIRED LOAD CAPACITY FOR THE UNDERRIDE GUARD TO PREVENT PASSENGER COMPARTMENT INTRUSION - CENTRIC IMPACT

further, hood penetration will increase the potential for occupant injury or death.

In every frontal impact the occupants will move forward with respect to the compartment as far as the restraints will allow. In the NHTSA underride crash tests the farthest forward that the passenger head progressed (belted with no airbag) was to the dash. The head of the unbelted but airbag restrained driver progressed far enough forward to contact the windshield in three cases. To prevent serious injury or death, it is clear that occupant head and torso should not be allowed to be contacted by any intruding object. Fatalities can occur even with low HIC values from contact with sharp surfaces such as intruding folded hoods and the various trailer components (tail light boxes, door locking rods, latches, frame edges).

Consequently, it is recommended for underride test evaluation that a safe distance for allowable underride be established as the distance to, say, 12 inches forward of the steering wheel hub whether PCI occurs or not. This should include structures such as the folded hood as well.

In the real world PCI can be avoided by locating the rear wheels of the trailer as far to the rear as possible.

CONCLUSIONS

The following conclusions are based primarily on the eight NHTSA underride crash tests reported in Ref 2. These tests were conducted with the cars aligned centrically at impact speeds of 30 mph, and the frame height at 48 inches.

o All injury measures from the tests conducted with the MCG were well within the allowables.

o PCI occurred in some of the tests and the driver head contacted the deformed upper structure. But injury measures were still well within allowables. Had the frame height been set at the lower typical trailer heights the PCI at a 30 mph impact speed would have been much greater. The injury measures would likely have been different, but it is suspected that they would not have exceeded allowables.

o Many rear underride accidents occur in the real world above 30 mph. Examination of the NHTSA test results indicates that the MCG would not provide sufficient protection for the front occupants at impact speeds above 30 mph (30-40 mph). At these speeds PCI will be quite severe with the potential for serious injury or death.

o Protection can be provided at impact speeds above 30 mph, but a guard strength higher than the minimum required value of 45,000 pounds (combined strength of both vertical struts) as specified in the new rule (Ref 1) will be needed. The studies herein show that on average, for the cars tested, the following minimun loads will be required to prevent PCI:

- At 30 mph -- 41,000 pounds
- At 35 mph -- 56,000 pounds
- At 40 mph -- 72,000 pounds

o A rear underride guard designed to meet the minimum static load requirements specified in the new underride regulation (Ref 1) will not provide adequate protection in offset impacts.

o A rigid guard would provide adequate protection in a centric impact for the properly restrained occupants at impact speeds of 35 mph and possibly at 40 mph. This is based on comparisons of NCAP and underride test results for the same vehicle. The rigid guard is expected to provide some improved protection in offset impacts over that with the MCG. Even though a rigid guard would provide protection at impact speeds above 30 mph, it would not comply with the intent of the energy requirement specified in Ref 1.

o Some of the NHTSA underride tests showed that the right strut of the MCG began to deform before the left one. This indicates that centric impacts into the guard do not neccessarily result in symmetric loading at the guard/car interface for certain vehicles. This unsymmetric condition caused the guard to produce a peak load that was significantly less than it was designed to provide. Consequently, for a guard to produce a 45,000 pound resistive force it would have to be designed for a load capability higher than 45,000 pounds. Some cars will not be protected as well as others.

o For crash test evaluation of the performance of an underride guard it is recommended that allowable underride be established to be not less than 12 inches to a laterally oriented vertical plane which passes through the center of the steering wheel whether PCI occurs or not.

o See also the sections of this paper which address the salient features and commentary of the NHTSA test results.

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NOMENCLATURE

CLR -- Clearance, distance between the intruding frame and windshield. The value is negative if intrusion past the windshield occurs.
FMCSR -- Federal Motor Carrier Safety Regulation.
FMVSS -- Federal Motor Vehicle Safety Standard.
MCG -- Minimally Compliant Guard.
NCAP -- New Car Assessment Program.
NHTSA -- National Highway Traffic Safety Administration.
PCI -- Passenger Compartment Intrusion.

An Algorithm for Detecting Heavy-Truck Driver Fatigue from Steering Wheel Motion

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Gunter P. Siegmund
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Paper Number 98-S4-O-10

ABSTRACT

This paper is the culmination of previous work to determine if steering behavior could be used to unobtrusively detect driver fatigue. The driving performance of 17 sleep-deprived heavy-truck drivers was monitored on a closed track. Functions in the time, frequency, and phase domains were developed to quantify changes in steering wheel input. The steering-based weighting functions which correlated most strongly with independent measures of driver fatigue and drowsiness were used to develop a simple algorithm. The algorithm predicted fatigue for all 17 volunteer drivers before the end of their test. The algorithm identified 12 drivers before a lane breach occurred, and only two drivers were not captured until a lane breach greater than 15 cm occurred. These data and the algorithm demonstrate the potential for a steering-based fatigue detection algorithm.

INTRODUCTION

Truck driver fatigue is more prevalent than either alcohol or drugs in fatal accidents (1). Therefore, being able to detect driver performance impairment in a non-invasive manner is desirable.

The driving performance of 17 sleep-deprived long-haul truck drivers was monitored on a closed-circuit track to determine whether changes in the drivers' control inputs or in the vehicle motion could be used to predict driver impairment due to fatigue. Steering measures which correlate well with driver fatigue have been previously identified (2,3). Measures of lane maintenance also correlated to driver fatigue, but not as strongly as steering-based measures.

An algorithm based on three functions derived from the steering wheel motion was developed to detect driver fatigue. A detailed explanation of this algorithm is presented and absolute limits for the cutoff values of the three functions in this algorithm are proposed.

METHODS

Test Description

A detailed description of the test configuration and instrumentation has been published (4). The test vehicle was a 1994 Freightliner conventional-cab tractor. The tractor was fitted with a short flatbed loaded with 5400 kg to improve ride-ability. The driver was instructed to maintain a constant following distance around a triangular track behind a 1992 Ford Aerostar pace vehicle. The 42 km/h test speed was maintained using the Ford's cruise control. The triangular 2.9 km track consisted of three "legs": 865, 535, and 565 metres long, respectively. Drivers attended an orientation day drive prior to reporting for their night test.

The following parameters were measured for each driver:

- vehicle speed and distance,
- steering wheel angle (θ) and angular velocity (ω),
- accelerator pedal angle and angular velocity,
- 20-lead electroencephalogram (EEG),
- heart rate (EKG),
- video of driver's face,
- vehicle lane position (using Global Positioning System [GPS]), and
- pace-vehicle following distance.

The drivers were required to remain awake for the night preceding their test. Each test began at about 11:00 p.m. and continued until either safety was compromised or the driver fell asleep. The night drives typically lasted between 2 and 3.5 hours. The safety observer intervened in three night sessions: two drivers failed to negotiate a corner in the test track; the third driver veered out of the lane toward test equipment.

Test Subjects

Seventeen volunteer male drivers completed the testing. The drivers are referred to as Drivers 1 through 19 (Drivers 5 and 17 dropped out). Table 1 lists the driver number, test duration, number of legs (straight sections completed), number of hours of sleep obtained in the preceding 24 hours, the total number of hours of sleep obtained in the preceding 48 hours, the length of an average night's sleep, and the percentage of average sleep obtained during the previous two nights. Drivers were asked not to sleep the night before the test, and therefore the ideal driver would have 50% of his normal sleep in the preceding 48 hours.

The night drives of Drivers 2, 9, and 12 were interrupted by planes landing at the airport used for the testing. This required that the safety observer communicate with the driver and the truck be stopped. The data acquired during these interruptions were discarded and the lap (consisting of 3 legs) of data surrounding the interruption was also discarded. Driver 6's night session was interrupted twice by electrical malfunction. Only the data acquired after the second interruption were used for analysis. The safety observer had to intervene for Drivers 2, 8 and 15.

Variables

Five independent variables were used to measure driver fatigue: Electroencephalography (EEG) activity in the theta band, EEG activity in the alpha band, heart interbeat interval, standard deviation of the heart interbeat interval, and subjective evaluation of drowsiness (SED) from the video data (5). Although eye blink rate can also be used to assess driver fatigue, it could not be reliably determined from the EEG or video data acquired in this study. Dependent variables in this study were steering wheel and accelerator pedal position and motion, the test vehicle speed variation, lane maintenance and car-following distance. Based on the results of previous work (2,3), only steering wheel data were used to develop the fatigue detection algorithm. Lane maintenance data were used for further evaluation.

Table 1.
Driver Information (2)

Driver Number	Total Test Duration (hr:min)	Actual Driving Time (hr:min)	Number of Legs	Sleep Acquired in Previous: 24 hrs	48 hrs	Usual Night's Sleep (hr)	Percent of Night's Sleep (24 hr avg)	Percent of Night's Sleep (48 hr avg)
1	2:47	2:17	99	0.5	3	8	6	19
2	2:27	1:51	78	0	8	8	0	50
3	2:59	2:24	102	4	10	6.25	64	80
4	3:47	3:38	144	0	8	8	0	50
6	1:24	0:55	39	0	6	6	0	50
7	4:11	3:39	156	2	9	7	28	64
8	2:14	1:43	75	0	5.5	6	0	46
9	2:44	2:13	93	4	11	6.5	62	85
10	2:45	2:11	93	2	9.5	7.25	27	66
11	3:16	2:45	120	5	9.33	7.5	66	62
12	2:48	2:17	96	1.5	4.5	7	21	32
13	3:23	2:51	120	5.5	12.5	6.5	85	96
14	3:47	3:14	135	3	10.5	6	50	88
15	1:26	0:50	35	1	6	8	13	38
16	2:24	1:49	69	4.3	11.8	6.5	67	91
18	3:17	2:44	117	2	9*	7	29	64*
19	3:06	2:31	108	3	8	6	50	67

* = Estimated Value

Scoring Steering Performance

Steering wheel position was analyzed in the time, frequency and phase domains. Scoring functions were devised in each domain to quantify different types of steering behavior.

Time-Based Functions - From the graph of steering wheel angle versus time (Figure 1) or steering wheel angular velocity versus time, differences in the steering performance early and late in the tests were evident. For instance, larger and longer duration deviations from the mean steering angle were noted as the test proceeded. Some sudden and rapid movements of the steering wheel were noted which may have been corrections after periods of inattention. Weighting functions that quantified these observations were constructed.

Frequency-Based Functions – Power spectra were calculated for the steering wheel angle and angular velocity data for each leg of a driver's test (Figures 2 and 3). Increases in the proportion of power in the lower frequencies (0 to 0.5 Hz) were noted in local areas (over 2 or more legs) and weighting functions were devised to quantify this transient behavior.

Phase-Based Functions - Phase plots of steering wheel angle (θ) versus steering wheel angular velocity (ω) were constructed (Figure 4). These plots simultaneously showed the position of the steering wheel relative to the mean and the direction in which the steering wheel was being moved. The phase plots of all drivers varied over the course of the test. Data clustered around the origin indicated a short feedback control loop and it was hypothesized that this behavior indicated an alert driver.

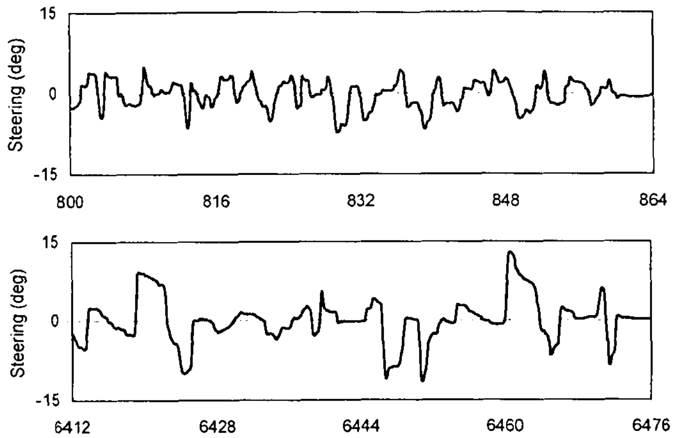

Figure 1. Early and late steering behavior in the time domain for Driver 8 (3).

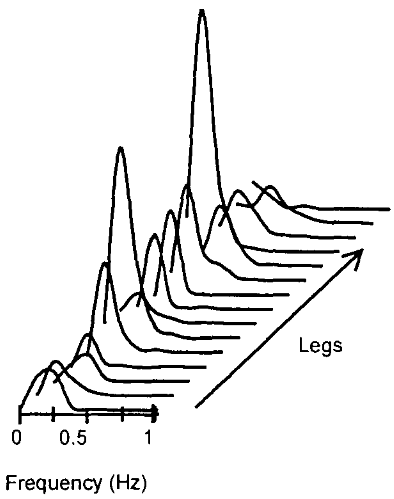

Figure 2. Variations in the power spectrum of steering wheel angle for Driver 6 (3).

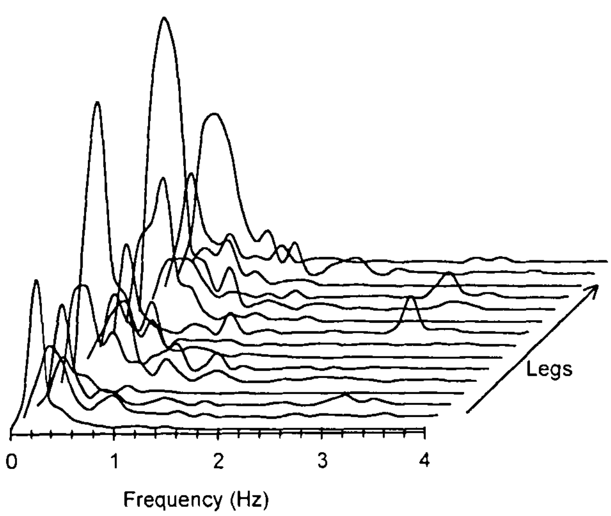

Figure 3. Variations in the power spectrum of steering wheel angular velocity for Driver 6 (3).

Loose loops, occasionally straying far from the origin, indicated longer-duration feedback, and also indicated that the driver was relying on larger and coarser steering wheel movements to control his vehicle. It was hypothesized that this behavior indicated the driver was fatigued. Small sub-clusters on the horizontal axis away from the origin (large steering angle but no angular velocity) were indicative of cornering and were particularly inappropriate on straight legs. A sample of this behavior can be seen between +5 and +10 degrees on the θ-axis of the Late Night phase plot in Figure 4. Weighting functions that quantified and penalized loose loops and small sub-clusters on the θ-axis were developed.

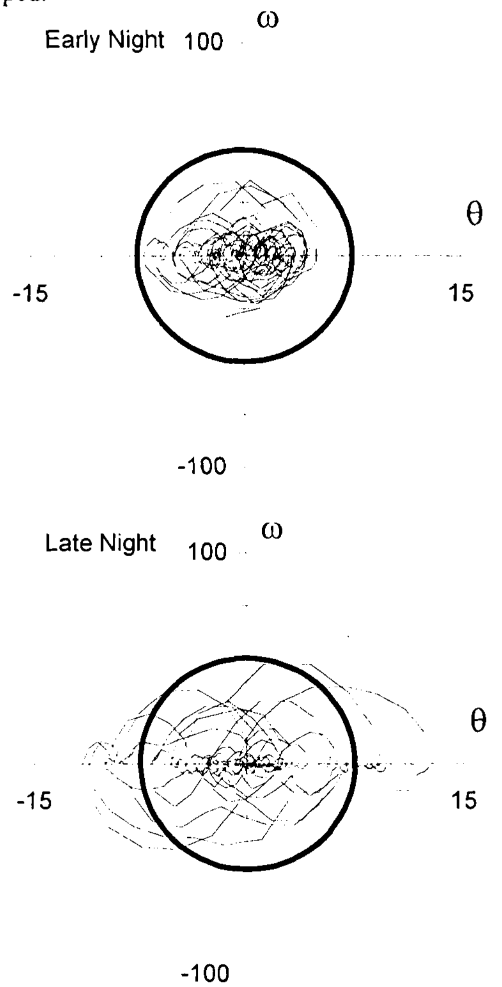

Figure 4. Sample Phase Plots from Driver 8 Showing Steering Behavior and Control Ellipse of $-7.5 \leq \theta \leq 7.5°$ and $-50 \leq \omega \leq 50$ °/s.

A subset of the phase-based weighting functions made use of a control ellipse. It was hypothesized that there was an area of the phase plot surrounding the origin in which alert drivers remained. Based on the phase plot shape of a number of early night legs from a number of drivers, a preliminary ellipse shape was chosen with a horizontal axis (steer angle, θ) of 15 degrees (from -7.5° to +7.5°) and vertical axis (steer angular velocity, ω) of 100 degrees/second (from -50 °/s to +50 °/s). Weighting functions that incorporated only portions of the phase plot outside the acceptable control ellipse were devised.

ALGORITHM DEVELOPMENT

As reported earlier (6), SED is a comprehensive measure of driver fatigue. SED was therefore used as the reference in the development of an algorithm to determine when a driver became fatigued.

To identify which weighting functions correlated best with fatigue, the coefficient of determination (r^2) between the rank order (Spearman) of each weighting function and SED was calculated. The mean r^2 across all drivers was then calculated. A minimum useful coefficient of determination was arbitrarily set to 0.5. As determined previously, ten weighting functions met this criterion (3). Of the ten, three functions were selected for the algorithm: Amp_D2_Theta, Wt Flat 0, and Outside (%) (Appendix A). The former two functions were selected because they correlated most strongly with SED. These two functions represented time-based and phase-based (control ellipse independent) measures. Of 7 phase-based measures which relied on the control ellipse, Outside (%) was selected because it correlated well with drivers who did not correlate well with the first two functions. Together, these three functions correlated with 15 of the 17 drivers. Only Drivers 3 and 4 did not correlate with these or any other functions.

The 6-leg averaged value of the three functions was calculated simultaneously from the fourth leg of each driver's test (the results from the first three legs were ignored). A simple algorithm that monitored the value of these three functions until one exceeded a specific value was used. These specific values (termed the cutoff limits) were determined by independently plotting the average SED value of all drivers over a range of possible cutoff limits (Figure 5). To select cutoff limits for each function, some level of fatigue must be used as a threshold above which a driver is deemed to be too tired to drive. The setting of this threshold level is outside the scope of this study. In order to develop a working algorithm, a SED range between 80 and 100 was arbitrarily used as the threshold above which a driver was too tired to continue driving. A SED score of 80 represents a "Moderately Drowsy" level and a score of 100 represents the level halfway between "Moderately Drowsy" and "Very Drowsy" on the SED continuum (6).

RESULTS

Based on SED levels of 80 to 100, cutoff limits (Table 2) for each weighting function were determined from the graphs in Figure 5. The lower end of the ranges in Table 2 resulted from the inclusion of all drivers and a SED cutoff level of 80.

Four drivers (3, 8, 13, and 15) were found to significantly alter the average SED and a similar series of graphs excluding these drivers was also examined (Figure 5). Three of these four drivers (3, 8, and 15) reached the maximum SED level ("Extremely Drowsy") within 30 legs (10 laps) of the start of the test. Both Drivers 3 and 15 reached a SED level of 100 within 10 legs of the start of the test. Driver 8 reached a SED level of 100 about 22 legs into his test, and fell asleep on leg 75.

For drivers 3, 8, and 15, the steering-based weighting functions lagged the rise in SED. Because of this lag and the rapid rise in SED, the three weighting functions did not reach their cutoff limits until maximum SED had been reached. It was hypothesized that in the real world the transition to "Extremely Drowsy" would not often occur this rapidly and therefore weighting-function cutoff limits excluding these data were also examined.

Table 2.
Proposed Cutoffs for Steering-Based Functions

Weighting Function	Outside (%)	Wt Flat 0	Amp_D2_ Theta
Cutoff Limits	3.1 – 10.3 (3.1 – 6)	11.2 - 16.0	5.0 - 6.3

The upper cutoff limits in Table 2 resulted from the exclusion of Drivers 3, 8, 13, and 15 and a SED cutoff level of 100.

Both the upper limits and lower limits of the ranges proposed in Table 2 were applied to the present data set of 17 drivers. The results are given in Appendix B. The upper limit of Outside (%) was assessed in greater detail, due to the relatively flat slope between SED values of 80 and 100 (Figure 5). An SED value of 100 corresponded to a Outside (%) value of 10, whereas a SED value of 93 corresponded to an Outside (%) value of about 6. Using an upper limit of 10 for Outside (%), only two drivers were captured (2 and 11). Decreasing the upper cutoff limit to 6 resulted in nine drivers being captured (1, 2, 3, 6, 9, 11, 12, 15 and 18).

Table 3 shows the average, minimum and maximum SED levels across all drivers for the upper and lower bounds of the proposed cutoff limits. Using the lower cutoff limits, all but four drivers were trapped before their SED level reached 100 ("Moderately to Very Drowsy"). Five drivers were caught before their SED level reached 40 ("Slightly Drowsy").

Table 3.
SED at Cutoff Limits

Cutoff Limits	Average SED
Lower	68 (12 - 127)
Upper	96 (39 - 152)

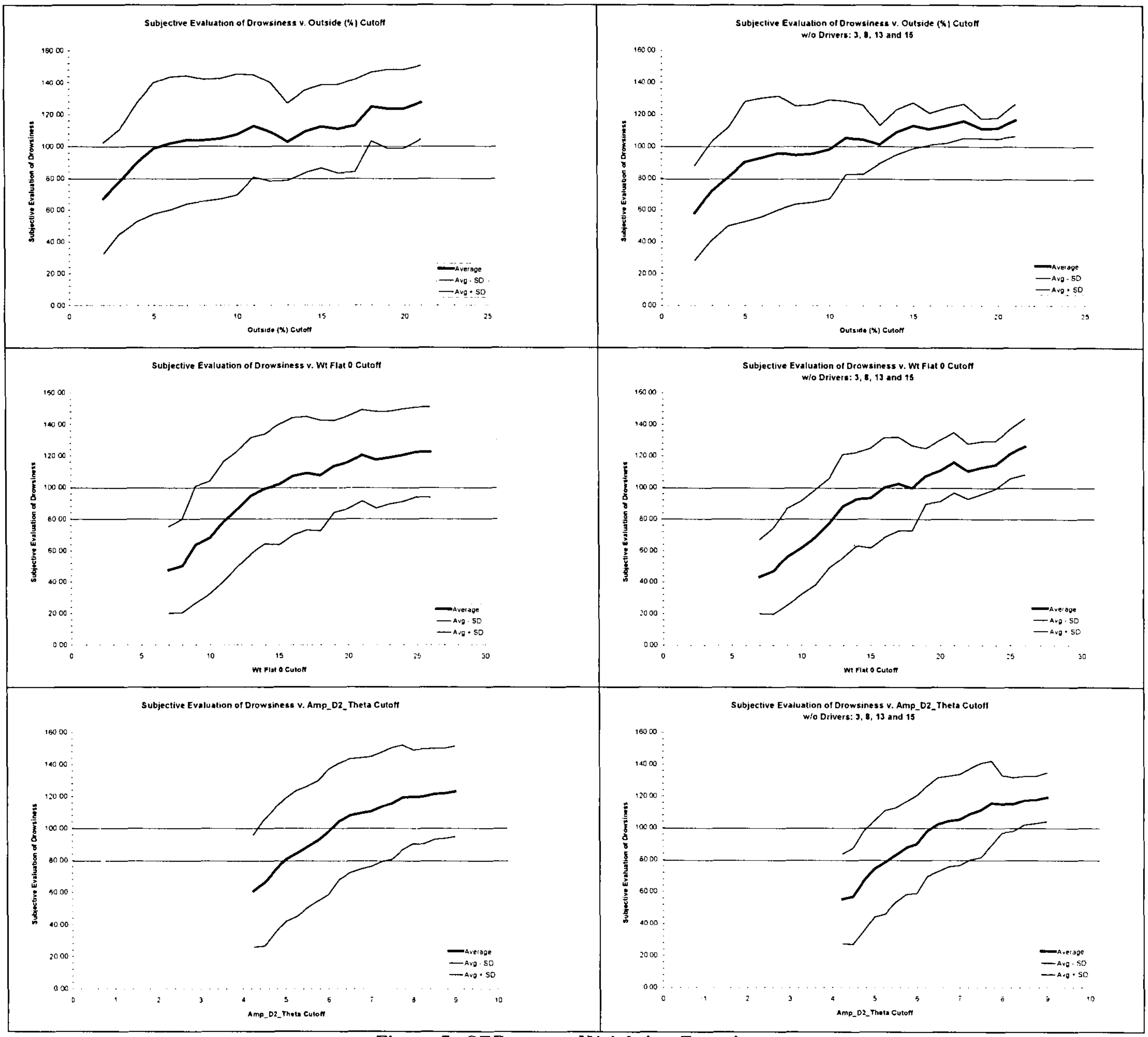

Figure 5. SED versus Weighting Functions.

Using the upper cutoff limits, eight drivers reached a SED level greater than 100, three of which were at about 150 when trapped. Only one driver was trapped before his SED level reached 40, but six were trapped before their SED level reached 80 ("Moderately Drowsy").

A comparison of the algorithm-predicted cutoff points with the lane breach data is shown in Figure 6. The horizontal axis of Figure 6, labeled "Legs", is the number of 6-leg averages. For instance, leg 20 on the horizontal axis corresponds to the average of legs 20 through 25.

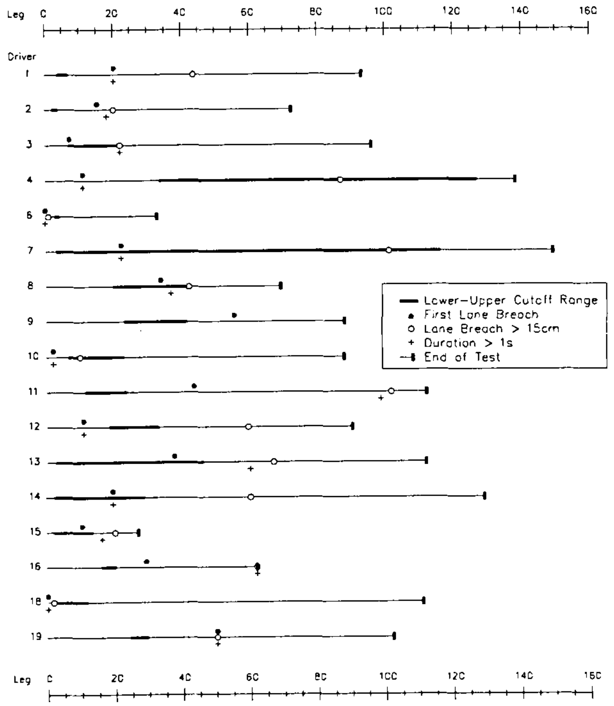

Figure 6. Summary of Algorithm and Lane Breach Cutoff Legs.

In Figure 6, the thin horizontal line terminated by the vertical mark represents the total number of 6-leg averages for each driver. This value is 5 less than the number of legs shown in Table 1 because of the effect of averaging 6 legs. The thicker portion of the line represents the range of cutoff points predicted by the algorithm using the lower and upper cutoff limits in Table 2. The lower cutoff limit corresponds to the left end of the thick line and the upper cutoff limit corresponds to the right end of the thick line.

The three symbols (•, o, and +) depict the points when the first lane breach occurred (•), the first lane breach greater than 15 cm occurred (o), and the first lane breach greater than 1 second in duration occurred (+). If a symbol is absent, then a lane breach meeting its criterion did not occur. To minimize the effect of corner-induced lane breaches, only lane breaches more than 4 seconds from the corner are shown. The relative position of the lane breach data to the thick horizontal line for each driver shows the effectiveness of the algorithm and cutoff limits.

DISCUSSION

The current algorithm and cutoff limits show that a fatigue detection algorithm based on steering wheel motion can be constructed. The algorithm trapped all 17 drivers before the end of their night drive. Figure 6 shows that for twelve of the 17 drivers, the algorithm predicted driver fatigue before or at the same time as the first lane breach occurred. For the remaining five drivers, the first lane breach and the first lane breach greater than 1 second occurred before the lower cutoff limit of the algorithm detected driver fatigue. For three of these five drivers (4, 7, and 10), the algorithm predicted fatigue before a lane breach greater than 15 cm occurred. Also, for three others among the same five drivers (6, 10, and 18), the lower limit of the algorithm detected fatigue within 5 legs of the first lane breach, i.e., within the period of the running average interval.

In only two of the five late-detection cases did a lane breach precede detection by more than 5 legs (Drivers 4 and 12). For both drivers however, the algorithm predicted fatigue before their first lane breach greater than 15 cm. Further examination of Driver 4's lane breach data indicated that his next lane breach (after the one shown at Leg 12) occurred at Leg 56 on this graph - above the lower cutoff limit of the algorithm. Driver 12's next lane breach, on the other hand, occurred at Leg 12 on this graph - still about 8 legs below the lower cutoff limit of the algorithm.

Only two drivers (6 and 18) were not captured by the algorithm before a lane breach of 15 cm. In both cases, the algorithm detected fatigue within five legs of the start of the test and within two legs of the breach. The algorithm failure for Driver 6 may be related to his initial elevated level of drowsiness. His test was interrupted twice by electrical failures and the start of his driving data was preceded by about one hour of lost data.

Driver 18's early lane breaches were a result of extended pre-corner maneuvers (he breached the lane for 8 seconds prior to one corner). It was not until leg 12 - near the upper end of the algorithm-predicted range - that he breached the lane at a distance from the corner.

The average driver reached the lower cutoff limit at Leg 12 and the upper cutoff limit at leg 36. Excluding Drivers 4 and 7, both of whom had long cutoff intervals, the average upper cutoff limit was reached at leg 24. If lane breach is a valid indicator of driver fatigue, then the results depicted in Figure 6 suggest that the lower cutoff limits proposed in Table 2 may be slightly high for some drivers. For other drivers, even the upper cutoff limit was low.

Driver 13 was the only driver who did not reach a SED level of 100 - his maximum SED was 91. He was the driver who received the largest portion of his normal sleep in the 48 hours preceding the test (96 percent). His gradual increase in SED may be more indicative of a real-world driver and suggests that cutoffs based on a SED between 80 and 100 are too high. This gradual increase in drowsiness of drivers not sleep-deprived should be explored further.

An optimal value for each cutoff limit has not been chosen for two reasons: first, data gathered at highway speeds with drivers who are initially alert and grow drowsy will be required to properly set the cutoff limits; and second, a decision on what level of SED constitutes a dangerous level must be addressed and resolved.

In addition, the question of absolute cutoff limits (applicable to all drivers) or relative cutoff limits (individual driver specific limits) has not been explored. To properly determine relative cutoff limits (e.g. doubling of a weighting function within a specific time interval), the alert values for the three weighting functions must be known. These data were not available for the drivers in this study.

The weighting functions and algorithms were developed from data gathered in straight leg sections with intervening corners. On average, half of each lap was spent cornering and the other half was spent on the straight sections, which means that only half of the data gathered was used. In a real world application, data would probably be gathered more continuously and the time length of the running averages may need modification. It is not known to what degree the intervening corners delayed fatigue development. Data gathered from truck drivers on the road will be required to confirm the appropriate time length for the running averages.

The cutoff values were developed from data gathered from a specific truck on a specific track under test conditions. Moreover, all of the data were gathered at a nominal speed of 42 km/h. Testing of other trucks on real roads at highway speeds must be conducted to validate the weighting functions, the algorithm, and the cutoff limits. Different steering-box ratios on other trucks may also alter the cutoff limits.

If a fatigue detection device is to be used predominantly on highways, then some means of determining that the vehicle is travelling at highway speed will be necessary. For example, the frequency of gear shifts could be monitored. Periods of high-speed travel and low gear-shifting frequency could be useful precursors to the onset of fatigue (7).

Almost all of the drivers in this study were sleep-deprived prior to starting their test. Because the drivers were not monitored from an alert condition into a fatigued condition while driving, the proposed cutoff limits may be subject to modification. Real-world testing of initially-alert drivers must be conducted to confirm or modify these cutoff limits.

Lane maintenance may be a valuable independent measure of driver fatigue as imaging technology develops and becomes more affordable. Combining lane maintenance and steering wheel data will reduce the potential for misdiagnosing driver fatigue.

In summary, three steering-based weighting functions are recommended for detecting driver fatigue: Outside (%), Wt Flat 0, and Amp_D2_Theta. The proposed absolute cutoff limits for the three weighting functions are shown in Table 2. These proposed cutoff limits were based on SED levels of 80 and 100, and on data acquired under controlled conditions. They are necessarily preliminary and are subject to confirmation by on-the-road testing. The proposed algorithm captured all 17 drivers before the end of their night test. Twelve of the drivers were detected before any lane breaches occurred. Only two drivers were not captured before a lane breach greater than 15 cm occurred, and both of these drivers were captured within two legs of this lane breach.

ACKNOWLEDGMENTS

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APPENDIX A - STEERING-BASED WEIGHTING FUNCTION FORMULAE

Various weighting functions based on steering angle (θ), steering angular velocity (ω), and combinations of the two were developed. Three ways of viewing the data were used to develop the weighting functions:

- Time-based: weighting functions developed from variations in θ or ω plotted against time,
- Frequency-based: weighting functions developed from variations in the power spectrum,
- Phase-based: weighting functions developed from variations in θ plotted against ω (no time dependence).

The three weighting functions referred to in this paper are outlined below:

Time-Based Weighting Functions

Both θ and ω were plotted against time and weighting functions were devised to score variations present in these variables as the driver tired. As discussed, Amp_D2_Theta was selected for determining a cutoff point:

__Amplitude Duration Squared Theta__ - (*Amp_D2_Theta*) - Each distinct area between theta and the mean of theta over the length of one leg was multiplied by the length of time the steering angle remained on that side of the mean. The area under the θ-curve was calculated using trapezoidal integration. Figure A1 shows the variables used to calculate Amp_D2_Theta.

$$Amp\_D2\_Theta = \frac{100}{N}\sum_{j=1}^{J}\left(A_j^{\theta} t_j^{\theta}\right) \quad \text{(A1)}$$

where A^{θ}_j = the *j*th area block in the (θ-θ_m) data of the leg,
t^{θ}_j = the length of the *j*th area block in the leg,
J = the total number of area blocks in the leg,
= Z+1 (see Zero Crossings below),
N = total number of samples in leg, and
100 is a scaling factor.

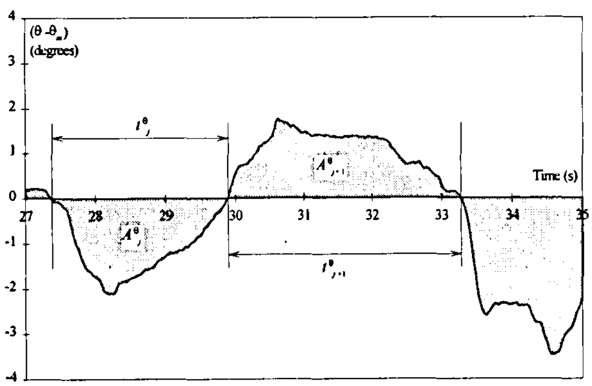

Figure A1. Definition of variables for calculating Amp_D2_Theta.

Phase-Based Weighting Functions

Phase-based weighting functions were developed by examining the phase plot of steering angle (θ) versus steering angular velocity (ω) (see Figure A2). These functions were broken into two sub-groups: functions dependent on a hypothesized control ellipse, and functions independent of the control ellipse.

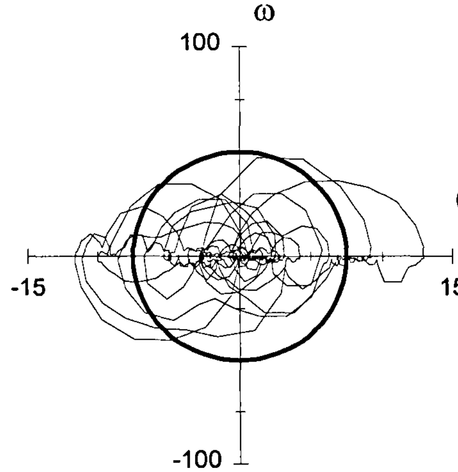

Figure A2. Example of Phase Plot with Control Ellipse.

Ellipse-Dependent Weighting Functions

A control ellipse with a horizontal (θ) axis length of 2*a* and a vertical (ω) axis length of 2*b* was superimposed onto the phase plot of θ versus ω. Steering behavior outside the control ellipse was penalized, whereas steering behavior inside the ellipse was considered normal. Different ellipse dimensions (*a*,*b*) were also investigated: *a* was varied between 3° and 9° in 1.5° increments, and *b* was varied between 20°/s and 60°/s in 10°/s increments. Values of ±7.5° and ±50°/s were selected.

__Outside (%) - (*Outside*)__ - The percentage of (θ,ω) points per leg outside the control ellipse including single point episodes.

$$Outside = 100\frac{n}{N} \quad \text{(A2)}$$

where n = number of points outside control ellipse,
N = total number of sampled points in leg, and
100 is a scaling factor.

Ellipse-Independent Weighting Functions

__Weight Flat Zero - (*Wt Flat 0*)__ – only (θ_i,ω_i) points in the phase space satisfying the condition $|\omega| \leq \omega_c$ with ω_c = 5 °/s are included in the calculation. All points satisfying this condition are weighted by the square of the distance from the origin.

$$Wt.\ Flat\ 0 = \frac{100}{N}\sum_{i=1}^{N}\left(\frac{(\theta_i - \theta_m)^2}{a^2} + \frac{\omega_i^2}{b^2}\right) \quad \text{(A3)}$$

only for $|\omega_i| \leq \omega_c$

where θ_i = ith value of the steer angle,
θ_m= mean value of all θ's for leg,
a = half axis length of ellipse in θ dimension,
ω_i = ith value of steer angular velocity,
ω_c = cutoff value of omega (5 °/s),
N = total number of sampled points in leg, and
100 is a scaling factor.

APPENDIX B – ALGORITHM PERFORMANCE

Two tables are presented, showing the results of running the algorithm through the current set of 17 drivers using first the lower cutoff limits (Table B1) and then the upper cutoff limits (Table B2).

ALGORITHM RESULTS

Table B1 Cutoff results for all Drivers using a SED value of 80

	Limit	Driver Number 1	2	3	4	6	7	8	9	10	11	12	13	14	15	16	18	19	Min	Avg	Max
Total legs driven		99	78	102	144	39	156	75	93	93	120	96	120	135	35	69	117	108	35	99	156
Cutoff Leg		4	3	8	35	3	3	21	23	7	12	20	3	3	4	18	3	27	3	12	35
Leg where SED = 80		17	16	1	74	2	128	10	30	3	21	21	106	47	2	15	88	28	1	36	128
SED at cutoff		39	54	122	67	86	18	127	69	109	60	79	12	35	92	103	19	75	12	68	127
Maximum SED for all legs		124	150	157	132	135	103	160	135	141	154	153	91	137	160	155	151	154	91	141	160
Maximum SED before capture		39	54	122	73	86	18	127	69	109	60	79	12	35	92	103	19	75	12	69	127
Outside (%)	3.1	3.93	6.06	3.34	1.61	8.99	0.85	3.01	3.72	2.36	3.70	3.20	0.63	3.89	3.22	1.23	2.30	2.36	0.63	3.20	8.99
Wt Flat 0	11.2	9.4	10.7	13.1	9.7	16.2	8.1	10.1	8.9	8.6	10.9	11.3	8.3	10.3	10.6	9.6	11.7	10.9	8.1	10.5	16.2
Amp_D2_Theta	5	4.72	4.6	5.8	5.1	6.27	5.49	5.49	3.71	5.11	3.28	3.83	5.04	3.92	3.36	5.1	4.34	5.22	3.28	4.73	6.27

Table B2

Cutoff results for all Drivers using a SED value of 100

	Limit	Driver Number 1	2	3	4	6	7	8	9	10	11	12	13	14	15	16	18	19	Min	Avg	Max
Total legs driven		99	78	102	144	39	156	75	93	93	120	96	120	135	35	69	117	108	35	98.8	156
Cutoff Leg		7	3	24	128	3	117	44	40	23	24	34	47	30	15	22	12	32	3	35.6	128
Leg where SED = 100		23	21	4	102	7	143	14	51	6	46	28	999	73	6	18	94	32	4	98	999
SED at cutoff		44	54	151	123	86	68	153	95	131	89	116	43	70	149	123	38	101	38	96	153
Maximum SED for all legs		124	150	157	132	135	103	160	135	141	154	153	91	137	160	155	151	154	91	141	160
Maximum SED before capture		44	54	151	132	86	69	158	95	131	89	116	43	70	149	123	38	101	38	97	158
Outside (%)	6	6.82	6.06	6.18	3.78	8.99	1.29	4.22	6.24	3.18	6.19	6.13	2.18	5.15	8.42	4.86	6.37	4.47	1.29	5.33	8.99
Wt Flat 0	16	13.6	10.7	13.8	14.4	16.2	8.5	13.6	14.4	13.1	12.3	13.4	12.4	16.4	17.9	14.9	15.4	15.3	8.5	13.9	17.9
Amp_D2_Theta	6.3	6.57	4.60	6.85	7.95	6.27	6.45	7.03	5.80	6.59	4.15	4.69	6.30	5.29	6.01	6.34	5.31	6.62	4.15	6.05	7.95

IMPROVEMENT OF CAR-TO-TRUCK COMPATIBILITY IN HEAD-ON COLLISIONS

Céline Adalian
Jean-Luc Russo
Dominique Césari
INRETS
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ABSTRACT

This paper presents the analysis of experimental crash program between small or large car and truck in order to characterize the effect of a Front Underrun Protection Device (FUPD) coupled with closing speed and overlap on mechanical and biomechanical characteristics. This device has been developped in order to improve the geometrical compatibility between cars and trucks in head-on collisions.

INTRODUCTION

Accidents between cars and trucks are among the most fatal accidents because of the car underrunning. This phenomenon leads to serious and fatal injuries for car occupants because of intrusion of the car structure into the passenger compartment. The ECE/UN Regulation n°93 which consists of a rigid beam in front of the truck has been created in order to avoid the car underrunning.

This regulation has been created thanks to researches on the development of test procedure for energy-absorbing front underrun protection systems for trucks made by an EEVC Working Group (WG14). In the EEVC WG14 report of March 1995, there is a summary of accident analysis of several European countries, where we can read that of the 48000 fatally injured people in road traffic accidents in 1992, 13000 people were killed in accident with trucks involved, about 7000 were car occupants and 4200 of them were killed in car-to-truck frontal collisions.

In the same time, in 1994, a collaboration in France between Renault VI (truck manufacturer) and INRETS has begun. The research program set up is based on a experimental design to determine the effect of the vehicle masses, the overlap and the closing speed and the effect of the FUPD on mechanical and biomechanical characteristics. This experimental design is presented in the next part of the paper and the global and in-depth analyses are presented after.

PRESENTATION OF THE EXPERIMENTAL DESIGN

The experimental design consists of a serie of 22 crash tests between small or large car and truck. The mass of the small car is about 1000 kg and the mass of the large car is about 1500 kg. There is no passive safety device such as pretensioner or airbag in all the cars we have used apart from the 3-pts retractor belt.

At the beginning of the program we have used two masses for the truck : 7.5 and 18 tons. But we have seen that there is little effect of the truck mass, so we have changed the 18 tons into 16 tons for technical reasons. For all the tests, the truck is stationary with transmission placed in neutral position and parking break disengaged.

We have also realized tests with one of the three following impact velocities for the car : 40, 56 and 65 kph and two overlaps : 1/3 and 2/3 of the car width. In most of the crash tests we have used two instrumented 50% Hybrid III dummies positionned on the front seats of the car.

Figure 1 presents one of the configurations we have tested : a crash between a small car and a truck fitted with the FUPD. The overlap was 2/3 and the impact velocity was 56 kph.

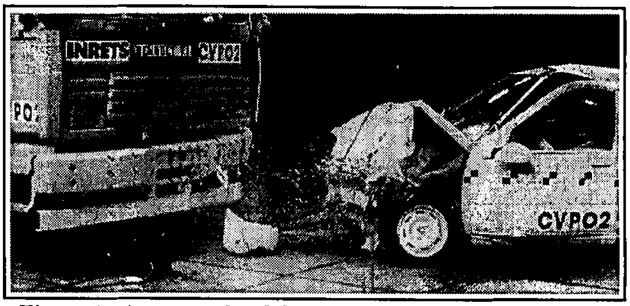

Figure 1. An example of the crash tests realized. Overall front view after impact (small car, truck with FUPD, 56 kph of impact velocity and 2/3 overlap).

Table 1 presents the characteristics of the 22 crash tests.

Table 1.
Characteristics Of The 22 Crash Tests Planed and/or Performed According to The Experimental Design

car type	FUPD	velocity of impact car (kph)	overlap	weight of truck (t)	Date of test
small	with	56	2/3	7.5	nov-94
small	with	40	1/3	7.5	dec-94
small	without	65	1/3	7.5	may-95
large	with	40	1/3	7.5	jun-95
large	without	40	2/3	7.5	jul-95
large	without	40	1/3	18	dec-95
small	without	40	2/3	7.5	feb-96
large	without	75	2/3	7.5	mar-96
small	with	65	2/3	7.5	apr-96
small	without	56	1/3	7.5	may-96
large	without	56	2/3	7.5	sep-96
large	without	65	1/3	7.5	nov-96
small	without	56	2/3	18	dec-96
small	with	65	1/3	16	feb-98
small	with	40	2/3	16	apr-98
large	with	75	2/3	16	
small	with	75	2/3	7.5	
large	with	56	1/3	16	
large	without	65	2/3	16	
large	with	75	1/3	7.5	
large	with	65	2/3	7.5	
small	without	75	1/3	16	

The data measured during these crash tests are standard data : accelerations and displacements for the car and the truck structures and accelerations and forces for the two Hybrid III dummies. In order to characterize and analyse the effect of a Front Underrun Protection Device (FUPD) in relation with the effect of closing speed and overlap, we have selected for comparison some of these mechanical and biomechanical data. The mechanical data choosen are the acceleration of the left B-pillar, the lower left external windshield corner displacement, the vertical and longitudinal steering-wheel displacement. The biomechanical data choosen are the driver HIC, the maximum 3 msec chest acceleration, the maximum femur and tibia driver compressive forces. All these data are relative to the impacting car.

The FUPD used for some of the test is a rigid one and it has been developped in order to improve the geometrical compatibility between cars and trucks in head-on collisions.

At the end of this research program we will be able to determine the characteristics of a deformable FUPD in order to distribute the energy absorption of the crash between the car and the truck structures.

As we can see in Table 1, 15 crash tests have been already realized. So we are not able to analyse entirely the effect of all the characteristics we have choosen. But we can assess some tendancies if we analyse in a global way the 15 crash test performed and if we analyse more closely the tests pair by pair as we will do later in this paper.

GLOBAL ANALYSIS

In this part, we are going to analyse the results of 13 of the 15 crash tests already performed in a global manner. That is to say that we will just classify the tests regarding the presence of the FUPD or not.

We have classified the 13 tests firstly by the presence of the FUPD or not, and secondly by the increasing magnitude of the acceleration of the left B-pillar. We can see that when there is a FUPD, the acceleration of the left B-pillar is directly related to impact velocity at the first order and then, for the same impact velocity, to the overlap (see figure 2). This is not the case for the crash tests without FUPD (see figure 3).

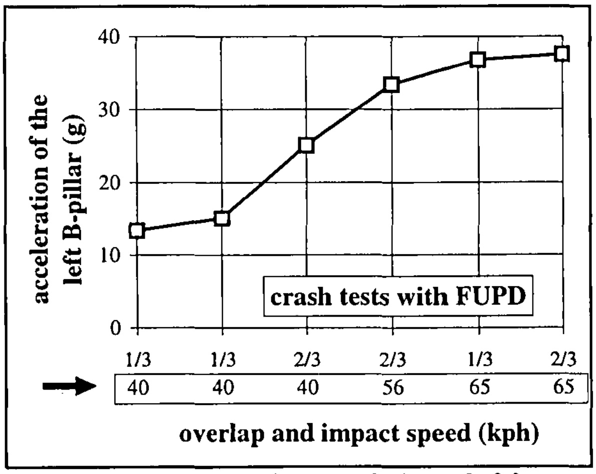

Figure 2. Influence of the impact velocity and of the overlap on the acceleration of the left B-pillar for crash tests with FUPD *

* there is no distinction between small and large cars

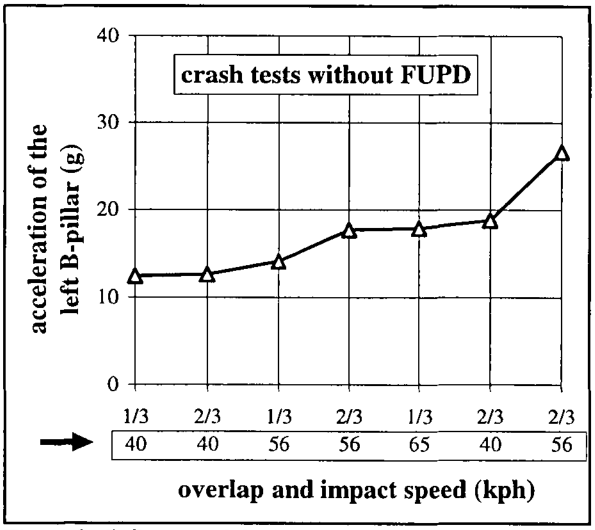

Figure 3. Influence of the impact velocity and of the overlap on the acceleration of the left B-pillar for crash tests without FUPD *

We also have classified the 13 tests firstly by the presence of the FUPD or not, and secondly by the increasing magnitude of the driver HIC (see figure 4). We can see that when there is a FUPD, the maximum 3 msec chest acceleration is increasing with the driver HIC (see figure 5). This is not the case for the crash tests without FUPD (see figure 6).

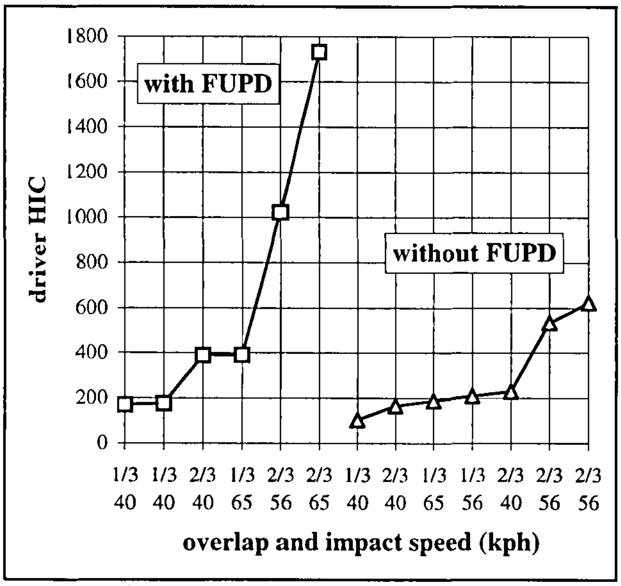

Figure 4. Classification of the crash tests with and without FUPD by increasing driver HIC *

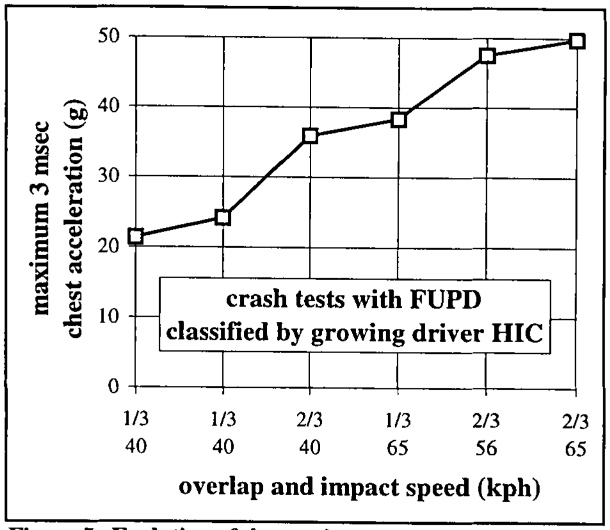

Figure 5. Evolution of the maximum 3 msec chest acceleration for the crash tests with FUPD classified by increasing driver HIC *

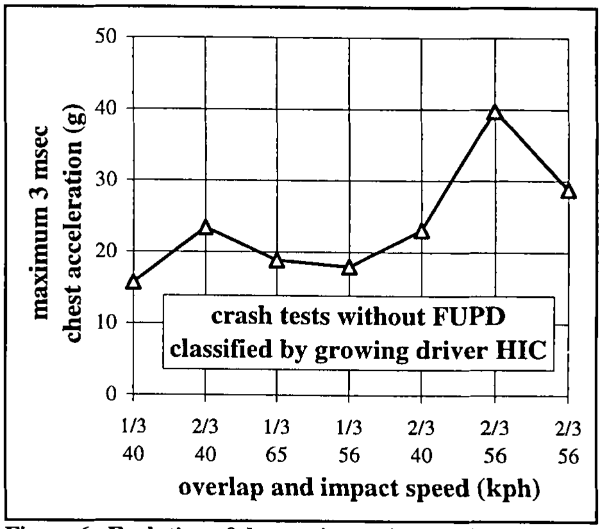

Figure 6. Evolution of the maximum 3 msec chest acceleration for the crash tests without FUPD classified by increasing driver HIC *

During the tests the thoracic deflexion was measured ; however this parameter seems to be independant from the test conditions, and then we have decided not to use it in the comparative analyses.

We can also notice that even if the driver HIC is greater than the criterion limit (HIC limit = 1000) for two tests with FUPD, all the 13 values of the maximum 3 msec chest acceleration are under the limit (max. 3 msec chest acceleration limit = 60 g).

In order to study the influence of overlap, FUPD and impact velocity on the mechanical and biomechanical characteristics choosen, we have grouped some of the 13 tests by pairs. For every pair, the two tests have the same characteristics except for one of the parameters mentionned before. As the analysis has shown a very small influence of the truck mass on test results, we have not taken into account the mass of the truck to group the tests by pairs.

IN-DEPTH ANALYSIS

The two first pairs we are going to study are tests with small car and 2/3 of overlap. The impact velocity is 40 and 56 kph and for each pair there is one test with FUPD and the other without FUPD.

After this analysis, we will study two other pairs : with small cars, with FUPD and with two impact velocity (40 and 65 kph). For each pair there will be one test with an overlap of 1/3 and the other with a 2/3 overlap.

Influence of the Front Underrun Protection Device

As we have mentionned before, all the results we will analyse in this part are relative to crash tests with the small car and 2/3 overlap. In figures 7 to 10, we present the results of the characteristics relative to the car structure (acceleration of the left B-pillar, lower left external windshield corner displacement, vertical and longitudinal steering-wheel displacement).

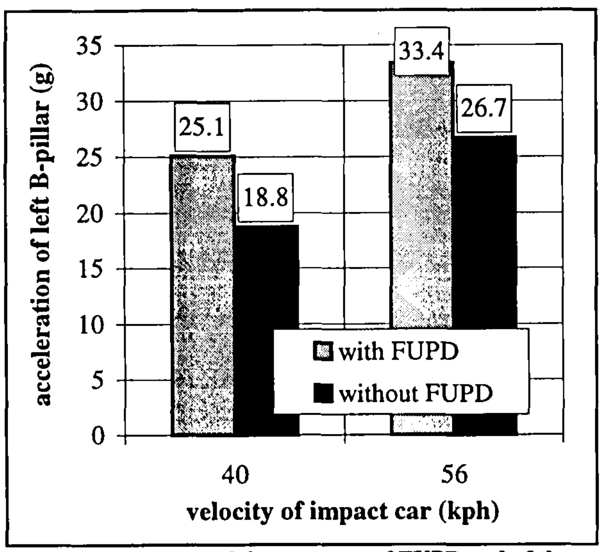

Figure 7. Influence of the presence of FUPD and of the impact velocity on the acceleration of the left B-pillar

We can see in figure 7 that the acceleration of the left B-pillar is greater when there is a FUPD whereas this is the contrary for the lower left external windshield corner displacement (see figure 8).

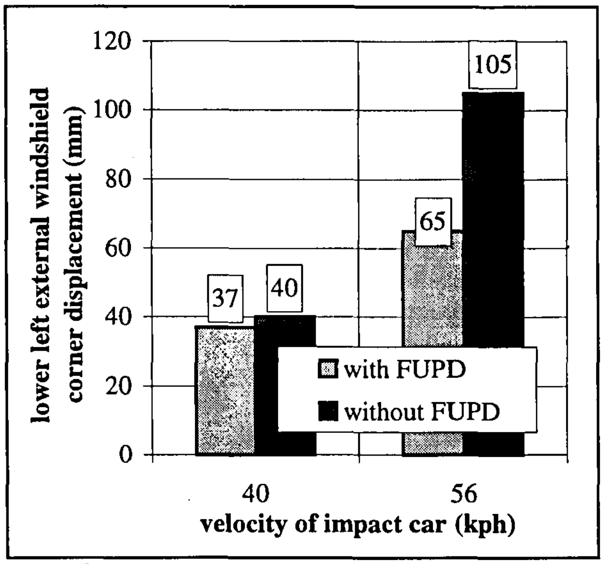

Figure 8. Influence of the presence of FUPD and of the impact velocity on the lower left external windshield corner displacement

We can also see that the evolution for the vertical steering-wheel displacement is the complete opposite of the evolution of the longitudinal steering-wheel displacement (see figures 9 and 10).

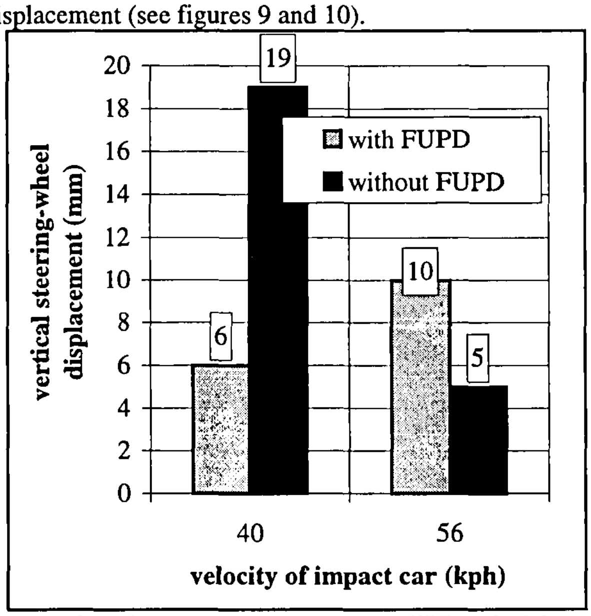

Figure 9. Influence of the presence of FUPD and of the impact velocity on the vertical steering-wheel displacement

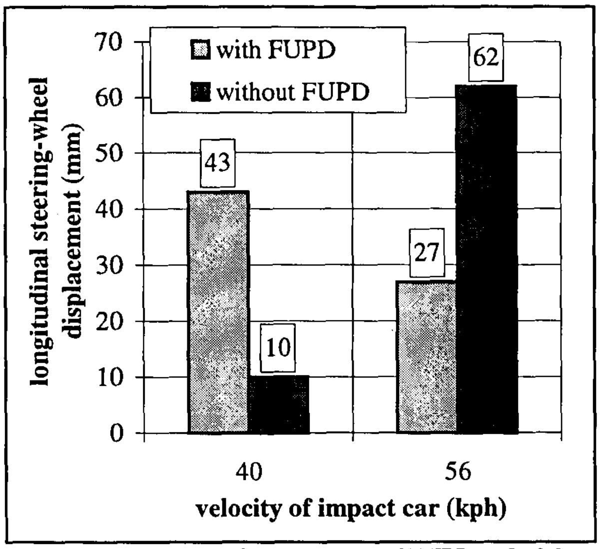

Figure 10. Influence of the presence of FUPD and of the impact velocity on the longitudinal steering-wheel displacement

In figures 11 to 16, we present the biomechanical results (driver HIC, maximum 3 msec chest acceleration, maximum force for femurs and tibias).

We can see in figure 11 that for one configuration (with FUPD at 56 kph) the driver HIC exceeded the limit HIC (1000). But we have to recall that there wasn't any passive safety device in the impacting car. The most important to say is, as we have noticed for the acceleration of the left B-pillar, the driver HIC is greater when there is a FUPD. We will comment it later.

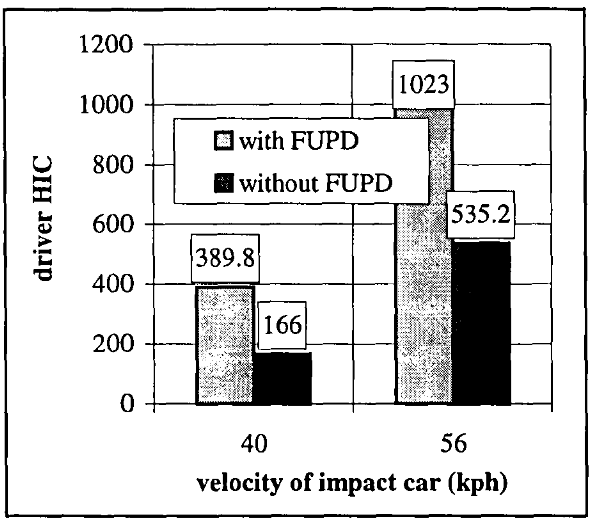

Figure 11. Influence of the presence of FUPD and of the impact velocity on the driver HIC

The same observation can be made for the driver HIC and the maximum 3 msec chest acceleration in agreement with the observation we have made in the global analysis part.

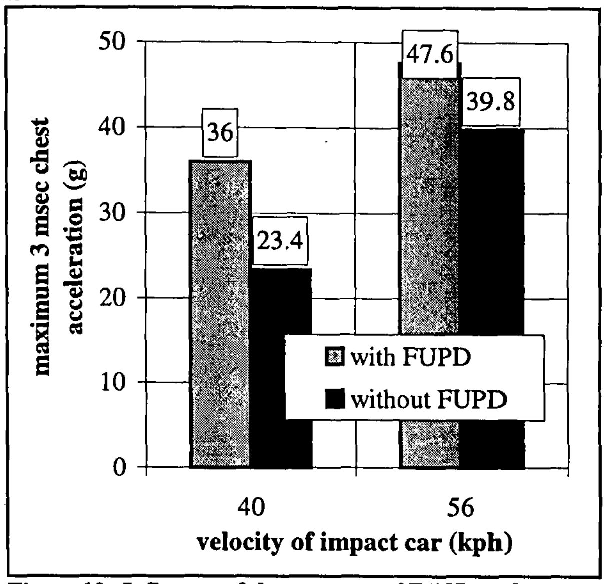

Figure 12. Influence of the presence of FUPD and of the impact velocity on the maximum 3 msec chest acceleration

The measure we have choosen for femurs is the maximum compressive force during 10 msec in order to have results to compare with the plateau limit (7560 N). In one case for the femur measures and in one test for the tibia measures we don't have any value. It is represented in the figure by the "?" symbol (see figures 13 to 16).

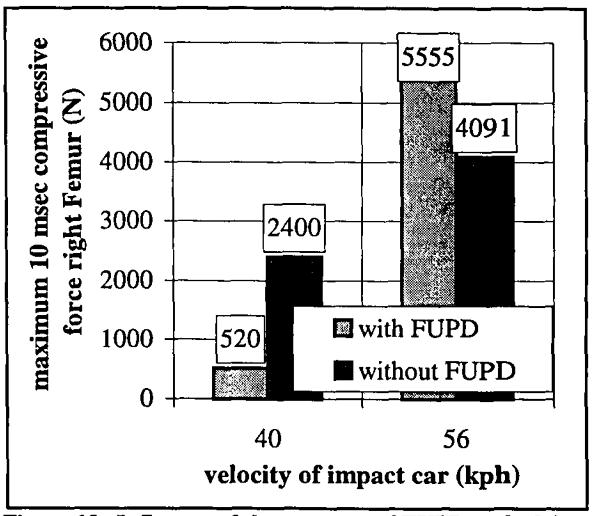

Figure 13. Influence of the presence of FUPD and of the impact velocity on the maximum 10 msec compressive force right femur

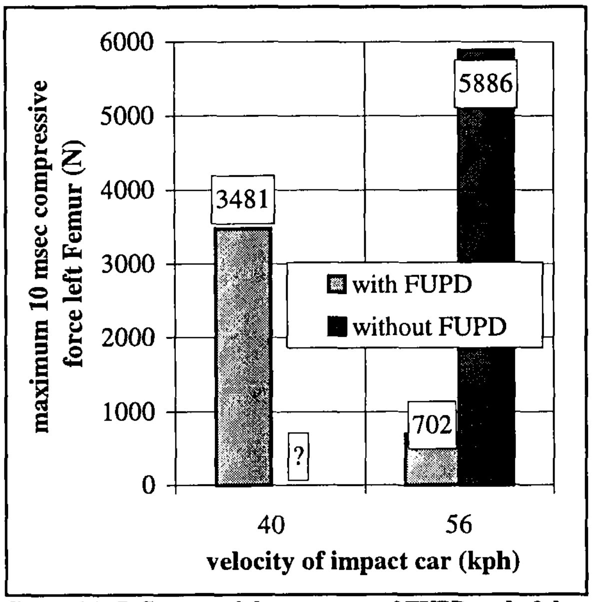

Figure 14. Influence of the presence of FUPD and of the impact velocity on the maximum 10 msec compressive force left femur

We recall that the limit for the maximum compressive force for tibias is 8 kN.

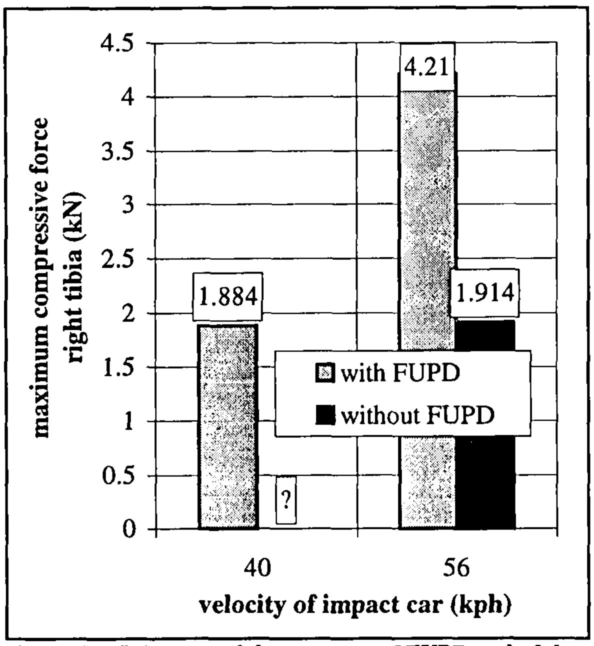

Figure 15. Influence of the presence of FUPD and of the impact velocity on the maximum compressive force right tibia

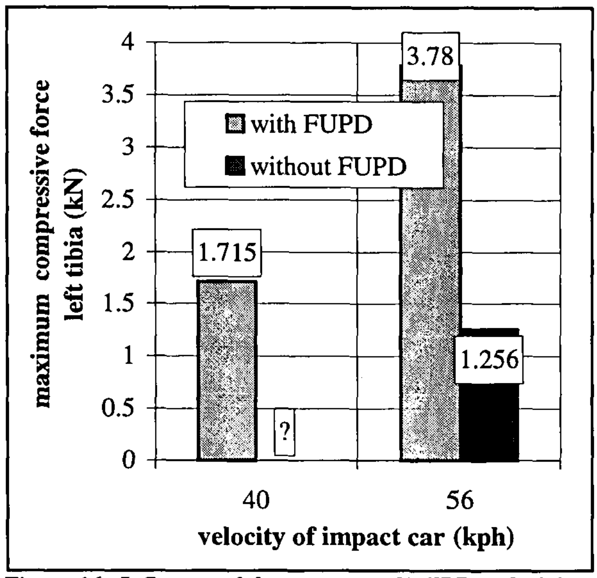

Figure 16. Influence of the presence of FUPD and of the impact velocity on the maximum compressive force left tibia

We can see in figure 13 to 16 that the limits for femurs and tibias are far to be reached.

Influence of the overlap

As we have mentionned before, all the results we will analyse in this part are relative to crash tests between small car and truck with FUPD. The presentation of the results is the same as for the study of the influence of FUPD.

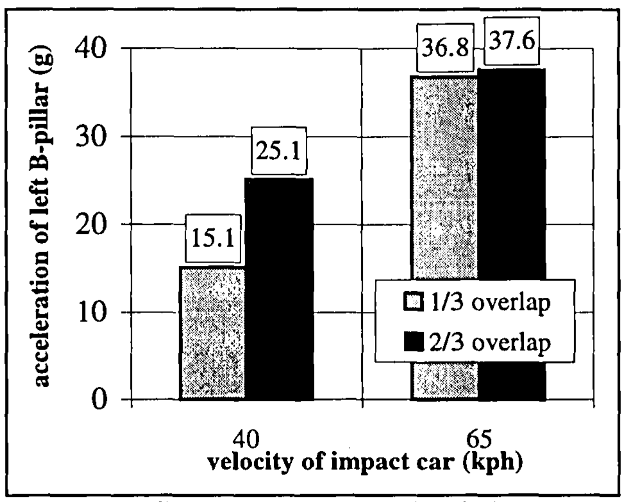

Figure 17. Influence of the overlap and of the impact velocity on the acceleration of the left B-pillar

We can see that the acceleration of the left B-pillar at 65 kph for 1/3 overlap is really close to the acceleration for 2/3 overlap. On the contrary, for the lower left external windshield corner displacement the two values are really different (the magnitude for 1/3 overlap is about twice the magnitude for 2/3 overlap).

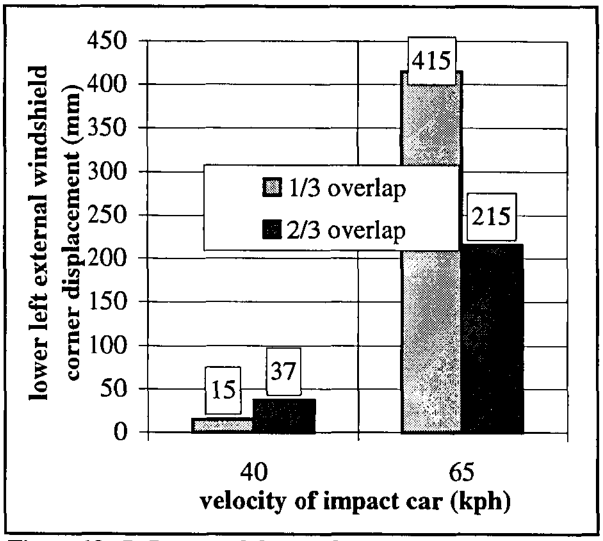

Figure 18. Influence of the overlap and of the impact velocity on the lower left external windshield corner displacement

Once again, we can see in figures 19 and 20 that the evolution for the vertical steering-wheel displacement is the complete opposite of the evolution of the longitudinal steering-wheel displacement.

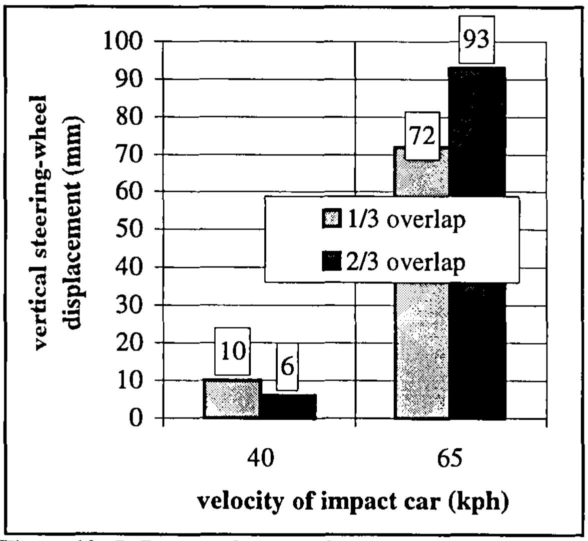

Figure 19. Influence of the overlap and of the impact velocity on the vertical steering-wheel displacement

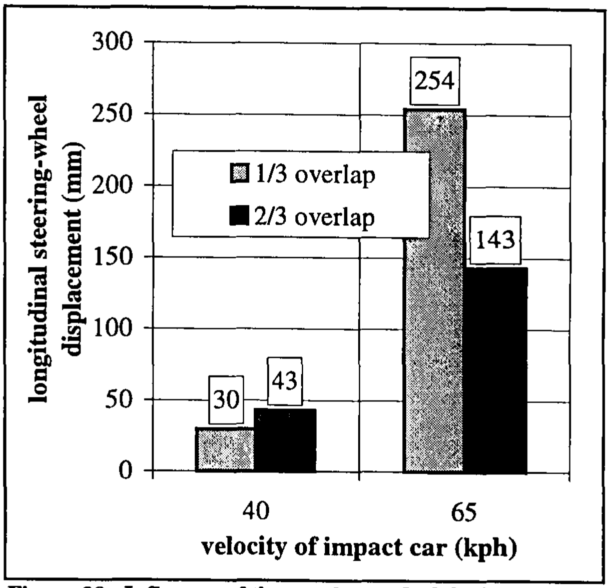

Figure 20. Influence of the overlap and of the impact velocity on the longitudinal steering-wheel displacement

As we can see in figure 21, the driver HIC is greater than the limit for 2/3 overlap at 65 kph.

But, in opposition to the first study (the influence of FUPD) the evolution of the driver HIC is not the same as the evolution of the acceleration of the left B-pillar and of the maximum 3 msec chest acceleration (see figure 17 and 22). These two characteristics have the same evolution in this case also.

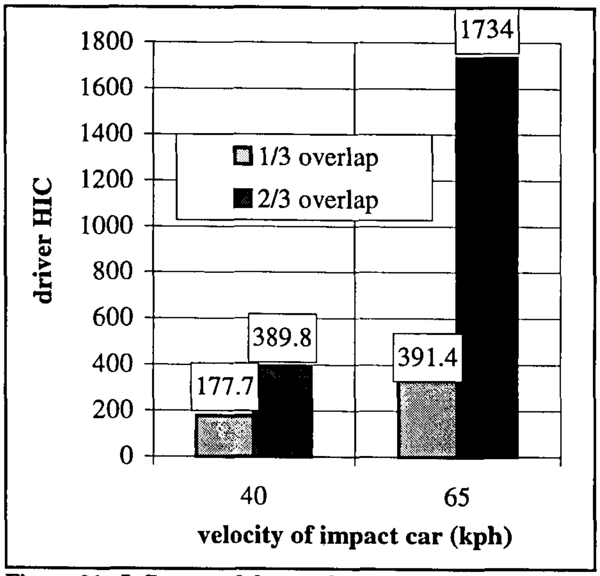

Figure 21. Influence of the overlap and of the impact velocity on the driver HIC

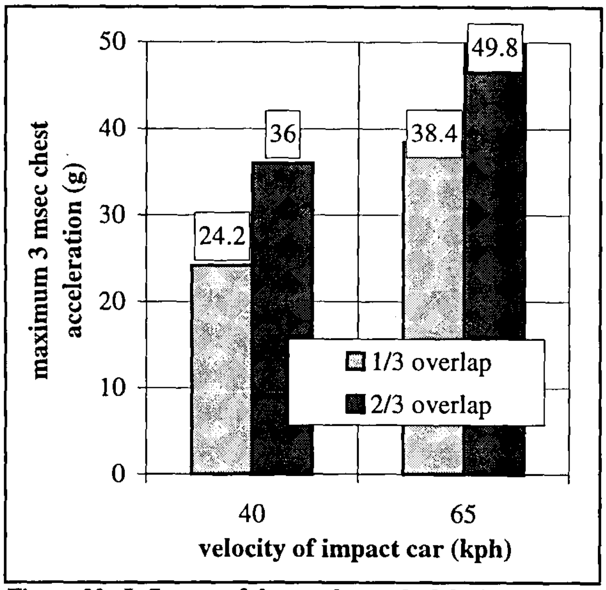

Figure 22. Influence of the overlap and of the impact velocity on the maximum 3 msec chest acceleration

On figures 23 to 26, we can see the evolution of the characteristics relative to femurs and tibias. In this study too, these values are far from the biomechanical limits.

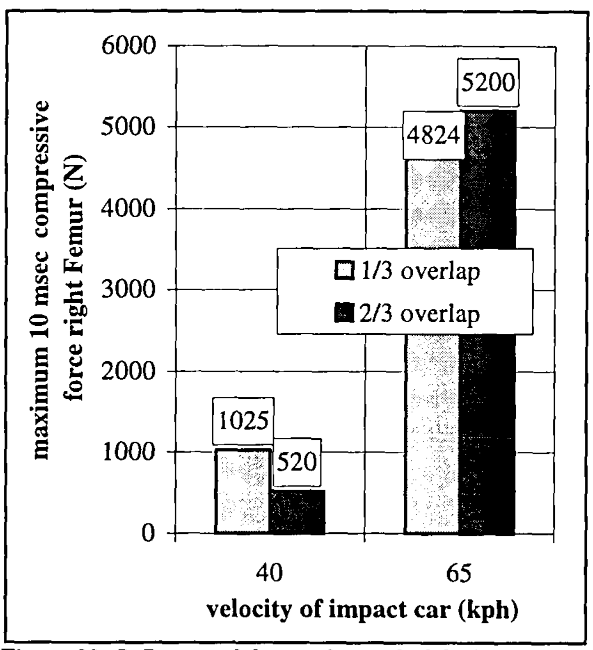

Figure 23. Influence of the overlap and of the impact velocity on the maximum 10 msec compressive force right femur

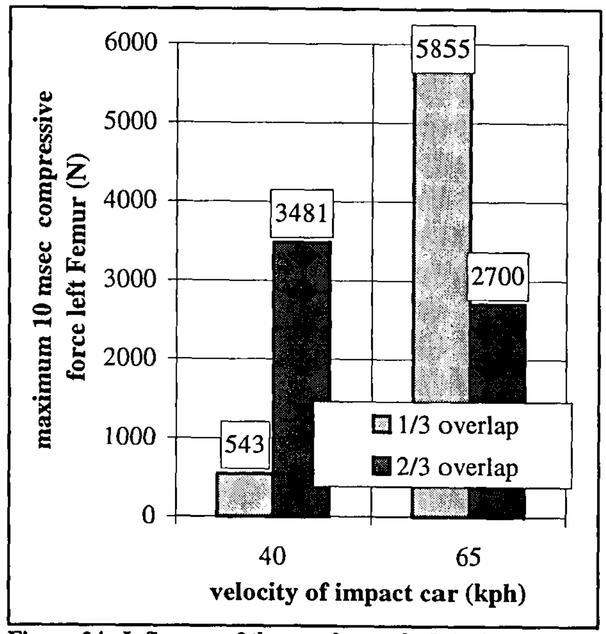

Figure 24. Influence of the overlap and of the impact velocity on the maximum 10 msec compressive force left femur

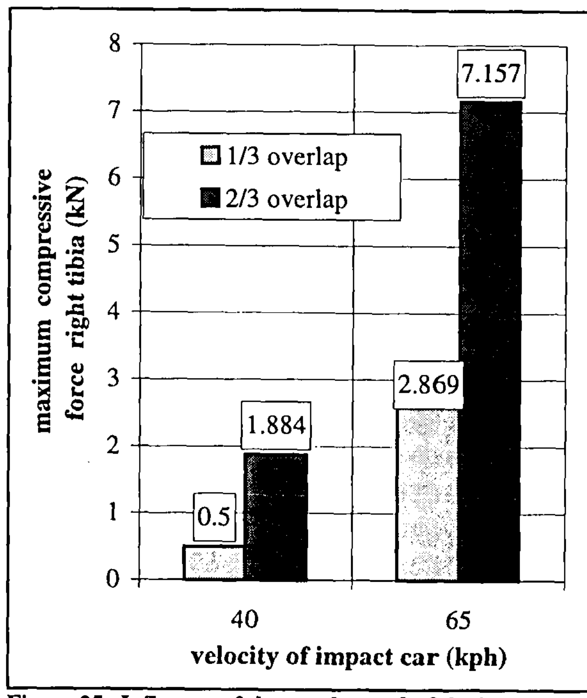

Figure 25. Influence of the overlap and of the impact velocity on the maximum compressive force right tibia

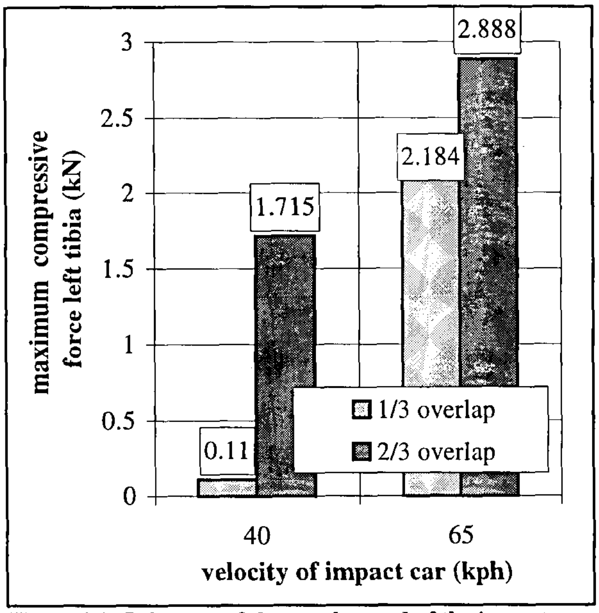

Figure 26. Influence of the overlap and of the impact velocity on the maximum compressive force left tibia

DISCUSSION AND CONCLUSION

The analysis of the results of 13 car to truck frontal impact tests allows to evaluate the influence of the front underrun protection device (FUPD) for different speeds and offset values.

Most of the characteristics we have studied are increasing with impact velocity for any configuration (presence or not of FUPD, 1/3 and 2/3 overlap), except for 4 cases. These cases show that impact velocity is not the only parameter that have to be taken into account in order to study the FUPD.

The FUPD controls the deformation of car limiting the intrusion ; but this increases the deceleration of the car and then provides higher biomechanical criteria values, compared to cases without FUPD. Nevertheless, these values are below or very close to protection criteria limits ; this means that for closing speed up to 65 kph it is possible to assess the protection in car-to-truck frontal collision when the geometrical compatibility.is guaranted by the FUPD

The influence of the intrusion on injury risk would probably appear more clearly at higher speeds.

After completion of the program, it will be possible to recommend some relevant characteristics for an energy-absorbing front underrun protection device.

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HEAVY DUTY VEHICLE CRASH TEST METHOD IN JAPAN

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ABSTRACT

In recent, safety measures for occupants in heavy duty vehicle collisions such as for buses and trucks have been studied intensively in Japan. However, domestic guidelines for crash tests for heavy duty vehicles were not available in Japan prior to this study. Japan Automobile Research Institute (JARI) has started to study standard guidelines for heavy duty vehicle crash tests with the contract by Japan Automobile Manufacturers Association (JAMA).

This paper investigated configurations of heavy duty vehicle accidents. Then guidelines for crash tests of buses and trucks have been formulated accordingly. The guidelines can evaluate occupant injuries similar to frontal impact regulation for passenger cars in Japan (Article 18, Safety Regulation for Road Vehicles). Vehicle crash tests have also been conducted to verify the guidelines. It is found that the guidelines are satisfactory for heavy duty vehicles.

INTRODUCTION

The number of fatalities caused by automobile traffic accidents amount to about 10,000 per year, still showing a quite serious situation. In order to improve this situation, governments and automobile manufacturers have been studying safety measures against accidents. In the studies related with heavy duty vehicles such as buses and trucks, their aggressiveness to the passenger car occupants and safety measures for the heavy duty vehicle occupants have been studied . For the aggressiveness, measures to prevent passenger car underrun in rear-end collision with heavy duty vehicles have already been made mandatory. Studies to prevent the underrun of passenger cars in head-on collisions have been made since then.

As regards to the safety measures for the heavy duty vehicle occupants, the active and passive safety measures have been studied by vehicle manufacturers. In recent years, attempts to improve crash safety measures for the heavy duty vehicle occupants have been made. The Bus subcommittee and the Cab subcommittee under the Heavy Duty Vehicle Committee of JAMA have been studying on crash safety of heavy duty vehicles since April 1996. At the end of 1995, "The Technical Committee for Safety Crashworthiness and Occupant Protection of the Bus" was established by the Japan Bus Association, and "Second Stage of Advanced Safety Vehicle (ASV)" was formed by the Ministry of Transport in early 1996. Moreover, "The Technical Committee for Safety Crashworthiness and Occupant Protection of the Truck" was established by the Japan Truck Association in late 1996, and studies on practical measures to improve the safety of heavy duty vehicle occupants have been conducted actively by these committees since then.

Under such circumstances, crash test methods to evaluate occupants safety performance for the heavy duty vehicle must be set first. However, guidelines for heavy duty vehicle crash tests were not available in Japan, even if each manufacturer in house has set crash test methods. Therefore, it was requested by JAMA that JARI has started to study domestic guidelines for heavy duty vehicle crash tests.

This paper studied real world accidents involving heavy duty vehicles, and proposed two guidelines for crash tests of bus and truck, based on the passenger car frontal impact regulation in Japan. Finally, crash tests for heavy duty vehicles were carried out according to the proposed guidelines in order to verify their feasibility, which will be also discussed in this paper.

ACCIDENTS

In order to obtain more realistic test conditions based on actual accidents involving heavy duty vehicles in Japan, national traffic accident statistics for three years (1992 to 1994) for buses and one year (1995) for trucks were analyzed. The accident statistics data on buses and trucks will be described in the following.

Buses

Occupant injuries on large buses with gross vehicle weight of 12 tons, or of heavier category, were analyzed.

Figure 1 shows the severity of occupant injuries classified by its seating positions - i.e., driver seat and passenger seats on the buses (including tour guide seat). The number of passengers who sustained serious or minor injuries is greater than the number of drivers. One of the reasons for the above should be attributed to the greater number of passengers than one driver in each bus. The number of fatal injuries, on the other hand, is greater for drivers.

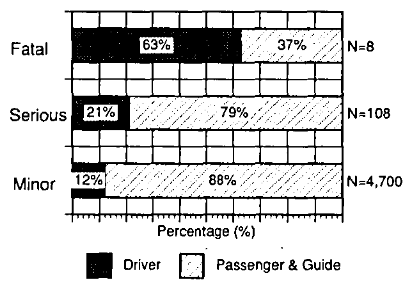

Figure 1 . Severity of occupant injuries classified by its seating position on the buses .

Figure 2 shows the severity of injuries on bus occupants divided into two categories: types of accidents - i.e., vehicle-to-vehicle accidents and single vehicle accidents, such as vehicle-to-object or rollover accidents, and seating position. It is found that vehicle-to-vehicle accidents account for more than 70 % of all severity of injuries, regardless of the seating positions. The rate of such accidents is particularly high (90 % or more) for fatal and minor injuries of passengers and minor injuries of drivers.

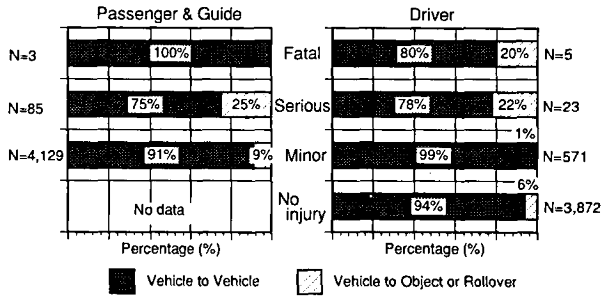

Figure 2. Severity of injuries on bus occupants divided into seating position and two types of accidents.

Taking into account such high percentages of vehicle-to-vehicle accidents, the damaged area of buses are classified into four types : frontal, side, rear and unknown, in Figure 3. Figure 3 also shows the incident rate according to the seating position and the severity of injuries. In case of fatal or serious injuries of bus occupants, frontal impacts account for approx. 70 % of the total, and the percentage is especially high for drivers (90 % or higher).

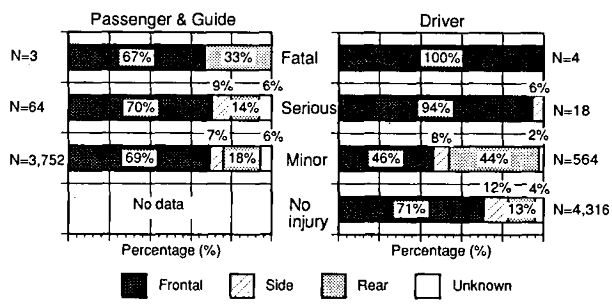

Figure 3. Severity of injuries on bus occupants classified by seating position and damaged areas of buses

Frontal impacts, with the highest incidence rate among the vehicle-to-vehicle accidents, are classified further into four types for buses. These are head-on, intersection, rear-end and others. The severity of injuries on bus drivers classified by accident type are shown in Figure 4. In case of driver fatalities, rear-end collisions show the highest percentage, while head-on collisions show the highest percentage of severe and minor injuries (excluding others). However, head-on collisions account for the highest rate of total number of fatal and serious injuries even if the number of the driver fatalities is very small (4 drivers only).

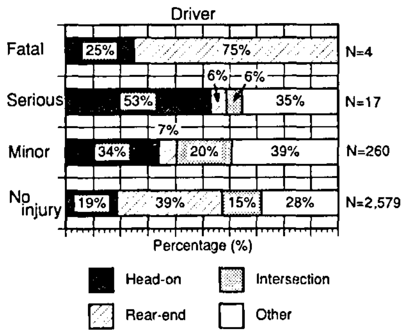

Figure 4 . Severity of injuries on bus drivers classified by the type of accidents.

Figure 5 shows the severity of injuries on bus driver in head-on collisions and rear-end collisions, classified by the type of opponent vehicles involved in such accidents. In the figure, the fatalities of drivers are so few that the fatal and serious injuries are combined into a single percentage. Large trucks (GVW> 12t) account for the highest rate of both fatal and serious injuries of bus drivers, while passenger car collisions account for the highest rate of minor or no-injury cases for the bus drivers.

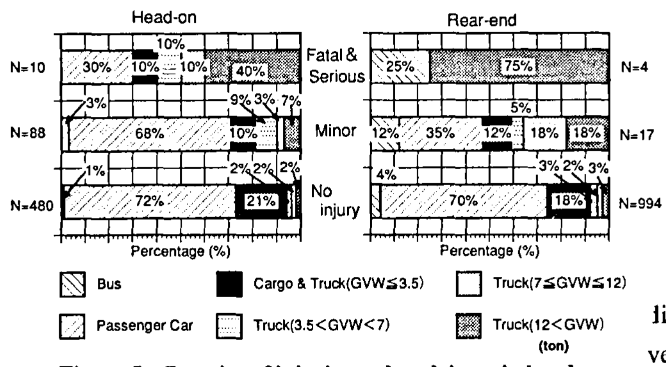

Figure 5. Severity of injuries on bus drivers in head-on collisions and rear-end collisions classified by the types of opponent vehicles

According to the above results, it is necessary to consider the injury reduction on bus drivers and passengers respectively for the establishment of large bus test conditions. As for the type of accidents involving bus, frontal impacts in vehicle-to-vehicle accidents should be in high priority, and that the head-on collision is a particularly important type of accident to be evaluated. As regards to the type of opponent vehicles involved in each accident, it is necessary to keep in mind that a passenger car is the most significant counterpart in terms of all types of accidents, though large trucks account for the majority of serious or fatal injuries.

2.2 Trucks

Occupant injuries on large trucks with the gross vehicle weight of 12 tons or more were analyzed, as in the case of truck occupants.

Figure 6 shows the severity of occupant injuries classified by its seating position on the trucks. It is found from the figure that the drivers account for more than 90 % of all injuries regardless of the severity of injury. Therefore, it was decided to consider only the drivers in the analysis as far as truck accidents were concerned.

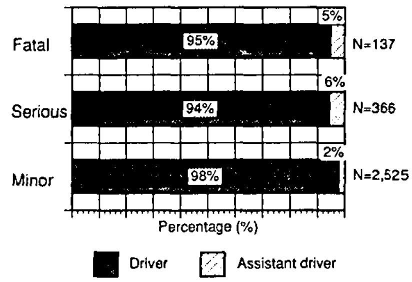

Figure 6. Severity of occupant injuries classified by its seating position on the trucks

Figure 7 shows the severity of injuries on truck drivers livided into two types of accidents. Injuries caused by vehicle-to-vehicle accidents account for more than 70 % of the total number of accidents, with the rate becoming even higher for serious and minor injuries.

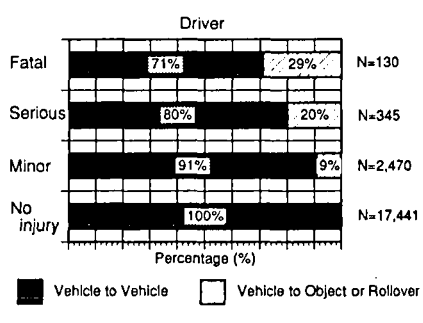

Figure 7. Severity of injuries on truck drivers divided into two types of accidents.

Figure 8 shows the severity of injuries on truck drivers classified by damaged areas of trucks, focusing on the vehicle-to-vehicle accidents that occur most frequently as described above. The more severe the injury becomes, the greater the number of occupants injured by frontal impacts becomes. This accounts for more than 80 % of the fatal and serious injuries.

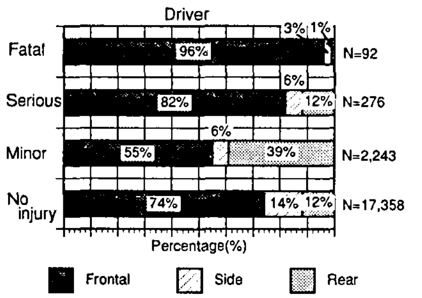

Figure 8 Severity of injuries on truck drivers classified by damaged areas of trucks

Figure 9 shows the severity of injuries on truck drivers classified by the type of accidents, focusing on frontal impacts that occur frequently as in the case of buses. It is found from the figure that rear-end collisions and head-on collisions show high percentages which amount to more than 70 % of the serious injuries and more than 80 % of the fatal injuries.

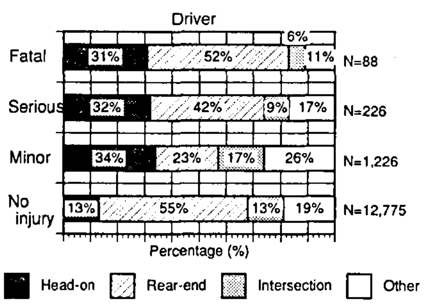

Figure 9. Severity of injuries on truck drivers classified by the type of accidents.

Figure 10 shows the severity of driver injuries in head-on collisions and rear-end collisions, classified by the type of opponent vehicles involved in such accidents. The more severe the injury becomes, the greater the percentage of large trucks becomes. This accounts for more than 80 % of fatal injuries for both head-on collisions and rear-end collisions. On the other hand, the percentage of passenger cars is greater than that of large trucks in case of minor injuries sustained by truck drivers in head-on collisions.

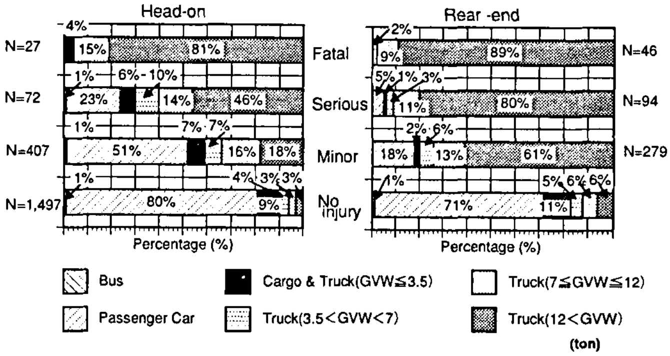

Figure 10. Severity of injuries on truck drivers in head-on collisions and rear-end collisions classified by the types of opponent vehicles

According to the results described so far, it is vital to evaluate accidents involving truck drivers for the establishment of large truck test conditions. It is particularly necessary to consider both head-on collisions and rear-end collisions. As regards to the type of opponent vehicle involved, large trucks are the most important type to consider. However, it is necessary to keep in mind that passenger cars and other types of vehicles should be also studied as the counterparts in the accidents.

CRASH TEST METHOD

Based on accidents involving buses and trucks, we have established crash test guidelines respectively for large buses and trucks. We have followed the procedure in Figure 11 showing the test method to be incorporated in the guidelines. Namely, the crash patterns for test was selected first, then the test speed was set for the selected crash patterns. These test conditions were compared with the existing frontal impact regulation for passenger cars in Japan, then Hy-III and Hy-II dummies were selected as evaluation tool and the number of dummies was determined.

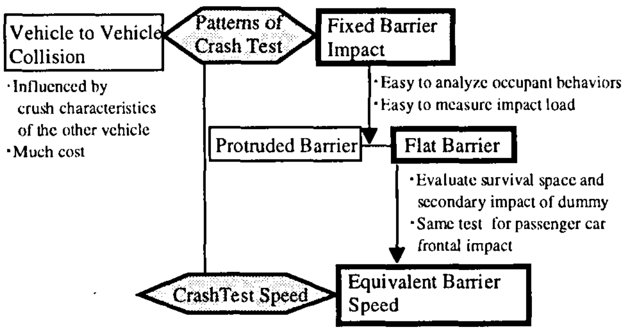

Figure 11. Crash test procedur

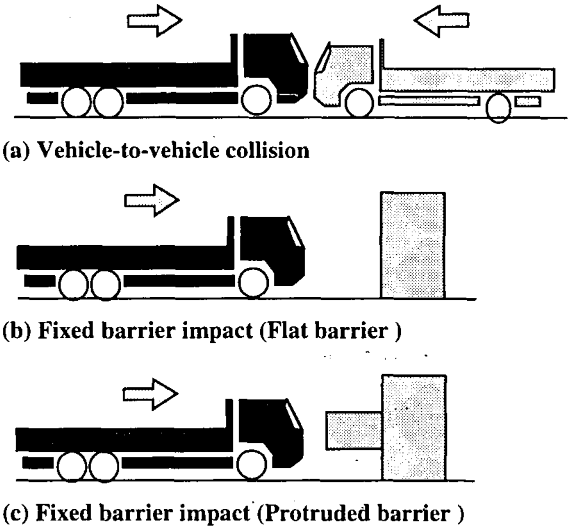

Figure 12 Patterns of crash tests

Patterns of Crash Tests

According to truck and bus accident data, frontal impacts in vehicle-to-vehicle accidents account for the majority. In this regard, the patterns of crash tests to simulate such frontal impacts were studied.

For heavy duty vehicles, two kinds of test methods - "vehicle-to-vehicle collision" and "fixed barrier impact" - can be considered as candidates. The vehicle-to-vehicle collision here refers to the crash tests shown in Figure 12 (a), in which a test vehicle collides against an equivalent vehicle. The fixed barrier test is to collide a test vehicle against a fixed barrier as shown in Figure 12 (b) and 12(c). We decided to use the fixed barrier test method due to the following reasons. The first reason is that the method is not influenced by crush characteristics of the front cab (structure) of opponent vehicle, and reproducibility is preferred. The second reason is that it is easy to analyze occupant behaviors and to measure impact loads. The third reason is the fact that it is the common method employed for the passenger car frontal impact tests, which makes standardization easy.

Two kinds of configurations were considered next for the plane of fixed barrier. These are "flat barrier" and "protruded barrier" which were considered as candidates for the configurations of fixed barrier. The flat barrier here means a flat plane against which the front of a large truck collides as shown in Figure 12 (b) as with the case of the passenger car frontal impact tests. The protruded barrier, on the other hand, represents the simulated configuration of the end of a truck cargo, assuming a rear-end collision as shown in Figure 12 (c). We decided to apply the flat barrier due to the following reasons. The primary reason is to evaluate the survival space which affects the severity of occupant injuries, and at same time, to measure the outcome caused by the secondary impact onto the steering wheel, instrument panel, etc. The second reason is that the flat barrier is the same as that used in the passenger car frontal impact tests, which makes standardization easy.

Crash Test Speed

The crash test speed was set as the equivalent barrier speed. The equivalent barrier speed, however, cannot be derived directly from the statistics analyzed in this study, as the crush characteristics of individual vehicles involved in accidents are not available in those data.

Therefore, it was decided to obtain the equivalent barrier speeds of large buses and trucks by means of the following. That is, each equivalent barrier speed was calculated by substituting the weight, impact speed and crush stiffness of the vehicle concerned into Equation (1). The equation is based on the energy conservation law and the momentum conservation law. In such calculations, the vehicle weight was set for each type of vehicle, taking into account the loading condition, which was obtained from the data. As for the impact speed, the value was obtained by multiplying by a given factor the travel speed obtained from the statistic data. The crush stiffness for each vehicle was set by using the value obtained by the heavy duty vehicle crash tests conducted thus far.

$$V_b=(V_{10}-V_{20})\sqrt{\frac{M_2k_2}{(M_1+M_2)(k_1+k_2)}} \quad \cdots (1)$$

V_b: equivalent barrier speed of bus (truck)
V_{10}: impact speed of bus (truck)
V_{20}: impact speed of the other vehicle
M_1: bus (truck) weight upon accident
M_2: weight of the other vehicle upon accident
K_1: crush stiffiness of bus (truck)
K_2: crush stiffiness of the other vehicle

Based on the assumptions described above, the equivalent barrier speed of each vehicle was calculated with Equation (1), according to the accident data of 280 large buses involved in head-on collisions and 9,270 large trucks involved in head-on and rear-end collisions. The crash test speeds of large buses and trucks were calculated respectively, and the speeds covering more than 90% of all accidents are as follows.

(1) Large bus : test speed, 35 km/h
(2) Large truck : test speed, 40 km/h

Dummies, etc.

Dummies of the same type (Hy-II and Hy-III) as those used in the frontal impact regulation for passenger cars in Japan were used in the test vehicles. Six dummies in total were set in each bus for the driver, tour guide and passengers , while two dummies (driver and assistant driver) were set in each truck. Test vehicle weight and other test conditions were set similar to those for the regulation for passenger cars. Table 1 shows the results of comparison between the bus and truck test conditions set according to the above.

Table 1
Test conditions for Bus and Truck

Vehicle		Large Bus (GVW > 12t)	Large Truck (GVW > 12t)
T	Pattern	Flat barrier impact	Flat barrier impact
E	Speed	35km/h	40km/h
S	Mass	Vehicle + Dummies	Vehicle + Dummies
T	Dummy	6 dummies (Hy-II or Hy-III)	2 dummies (Hy-II or Hy-III)

EXPERIMENTS

Large bus and large truck crash tests were conducted according to the guidelines set for frontal impact tests. Figures 13 and 14 show examples of the test results of bus and truck driver dummies after the crash tests.

The test results such as interior damage, steering wheel contact of the bus driver dummy, etc. after the experiment are shown in Figure 13. The legs of the driver are caught between the instrument panel and the seat, and the abdomen is pressed by the steering wheel and the seat due to narrowing survival space for drivers. Such conditions are similar to those found in real world accidents which result in serious and/or fatal injuries of drivers [2), 3)].

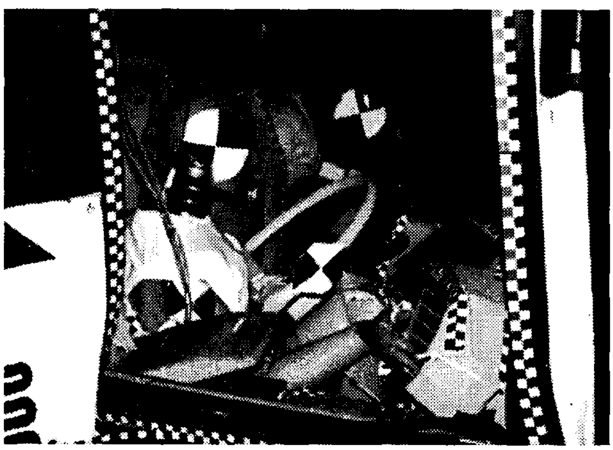

Figure 13. Interior damages and conditions of driver dummy on large bus after the experiment.

Figure 14. Conditions of driver dummy with deployed airbag on large truck after the experiment.

As described so far, the frontal impact test of large buses have reproduced the situations found in real world accidents, showing the appropriateness of the test conditions for the evaluation of crashworthiness of heavy duty vehicles. Although it is necessary to make further studies on dummies as the abdomen injuries cannot be evaluated quantitatively using existing dummies, evaluations of indices of other injuries have become possible as in the case of passenger cars.

Figure 14 shows the situation around a large truck driver. This truck was equipped with the most advanced crash safety devices such as an airbag, pretensioning seat belt, etc. It is possible to evaluate the dummy injuries in relation to such advanced crash safety devices under the test conditions we have set, same as in the case of frontal impact test for passenger cars.

It will be necessary to collect more basic data on bus and truck crush characteristics and occupant injuries and to evaluate abdominal injuries which typically occur in heavy duty vehicle accidents for the enhancement of safety measures.

CONCLUSIONS

Configurations of heavy duty vehicle accidents were investigated, and guidelines for crash tests of bus and truck have been formulated. Vehicle crash tests have been also conducted according to the guidelines. The main results are as follows.

1) It is found from the analysis of accident data that frontal impact against the other vehicle shows the highest rate. In particular, head-on collisions are the highest for buses, while both rear-end and head-on collisions account for the majority for trucks.
2) Guidelines for crash test of heavy duty vehicles has been formulated based on the analysis. Flat barrier impact is used for the frontal crash test, and the test speed is set at 35 km/h for large buses and at 40 km/h for large trucks.
3) Crash tests have been conducted according to the proposed guidelines. As a result, it is found that the guidelines are satisfactory for heavy duty vehicles.
4) It will be necessary to carry out further studies on the evaluation of typical injuries in heavy duty vehicle collisions, abdominal injuries in particular.

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SAFETY OF SEATS IN MINIBUSES - PROPOSAL FOR A DYNAMIC TEST

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ABSTRACT

The paper discusses the safety of minibus seats in the light of the current European Safety Directives, general safety requirements regarding structural behaviour and occupant protection, accident investigation, full scale tests on minibuses and vans and numerical simulation studies. The evidence strongly supports the view that the current static testing of the seat belt anchorages ought to be extended to dynamic complete seat tests with instrumented dummies, for which a test acceleration corridor and safety requirements have been proposed.

INTRODUCTION

A 'minibus' (usually referred to as an 'M2' vehicle) represents a small public service vehicle that carries more than 8 seated passengers (normally without standees) and the upper bound is referred to either a maximum number of 16 passengers, or to a maximum gross vehicle mass (GVM) of 5000 kg. Almost all modern European minibuses are produced as van conversions, where the front end with engine, transmission, steering, wheels and (usually) the complete floor pan are kept. The van body structure is either basically unchanged, or replaced by a variety of purpose-built new bodies. A very large majority of minibuses have the GVM less than 3,500 kg. In comparison with cars, the minibus transport is statistically rather safer, but accidents do happen attracting much media attention and public concern.

The safety of minibus seats is currently affected in the European Union by the Safety Directives, whose latest revisions 96/36/EC, 96/37/EC and 96/38/EC were largely based upon the results of the research programme summarised in Ref. [1]. Seatbelts will be gradually phased-in from October 1997, 1999 and 2001, with 3-point belts compulsory in minibuses with the GVM less than 3,500 kg, while lap-belts are allowed in heavier vehicles. Safety belts are usually mounted on the seats and the current Requirements are defined only in terms of the *static* forward pull loads. The seat may be rigidly mounted on the test rig (for seat Approval) or on a representative segment of the vehicle body (for the system, i.e. seat and installation Approval).

The car (M1) seats and headrests must be tested (without anthropometric dummies) under a series of static and dynamic loads. The large coach (M3) seats are tested under reverse acceleration between 8g and 12g and with Δv = 30 km/h, loaded with 50%ile male instrumented dummies whose injury criteria are limited to : HAC (head)=500, ThAC (thorax) = 30g and FAC (femur) = 10 kN (8 kN for not more than 20 ms).

The objective of the current research was to establish whether a new, dynamic safety test method of the minibus seats may be appropriate and, if so :

(a) what test acceleration pulse should be used to reproduce loading in 'typical' real accidents ;
(b) what other test conditions and requirements would be most suitable.

ACCIDENT RESEARCH

VSRC examined for many years the crash performance of vans and minibuses in the UK (a total of 265 cases) on behalf of the Ford Motor Company. The study included inspection of the crashed vehicles, collection of occupant injury data, accident reconstruction and assessment of the sources of injury.

The *objects struck* were : lighter collision partners - passenger cars (49%), heavy (and stiff) goods vehicles (20%), light goods vehicles of similar mass (5%) and a wide variety of on- and off-road obstacles, such as trees, posts, etc. Most (50 %) of the accidents took place on 'A-roads' (primary arterial routes), 37 % in local traffic, 10 % on 'B'-roads and 4% on high speed motorways.

The *impact severity* was measured by the equivalent energy speed (EES). This was based on measurements of the *vehicle structural* damage, subsequently processed by the program CRASH3. The main cluster of cases spreads between 10 and 80 km/h (Figure 1.), with the median (50th percentile) speed of 35 km/h and the 90th percentile of 65 km/h. Most accidents happened between 20 and 50 km/h.

The frequency of the *front end overlaps* with the collision partner is shown in Figure 2. The distribution of

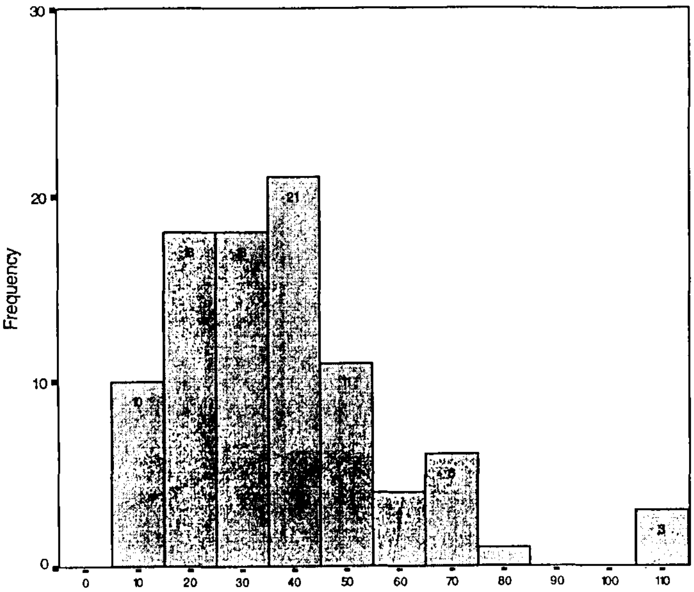


Figure 1. Equivalent Test Speed at impact (km/h)

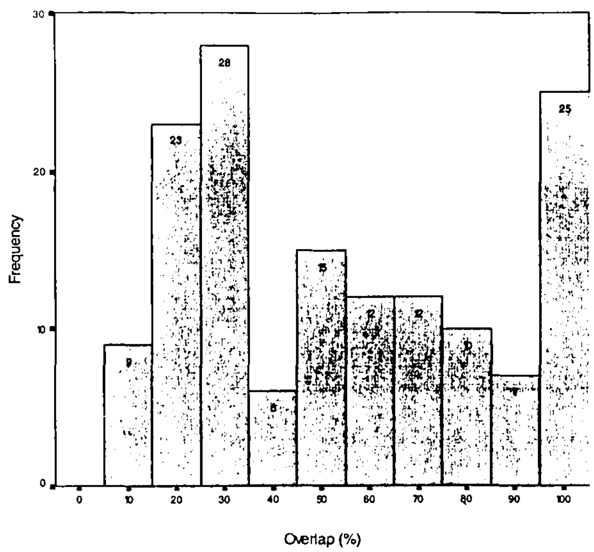


Figure 2. Front end overlap with collision partner

the *location of the contacts zone* was : the left, right and central third - 12 %, 21% and 5 % respectively, left and right two thirds 12% and 16 % and all three thirds 34 % (possibly with less than 100% overlap). The EES and front end overlap were broadly independent (Figure 3), with a relatively even spread of impact speeds over the full spectrum of highly offset (10% overlap) to full frontal impacts.

The *gross vehicle mass* of most minibuses and vans was 2500 kg to 3500 kg (Figure 4a), with the actual *mass at impact of 1500 kg to 2500 kg* (Figure 4b). Hence it was concluded that van conversions with GVM less than 3500 kg ought to be regarded as reference for the pos-

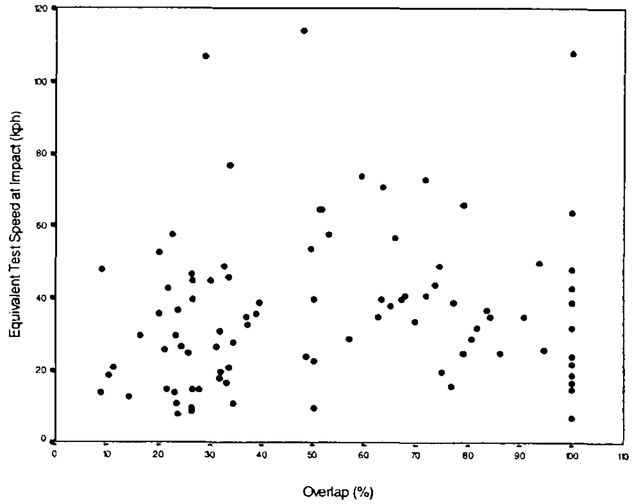
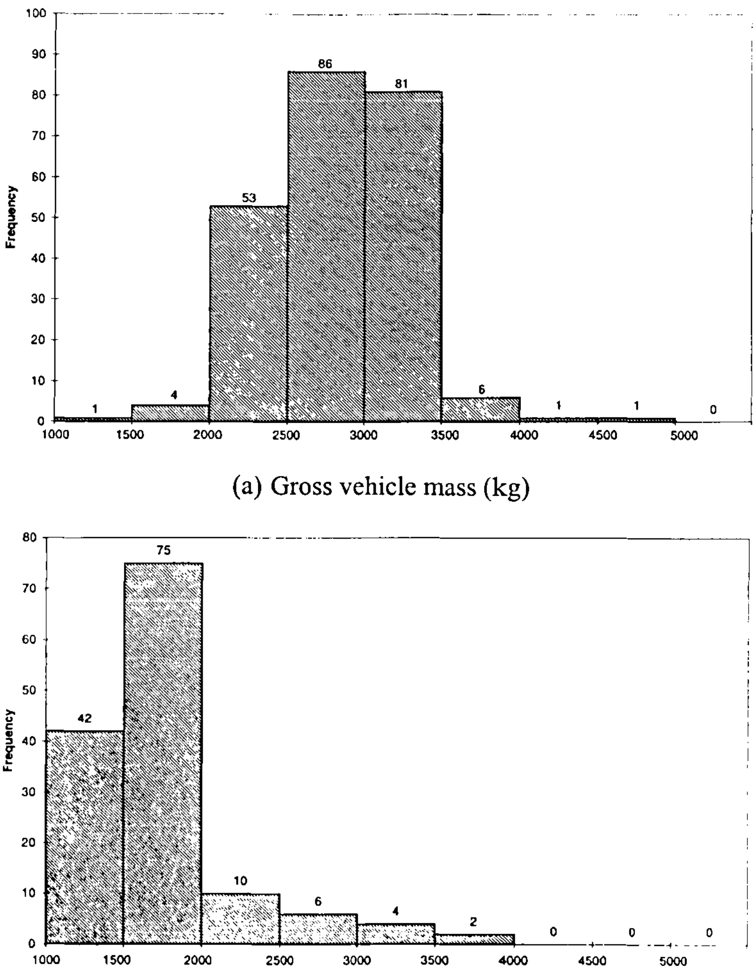


Figure 3. Overlap vs. Equivalent Test Speed



(a) Gross vehicle mass (kg)

(b) Mass at impact (kg)

Figure 4. Vehicle Mass distribution from accident data

sible future amendments of the EEC safety Directives for all minibuses.

The 25 vehicles from the frontal impacts sample had eight or more passenger seats, out of which 18 contained information on the seating positions and injuries to the vehicle occupants. Selected typical accident scenarios (front and rear impacts, collision with other vehicles with different offsets, crash against a tree, etc.), were studied including the circumstances within the passenger compartment (forward /side facing seats, etc.) and the injuries to occupants. Over half of the vehicles in this sample had occupants who were at most slightly injured (57%), but more than half were travelling on class A roads or motorways, or on roads with a speed limit of 60 or 70 mph.

Most back passengers had no seat belts to use and they generally moved into or over the seat in front. A relatively small proportion of these passengers received isolated bone fractures of the hand, arm, leg, nose or chest, but no fractures of the skull were recorded, nor any damage to the internal organs (brain, heart, lungs, liver, etc.). It is likely that the use of three-point seat belts would have prevented the occurrence of almost all these injuries. Two cases presented involved restrained drivers whose injuries were almost certainly aggravated, if not caused, by occupant impact from behind. The need for seats to protect both the restrained and the rear unrestrained occupants becomes increasingly important as the fitment and use of seat belts in minibuses increases.

The worst case involved a high speed front impact followed by fire of a minibus with side facing bench seats in which 10 young teenagers died on site.

In the vast majority of (frontal) minibus impacts, the front region of the passenger compartment - dashboard, steering wheel, windscreen and so on - does not intrude into the vicinity of the back seats. Provided a satisfactory restraint system is fitted to these seats, the back passengers therefore have the opportunity to survive exceedingly severe impacts, as has been documented many times in passenger cars. The primary requirement is that the restraint system does not fail, including no separation of the seat and belt anchorages from the floorpan. Such separation turns the passengers into flying objects, to the detriment of themselves and their fellow occupants, despite having secured their seat belts before the impact. In modern passenger cars, the restraint failure in the back seats is very rare, hence safe seat belts and anchorages in minibuses aim to provide protection similar to that of the back seat passengers in cars.

It is not necessary to optimise the whole seat design (structural and injury criteria) for the most severe impacts that cause the most serious and costly injuries, but are relatively rare. A seat optimised only for the most severe impacts with *combined* loading, from the belted occupant(s) in the seat and unbelted sitting behind, might present harder and stiffer surfaces to the unrestrained or lap-belted passenger than is desirable over the *whole range* of accident circumstances. The overall cost of head and lower limb injuries, in particular, may thus not come down towards the best achievable level. The general seat design (i.e. including the injury criteria) should therefore be optimised for the 'intermediate' crash severity of real-world impacts - high enough for a significant risk of injury to back seat passengers, but low enough for the effective countermeasures, particularly including the combined loading.

The 'intermediate' crash severity test acceleration pulse can be based on a 48 to 55 km/h (30-35 mph) rigid barrier front impact complete minibus test, with an overlap (offset) of approximately 50%. This speed range would stand at around the 85th percentile level for the cases in the VSRC database and has already been widely adopted as a reference speed for crash testing. In view of the wide spread of overlaps observed in real crashes, a mid-range value of 50% may be regarded as representative.

It would, however, be desirable that the *structural* strength of the seat and seat belt anchorages is extended to sustain a higher load than that associated with optimisation for the 'general', i.e. injury-criteria inclusive, seat design. It is, for example, known that even with sub-optimal seat performance, restrained passengers in the front seat of cars (with belts holding while attached to the car body) endure the impact from behind of unrestrained rear passengers. An acceleration pulse based on a full scale minibus crash against a rigid barrier at 55 km/h (35 mph) with full overlap, would represent a moderate requirement for the structural integrity of the seat and seat belt anchorages. With the seat and belt anchorages capable of sustaining combined loading under these conditions, it is likely that a restrained occupant not struck from behind by an unrestrained occupant would be protected in most of the accidents documented in the VSRC archives. This may not apply to all occupants in seats under combined loading, since there were accidents at even higher speeds and full overlap. Still, the higher impact speeds need not always generate higher maximum decelerations, as may be strongly influenced by the vehicle mass at impact, whether occupants are belted and on the properties of the collision partner. However, there is a difficulty in comparing the recommended test condition to impacts at greater speed (higher severity acceleration pulse) but less overlap (lower severity acceleration pulse). The matter is further complicated by the fact that the mass of the same vehicle may vary depending on payload and whether and how the passengers are belted.

EVIDENCE FROM THE FULL SCALE MINIBUS / VAN CRASH TESTS AND SIMULATIONS

A study was made of the deceleration pulses measured during the full scale minibus and van crash tests under different conditions. To start with, a method was needed to transform the highly oscillating full scale test deceleration pulse (Figure 5-a), with a high scatter amongst vehicles, into an equivalent, 'smooth' one for repeatable, standardised laboratory sled testing. This was achieved by first fitting a polynomial function to the full scale *velocity* pulse (Figure 5-b), usually obtained by integration of the acceleration signal, or from the high speed film analysis. The first derivative of the polynomial is then plotted (Figure 5-c) to obtain the smooth accelera-tion signal for the laboratory test. The method was justified by the fact that the maximum seat / belt loading and dummy injury results are primarily influenced by the *relative speed at contact between the dummy and seat*, rather than the peak vehicle acceleration which usually happens while the occupants are still freely moving.

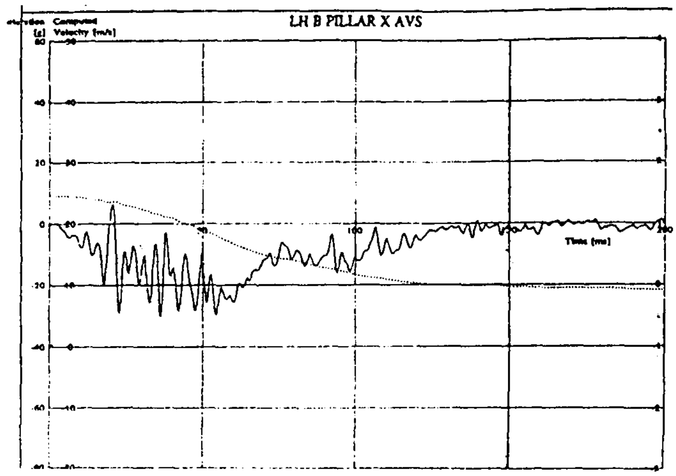
Background full scale frontal crash tests on typical light European vans and minibuses of different make provided 8 deceleration pulses obtained at different masses (1633 kg to 3500 kg), impact speeds (48.6 km/h to 64 km/h) and offsets (40% to 100%) into rigid barrier and stationary minibuses (Table 1. - tests 1 to 4 and 6 to 9).

Two *foreground full scale tests on minibuses* were designed to complement the background evidence in terms of deceleration pulses and demonstrate the safety phenomena related to the non-forward facing seats. Both tests exceeded by far the front impact legislative requirements for the light vans (GVM less than 1500 kg) with driver mass only and impact speed of 48 km/h (30 mph).

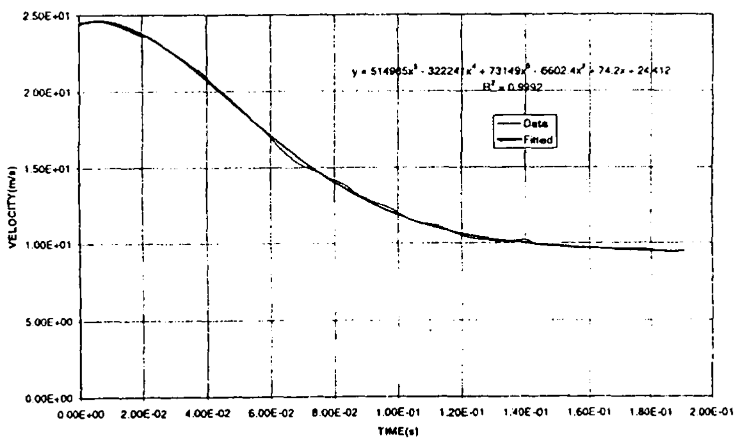
The first test (Figure 6-a and Test 5 in Table 1) was done on a typical European minibus with seating capacity of 15 including the driver, fully laden with sand bags belted in seats (total vehicle mass 3300 kg) and run at approximately 57.7 km/h (36 mph) into a rigid barrier. The 'seat-test equivalent' pulse is shown in Figure 6-b. All seats and anchorages (approved to M1 level) held well.

The second test (Figure 7-a and tests 10/11 in Table 1.) involved a similar vehicle, laden with six anthropometric dummies in side, forward and rear-facing seats (total mass 2609 kg), running into the back of the first test specimen (still fully laden) at 88.5 km/h (55.3 mph). The 'seat-test equivalent' acceleration pulse for the bullet vehicle is shown in Figure 7-b.

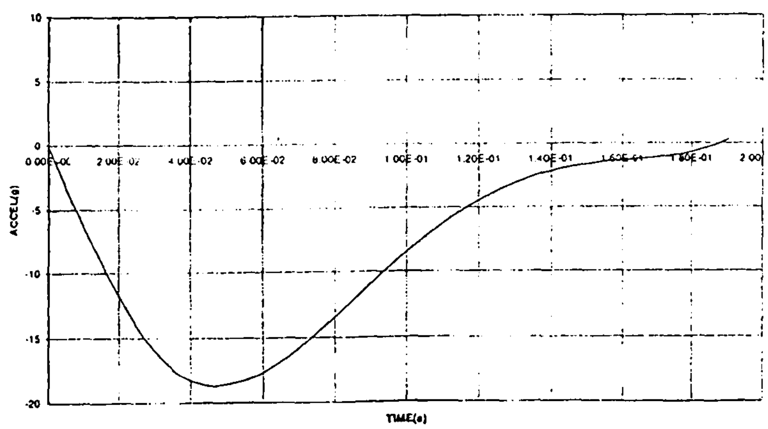
The *full scale test simulations* contributed useful additional evidence on the effect of vehicle mass and obstacle on the deceleration pulse. The background



(a) Crash acceleration and velocity time histories



(b) The true and fitted vehicle velocity curves

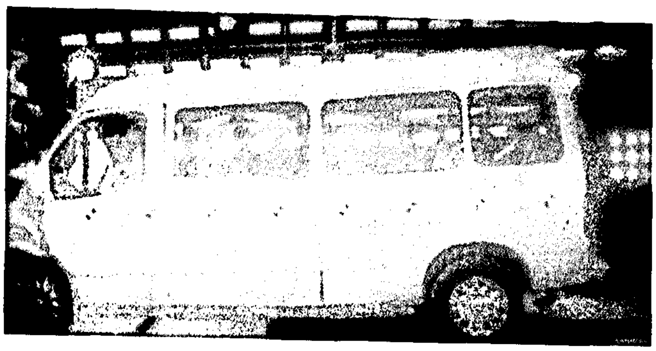


(c) The 'equivalent' acceleration seat test pulse

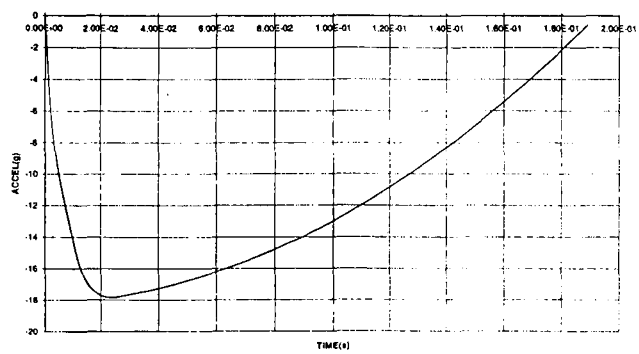
Figure 5. Derivation of the equivalent seat test pulse

Table 1.
Summary of the full scale crash test data

Test No.	Vehicle Mass (kg)	Impact Speed (km/hr)	Impact Scenario	Max. Equivalent Acceleration (g)	Time at Accelmax (ms)	Duration of Accel. (ms)	Comment
1	3500.0 (Target)	64.0	50% frontal impact into front of minibus	6.8	58	170	Target vehicle data inc. 2 dummies + 1180kg
2	3493.0	50.0	50% frontal impact with barrier	11.6	70	200	1850kg ballast
3	1989.0	56.2	50% frontal impact with barrier	22.1	45	140	inc. 3 dummies + ballast
4	1633.2	51.1	40% frontal impact with barrier	17.9	48	140	inc. 2 dummies + test instrumentation
5	3300.0	57.7	100% frontal impact with barrier	17.8	25	190	**Foreground test**
6	2209.0	56.0	100% frontal impact with barrier	24.3	32	120	inc. 3 dummies + 300kg ballast
7	2194.5	48.6	100% frontal impact with barrier	27.1	36	105	inc. 3 dummies + test instrumentation
8	2001.0	48.9	100% frontal impact with barrier	28.0	33	95	
9	1959.0	57.2	100% frontal impact with barrier	28.7	25	105	inc. 3 dummies + test instrumentation
10	2609.0 (Bullet) 3300.0 (Target)	88.5	100% frontal impact into back of minibus	18.7	45	150	**Foreground test** Bullet vehicle data
11	2609.0 (Bullet) 3300.0 (Target)	88.5	100% rear impact from minibus	14.8	14	180	**Foreground test** Target vehicle data



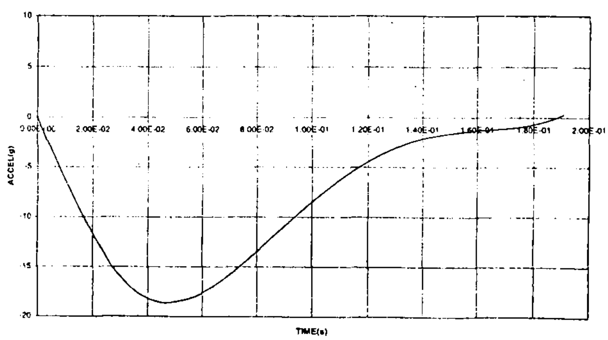
(a) Extract from the high speed film



(b) The 'equivalent' seat test pulse

Figure 6. Full frontal rigid barrier test at 57.7 km/h

(a) Extract from the high speed film



(b) The 'equivalent' seat test pulse

Figure 7. Vehicle-to-vehicle crash test 88.5 km/h

detailed finite element model of a typical light van (mass 2600 kg) was validated under the 56.9 km/h full frontal and 50% offset frontal impacts into an oblique barrier (Figure 8-a,b). The new parametric variations involved the full frontal 56 km/h (35 mph) impact of a vehicle with mass of 3500 kg, once into a rigid and then into a mobile deformable barrier (Figure 8-c,d).

The above full scale tests and computer simulations confirmed the effects of vehicle mass, obstacle characteristics, front end overlap and impact speed, with trends of higher and shorter acceleration pulses in lighter vehicles, stiffer barrier and higher overlaps.

The 'intermediate' severity crash tests, described as 50 % offset into the rigid barrier, produced the maximum equivalent HyGe sled accelerations: 11.6g (3500 kg), 22.1g (1990 kg) and 17.9 g (1630 kg), while the simulation model gave 29g (2600 kg). The timing of those maxima were mainly in the region of 40 to 50 ms.

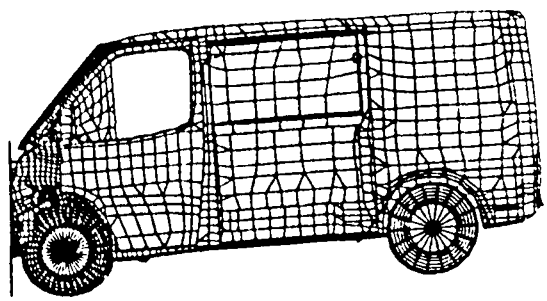
The 'more severe' crash tests described as 100 % overlap into the rigid barrier, produced the maximum equivalent HyGe sled-type accelerations : 17.8 g (3300 kg), 24.3g (2210 kg) and 27.1 g (2195 kg), 28 g (2000 kg) and 28.7 g (1960 kg), while the simulation model gave 29g (2600 kg). The timing of those maxima were in the region of 25 to 35 ms.

Impacts against other minibuses produced the equivalent acceleration maxima of 6.8 g (50 % offset front impact into a 3500 kg minibus) and 18.7 g (very severe impact at 88.5 km/h of a 2610 kg bullet vehicle into the rear of a 3300 kg target with 100 % overlap).

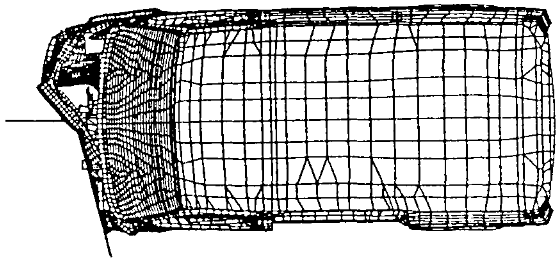
PROPOSAL FOR THE NEW DYNAMIC TESTS FOR APPROVAL OF THE MINIBUS (M2) SEATS

The research background summarised above served as basis to propose the following new dynamic tests for minibus (M2) seats :

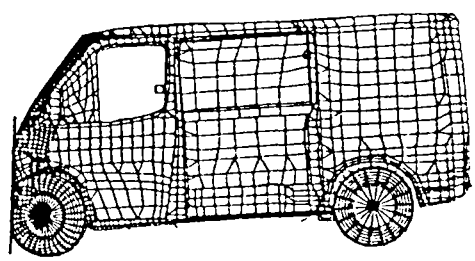
1. The test reference ought to be developed on the basis of minibuses with gross vehicle mass (GVM)less than 3,500 kg. As regards minibuses with GVM more than 3500 kg (up to 5000 kg):
   (a) their *mass at impact* is likely to be lower than or close to 3500 kg ;
   (b) they are often converted for transport of people in wheel chairs, for which the deceleration pulse (currently under discussion) is converging towards 20 g maximum at Δv = 48 km/h ;
   (c) it is commercially better (higher numbers - lower price) to have only two seat types - M2 and M3, rather than three - 'light' and 'heavy 'M2 and M3.
2. The M2 vehicle seats ought to be tested in isolation (seat Approval), or mounted on a representative segment of the vehicle body (system Approval).



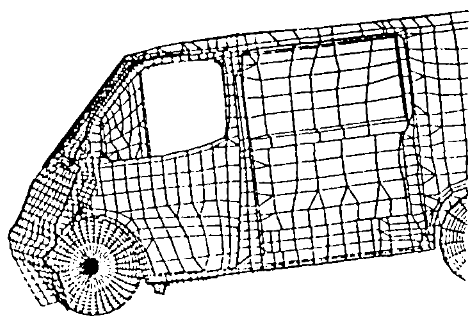
(a) Full frontal, rigid barrier, 56.9 km/h, m = 2600 kg (background information - courtesy : Ford)



(b) Oblique rigid, 50 % offset, 56.9 km/h, m = 2600 kg (background information - courtesy : Ford)



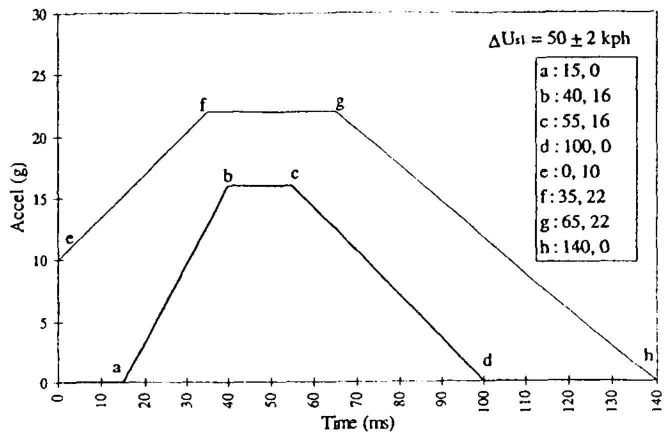
(c) Full frontal, rigid barrier, 56 km/h, m = 3500 kg



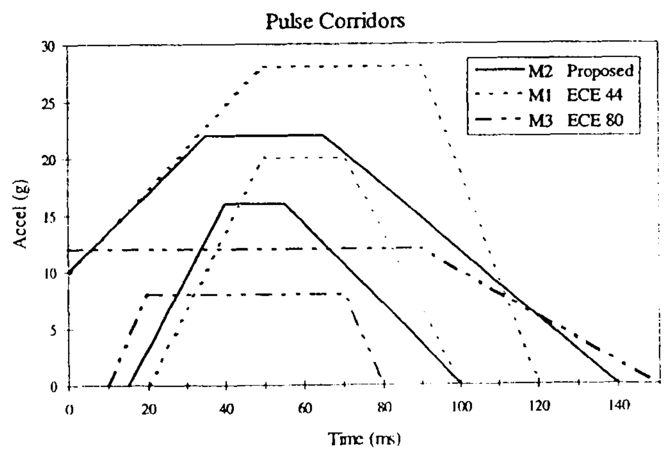
(d) Full frontal, deformable barrier, 56 km/h, m = 3500 kg

Figure 8. Numerical simulation scenarios

3. The *'intermediate' test pulse corridor* is shown in Figure9-a, with co-ordinates of characteristic points. The velocity change is between 48 and 52 km/h (30 and 32.5 mph), corresponding to the maximum HyGe sled speed in the reverse direction, or to the forward impact speed in deceleration tests. For comparison, the new M2 test pulse is overlaid in Figure 9-b with the corridors: ECE44 for child restraints in M1 cars and ECE80 for seats in M3 large coaches. The seat would have to meet both the injury and structural criteria under the test scenarios below.



(a) The proposed test corridor for minibus (M2) seats



(b) The M2 test proposal vs. the M1 and M3 corridors

Figure 9. The proposed test corridor for M2 seats

4. *Test scenarios* :
   (a) *Single loading by the belted occupant(s)*, with belt types specified in the EC Directives ;
   (b) *Single loading of an empty seat* i.e.:
      b1 : empty seat loaded by unbelted occupant(s) sitting behind,
      b2 : if applicable, empty seat loaded by lap-belted occupant(s) behind (for GVM>3500kg);
   (c) *Combined loading* produced by the belted occupant(s) in the seat (belt types as specified in the EC Directives) and :
      c1 : unbelted occupant(s) sitting behind,
      c2 : if applicable, lap-belted occupant(s) behind.

   The occupants would be simulated by the 50 %ile Hybrid III dummies including the neck injury transducers, although the Hybrid II dummy would also be allowed for a limited period (see 5(b) below).

5. The proposed *injury criteria* for all unbelted and lap-belted dummies interacting with seat in front under single and combined loading scenarios :
   (a) while appreciating the car- and minibus-related differences in the relative position of the occupant body and its immediate environment, still apply the best researched injury criteria for the front impact of the (M1) cars (Directive 96/79/EC), i.e. :
      a1: *head* HAC ≤ 1000 and acceleration shall not exceed 80 g for more than 3 ms ;
      a2: *thorax* - either use the new compression criterion - ThCC ≤ 50 mm and viscous criterion V*C ≤ 1.0 m/s, or apply the already specified ThAC ≤ 30 g for M3 coaches;
      a3: *femur*- either use the new FAC or FFC ≤ 9.07 kN and ≤ 7.58 kN for > 10 ms, with linear interpolation between 9.07 kN (duration zero) and 7.58 kN at duration 10 ms ; or apply the already specified FAC ≤ 10 kN (8 kN for less than 20 ms) for M3 coaches ;
   (b) *Neck injury criteria* neck (NIC), as in the front impact safety Directive for cars, i.e. :
      b1 : *Tension criterion* described, in the coordinate system : duration of loading over given tension (ms) vs. axial tensile neck force (kN), by the border line connecting points: (0, 3.3), (35, 2.9) and (≥ 60 , 1.1) ;
      b2 : *Shear criterion* described, in the coordinate system : duration of loading over given shear force (ms) vs. AFT neck shear force (kN), by the border line connecting points: (0,3.1), (25 to 35, 1.5) and (≥ 45, 1.1) ;
      b3: *Bending moment* about the lateral 'y' axis forcing the chin away from the chest *(extension)* ≤ 57 Nm.

      As in the Directive 96/79/EC, the neck criteria would be recorded during Approval tests, but shall not be pass/fail values to grant Approval until a specified date. Thereafter, the above figures would count unless or until alternative values are adopted.

6. *Structural integrity* criteria would specify that the seatbelts must remain attached to the seat, the seat must remain attached to the vehicle structure and that there should be no sharp edges in the occupant body contact regions.
7. *Seat anchorage test for combined loading under the higher, 28g pulse* is not proposed in either dynamic or static form for the following reasons (supported by other evidence to be reported elsewhere):
   (a) the seat anchorage loads were higher under the combined loading during the proposed 'intermediate' severity test for minibus seats than under the single loading at the 28g pulse,
   (b) simultaneous occurrence of the very severe accidents *and* combined seat loading are perceived to be so rare that the additional costs to the industry are difficult to justify.

   If such extreme conditions were to be included in the future Regulations, then additional work ought to investigate the feasibility, procedures and requirements for a cheaper *static* test.

RECOMMENDATIONS

The proposal above reflects the author's views in the relevant, but 'purely technical' terms. Whether this or a similar submission may be adopted for the future Safety Regulations for minibus seats ought to be also considered from the point of view of their technical and *commercial* feasibility and the overall cost benefits to the society. A further study covering these aspects would be desirable.

Not being specifically prepared, many of the current minibus seats may not meet the proposed criteria. It could therefore be useful to demonstrate the *technical* and *commercial* feasibility of such seats *prior* to Legislation. Based on the past experience, Cranfield Impact Centre is confident that both would be shown as effectively as with the *Universal Coach Safety Seat* [2] that *followed* Project [1]. This seat was conventional in all the production, size, weight and cost aspects, yet met and exceeded the new EC requirements, including the combined loading (with protection of unbelted and lap-belted rear occupants) and the neck criteria even with some 95th and 5th %ile dummies. The new M2 pulse is higher, but so is the critical HAC, and the most difficult case of protecting lap-belted occupants may be dropped.

As a longer term interest, the inherent problem with the 'narrow' scope test conditions in all modern Safety Regulations lies with the versatility of the accident impact conditions and the human body sizes, injury tolerance levels, etc. A system may be designed to solely meet a specific safety requirement, even at the expense of making it less safe in the overall sense. While appreciating and fulfilling the specific objectives of the current Project, the authors recommend that some Regulation-related future effort also addresses the wide variety of accident scenarios and human injury tolerances observed.

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1. D Kecman, "Research background to the new EEC directives on technical requirements for seats and seat belts in minibuses and coaches", Int. Congress FISITA, Prague, 1996
2. D Kecman, A J Dutton, "Development and testing of the Universal coach safety seat", Paper No 96-S5-O-11, 1996 ESV Conference, Melbourne, 1996

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RESEARCH TESTS TO DEVELOP IMPROVED FMVSS 301 REAR IMPACT TEST PROCEDURE

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Paper Number 98-S4-P-16

ABSTRACT

A test series was conducted with a moving deformable barrier similar to the FMVSS 214 (Federal Motor Vehicle Safety Standard 214) barrier impacting the rear of the subject vehicle in a partial overlap configuration to evaluate fuel system integrity. The tests were conducted in two phases. The first phase examined rear impact test configuration differences such as overlap, speed and alignment; the second phase examined the performance of various vehicles using a consistent test protocol based on the first phase of testing and crash data analysis. This paper presents the results of these fuel system integrity tests.

INTRODUCTION

A rear impact crash test program was conducted with a moving deformable barrier to simulate real world crash conditions which produced loss of fuel system integrity. The impactor was chosen on the basis of the aluminum honeycomb impactor face and barrier cart used in FMVSS 214 (Federal Motor Vehicle Safety Standard 214), dynamic side impact standard. The moving deformable impactor (MDB) represents a medium weight vehicle of moderately high stiffness. The rear impact configuration used in this test series is shown in Figure 1, where the overlap is on the side of the filler neck.

The tests were conducted in two phases. The first phase examined rear impact test configuration differences such as overlap, speed and alignment; the second phase examined the performance of various vehicles using a consistent test protocol, judged to be survivable yet severe enough to distinguish levels of fuel system integrity performance. Table 1 shows the complete test matrix and test conditions, including overlap percentages and overlapped side, impact speeds, weights and vertical bumper alignment.

PHASE 1 - BASELINE TESTING

In the first phase of testing, 1993 Ford Mustangs were chosen as the subject vehicles. This vehicle model was chosen based on its compact size and its placement of the fuel tank between the bumper and the rear axle. This fuel tank location is known to present difficult design challenges in terms of fuel system integrity. Four 1993 Mustangs were subjected to different test conditions as shown for test numbers B1-B4 in Table 1. In the B1 test as described in the FMVSS 301 advanced notice of proposed rulemaking (docket number 92-066N3), the fuel tank ruptured and spilled an excessive quantity of Stoddard solvent which was used to replace the gasoline in the tank. This test was conducted using a standard FMVSS 214 moving

Table 1.
Test Matrix of Moving Barrier Deformable Rear Impact Crash Tests

FMVSS 301 Rear Impact Test Procedure Development - Test Matrix

	Vehicle				Test			
Test Number	Make	Model	Yr.	No.	Speed, kph	Weight, kg	Overlap Percent	Impactor Height
Baseline:								
B1	NHTSA	MDB			84.0	1329		FMVSS
	Ford	Mustang	'93		0.0	1520	80%	214
B2	NHTSA	MDB		1	80.3	1349		FMVSS
	Ford	Mustang	'93	2	0	1565.0	88%	214
B3	NHTSA	MDB		1	79.7	1349		FMVSS
	Ford	Mustang	'93	2	0.0	1525	80%	214
B4	NHTSA	MDB		1	80.1	1333		
	Ford	Mustang	'93	2	0.0	1554	50%	raised 2"
Comparison:								
1	NHTSA	MDB		1	80.3	1344		lowered 2"
	Ford	Mustang	'96	2	0.0	1628	70%	
2	NHTSA	MDB		1	81.5	1342		lowered 2"
	Plymouth	Voyager	'96	2	0.0	1946	70%	
3	NHTSA	MDB		1	81.6	1344		lowered 2"
	Suzuki	Sidekick	'96	2	0.0	1370	70%	
4	NHTSA	MDB		1	81.8	1343		lowered 2"
	Chev	Blazer	'96	2	0.0	1906	70%	
5	NHTSA	MDB		1	82.1	1344		lowered 2"
	Dodge	Neon	'96	2	0.0	1360	70%	
6	NHTSA	MDB		1	81.9	1337		lowered 2"
	Geo	Prizm	'96	2	0.0	1326	70%	

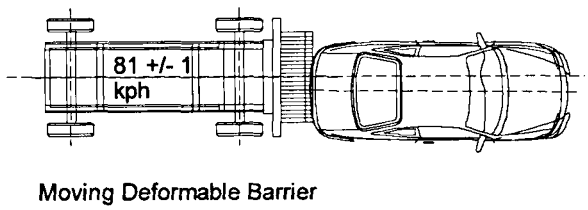

Figure 1. Moving Deformable Barrier rear impact partial overlap test setup.

deformable barrier (MDB) impacting the rear of the Ford Mustang on the filler neck (right) side with an 80% overlap at 84 kph (52 mph).

In the B2 Mustang test, the overlap was increased to 88% (also right side) and the speed reduced slightly to approximately 80 kmph. The vehicle leaked Stoddard only during post test rollover. Since this test condition caused both frame rails to be engaged, it was concluded that 88% overlap produced insufficient loading of the tank. Therefore this test speed of 80 kmph was repeated for the B3 Mustang test, but the overlap was adjusted back to 80% as in the B1 test. In the B3 test some Stoddard spillage was recorded but the leakage was within the spillage requirements of FMVSS 301. This result was unexpected since the difference in impact speed was small. It was also observed that the damage pattern was inconsistent with the B1 test, indicating differences in crash forces. Further investigation from film analysis revealed that the vertical bumper alignment was different between the two tests which resulted in more tank penetration and more tank damage in the B1 test. It was noted that the ride height of the Mustang was lower in test B3 by approximately 2 inches. This resulted in the moving deformable barrier overriding the rear bumper of the Mustang in test B3, thus indirectly loading the fuel tank. The difference in ride height could not be explained by vehicle loading and weight distribution differences because they were nearly identical. Since the vehicle was previously used before being purchased for test B3, the springs were believed to be sagging from normal wear of the vehicle. The B2 test vehicle on the other hand was new when purchased and was not subject to this potential problem. In the B4 test, to be sure that override did not occur, and to assure maximum fuel tank penetration, it was decided to test with the Mustang rear-end raised by two inches as measured at the rear bumper. Coincidentally, it was decided that bumper mismatch made sense for rear impacts after determining that the average pitch from panic braking caused approximately 2" dip at the front bumper and a 2" rise at the rear bumper. Therefore, this condition simulates either braking of the striking car or braking of the struck car prior to impact. Thus, the B4 Mustang was tested with the Mustang rear springs raised by spacers to accomplish a 2" height rise at the rear bumper. The speed was held to 80 kmph as in prior tests, but the overlap was reduced to 50% which was believed to produce more penetration into the tank. This test did produce spillage of Stoddard solvent (in excess of FMVSS 301 requirements) upon impact, but leakage was at a somewhat slower rate. The B4 test produced less penetration into the tank than the B1 test and it was concluded that a smaller overlap, such as 50%, actually produces less penetration into the fuel tank because the fuel tank is not full engaged.

Table 2.
Stoddard Fuel Leakage Measurements for Rear Impact Crash Tests with MDB

FMVSS 301 Rear Impact Test Procedure Development - Fuel Leakage

Test Number	Model	Impact 28g	5 min 140g	25 min 28g/ min.	Rollover 142g/ 5 min.
Baseline:					
B1	Mustang	failed	Fail 2 gal	NA	NA
B2	Mustang	Pass	Pass	Pass	Fail 472g
B3	Mustang	Trace	Pass 46 g	Pass 0 g	Pass 59 g
B4	Mustang	Trace	Fail 971 g	NA	NA
Comparison:					
1	Mustang	Trace	Pass	Pass	Pass
2	Voyager	Pass	Pass	Pass	Pass
3	Sidekick	Fail (not meas.)	Fail 2674 g	Fail 7349 g	Na
4	Blazer	Trace (carbon cannister line)	Pass	Pass	Pass
5	Neon	Fail (not meas.)	Fail 2200 g	Fail 8706 g	NA
6	Prizm	Trace	Pass	Pass	Fail 281g

PHASE 2 - COMPARISON TESTING

In the second phase of testing, also shown in Table 1, six vehicles were selected representing a cross section of vehicle types (minivan, sport utilities and passenger cars). The 1996 Ford Mustang was also tested since it was believed to have been improved over the 1993 version in terms of fuel system integrity. To accomplish full engagement of fuel tanks while avoiding engagement of opposite side frame rails required approximately 70% overlap. Coincidentally, fatal crash cases (1) were reviewed for rear impact fatalities which were survivable in the absence of fires. From these cases 70% overlap was the approximate average observed from the rear impact fatal fires. Therefore the test condition chosen for phase two testing was at 70% overlap, 81 +/- 1 kph, and the bumper alignment adjusted by lowering the barrier face height by 2 inches.

Table 2 shows the test results for fuel system leakage. Two of the six vehicles exceeded the FMVSS 301 leakage requirements directly following impact and one vehicle leaked in excess of FMVSS 301 requirements only in the rollover phase of the FMVSS 301 procedure. It is interesting to note that three of the six vehicles had tanks located aft of the rear axle, but only one of these vehicles exceeded the leakage requirements in FMVSS 301. It is also quite significant to note that one of the vehicles, a 1996 Ford Mustang, passed the test with much less crush, better tank protection, and better occupant protection (discussed later) than previously seen with the earlier 1993 Mustang. Ford has informed NHTSA that the Mustang was redesigned in 1994. The new version was based on the old chassis with extensive modifications, but the tank location was maintained. Therefore it may be concluded that regardless of tank location, it is possible and practical to design a fuel tank system which offers reasonable protection from rear impact fires at this severity level.

ANTHROPOMORPHIC TEST DEVICE RESPONSES

Table 3 shows the responses of both driver and passenger Hybrid III anthropomorphic test devices (ATDs) used in phase one and phase two testing. Head and chest measurements are shown in the table. Neck measurements were taken, but due to lack of widely accepted injury criteria for rear impacts, data are not presented. It should be noted that the injury assessment reference values and the Hybrid III ATD were developed for frontal impacts. Therefore, injury measurements recorded during these rear impact tests are presented for relative comparisons and with less confidence in predicting injury risk than in frontal impacts. FMVSS 208 limit is 1000 for HIC (Head Injury Criteria) and 60 g's for 3 milliseconds of chest acceleration in frontal impacts. In the baseline Mustang tests, both head and chest injury indicators exceeded 208 criteria, with one HIC at 1332 and one chest reading as high as 108.8 g's. In the six phase two tests, four of the twelve ATDs exceeded the value of 1000 for HIC, with values ranging from 389 to 2552. Three of these four HICs exceeding 1000 occur

Table 3.
Results of Hybrid III Dummy response in MDB crash tests based on FMVSS 208 criteria

FMVSS 301 Rear Impact Test Procedure Development - Dummy Response

Test Number	Vehicle Model	Dummy Position	Head HIC	Chest 3 ms clip	Contact surface
Baseline :					
B1	Mustang	driver	1109	97.6	Rear seat back
		passenger	1238	108.8	Rear seat back
B2	Mustang	driver	198	22.8	
		passenger	913	53.9	
B3	Mustang	driver	892	38.0	
		passenger	1191	60.4	Rear seat back
B4	Mustang	driver	721	44.9	
		passenger	1332	66.4	Rear seat back
Comparison:					
1	Mustang	driver	1586	41.8	Rear seat back
		passenger	583	53.6	
2	Voyager	driver	690	15.8	
		passenger	1578	15.5	Rear seat bottom
3	Sidekick	driver	389	39.5	
		passenger	569	39.7	
4	Blazer	driver	783	22.6	
		passenger	2552	18.9	Floorpan
5	Neon	driver	739	22.2	
		passenger	1423	43.0	Rear seat back, rear door panel
6	Prizm	driver	829	37.2	
		passenger	604	19.6	

in vehicles which "passed" the fuel leakage requirements. High HICs in rear impact testing may be significant since HIC was developed as an indicator of skull fracture which is related to serious head injury. This may be particularly relevant in the event of a post-crash rear impact fire, in which rapid evacuation is critical for survival. This research suggests that more attention to head protection may need to be directed for rear impact occupant protection with and without fires.

The B1 '93 Mustang test and the '96 Mustang test (test number 1) are used to compare ATD and vehicle structural response under similar crash test conditions. In comparing these Mustang tests, it may appear at first glance that the '96 Mustang with a driver HIC of 1586 is worse than the '93 Mustang with a driver HIC of 1109, but further examination is necessary to understand conflicting data. First, the driver ATD in the '96 Mustang had chest resultant acceleration of only 41.8 g's as compared to 97.6 g's for the driver ATD in the '93 Mustang. Secondly, the passenger ATD in the '96 Mustang "passed" 208 injury criteria, whereas the passenger in the '93 Mustang "failed" head and chest criteria (1238 HIC and 108.8 chest resultant acceleration). These phenomena can best be explained by film analysis. From the film analysis it is observed that in the B1 '93 Mustang test, the rear seat was pushed forward into the backs of the front seats before significant ATD motion occurred, thus thrusting the dummies forward by loading the chest. Also the dummies' heads were carried forward by the chest, reducing the contact velocity of the head with the rear seat back. In the '96 Mustang, the passenger compartment remained relatively intact, particularly on the driver side, allowing the seat backs to deform. This deformation of the seat allowed the driver's head to move rearward and strike the seat back with sufficient force to create the high HIC. Some intrusion on the passenger side helped to restrain the dummy without excessive force as seen in the baseline test. Though intrusion in this case may have helped lower the HIC, prudence for protection of rear seat occupants would favor a seat back stiffening and intrusion reduction countermeasures to achieve the same result. Thus, the '96 Mustang performed better than the '93 in terms of vehicle structural performance and ATD response. This difference in performance appeared to be due to design changes made on the 1996 Mustang in improving structural integrity. It is particularly noteworthy that the '96 Mustang rear seat area did not completely collapse as in the test of the '93 Mustang providing space for survivability of rear seated occupants.

For the other five vehicles and 10 ATDs, three ATDs exceeded a HIC frontal criterion of 1000. One vehicle, the Chevrolet Blazer, had a particularly high HIC for the right front passenger of 2552. This high HIC occurred due to the lack of a rear passenger seat and the seat back failure which allowed the right front ATD's head to strike the rear floor surface.

CONCLUSIONS

From the test series we may conclude that the moving deformable barrier impact used in phase two of the test series distinguished between vehicles with marginal performance and improved performance. For example, the '96 Mustang with a rear-mounted tank (improved over the 1993 Mustang), did not leak Stoddard, and a '96 Geo Prizm with a tank forward of the axle did leak excessive Stoddard. With minor improvements it appeared the Geo Prizm could prevent fuel leakage in the proposed test. Another vehicle, the Dodge Neon, with a tank forward of the axle leaked excessive Stoddard. This vehicle leaked due to a particularly vulnerable location for the sender unit. Therefore, more difficult design changes may be needed for this vehicle.

Since all of the vehicles that leaked excessive Stoddard were small ($\leq$ 1370 kg), the one question after completing these tests was whether any small car could pass the test procedure. To answer this question, GM conducted five rear impact tests of small cars under the GM/NHTSA settlement agreement (docket number 92-066N3). GM and NHTSA selected five small 1998 vehicles based on production volumes from Asian, American and European manufacturers. These vehicles were Nissan Sentra, Honda Civic, Ford Escort, Chevrolet Cavalier and Volkswagen Jetta. The Civic and the Sentra passed the leakage requirements of FMVSS 301, but all cars showed potential to prevent fuel spillage with minor modifications. Most important, the test produced damage to the vehicles that was similar to that observed in case studies of fatal crashes which would have been survivable in the absence of fire.

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THERMAL PROPERTIES AND FLAMABILITY BEHAVIOR OF AUTOMOTIVE POLYMERS

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Paper Number 98-S4-P-17

ABSTRACT

The work described in this presentation is being conducted under the "flammability of materials" project which is part of the fire safety research program of March, 1995 General Motors/U.S. Department of Transportation Settlement Agreement. For this report twenty two components, consisting of seventy one polymeric parts used on a 1996 model year passenger van were studied.

A high resolution thermal gravimetric analysis (TGA) was used to determine thermal decomposition temperatures, and rates of decomposition. TGA runs were conducted in nitrogen and air atmospheres. For the different polymers investigated the ranges of decomposition temperatures were between 223°C and 552°C in nitrogen, and 240°C to 565°C in air.

Correlation was made between the thermal properties and the flammability characteristics quantified in this study. Ignition temperatures estimated from the Critical Heat Flux (CHF) values were about 14% higher than the decomposition temperatures from the thermal properties measurements. The experimental Thermal Response Parameter (TRP) values were about 28% higher than the TRP values calculated from thermal analysis. A rigorous correlation between the thermal properties and flammability characteristics of the plastics in components and parts of vehicles will be sought.

INTRODUCTION

Several complementary research projects for studying different aspects of the flammability characteristics of polymeric materials used in passenger vehicles and light trucks are being conducted at the National Institute for Science and Technology (NIST), Factory Mutual Research Corporation, and at the GM Global R&D Operations. Four segment leader vehicles were chosen for the investigation; namely: a passenger van, a utility sport vehicle, a front wheel drive vehicle and a rear wheel drive vehicle. This particular study deals with the investigation of thermal characteristics and flammability behavior of twenty two polymeric components used on a 1996 model year passenger van.

EXPERIMENTAL

Polymer Composition Analysis

The compositions of most of the polymeric parts chosen for this investigation were not known. A Nicole magnum-IR.550 Fourier transform infrared spectrometer (FTIR) was used to identify the nature of the polymer and in some cases identify the type of additive used. The amount of inorganic filler used in the polymer compositions was determined using thermal gravimetric analysis:

Qualitative and semi-quantitative elemental analysis of fillers was conducted by X-ray fluorescence spectroscopy. In some instances the crystalline structure of the filler, determined by X-ray diffraction, was used for identifying the filler type.

Thermal Gravimetric Analysis (TGA) was conducted using a TA 2100 controller (TA Instruments, Inc.). A TA 2950 module operated in high resolution mode where suppression of heating rate is automatically applied when degradation of the polymer proceeds at a fast rate. The heating rate was set at 50°C/minute, and the resolution factor was set at an intermediate value of 4. All samples were heated from room temperature to 980°C. For each sample, decomposition temperatures and the maximum rates of decomposition were determined.

Modulated Differential Scanning Calorimetry (MDSC) was conducted using a TA 2920. Measurements were made at temperatures of -62°C to 270°C. The heating rate was set at 5°C/minute. The degree of modulation was set at ±0.531°C, every 40 seconds. Glass transition temperatures, melting points, heats of fusion, and heat capacity values were all determined from these measurements.

Specific gravity values of all solid samples except foams were determined from weight in air and weight in water. For sponge samples the density was determined from measurements of weight and volume of uniform cylinders cut from these samples.

The Flammability Apparatus used in the study is shown in Figure 2.* The Apparatus consists of a lower and an upper section. The lower section is used to measure: time-to-ignition and mass-loss rate, as well as, visual observations of flame heights, smoke color, and fire propagation. The upper section, consisting of sampling duct and an exhaust pump, is used for measuring gas temperature, optical transmission through the product-air mixture flowing through the sampling duct, and concentrations of CO, CO_2, O_2, and total hydrocarbons.

The ignition tests were performed to determine Critical Heat Flux (CHF), defined as the externally imposed heat flux at or below which sustained piloted ignition does not occur, and the Thermal Response Parameter (TRP) which is an indicator of ignition time delay and relates the time-to-ignition to the net heat flux.

Ignition tests were performed in air under natural flow, with an external heat flux in the range of 20 to 60 kW/m^2. The sample was placed horizontally in the flammability apparatus. The time-to-ignition was taken as the time at which a self-sustained flame was observed. At the completion of the ignition test series, data for the time to ignition versus external heat flux were used to determine the CHF and TRP.

The combustion tests were performed in normal air under co-flow condition at a fixed external heat flux value of 50 kW/m^2. The inlet flow rate of air was $3.3 \times 10^{-3} m^3/s$. The combustion tests were performed to determine the chemical heat release rate, generation rates of CO, CO_2, total hydrocarbons, smoke density, consumption rate of oxygen, chemical heat of combustion, and yields of products.

RESULTS & DISCUSSION

Location of Polymeric Parts on the Vehicle

The locations of the selected polymeric components on the van are schematically shown in Figure 1. Table 1 lists the components along with the name and part numbers of all polymeric parts that make up these components, and the type of polymer used to make the parts. Weights of most of the components and some of the parts are also shown in the table.

* Chu, F., and Tewarson, A., "Standard Method of Test for Material Properties Using the FMRC Flammability Apparatus", Technical Report FMRC J.I. OBOJ4.BU. Factory Mutual Research Corporation, Norwood, MA 02062, February 1997.

Composition of Polymers

Automotive polymers are commodity polymers that are easily processable and have good aging resistance to withstand severe automotive environments. Table 2 lists the most highly used polymers arranged in a descending order with respect to the amount used per 1996 model average car. * Typical applications for each of the polymers are also shown in the table. The top ten most widely used polymer types are polyurethane (PU) including both foam used in seats and reaction injection molded polyurethanes used for body panels, followed by polypropylene (PP), polyvinyl chloride (PVC), polyethylene (PE), nylon (polyamide (PA)), poly(acrylonitrile/butadiene/styrene(ABS), sheet molding composites (SMC/BMC), polycarbonate (PC), polyesters (PET & PBT), and styrene/polyphenylene oxide blends (PS/PPO). Other large volume automotive polymers are phenolics, styrene-maleic anhydride copolymer, acrylic polymers, acetals, and epoxy compounds.

The polymers selected for the flammability investigation are shown in Table 1. For few of the parts a label showed the type of polymer used. However, for most of these parts identification was carried out using infrared spectroscopy. A great majority of the parts are made of polyolefins (i.e., polypropylene, polyethylene, and plypropylene/polyethylene blends and copolymers including cross linked elastomers and thermoplastic elastomers). Other polymers used in these parts include polyurethanes polyvinyl chloride, nylons, ABS, polycarbonate, SMC, polyethylene terephthalate polyester, polyacetal, polyimide, polyether copolyester thermoplastic elastomer, and natural rubber and acrylonitrile-butadiene elastomers. Some of the polymer parts contained no filler while others contained as high as 53% filler. Glass, talc calcium carbonate, kaolin, clay, silica, barium sulfate, and carbon black are some of the typical filters used. Density values for the different polymer composites ranged between 0.075 g/cc for a foamed seal used in the heating/ventilation/air conditioning (HVAC) housing (part number 4734370) to 2.10 g/cc for a very highly talc filled part used as a unit seal in the HVAC system (4734067B).

* Automotive Plastics Newsletter, April, 1996, Market Search, Inc.

For some samples, such as polyethylene obtained from the fuel tank, a simple decomposition pattern was observed. In nitrogen atmosphere the polymer shows no sign of degradation as it is heated up until the temperature approaches 440°C (Figure 3). A one step degradation is observed at that temperature with a decomposition rate of 16.79% per °C. The rate was calculated with respect to temperature rather than time because of the variable heating rate programmed into the instrument to give a higher resolution of decomposition peaks. The high density and high molecular weight polyethylene used for making the fuel tank is essentially filler free. The 0.3% residue that remains after heating to 900°C is probably the carbon black used in the resin for coloring.

When the same polymer is degraded in air, different degradation mechanisms are observed as seen in Figure 4. Decomposition starts at a lower temperature of 290°C. The main decomposition peak occurs at 418°C, and has a lower decomposition rate (5.88%/°C) than when the sample was degraded in nitrogen (16.79%/°C). Apparently, oxidation reactions taking place at lower temperatures slow down the decomposition of the polymer at higher temperatures either by increasing the formation of cross links or the formation of char and forcing the pyrolysis to occur over a wider temperature range, thus leading to lower rates of decomposition.

In the case of rubbers, which are molecularly cross linked polymers, we find that the decomposition rates are lower both in nitrogen and in air than for comparable thermoplastic uncross linked polymers. For example, the maximum decomposition rates of ethylene-propylene (EPDM) rubber, taken from the grommet used for the wire harness entry into the passenger compartment (part number 3009), are lower in nitrogen (1.54%/°C) and in air (1.29%/°C), than the rates observed for the two polymers that make up the rubber, namely polyethylene (16.79 & 5.88%/°C) and polypropylene (15.12 & 1.82%/°C).

Most foams used in the car are also thermoset cross linked polymers. Hence, their rates of degradation are lower than rates measured for thermoplastics.

For most polymeric compositions, decomposition starts at higher temperatures in nitrogen as compared to air, but the rate of decomposition is lower in air. One exception is the polyacetal (polyoxymethylene), used in the headlight. This is a polyether which upon heating unzips very fast via a free radical mechanism to yield the monomer. The decomposition of this polymer occurs at lower temperatures (252°C versus 310°C) and at a faster rate (71.0 vs 3.3%/°C) in the presence of oxygen.

Modulated Differential Scanning Calorimetry (MDSC)

Heat absorption or evolution measurements are conducted in a nitrogen atmosphere at programmed heating rates of 5°C per minute with a modulation in rate of ±0.531°C every 40 seconds. The technique is capable of identifying reversible and non-reversible transitions that are measured during the heating run. The reversible transitions measured are first order transitions such as heats of fusion or heats of recrystallization, and second order transitions such as glass transitions. Non-reversible transitions are those associated with an entrapped unstable polymeric morphology that upon heating would relax to a more thermodynamically stable structure.

Crystalline polymers such as high density polyethylene (HDPE) show very well defined melting peaks and large values for the heat of fusion (128°C and 161 Joules/gram, respectively, for HDPE).

For amorphous polymers melting does not take place, instead the polymer undergoes softening at the glass transition temperature. This is the temperature at which a polymer goes from a stiff glassy state to a soft rubbery state. At the glass transition, polymers have enough free volume to allow the chains to suddenly become free to move resulting in a sharp increase of heat capacity. The rate of change in the value of heat capacity with temperature is lower in the rubbery state (0.00251 J/g.°C.°C) than in the glassy state (0.00364 J/g.°C.°C) as in the case of polycarbonate. For a crystalline polymer (polyethylene terephthalate, used in the door lock), heat capacity increases in a uniform manner as the sample is heated from -60°C to melting. A large peak in heat absorption is observed at melting. As in the case of amorphous polymers, the slope or the rate of increase in heat capacity with temperature is lower for the liquid state (0.000946 J/g.°C.°C) than for the solid polymer (0.00200 J/g.°C.°C)

Ignition

The measured thickness versus the thermal penetration depth governs the ignition behavior of the samples.* In these studies, the thermal penetration depth was calculated from the thermal diffusivity values and measured times-to-ignition.** The calculated values show that beyond about 30 kW/m^2, the thermal penetration depth is less than the actual thickness of the samples and thus time to ignition is expected to follow the relationship:

$$\sqrt{1/t_{ig}} = \left(\dot{q}''_{e} - \dot{q}''_{cr}\right) / \Delta T_{ig}\sqrt{(\pi/4)(k_v \rho_v c_v)}$$

where $\dot{q}''_{e}$ = external heat flux

$\dot{q}''_{cr}$ = critical heat flux

and $\Delta T_{ig}\sqrt{(\pi/4)(k_v \rho_v c_v)}$ is the Thermal Response Parameter (TRP) of the plastic (kW-2$^{1/2}$/m^2). k_v, ρ_v, and c_v are the thermal conductivity, density and specific heat of the sample, respectively. Figure 5 shows a typical example of the ignition time versus heat flux for plastic part VAC #870. The experimental TRP value is obtained from the slope of the line in this figure. The calculated TRP value is determined from the ignition temperature, thermal conductivity and specific heat value obtained from the thermal analysis study. Good correlation is observed as seen in Figure 6.

The ignition temperature calculated from critical heat flux values ($\dot{q}''_{cr}$) by the relationship

$$T_{ig} \approx [(\dot{q}''_{cr})^{0.25} \times 364]$$

is compared in Figure 7 with the decomposition temperature (T_d) obtained from thermal gravimetric analysis. As expected for most samples T_{ig} values fall above the perfect correction line with respect to T_d values.

Combustion

After ignition combustion of the polymer starts. During combustion the variables measured include mass loss rate, generation rates of combustion products, such as CO and CO_2, and the depletion of oxygen. In addition, the chemical heat release rate ($\dot{Q}''_{ch}$) is calculated. $\dot{Q}''_{ch}$ is in turn used to calculate a Fire Propagation Index (FPI) by the following semi-empirical relationship,

$$FPI = 1000\,(0.42\,\dot{Q}''_{ch})^{1/3}/TRP$$

Comparisons with large-scale fire tests indicate that the rate of fire propagation increases with increase in the FPI value. The estimated FPI values for some of the plastic parts used on the van are listed in Table 3. Three parts, namely, polyethylene fuel tank (VAC #201), polycarbonate headlight lens (VAC #798), and SMC windshield wiper structure (VAC #967) with FPI values less than 10 are expected to have decelerating fire propagation, whereas the other 12 plastic parts shown in the table are expected to have steady or accelerating fire propagation beyond the ignition zone.

In summary, thermal properties of plastic parts used on a 1996 passenger van were determined. High resolution thermal gravimetric analysis (TGA), and modulated differential scanning calorimetry were the two techniques employed. Thermal analysis results were compared with flammability parameters obtained using a flammability apparatus capable of measuring ignition, combustion and heat release variables.

Good agreement was observed between measured flammability parameters, such as ignition temperature, critical, heat flux and thermal response parameter and the thermal analysis results such as specific heat, thermal conductivity and a decomposition temperatures.

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** Murty Kanuary, A., "Flaming Ignition of Solid Fuels", *The SFPE Handbook of Fire Protection Engineering*, Section 2, Chapter 13, pp. 2-190 to 2-204. The National Fire Prodction Association Press, Quincy, MA, 1995.

** Quintiere, J. G., "Surface Flame Spread", *The SFPE Handbook of Fire Protection Engineering*, Section 2, Chapter 14, 2-205 to 2-216. The National Fire Association Press, Quincy, MA, 1995.

Table 1.
Mass of Selected Polymeric Components and Parts

Component Number	Part Number	Part Description	Polymer Identification	Mass kg
743	GJ42SK4A	headliner, backing - top layer, structual support	polyethylene terphthalate (PET)	
	GJ42SK4B	headliner, high density foam - layer 3	polyether urethane (PPO + MDI)	
	GJ42SK4C	headliner, low density foam - layer 2	polyester urethane with Surlyn film	
	GJ42SK4D	headliner, fabric - exposed surface, bottom layer	nylon 6	
	GJ42SK4E	headliner, center - structural support	PET Binder on glass	
		Whole system		2.61
654	JF48SK5A	instrument panel, foam - between structure and cover	polyether urethane (PPO + MDI)	
	JF48SK5B	instrument panel, cover - exposed surface	polyvinylchloride (PVC)	
	JF48SK5C	instrument panel, structure	polycarbonate (PC)	
		Whole system		3.61
611	PL98SX8A	instrument panel shelf, main panel	PC	
	PL98SX8B	instrument panel shelf, foam - small seals	polyether urethane	
		Whole system		2.75
256	4612512A	resonator, structure	polypropylene (PP)	0.71
	4612512B	resonator, intake tube	ethylene propylene diene monomer (EPDM) elastomer	0.29
	4612512C	resonator, effluent tube	EPDM	0.14
		Whole system		1.14
788	4674711A	kick panel insulation, foam	polyether urethane	
	4674711B	kick panel insulation, backing	PVC	
		Whole system		4.82
732	4678345A	air ducts, small ducts	polyethylene (PE)	
	4678345B	air ducts, large ducts	PP	
		Whole system		4.26
673	4680250A	Steering column boot, inner interior boot	natural rubber (NR)	0.04
	4680250B	Steering column boot, cotton shoddy	mixture of cotton, polyester and other fibers	0.02
	4680152C	Steering column boot, outer interior boot	polyether copolyester elastomer	0.10
		Whole system		0.17
736	4683264A	brake fluid reservoir, reservoir	PP	0.67
	4683264B	brake fluid reservoir, cap	PP	0.07
		Whole system		
3008	4707580	wire harness tube,	PE	0.07
1019	4707808A	door lock contact, wire coating		
	4707808B	door lock contact, wire mesh - groups wires together		
	4707743C	door lock contact, structure	poly(acrylonitrile-butadiene-styrene) ABS	
		Whole system		
967	4716051	windshield wiper tray, structure	sheet moulding compound (SMC)	3.40
868	4716345A	fender insulaton, low density foam - sound reduction	polystyrene (PS)	
	4716345B	fender insulation, high density foam - sound reduction	PS	
		Whole system		0.11
870	4716832A	hood liner, insulation (back)	PET, cellulose and epoxy	
	4716832B	hood liner, face	PET	
		Whole system		1.00
208	4716895	wheel well cover, fuel tank shield	PP	0.56
676	4734025	HVAC unit, door - foam covering		0.29
	4734033	HVAC unit, door - for thermostat	PVC	0.08
	4734039A	HVAC unit, door - structure	nylon 66	
	4734039B	HVAC unit, door - rubber seal	thermoplastic polyolefin (TPR)	
		Whole system		0.23
	4734041A	HVAC unit, door - structure	nylon 66	
	4734041B	HVAC unit, door - rubber seal	TPR	
		Whole system		0.11
	4734042A	HVAC unit, door - structure	nylon 66	
	4734042B	HVAC unit, door - rubber seal	TPR	
		Whole system		0.10
	4734063	HVAC unit, cover	PP	0.13
	4734067A	HVAC unit seal, foam - heating coil entrance	acrylonitrile-butadiene rubber and PVC blend	
	4734067B	HVAC unit seal, backing - heating coil entrance	ethylene vinyl acetate	
		Whole system		0.05
	4734071	HVAC unit, top main housing - contains coils, doors and fan	PP	0.87
	4734072	HVAC unit, bottom main housing - contains coils, doors and fan	PP	1.61
	4734073	HVAC unit, fan top cover	PP	0.29
	4734074	HVAC unit, fan bottom cover	PP	0.11

Table 1 (cont'd).
Mass of Selected Polymeric Components and Parts

Component Number	Part Number	Part Description	Polymer Identification	Mass kg
	4734080	HVAC unit, cover - for directional control	PP	
	4734081	HVAC unit, deflector - for air flow	PP	0.09
	4734225	HVAC unit, actuator - casing	PP	0.15
	4734367	HVAC unit, housing	PP	0.25
	4734370	HVAC unit, Seals - both large and small	acrylonitrile-butadiene rubber and PVC blend	0.04
	4734396	HVAC unit, seal		0.00
	4734650	HVAC unit, seal		0.02
	4734651	HVAC unit, seal		0.01
	4734724	HVAC unit, defogger tube	TPR	0.03
201	4883140A	fuel tank, tank	PE	
	4883140B	fuel tank, hoses	nylon 12	
	4883140C	fuel tank, threads/seal - for fuel pump	PE	
		Whole system		8.48
798	4857041A	headlight, lens	PC	
	4857041B	headlight, backing	PC	
	4857041C	headlight, retainer	polyacetal (polyoxymethylene)	
	4857041D	headlight, bulb support structure - halogen	polyimide	
	4857041E	headlight, leveling mechanism	PC	
		Whole system		1.70
222	4364944A	battery casing, top	PE/PP blend	
	4364944B	battery casing, sides & bottom	PE/PP blend	
		Whole system		17.30
230	5235267	battery cover,	PP	0.36
971	4675359A	hood to cowl weather stripping, foam	EPDM	
	4675359B	hood to cowl weather stripping, rubber base	EPDM	
		Whole system		0.44
959	4716896A	Bulkhead insulation engine side, exterior/face	mixed fibers: cotton, nylon 66 and glass	
	4716896B	Bulkhead insulation engine side, insides	PVC coating over glass	
	4716896C	Bulkhead insulation engine side, support structure	PVC-hydrocarbon elastomer	
		Whole system		2.38
3009		grommet, wire harness cap for 3008	EPDM	

Table 2.
Polymers Most Used in Cars and Light Trucks

Polymer Type	Average Weight lb./1996 Vehicle	Typical Applications in Vehicles
Polyurethane PU	44 (RIM & Foam)	Body panel, fender, roof panel, bumpers, headliner, seat, upholstery
Polypropylene PP	40	HVAC, fan & shroud, battery tray, console, radiator, cowl vent, air duct, instrument panel, package shelf
Polyvinyl Chloride PVC	21	Bumper trim, electrical wiring, boots, bellows, seat cover, steering wheel, floor
Polyethylene PE	20	Gas tank, bumper, electrical wire, reservoir, fuel filler pipe
Nylon(Polyamide) PA	18	Fuel system, fuel line, gas cap, canister, grille head lamp support, brake, radiator end tank, engine cover, intake manifold, lamp housing
Acrylonitrile/styrene/ butadiene ABS	16	Bumper beam, console, cowl vent, engine cover, fascia, head liner, duct
Thermoset Polyester (SMC/BMC)	16	Door lift gate, fenders, hood, quarter panels, rear deck, spoiler, body panel
Polycarbonate & ABS/PC	9	Bumper trim, electrical, grille, lamp support, lens, lamp, instrument panel, console, door fender, instrument panel
Thermoplastic Polyester PET/PBT	8	Body panel, hood, connector, door, fuse junction, HVAC components, fuel rail
Styrene/polyphenylene oxide PS/PPO	7	Connectors, console, engine air cleaner, instrument panel
Styrene Maleic Anhydride Polymer SMA	4	Console, head liner, instrument panel
Phenolic	4	Brake system, engine pulley, ash tray, transmission component
Acrylic Polymers	3	Emblems, lamp and instrument panel lenses
Polyacetals	2	Radiator fan, door handle, carburetor, fuel pump, fuel filler neck.
Epoxy Resins	0.3	Electrical, fuel tank(filament wound), adhesives

Table 3
Estimated Fire Propagation Index Values for the Plastics
in Parts of the 1996 Passenger Van Examined in this Study

VAC#	Dodge Part #	Description	Plastics	FPI
201	4883140A	Fuel Tank	PE	8
208	4716895	Wheel well cover, fuel tank shield	PP	13
230	5235267	Battery cover	PP	12
256	4612512A	Resonator structure	PP	14
611	PL98SX8A	Instrument panel shelf, main panel	PC	11
654	JF48SK5B	Instrument panel cover, exposed surface	PVC	15
676	4734071	HVAC unit, top main housing, outer top	PP	12
	4734370	HVAC unit, seals-both large and small	ABS-PVC	57
732	4678345B	Air ducts, large ducts	PP	11
743	GJ42SK4D	Headliner, fabric-exposed surface	Nylon 6	26
788	4674711B	Kick panel insulation backing (silencer?)	PVC	18
798	485041A	headlight lens	PC	9
868	4716345B	Fender sound reduction foam	PS	27
870	4716832B	Hood liner face	PET	23
967	4716051	Windshield wiper structure	SMC	8

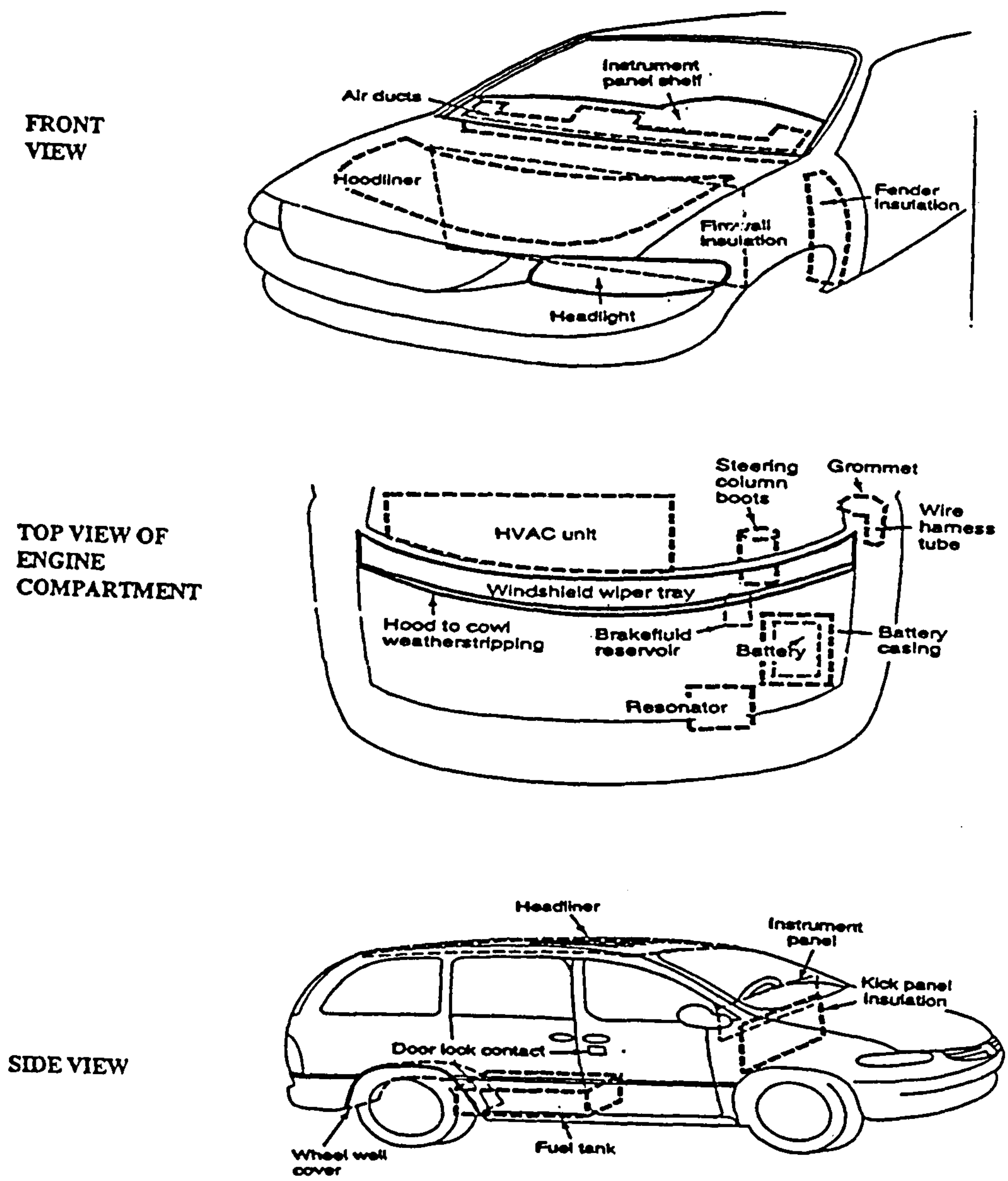

Figure 1. Schematic diagram showing the locations of components and parts of a 1996 passenger van.

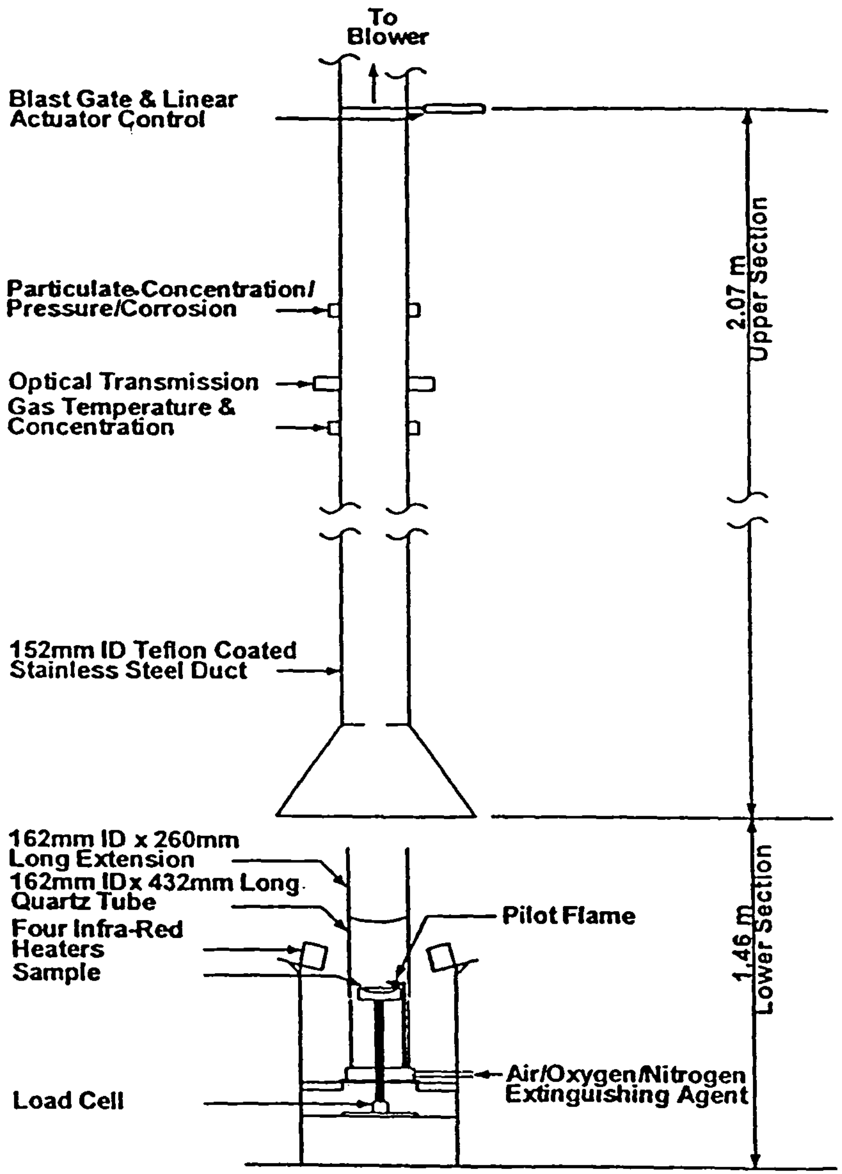

Figure 2. Flammability apparatus.

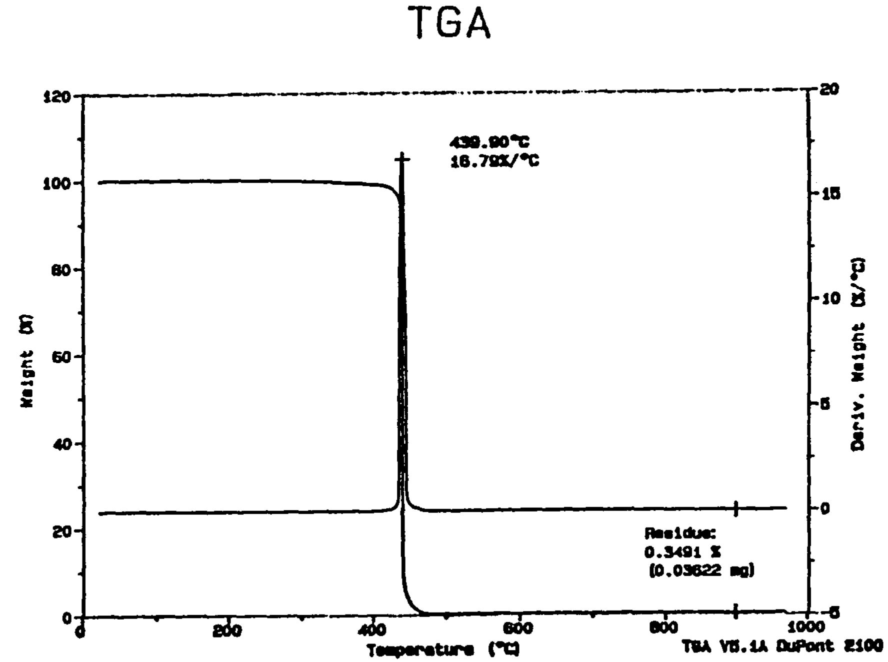

Figure 3. High resolution thermal gravimetric analysis of high density polyethylene conducted in nitrogen.

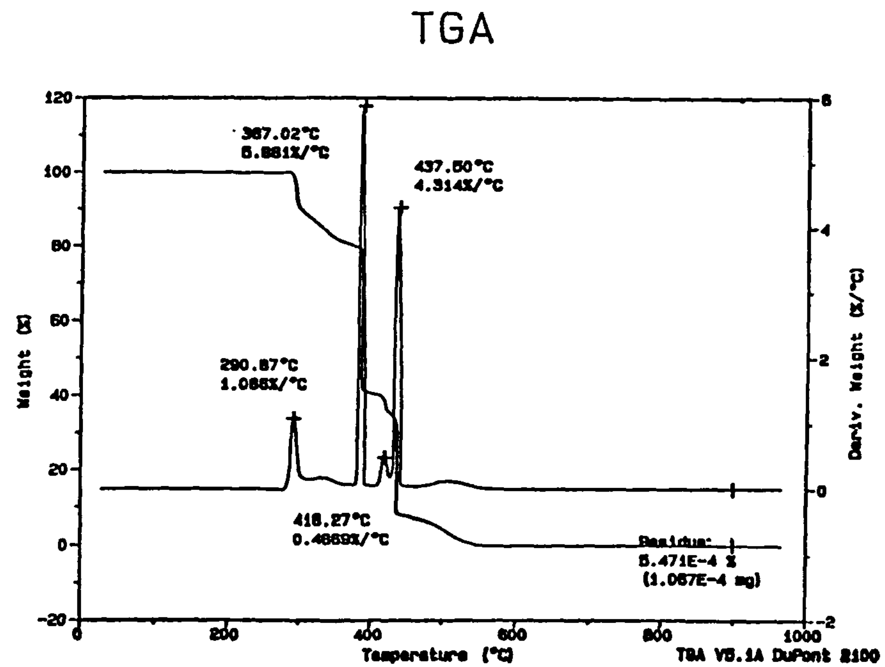

Figure 4. High resolution thermal gravimetric analysis of high density polyethylene conducted in air.

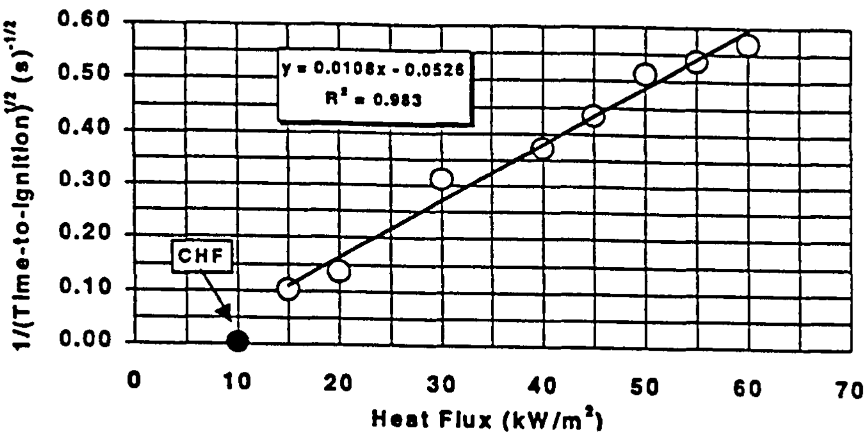

Figure 5. Inverse of the square root of time to ignition versus external heat flux for 25-mm thick sample of VAC #870 (part #4716832B, polyethylene terephthalate hood liner face). Measured CHF value (dark symbol) = 10 kW/m^2; TRP (inverse of the slope) = 93 $kW\text{-}s^{1/2}/m^2$.

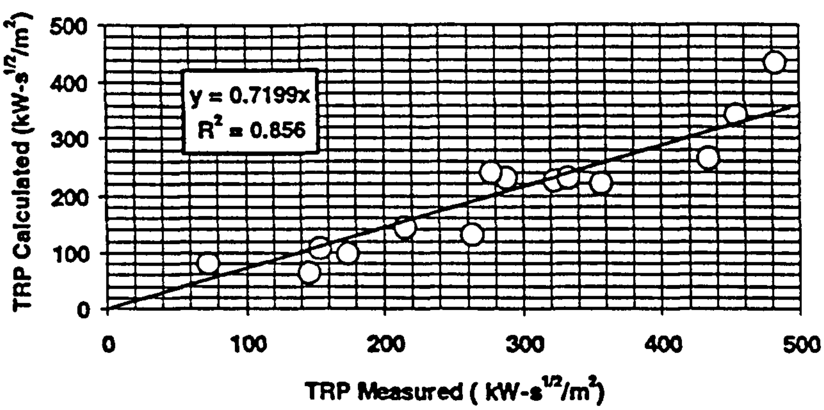

Figure 6. Correlation between the measured and calculated Thermal Response Parameter Values for the plastic parts examined in this study. Ignition data were measured in the Flammability Apparatus.

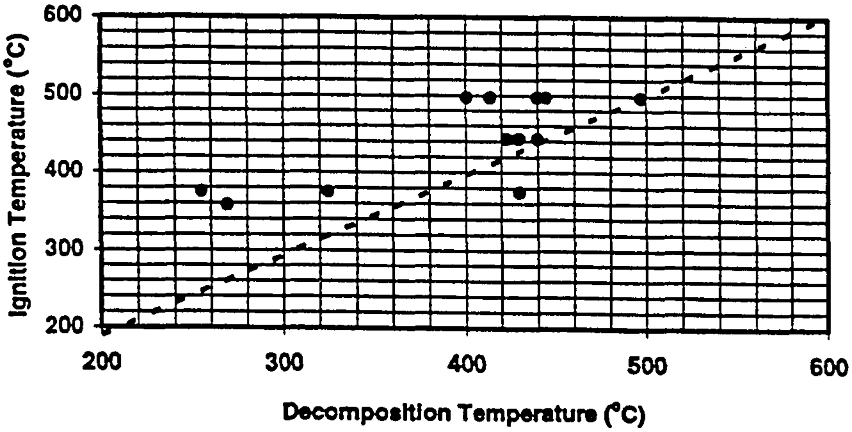

Figure 7. Decomposition temperature versus the ignition temperature for plastic parts.

EUROPEAN TEST METHODS FOR SUPERSTRUCTURES OF BUSES AND COACHES RELATED TO ECE R66 (THE APPLIED HUNGARIAN CALCULATION METHOD)

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Paper Number 98-S4-P-18

ABSTRACT

The first full-scale roll-over tests of coaches and buses, in Europe, have been started at the beginning of 70's in Hungary. Later in 1986, the European Committee of Economy has accepted and issued a new regulation related to the bus and coach superstructures' strength.
The previous methods and all the four test methods, accepted in the ECE R66, are discussed technically and critically in this paper.
The recently used combined Hungarian method based on quasi-static tests of bus-frames and simplified computer simulation of roll-over process is presented too.

BÉLA BARÉNYI, THE CREATOR OF MODERN PASSIVE SAFETY

The Hungarian-Austrian born automobile constructor Béla Barényi (1907-1997) was the *Nestor of vehicle passive safety* of our modern time. His predominant activities have served the Daimler-Benz.
The concept of passive safety originates from his patent of "Front and Rear Impact Zones" in 1951. (The division of vehicle safety into two parts: passive and active safety is firstly published by an Italian journalist Luigi Locati in 1964.)
Two basic patents of Béla Barényi related to our theme can be emphasized: Rollbar (1949) and Multiple-Purposed Safety Roof (1955) for automobiles.
His name, as an outstanding inventor of our age, can be rightly read on the wall of "Automotive Hall of Fame" in Midland, Michigan.

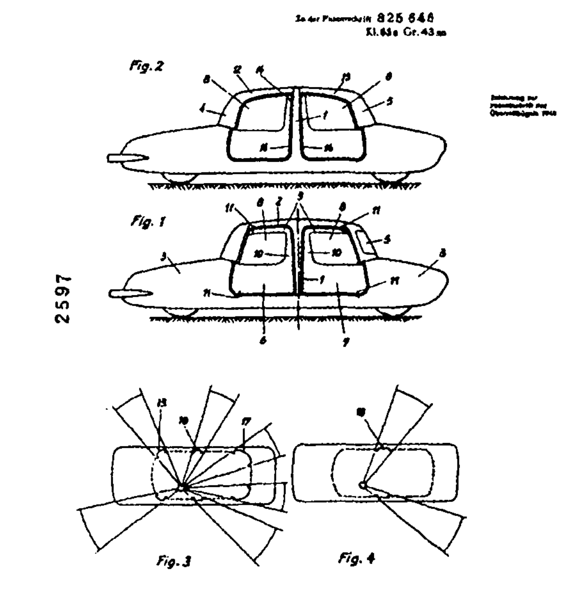


Fig. 1. Patent of Béla Barényi: Protective rollover bars for automobiles (1949). First application was at Porsche 911 Targa in 1967.

BUS ROOF STRENGTH RESEARCHES IN HUNGARY

Passive safety researches of buses and coaches has been started at Ikarus Co. in Hungary at the end of 60's effected by the next coincidences:

- serial production of IK 200 bus-family has claimed new demands from the world's largest bus manufacturer and in the same time the development work of national (Hungarian) technical specifications for buses has been also started;
- several fatal home accidents have pointed out the weakness of coach and bus superstructures and the necessity of more rigorous passive safety requirements;
- initiative of the world-wide ESV program.

What kind of basic accident situation were examined?

- fall down from overpass,
- rollover on a slope.

In both situations the longitudinal speed was neglected for the better repeatability. The research process was concentrated on three principal elements:

- to work out a standard accident situation,
- determination of a so-called survival zone for passengers,
- to develop approval methods for substitution of full-scale test.

Basic necessity for these is to determine a well-conditioned *standard* or *representative accident situation*. The vehicle shall have sufficient strength to ensure that during and after the given accident situation the examined passive safety system of coach or bus protects the occupants from injury. Therefore the detailed data collection of accident is the starting point of each passive safety specification.

Beside the officially used static kerbweight loading of bus and coach roofs, comparative test series were carried out with the coaches of IK 55 and IK 255 between 1970 and 1972 in Hungary:

- quasi-static tilting tests on the ground
- and real turnover tests on different slopes.

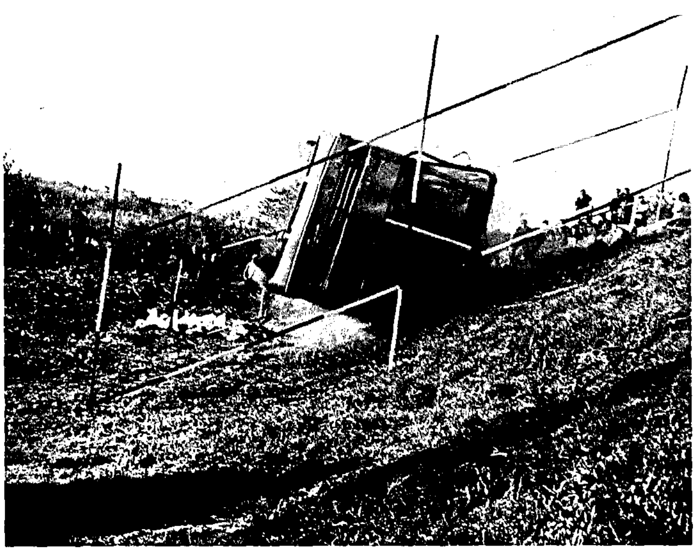


Fig. 2. After the fullsteal structural automobile's rollover tests in 1930, Hungary was the first to carry out real rollover test with complete bus in 1972. The test was accomplished with different reinforced compartments of IK 255 type bus on a 6/4 (33,6°) slope.

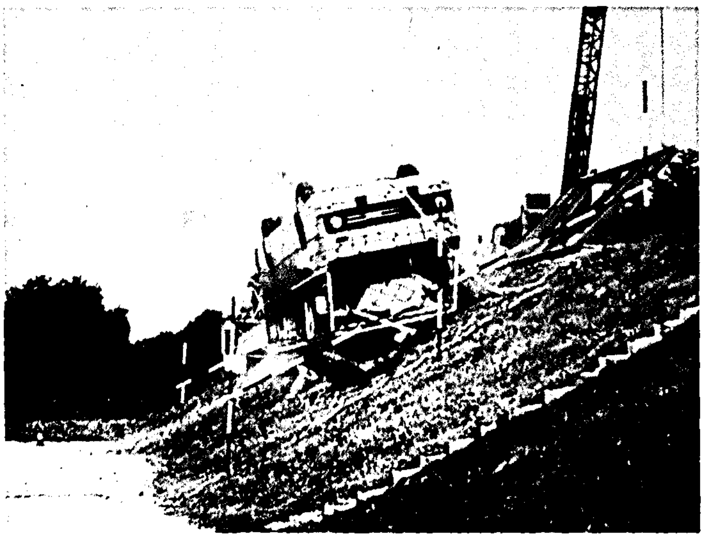


Fig. 3. This 1983's rollover test of Ikarus 255 bus demonstrated the applicability and repeatability of this kind of dynamic test method.

Hungary has played pioneer role in the development of the test specifications for coach rollover safety.
The actuality and importance of this subject was shown by the fact, that Britain, accepting the basic concept, had developed an own test method too. At the end a simplified common British-Hungarian rollover method was accepted as the new European Regulation ECE R66 in 1986.

EUROPEAN REGULATION ON BUS AND COACH SUPERSTRUCTURE'S STRENGTH - ECE R66

The superstructure of the vehicle for passengers' surviving shall be of sufficient strength to ensure that during and after the standard rollover accident situation no displaced part of vehicle intrudes into the residual space or projects outside the deformed structure.
Each type of vehicle carrying more than 16 passengers shall be verified on the basis of a full-scale rollover test or according to an alternative method approved by the competent authority.

This regulation allows four different methods given possibility for the Type Approval of vehicles:

- Full-scale rollover test on a complete vehicle;
- Rollover test on body segment or segments;
- Pendulum test on body segment or segments;
- Verification of strength of superstructure by calculation.

All of these four methods were carried out at AUTÓKUT in Hungary.

Full-scale Rollover Test

The vehicle with unladen kerb mass (explosive or corrosive materials may be substituted) should be rolled down from 800 [mm] height to a horizontal concrete surface without any dynamic effect. The axis of rotation is parallel to the longitudinal axis of the coach.
Seven coaches of three countries were tested till this time at AUTÓKUT in Hungary.

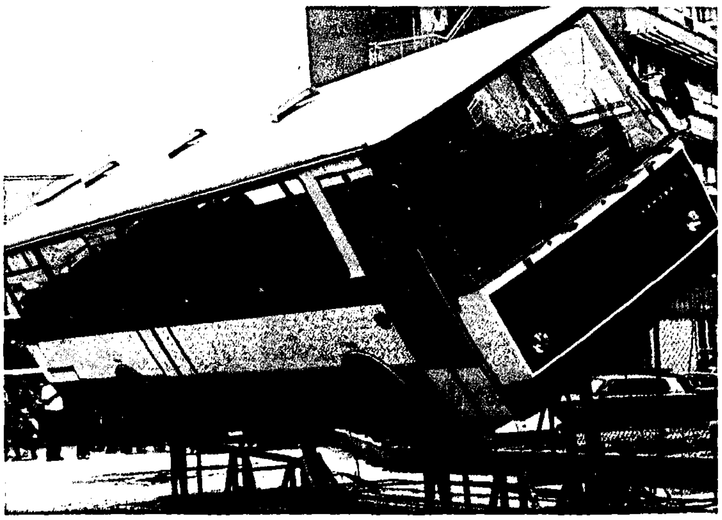


Fig. 4. General arrangement of full-scale test according to ECE R66. A computer controlled hydraulic system with multistep actuators is the basic equipment.

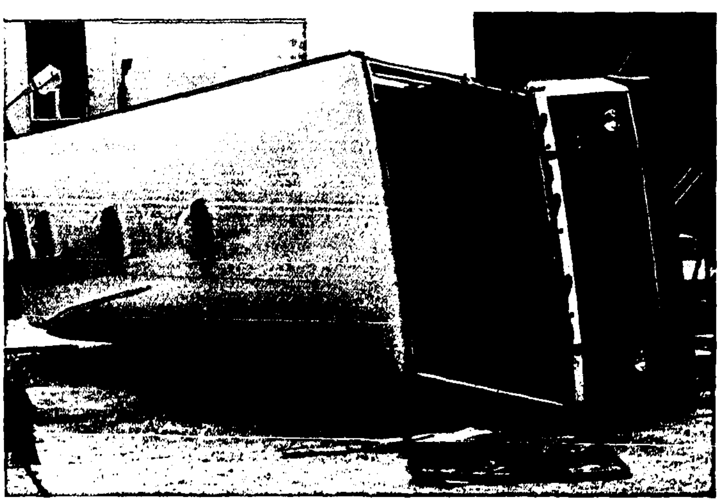


Fig. 5. Usual deformation shape of the superstructure after rollover test from 800 mm height.

Rollover Tests on Body Segment

It was the finally suggested alternative test method for checking of bus roof strength.
Using one or more rings with shorted exact cross-sectional geometry and mass distribution of buses or coaches you can carry out the rollover tests on this kind of segments, having modeled and represented all the main load-bearing beams and columns of bus compartment.

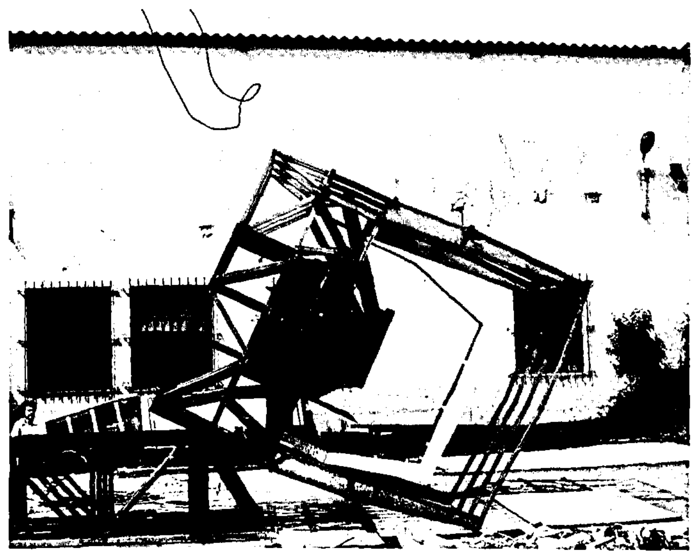


Fig. 6. Rollover test on a contracted multiple ring of IK 255 bus in 1985. This 2,5 m long, 8120 kg frame-segment contained 2 reinforced rollbars and 2 window-rings. (There was used a wood-surface.)

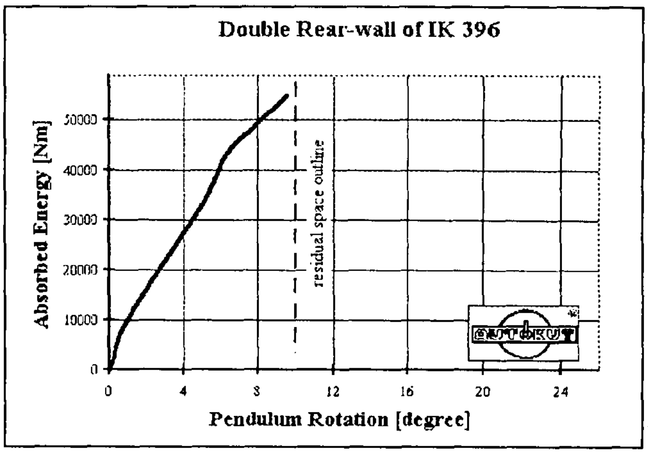
The main conclusions of the segment's rollover test were the next:

- the tested segment shall contain all the essential energy-absorbing elements (seat-frames, sheet-coverings,..);
- the tested segment shall be capable to absorb at least 80 % of the energy of the complete bus;
- main dimensions, mass distribution shall exactly be the same as at the original complete bus;
- the genuine manufacturing technology is very important.

Pendulum Tests

The fulfillment of requirements of rollover safety can be verified by pendulum test according to the text of Annex 5 of Regulation No 66.
At the moment of impact the direction of motion of the pendulum makes an angle of 25 degrees to the longitudinal vertical plane of the body sections.
The tested body sections were designed to be symmetrical to the vertical cross plane, not to cause any rotation of pendulum. Attachments of the sections to the mounting base are different, the only common feature is that each of them were fixed at the floor level with shape-closing link to the mounting base. The total energy to be divided to different body sections is equal to the energy of complete vehicle to be tilted from 800 [mm] height.
At AUTÓKUT a test series was carried out with eight double frame sections, one of them is shown in Fig. 7, and the comparison of this qualifying method to the complete vehicle rollover test has implied the next critical remarks:

- Anchorage, attachments of sections are not unambiguously determined and the absorbed energies depend on these.
  (Fixing at the upper level of underfloor cross-beam gives different result as the fixing at the lower level of underfloor structure.)
- The change of the impact force during the collision process is the opposite of that of the complete rollover test.
- Extra weights on the roof additionally increase the energy to be absorbed during the pendulum test according to the requirement, in contrast to the full-scale test where, in such a case the energy dissipated by pillars is lower.
- Different impact investigations regarding to the coach structures prove that 25-45% of initial impact energy avoids our measuring system of the deformation energy and leaves the tested system as noise, heat energy and mostly as vibration-wave through the fixings and the ground! This percent strongly depends on the fixings and makes uncertainties in the final calculations.



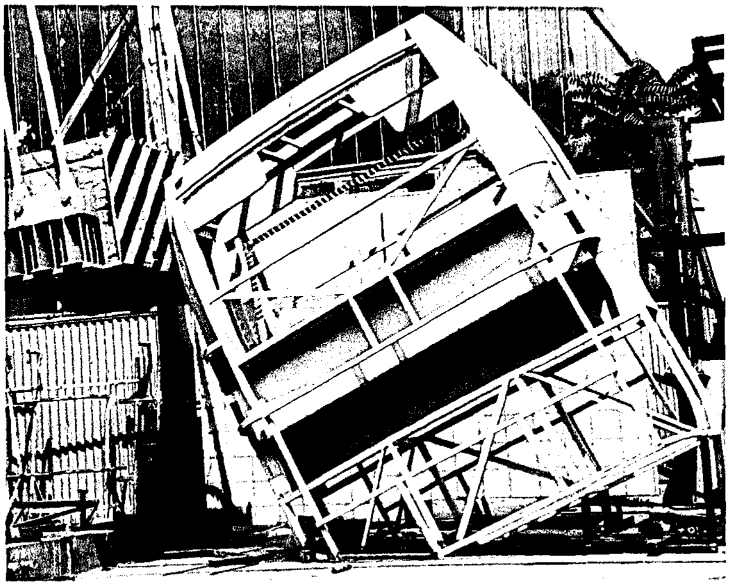


Fig. 7. Pendulum test on a double rear-wall segment of bus IK 396. The results of quasi-static laboratory bending test and the pendulum test indicate big differences on the same segment.

Numerical Calculation

The Regulation allows to carry out the type approval process by mathematical calculation based on the needed measurements of vehicle elements or segments. This is probably the fastest and perhaps the cheapest but the most arguable method.

THE APPLIED HUNGARIAN CALCULATION METHOD

On the basis of the previously carried out full-scale rollover tests and special quasi-static tests of relevant coach frames the Vehicle Mechanics Laboratory of AUTÓKUT has developed a new calculation algorithm in 1989.
The principle is simple:

- During the rollover test of a complete vehicle the cross-sectional rings of the superstructure determine the energy-absorbing capability of the whole coach. Rings contain cross members of underframe structure, side wall columns, window (door) pillars, roof ribs.

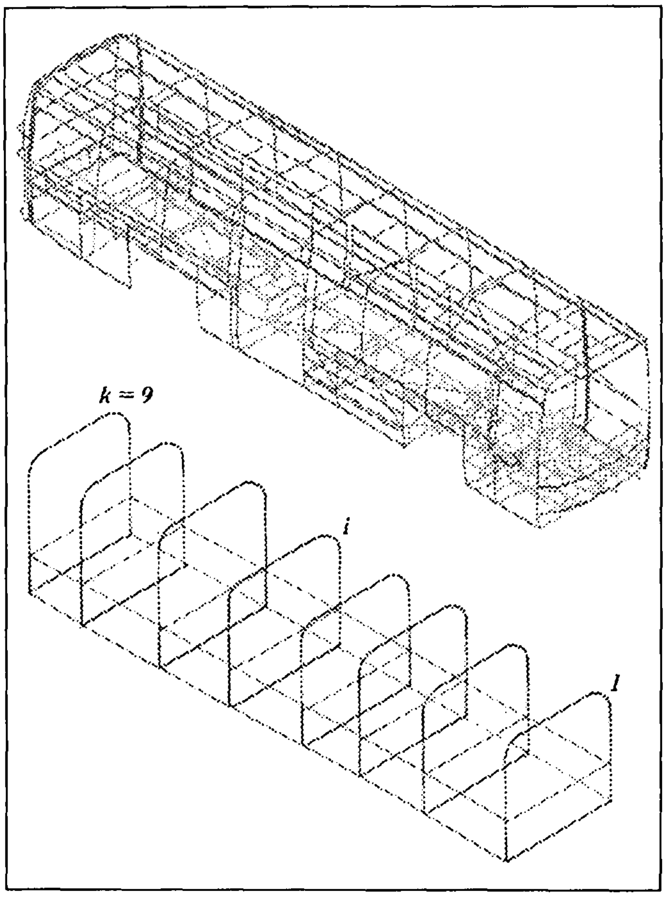


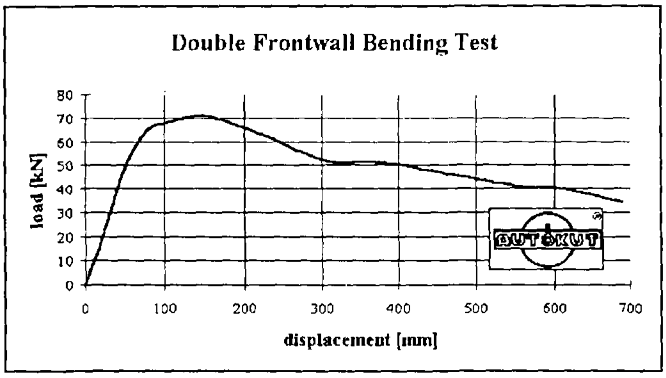
Fig. 8. Each bus or coach can be modeled with plane cross-sectional segments.

- These cross-sectional rings -excepted the front and rear walls- can be modeled with perfect plane-frames. The front and rear parts of coaches as extended sections also can be substituted with plane-frames measuring the bending stiffness and rigidity of the original front-wall - driver cabin and extended rear wall units. Geometrically the substitutive plane-frames can be positioned into the center plane of bending stiffness for the expanded sections.
- Basic condition: the roof cantrail has to be remained in straight line during the deformation process!
- 'k' pieces of coach cross-sectional rings as deformable units are substituted by 'k' pieces of non-linear springs in the mechanical model.
- Torsion displacements of rings may be neglected due to the (coach)chassis torsion rigidity. In spite of this the exact approach of the algorithm considers the non-infinitive rigidity of coach, possible rotation of the pillars of different plane-frames regarding to the original position around the initial centerline. The basic algorithm calculates constant torsional rigidity along the whole length of coach but there is a possibility to calculate with changing torsional stiffness of body sections along the coach length.
- This method contains the transloading opportunity of pillars. After given deformation and angle rotation the contact may transfer from the cantrail to the waistrail or to the lower side of (window)pillars. (Anyway the maximum deformations of coach were reached before the waistrail touched the ground at the real full-scale rollover tests.)

Quasi-Static Bending Tests for Calculation

At first the representative rings of the bus have to be chosen.
Collapse mode of a cross-sectional segment at quasi-static bending test and at a complete rollover test of the coach is very similar due to the low impact speed and similar loading position.
Segments to be tested are duplicated for easy deformation control and prepared on the factory's manufacturing line, so the joints of the roof-rails and side pillars or side pillars and underfloor beams are original factory-style as the used welding technology too.
Technology has a very strong influence on the stiffness of section, the collapse process depends on it. It is one of the main advantages of this method comparing with the very complicated finite element method where the technology effect can generally be approached slightly. Each segment has to be attacked by load at the cantrail with 60 degrees to the central longitudinal vertical plane of the body section. Sections to be tested are fixed under the floor-level at the plane of lowest cross-beam.
The effect of windscreen or side and rear windows can be measured too, considering the widely used glued windows.
Displacements are measured at two levels: at the cantrail and above the expectable lower plastic hinge on the side pillar. Measuring the cantrail's displacement the force magnitude and position is obtained.

The load-displacement curves are approached by twentieth-degree polynoms or spline curves. A test of duplicated front-wall unit and obtained polynome curve is shown in Fig. 9.



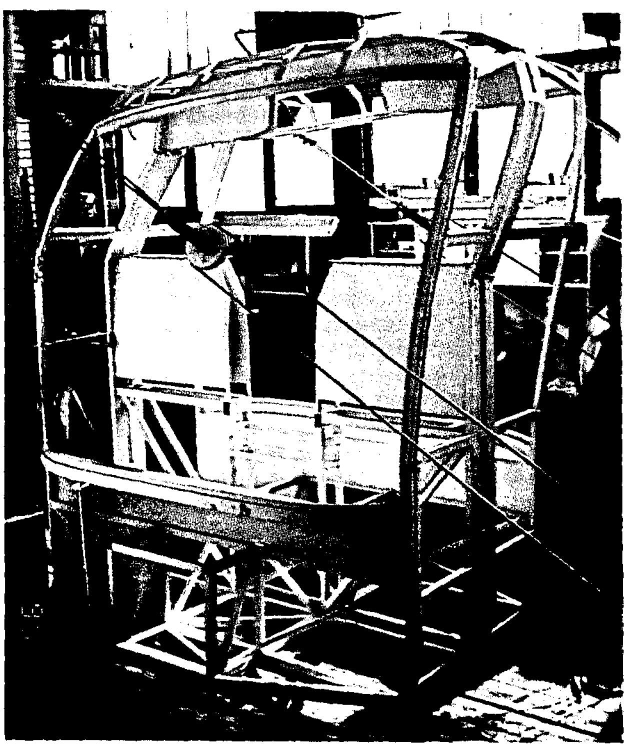
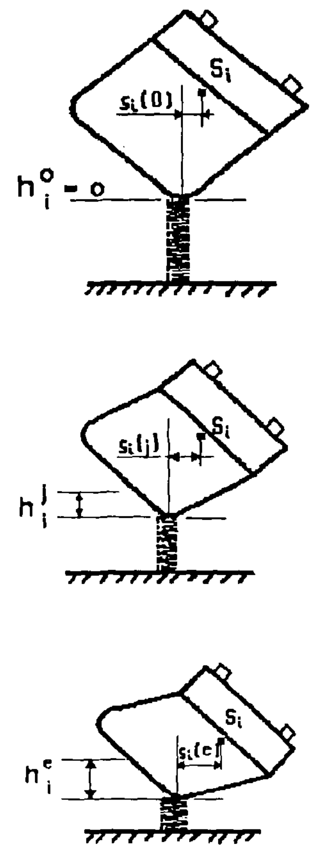


Fig. 9. Laboratory bending test for mathematical calculation of bus roof strength. Measuring the whole deformation process and the exact places of real plastic hinges the rollover simulation can be easily carried out with a simple iteration.

A 12 m long coach generally can be modeled with 7-9 pieces plane-rings linked to the chassis using the practically measured force (moment) curves of real coach rings by bending test. Having fixed the initial geometry of loading arrangement the force direction can be calculated in any internal position of deformation process by computer simulation.

Calculation Algorithm

The whole energy-absorbing process of rollover can be simulated as behavior of non-linear elastic support. Deformation displacements of 'k' pieces of cross-section frames are modeled with 'k' pieces of non-linear springs. (The deformations are marked two times, at the spring deformations and at the frame deformations in Figure 10.)



$$E_i^0 = 0$$

$$E_i^j = \int_0^{h_i^j} F_i(s_i, h_i)dh_i$$

$$E_i^e = \int_0^{h_i^e} F_i(s_i, h_i)dh_i$$

Fig. 10. Modeling of the deformation process as the behavior of non-linear elastic support.

symbols:

- i - serial number of frames $i = 1,2,...,k$;
- k - number of plane-frames;
- j - time from the beginning of simulated rollover impact [s];
  - 0 - initial time;
  - e - total time;
- h_j^i - compression of the i^{th} non-linear spring (serial number) in the j^{th} second;

E_j^i - absorbed energy in the j^{th} second in the i^{th} non-linear spring;

s_i - horizontal displacement of center of gravity of i^{th} frame.

The calculation process is next:

a) Touching the ground these coefficients are known (or were calculated previously):

v_s^0 - velocity of center of gravity of coach;

a_s^0 - acceleration of center of gravity of coach;

ω_s^0 - angle velocity to the cross axle of center of gravity of coach;

ε_s^0 - angle acceleration to the cross axle of center of gravity of coach;

$F_i(h_i)$ - force-displacement curve obtained by quasi-static bending tests;

ϑ_0 - moment of inertia to the cross axle of center of gravity of coach;

Θ_0 - torsional rigidity of coach;

M - unladen kerb mass of coach;

E - is the total energy to be absorbed by the complete structure of the vehicle.

The duration time can be divided into dt intervals (δt= 0,001 s) and the program calculates constant forces during this interval.

b) The new motion's characteristics ($h, v_s, a_s, \omega_s, \varepsilon_s, \alpha$) can be calculated from the equations of motion, where

α - angle between initial force-effect and actual force-effect.

c) Using the $F_i(h_i)$ functions the new forces may be calculated to the connected new displacements. Taking these forces constant in a given interval the determination of new motion characteristics needs the previous step from the beginning.

d) This way the maximum deformation's length of cantrail for segment by segment can be calculated according to the required energy to be absorbed, then using the correct places of plastic hinges, obtaining from the laboratory bending tests, the exact deformation shape of the cross-sections can be easily determined comparing to the residual space.

The energy to be absorbed shall be calculated by initial potential energy of rollover situation or by appendix 1 of annex 5 to the Regulation.

CONCLUSIONS

Experience with this Regulation has some uncertainties to be cleared. The reliability and reproducibility of Type Approval tests are the most important.

The fulfillment of the full-scale test and of the whole process simulation of it requires suitable strength from the bus roof, which effectively increases the bus and coach safety.

The described numerical simulation and attached bending tests consider the whole practical collapse process of coach compartment based on factory's technology. It is more effective than a sophisticated FEM calculation, which calculates mostly with theoretically approached independent plastic hinges.

This simulation program needs obtained force (moment) curves of only 3-4 pieces of coach structural sections manufactured by factory's technology and so it makes any control test easier and cheaper.

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SIMULATIONS OF BUS-SEAT IMPACT TESTS ACCORDING TO ECE REGULATIONS

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Paper Number 98-S4-P-19

ABSTRACT

This paper deals with bus passenger seat and seat anchorage strength according to the official ECE Regulation 80 and partly to the ECE R14.
The regulations are based on a standardized real accident situation. In spite of this, the requirements don't follow the new demands, e.g. the compulsory usage of seat belts.
AUTÓKUT Hungary has just started a new project to develop a new alternative method for testing bus seat and seat anchorage strength.

REGULATIONS FOR BUS SEATS

ECE Regulation 80: *Uniform provisions concerning the approval of seats of large passenger vehicles and of these vehicles with regard to the strength of the seats and their anchorage. (Date of entry into force: 1989.)*

This regulation applies to vehicles constructed for the carriage of more than sixteen passengers, with passenger seats having reference height of at least 1m intended to be installed facing forward.
The requirement: in the case of an impact with 30 [km/h] velocity, the seats shall retain the passengers in the predetermined zone. The heads of dummies shall not pass forwards more than 1.6 [m]. The braking acceleration shall be kept between 8÷12 [g]. Biomechanical acceptability criteria are also determined in accordance with human tolerance capability.
Interesting and confusing is that this approval mark can be obtained with quasi-static test too, although the correlation between the two types of tests is deeply doubtful, not mentioning the biomechanical criteria. (The static test simulate the chest and knee impact simultaneously with two load cylinders at each sitting position.)

ECE Regulation 14: *Uniform provisions concerning the approval of vehicles with regard to safety-belt anchorage. (Date of entry into force of Rev. 03. for coaches: 1992.)*

During the test of coach lapbelts the test load of 740 ± 20 [daN] shall be applied for at least 0.2 [s] duration to a traction device attached to the two lower anchorage. Additive longitudinal load of 6.6 times the weight of the complete seat shall be applied at center of gravity of the seat. (In configuration of 3-point belt the test load to be applied is 450 ± 20 [daN] for both belt sections.) The basic standard accident situation is an impact with 10 [g] deceleration. It is same as at the Regulation ECE R80.

TESTING TO ECE R80 AND ECE R14

AUTÓKUT carries out seat tests from the mid 70's, participating in different developing phases of the ECE R80. Test method's improvement has been performed gradually.
In our tests no compliance has been found in the results of static and dynamic tests.
According our previous full-scale bus impact tests the occupant protection in a 10g crash situation is acceptable and sufficient requirement. (Some studies of crashes lead more serious conclusions to demand 20g crash condition. [4])
Figure 1 shows the ECE R80 test of a Hungarian double coach seat.

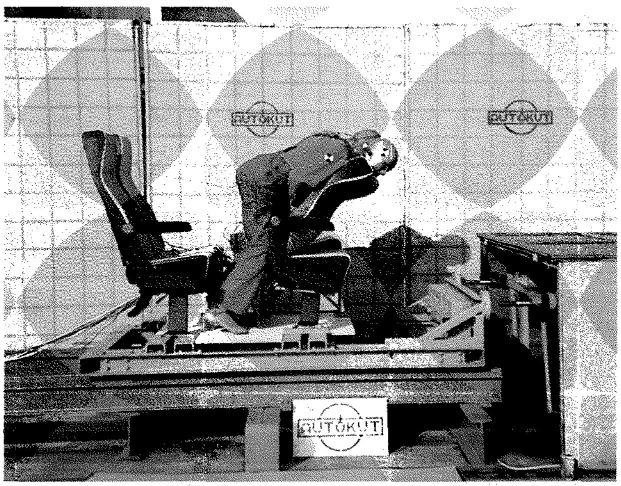

Figure 1. Seat test on a double coach seat with rail-type anchorage according to ECE Regulation 80. The seat fulfills the requirements.

At the first seats of the buses and coaches the passengers shall tighten the installed belts as prescribed in other regulations and national traffic rules. In this case the flying passenger, in the second row, impacts to the seat-back of the first row preloaded with a belted passenger. This type of seat loading is not examined by the ECE R80.

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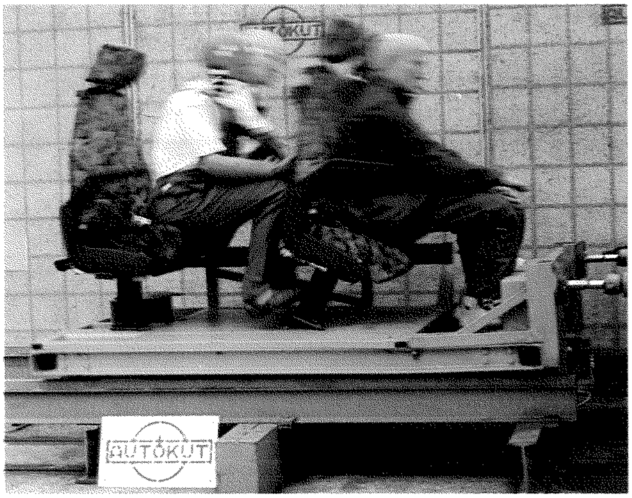


Figure 2. Crash situation of a coach front double seat with two belted dummies in the test condition of ECE R80. The seat previously passed the normal regulated test, but it doesn't withstand the increased loading and isn't able to keep the dummy in the required zone.

The mandatory usage of lapbelts claims the change of test conditions of ECE R80.
The second ECE Regulation for bus passenger seats is the ECE R14 concerning the belt and seat anchorage.
Carrying out this type of test for a few double coach seat, the result was astonishing. Although the double passenger seats previously got the type-approval related to ECE R80, some of them failed the test of Regulation 14. (Fig. 3.) The seat-leg got bigger bending moment and the absorbed energy was more in this investigation than during the ECE R80 test.

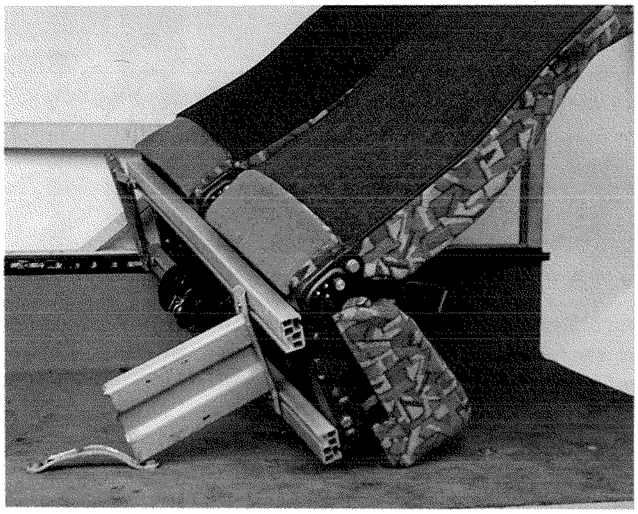


Figure 3. Double coach seat test according to ECE R14. The seat-leg couldn't withstand the loading.

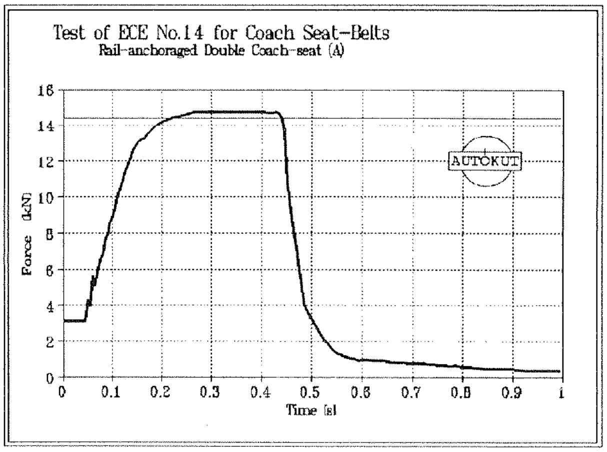


Figure 4. Force-time diagram of a successful double seat test according to ECE R14.

The conclusion is that the requirements of regulations of ECE R14 and ECE R80 are not independent, moreover the Regulation ECE R4, concerning the seat anchorage, is more rigorous.
Before carrying out the test by Regulation 80, it may be very reasonable for the coach and seat manufacturing companies to accomplish the seat belt anchorage controlling by test of ECE R14. It is faster and cheaper than the dynamic or static tests of ECE R80 and a good tool in the development process, specially for aftermarket seat manufacturers.

The critical notices according to the ECE R80 are the next:

- The Regulation allows two types of approval test, there is a dynamic one and a quasi-static one, but the results are different.
- The Regulation doesn't regard to the belted seats.
- Our previous investigations showed, that the seats having reference heights of 1÷1.3 [m], can cause fatal throat-hit which could be only controlled with added requirements for the biomechanical criteria concerning to the neck.

Some notices for ECE R14:

- The time rate of the force is not regulated. At our tests the applied forces had reached the regulated level in 0.15-0.2 [s]. Different run-up leads to different result.
- We have used preloadings of 150-200 [N] not required by the Regulation. By our explanation it is the preloading of the knee impact.

SIMPLE EXPERT SYSTEM FOR BUS SEAT IMPACT

The tests and the test equipment are expensive related to the above mentioned regulated bus seat test methods.
The goal is to develop a good tool which is easier and cheaper and examines the same accident conditions in compliance with the results.

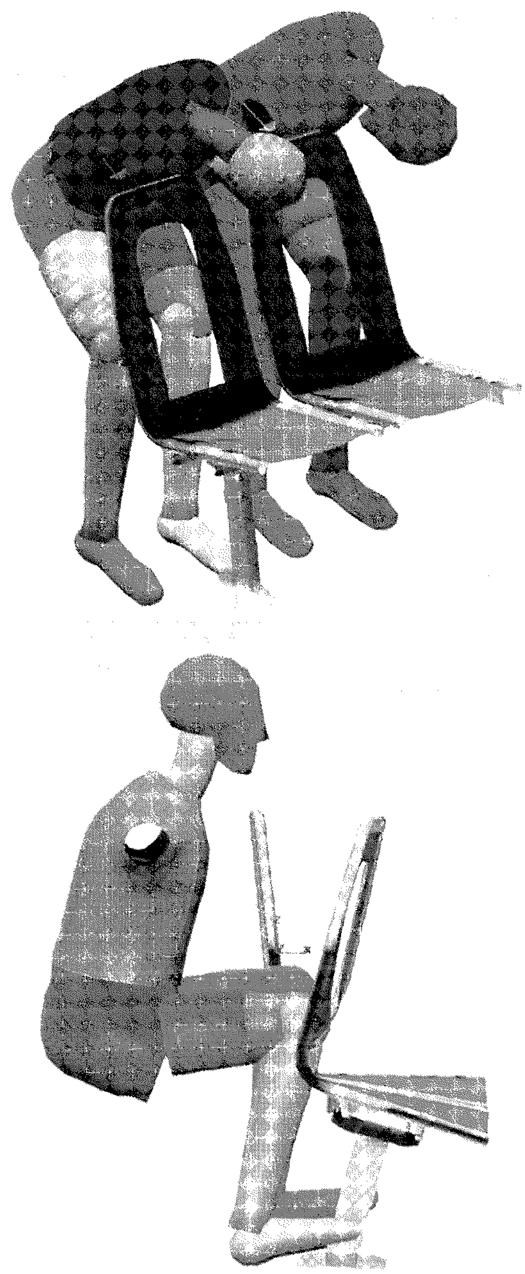


Figure 5. Complete simulation of dummy - bus seat impact by PAM-CRASH using an Ansys model of the seat. (Cooperative work with Tarok Ltd., Hungary.)

This kind of computational method is available, but it has big disadvantages: expensive and neglects the manufacturing technology.

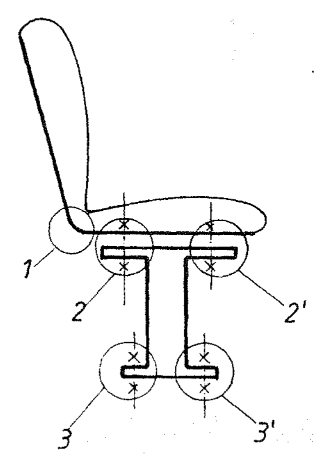
Simulation Principle

What are the main features of an acceptable inexpensive simulation method?

- It simulates the real accident situation.
- Secondly it is based on simplified laboratory tests.
- Finally it considers the manufacturing technology (e.g. welding joints)

Seat Model

All the used bus seats according to previous detailed investigations can be modeled as a unit of rigid elements and plastic hinges.



1	seat back curve
2 2'	anchorage of seatleg and seat-frame
3 3'	seatleg anchorage
4	fixing environment o coach side-wall and seat-frame

Figure 6. General layout and plastic hinges of a bus seat

To set up a good seat model there are no more necessary than the exact masses, geometry of seat parts and the characteristics of plastic hinges.

Laboratory Tests

The moment-angle functions of the plastic hinges, shown on the drawing of Figure 6, can be measured in simple laboratory conditions.
The most important thing for getting the best approach is to measure the seat parts made with real manufacturing technology, not with any other (experimental) technology.

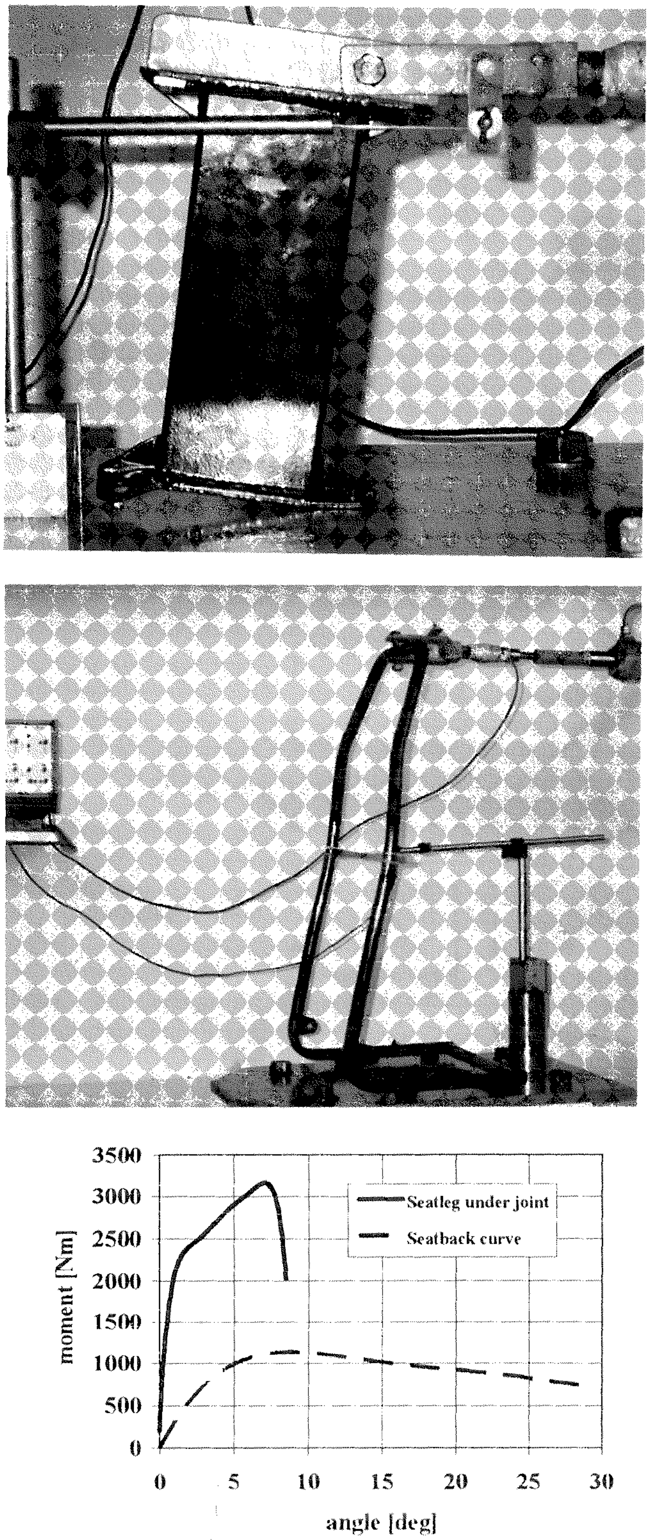


Figure 7. Laboratory bending test of a seatleg and seatback with the measured functions.

Computational Background

The results of laboratory dynamic tests can be built up to any sophisticated and expensive FEM software (Pam-Crash, Dyna,...), but the multi-body systems with suitable dummy module give easier, faster and cheaper approach. Not necessary to use the expensive M-B programs as Madymo or Adams, we have chosen the Alaska (Germany) software and just started the studying of ATB (USA) program's possibilities.

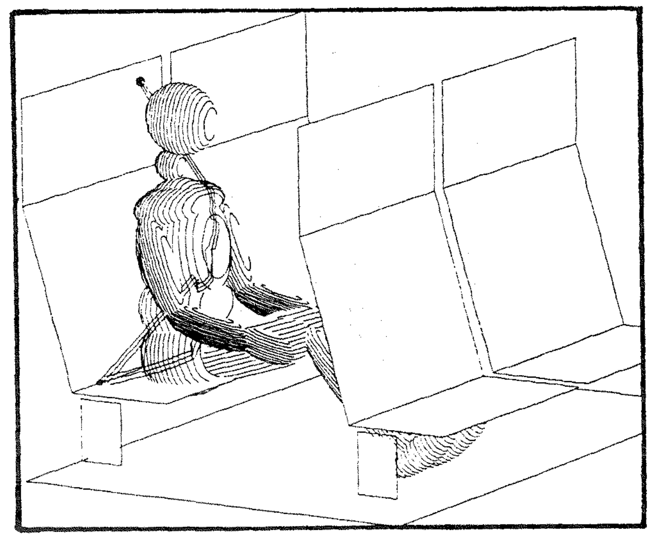


Figure 8. General arrangement for simulation of ECE R14 with multi-body software.

Using this method we can check all the parameters required for bus seats in ECE Regulations

CONCLUSIONS

The regulations related to the coach passenger seats should be integrated. It is not allowable that different test methods come to significantly different results. The compulsory usage of safety belts is reasonable and it claims changes on ECE R80. The described simulation method can be applied as alternative test method in compliance with dynamic test methods, even it gives a good tool for the designer on the design and development of strength of passenger seat-frame.

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SAFETY REAR UNDERRIDE GUARDS WITH AN OPTIONAL REVERSE IMPACT BRAKING SYSTEM

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Paper Number 98-S4-P-20

ABSTRACT

This paper describes the Safe-T-Bar and Sens-N-Stop, two products aimed at reducing personal injury and damage resulting from rear impacts.

The **Safe-T-Bar** is a rear underride protection guard. It can be fitted to all vehicle types, including straight trucks and semi-trailers, up to the maximum gross vehicle weight.

There are two versions of the guard, one incorporating rubber springs, the other friction plates. Collision damage to light vehicles occurring at average speeds is radically reduced or in some instances entirely eliminated.

Both versions of the Safe-T-Bar have been laboratory tested. The rubber spring version meets EEC Directives e11-011 and e11-013. The friction plate version fully complies with the United States Federal Motor Vehicle Safety Standards FMVSS 223 and FMVSS 224.

Sens-N-Stop is an automatic impact-sensing and brake-activating system for reversing vehicles for use in conjunction with the rubber spring version of the Safe-T-Bar. Immediately the beam comes into contact with an obstruction the vehicle brakes are applied.

INTRODUCTION

Hope Technical Developments Ltd specialise in the development and manufacture of safety equipment for the road transport industry. In addition to the Safe-T-Bar and Sens-N-Stop, our products include the widely acclaimed Hope Anti Jack-Knife Device and the Scrutineer trailer test unit.

This paper is intended for general information only and does not form part of any contract with Hope Technical Developments Ltd or their agents.

The views expressed at then end of the paper are intended as a contribution to the on-going debate surrounding rear impact guards.

SAFE-T-BAR

Development History

The rubber spring version of Safe-T-Bar was first introduced in the UK and Europe in 1981. It gained EEC Type Approval in 1984, thus making it acceptable for use in all EEC Member States.

Major UK fleet operators, including the Royal Mail and the Ministry of Defence, are currently using the guard.

The design of this version of the guard has remained generally the same over the years, although modifications have been made and continue to be made in line with company product improvement policy.

Recently a new version of the Safe-T-Bar was introduced specifically to meet the needs of the USA market. This design uses friction plates to absorb energy. It has recently been tested in the United States at MGA Research Corporation according to the Laboratory Test Procedure for Federal Motor Vehicle Safety Standards 223 and 224. It exceeds the requirements of these Standards.

General Design Characteristics – Rubber Spring Version

Figure 1 shows the general arrangement of the rubber spring version of the Safe-T-Bar.

The beam is welded or bolted to the two arms. Within each arm there are two rubber springs and a simple cam mechanism. The arms are attached, via hinge pins, to mounting channels. The mounting channels are welded or bolted, via the use of brackets, to the vehicle or trailer chassis, or to a suitable mounting provided by the vehicle or trailer manufacturer. Beams and arms of various lengths are used to accommodate different vehicle types.

The larger of the springs provides progressive, low-speed impact absorption as illustrated in Figure 2. A very small force, depending on the beam and arm lengths but generally less than 0.5 kgf, is all that is required to

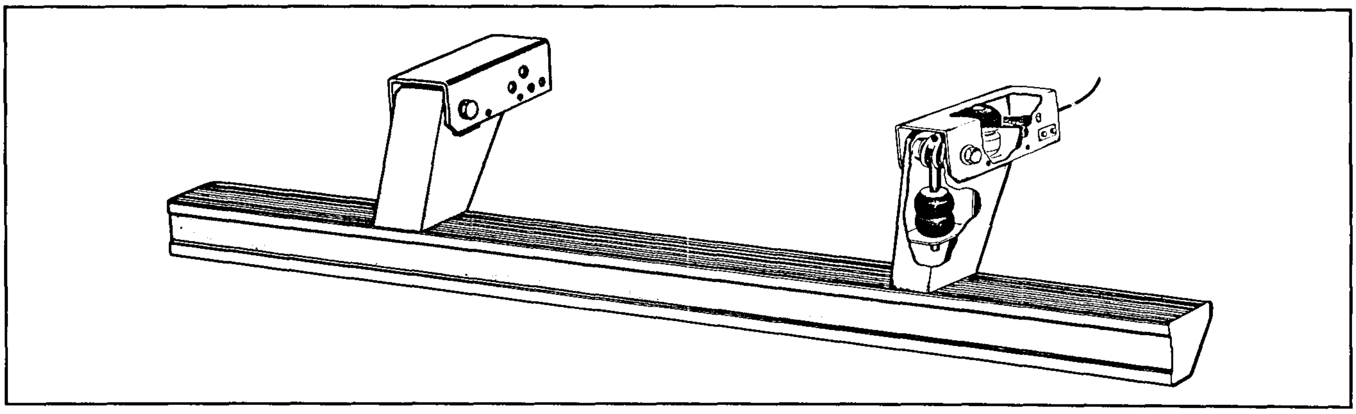


Figure 1: General arrangement – rubber spring version.

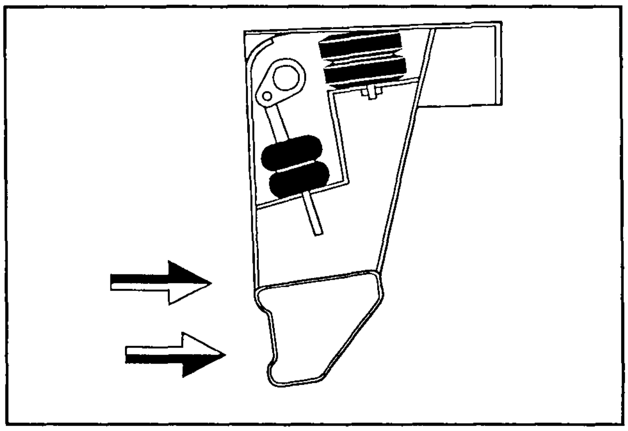


Figure 2: Low speed impact absorption.

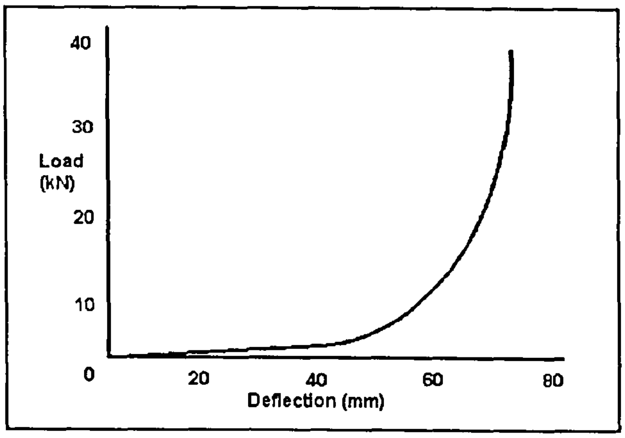


Figure 3: Spring load/deflection.

cause initial movement of the beam. Full radial movement of the arm, and full compression of the rubber spring, is reached after a vehicle movement of approximately 3" (75mm). The total force required to cause this movement is approximately 30kN (3 tonne). Figure 3 shows the load deflection curve for the spring.

When the vehicle is moving forward, the hinge action of the arms enable the beam to automatically lift, as illustrated in Figure 4, whenever an obstacle or raised obstruction such as a ramp is encountered. The lead angle on the beam aids this action. When the obstacle has been cleared, the beam drops down into its normal operating position.

At the full extent of the upward arm movement, the smaller rubber spring acts as a cushion and, when compressed, it provides an impetus to reset the beam.

Alternatively, the beam can be locked in the raised position, a feature which is particularly useful if access to ancillary equipment fitted at the rear of the vehicle is required, or if the vehicle is being used off the road in rough terrain, such as on construction sites.

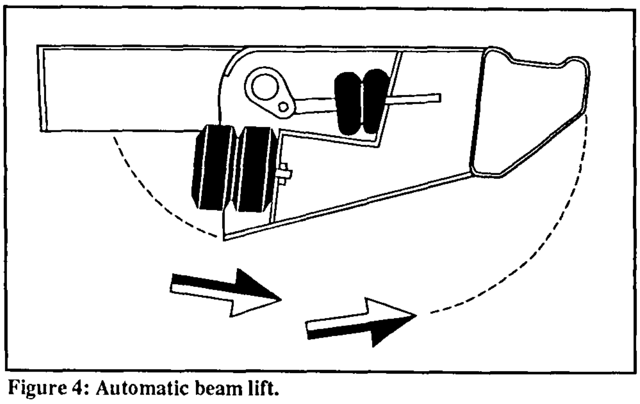


Figure 4: Automatic beam lift.

The Safe-T-Bar is fitted with a full-length, red, reflective strip and plastic endcaps. The overall design is 'non-aggressive' and generally enhances the appearance of a vehicle. It is quiet in operation and the life expectancy of the rubber springs exceed the expected life of the vehicle.

General Design Characteristics – Friction plate version

Figure 5 shows the general arrangement of the friction plate version of the Safe-T-Bar.

The assembly consists of the beam and two sub-assemblies, one right-hand and one left-hand. The sub-assemblies incorporate the power absorption feature and the means of attaching the complete assembly to the vehicle.

Each sub-assembly includes two quadrant plates, and a mounting bracket. The two quadrant plates, separated by three steel spacers, are bolted in a fixed position to the chassis rails or to a suitable location provided by the vehicle or trailer manufacturer. The mounting bracket is sandwiched between the two quadrant plates. At the fulcrum, the surfaces of the quadrant plates and the mounting brackets are separated by two nylon spacers. At the outer radius, the surfaces are separated by two friction pads. A second set of friction pads is sandwiched between the outer surface of the quadrant plates and two clamping plates. When the beam is under load, the mounting bracket swivels downward in relation to the quadrant plates.

The beam is clamped to the mounting bracket by means of a clamp plate inside the beam. To complete the assembly, the Safe-T-Bar is fitted with plastic end caps and a full-length, red, reflective strip.

On impact, energy is initially absorbed by the friction pads. Further loading results in the quadrant arms swinging downwards until they 'bottom', this occurring after a horizontal movement of 5 inches. Within this movement, when the pressure on the friction pads is correctly set using the torque values provided by the manufacturer, the guard will withstand a force in excess of 40000 lbs and absorb 13000 Joules of energy.

If an impact on the guard is off-centre, the swing of the quadrant plates will differ, thus producing a 'snowplough' effect whereby the impacting vehicle is deflected, thus reducing the possibility of a more serious underride.

The expected life of the friction pads exceeds the expected life of the vehicle.

Application

Both types of Safe-T-Bar can be fitted to all vehicle types, including rigid vehicles (trucks) and semi-trailers, up to 38 tonnes gross vehicle weight, with a channel, 'I' beam or box chassis. Because of the hinge action of the

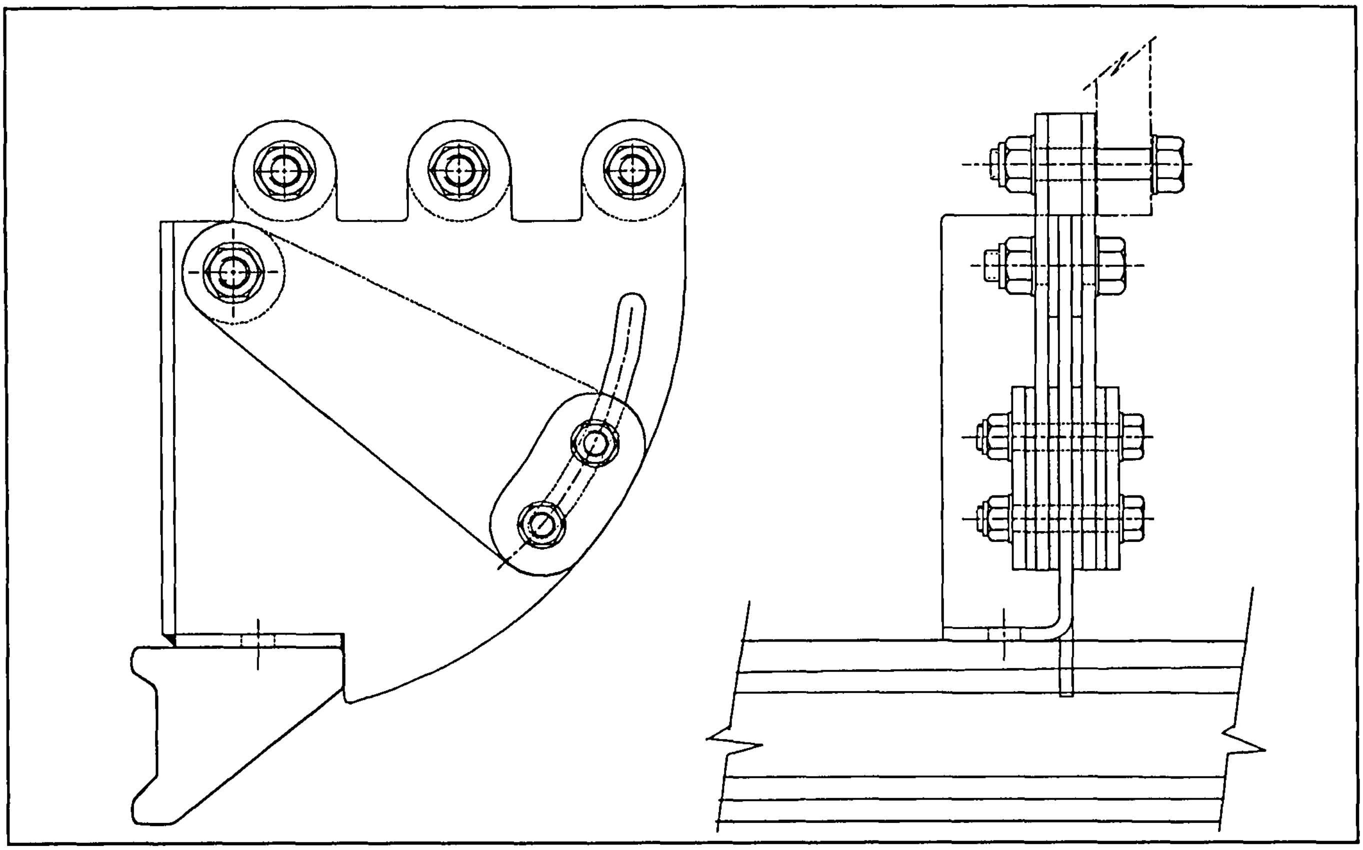


Figure 5: General arrangement – friction plate version.

Safe-T-Bars, the chassis members must be parallel to each other and in horizontal alignment.

Fitting options include incorporation in the initial vehicle design and manufacturing cycle, or retrofitting. Guards for retrofitting are supplied in kit form. To retrofit a rubber spring version of the Safe-T-Bar requires basic fitting and welding skills, basic fitting skills only are required to fit the friction plate version. To fit either type takes 1 to 2 hours.

Weight

The weights of Safe-T-Bar assemblies vary according to the length of the beam or either the size of the arms or the quadrant plates and mounting bracket, depending on the version. The maximum and minimum weights are given in the table below.

Table 1.
Safe-T-Bar Weight

Beam length (max/min)	Assembly weight (max/min)	
	Rubber spring version	Friction plate version
(81.5" – 94.5") (2070 – 2400 mm	99 – 112 lb (44.9 - 51.0 kg)	100 – 120lb (45.4 – 54.5lb)

Beam Design

A cross-sectional view of the beam is shown in Figure 6.

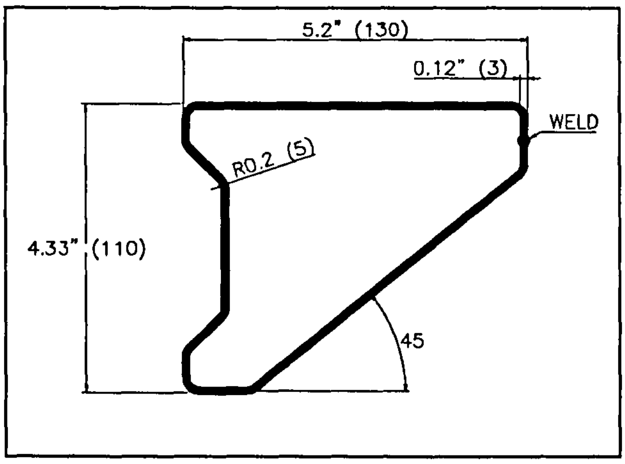


Figure 6: Beam cross-section

FMVSS 223 states that the cross-sectional height of an underride beam must not be less than 100 mm. The Safe-T-Bar beam exceeds this dimension by 10mm.

The beam is of box construction with a single, induction-welded butt joint. The top face of the beam can be used as a step. A 45° leading edge angle reduces airflow turbulence. A rear-facing recess strengthens the beam and also provides a convenient mounting for the full-length reflective strip and the product conformance label.

Test Overview

Both types of Safe-T-Bar have been laboratory tested and they comply with the requirements of FMVSS 223 and FMVSS 224. An overview of the results for the friction plate version is given below.

A Safe-T-Bar suitable for fitting to a vehicle of 20 tonne gross vehicle weight and above was subjected to the guard strength and energy absorption tests as defined in FMVSS 223. The guard was mounted on a rigid test fixture.

The test requires forces to be progressively applied as follows: 5000N at test position P1, 500N at test position P2 and 100000N at test position P3. For reference, the test positions are shown in Figure 7.

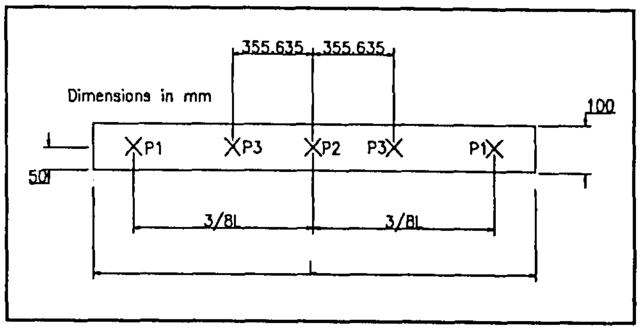


Figure 7: Test positions.

Force/displacement graphs were plotted for each test. Energy absorption rates were then calculated by determining the area below the force vs displacement curves using the Trapezoid Rule.

An example of a graph produced for a test carried out at P3 is shown in Figure 8.

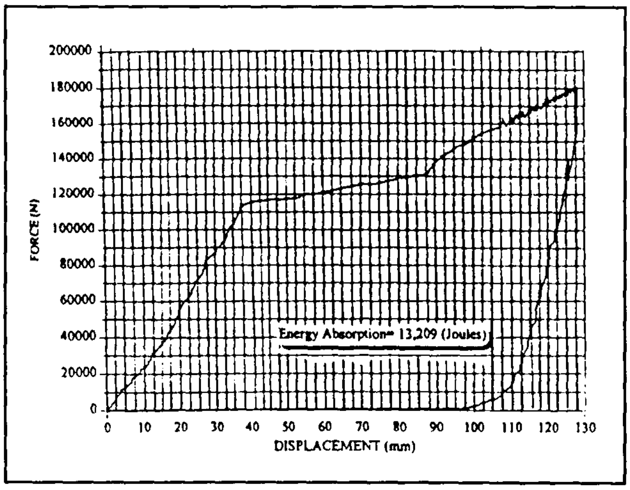


Figure 8. Example force/displacement graph.

A summary of the resulting data from tests carried out at P1, P2 and P3 is given in Tables 2 and 3.

Table 2.
Guard Strength Tests Results

Test No.	Test Location	Maximum Load	Maximum Displacement
1	P1	12,274 lbs (55 kN)	2.03 ins (52 mm)
2	P2	14,774 lbs (66 kN)	0.74 ins (19 mm)
3	P3	40,628 lbs (181 kN)	5.04 ins (128 mm)

Table 3.
Energy Absorption Test Results

Test No.	Test Position	Energy Absorption
1	P1	50,688 in-lbs (5,727 Joules)
2	P2	45,100 in-lbs (5,096 Joules)
3	P3	116,893 in-lbs (13,209 Joules)

Positioning

FMVSS requires the beam to be mounted as close to the rear of the vehicle as is practical. It must not be inboard of the vehicle rear extremity by a distance in excess of 305 mm. It must extend outward to within 100mm of the vehicle sides and the lower edge of the beam must not be more than 560mm from ground level.

To ensure each Safe-T-Bar fitted meets these requirements, various sized beams, arms or quadrant plates (depending on the version) and mounting brackets are available. To ensure the correct fittings are shipped, customers are asked to complete the Vehicle Specification form shown in Figure 9.

Production Conformance

To ensure the quality of its products, Hope Technical Developments Ltd has adopted a Quality Management System that conforms to ISO 9002:1994.

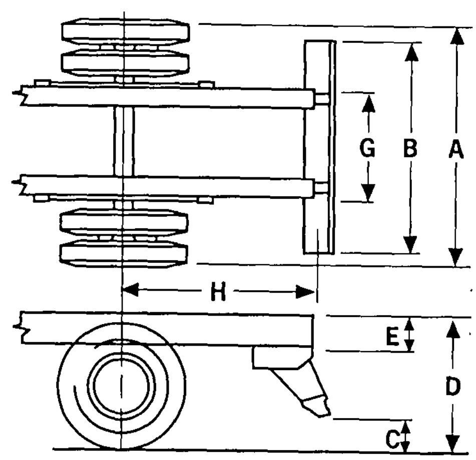
Options:

Audible Impact Warning ☐ **Sens-n-Stop** ☐

Vehicle make ______ GVW ______ Model No. ______

Trailer make ______ GVW ______ Model No. ______

Code	Description	Dimension
A	Max. width over tyres (widest axle)	
B	Min. beam width 'A' minus 200 m/m	
C	Ground clearance	
D	Unladen height on to top of chassis	
E	Depth of chassis	
F	Width of chassis flange	
G	Chassis width to outside	
H	Centre of rear axle to end of chassis	



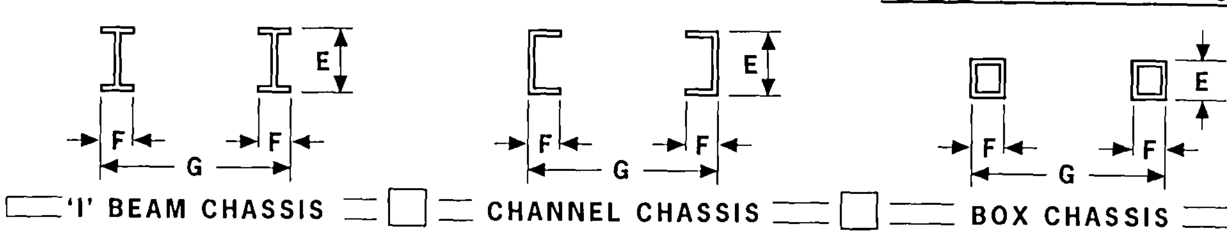


Figure 9: Positioning data.

SENS-N-STOP

Development History

Sens-N-Stop is an automatic impact sensing and brake activating system for reversing vehicles for use in conjunction with the Safe-T-Bar. It is available as an optional extra.

Sens-N-Stop was developed to combat the problem of personal injury and damage to vehicles and property caused by vehicles reversing in areas where the driver's vision is restricted. A classic example of this type of situation is the reversing of large tankers on gas station forecourts.

The system was introduced in 1988 and, like the Safe-T-Bar, is currently being used by many major UK fleet operators.

UK Reversing Accident Statistics

According to an article recently published in a UK trade journal, prior to the introduction of alarms nearly 300 persons were killed or seriously injured by reversing vehicles per week. Since their introduction there has been a 41% reduction in fatalities. However, accidents involving reversing vehicles continues to be a major safety problem as is evident by the following statistics which were also included in the article:

- 17% of transport accidents investigated by the in 1995 involved reversing vehicles (UK Health and Safety Executive)
- Reversing of commercial vehicles accounts for one UK insurance claim in every six (Association of British Insurers)
- Reversing accidents comprise the largest category of all (non-car) claims (Municipal Mutual Insurance Ltd)

Figures published by the UK government confirm the seriousness of the problem; there were 4533 reversing accidents in the UK in 1995. (1).

Recent reports in the UK trade press have stated that nearly 25% of deaths involving vehicles at work are caused by reversing, with small trucks posing the greater hazard because they are more of them, they often reverse in crowded public locations, and are legally driven by unqualified and inexperienced people.

The above figures derive from a UK vehicle population of approximately 10 million. In countries where the vehicle population exceeds the UK vehicle population, as in the USA for example, the corresponding figures will almost certainly be proportionally higher. But even these figures do not portray the full extent of the problem which can only be placed in context if the relative short time spent in reversing is taken into consideration.

If a driver is obliged to reverse without having at his disposal some form of reverse warning system then he may do so negligently. Not only may the driver and the vehicle operator be held to be negligent, they may also be liable to criminal prosecution. A recent prosecution in a UK court resulted in a building company being fined a six-figure sum when an employee was crushed against a wall by a vehicle not fitted with a reverse-in-safety system.

Reversing Warning Devices

The most widely used warning device is the audible siren, but the effectiveness of this type of device depends on people other than the vehicle driver taking evasive action. The siren may not be audible to people with a hearing impairment whilst others, such as elderly, blind or physically handicapped people, may not be capable of moving out of the way. Audio devices are not effective with regard to inert objects. There can also be problems with environmental noise pollution if vehicles are constantly in use close to dwellings, particularly at night.

Other devices include the use of electronic voice warnings, microwave sensors, radar, and camera systems, some of which depend on visibility and may also require in-cab monitoring by the driver.

By comparison, the Sens-N-Stop system is a low-cost, all-weather, light-independent system that is silent in operation and requires no additional driver involvement other than that generally associated with vehicle reversing.

General Arrangement

Figure 10 illustrates the general arrangement of the Sens-N-Stop system. Note that if Sens-N-Stop is fitted, it is essential that the Safe-T-Bar is fitted as close to the vehicle extremity as possible. The sequence of operation is as follows:

1. Reverse gear is selected - ***the system is functional only when reverse gear has been selected.***
2. As the vehicle reverses, any slight beam movement (12-15 mm) is detected by the sender unit which is mounted within one of the Safe-T-Bar arms. A force of just 0.25 kgf is sufficient to cause this movement.

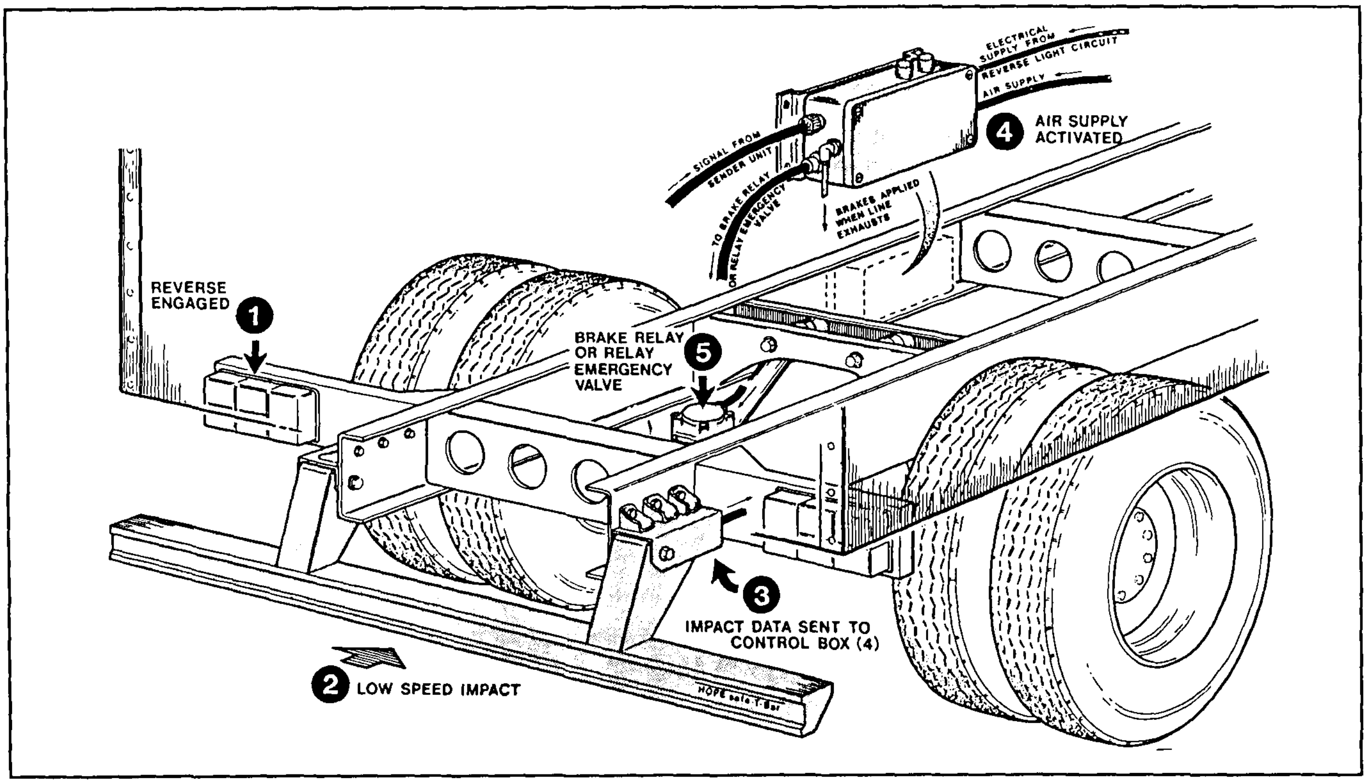


Figure 10: Sens-N-Stop general arrangement.

3. The sender unit sends a signal, by interrupting an electrical circuit, to a control box mounted on the vehicle chassis.
4. A pressure sensitive switch (signal receiver) activates the diaphragm solenoid valve.
5. Air is released from the brake relay emergency valve (trailers) or hand brake relay valve (rigid vehicles) and the brakes are automatically applied.

The brake line installation method is UK Ministry of Transport approved. Basic electrical and mechanical fitting skills only are required to fit the system and the task takes approximately one hour.

CONCLUSION

Both Safe-T-Bar and Sens-N-Stop have been widely accepted in Europe as being worthy contributions to the on-going problem of road and vehicle operating safety, the former with regard to vehicle underride and the latter with regard to reducing personal injury and damage caused to both vehicles and property caused by low-speed reversing impacts. However, the effectiveness of these and similar devices depends on other factors other than the inherent design characteristics. Therefore, I make the following observations:

- All fitted underride guards should be subjected to periodic inspection that ensures they comply ***in all respects*** to current legislation.
- Underride guards should not be permitted to be fitted unless they have official type approval and are labelled accordingly. This would eliminate the possibility of a sub-standard design being fitted particularly when changes are made to the original bodywork of the vehicle.
- Since fleet operators are ever conscious of payloads, consideration should be given to excluding the weight of underride guards, and possibly other safety equipment, from the gross vehicle weight. The initial excess weight would be rapidly balanced out by the weight of the fuel consumed early in any journey.
- Rigid vehicles should not be excluded from having underride guards fitted. Some vehicle designs present underride possibilities equally as dangerous as those associated with trailers.
- The fitting of underride guards to trucks is as important as fitting seat belts and air bags, or the inclusion of crumple zones and impact guards, to private motor cars. It needs to be given a much higher priority in vehicle design.

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SENSITIVITY OF AIR-BRAKED VEHICLES TO MAINTENANCE UNDERSCORES THE NEED FOR RELIABLE LOW-COST CAB-DISPLAY BRAKE FAULT INDICATOR LAMP

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ABSTRACT

A collection of information on the regulation, design, performance, operation and maintenance of air-braked vehicles was reviewed. These data indicate that performance decrements arising from the sensitivity of air-braked vehicles to maintenance has been a safety issue for a considerable period of time. The predominant reason why air-braked vehicles are placed out-of-service at roadside inspections continues to be, predictably, due to maintenance-related braking problems. The ability of drivers to safely maintain control of air-braked vehicles can seriously be restricted when maintenance-related braking problems reduce the braking performance or the limited reserve braking capacity of service (foundation) brakes. Primary safeguards that mainly rely on the vigilance and knowledge of drivers to know whether brake repairs are warranted when daily pre-trip inspections are conducted may be inadequate. There are currently no requirements for a cab-display device to readily alert drivers when the stopping capability of air-braked vehicles has deteriorated to an unsafe level. Comments about the need, feasibility and merits of a low-cost cab-display brake fault indicator lamp for air-braked vehicles are presented.

INTRODUCTION

The sensitivity of air-braked vehicles to maintenance cannot be underscored enough. Regulations require that service (foundation) brakes are checked as part of a duty to perform daily pre-trip inspections on air-braked vehicles. Despite this requirement, maintenance-related braking problems have historically, and moreover, continue to be the number one reason why air-braked vehicles are placed out-of-service by enforcement officials at roadside inspections. Brake-related deficiencies include oil-soaked lining, cracked drums, applied pushrod stroke (with reservoir pressure @ 90-100psi) beyond re-adjustment limits, and excessive component wear (e.g. lining thickness). Left undetected, maintenance-related braking problems can significantly limit the ability of drivers to control the speed or directional stability of air-braked vehicles. This often occurs when air-braked vehicles are descending steep grades or after a hard brake application is made while travelling on wet or slippery road surface. This raises the question - why are so many air-braked vehicles placed out-of-service? Do drivers of air-braked vehicles just simply ignore or inadvertently overlook maintenance-related braking problems when daily pre-trip inspections are performed? Whatever the reason, for the safety of all road users, can reasonable measures be taken to ensure that drivers become acutely aware about brake-related deficiencies *before* air-braked vehicles are driven?

Societal Cost of Surface Transportation

Transportation of goods has been regarded as vital to the economy and indispensable to society. Despite obvious benefits from surface transportation, there are also costs. A review of the scope and conclusions of major studies to estimate the social cost of motor vehicle use in the United States found little agreement in the distribution and size of transportation costs or whether the use motor vehicles was under-priced. Heavy trucks contribute to the transportation of retail and commercial products. In 1993, for-hire and private heavy trucks delivered 52 percent of U.S. freight shipments. A rise in the volume of goods transported by heavy trucks generally corresponds to an increase in the number of air-braked vehicles that share space on highways with other road users. Between 1990 and 1995, the exposure of single unit and combination heavy trucks (by vehicle miles) surpassed that of passenger cars, taxis, vans, pickup trucks and sport-utility vehicles (21% v. 12%). During that time, there was a modest increase in the number of heavy trucks involved in fatal (mean = 4,496) and injury crashes (mean = 53,600).

According to responses in 1988 to a 19 item questionnaire, Rothe (1991) reported that 72 percent of 145 tractor-trailer truck drivers thought that motorists believed heavy trucks were a threat to passenger vehicles. A poll conducted in Canada in 1996 found that nearly one-half of 1516 respondents (49%) perceived that roads and highways were less safe today than in the past. More than three-quarters of the same respondents (78%) would prefer that government adopt regulations rather than make it voluntary for the trucking industry to improve maintenance standards and practices. Similar sentiments were expressed by 79 percent of 4,000 respondents involved in a 1995 national survey in the United States who characterized government's involvement in regulating the safety of heavy trucks as very important.

Heavy Truck Brake Systems

Air-braked vehicles are equipped with a supply system and control system that generate and deliver pressurized air to activate a series of pneumatic valves that control pressure to the service (foundation) brakes. Three different approaches are generally taken to apply service (foundation) brakes on air-braked vehicles - cam-actuated, wedge-type or disc. The S-shaped cam and wedge serve the same purpose to extend the lining to the inner surface of the brake drum. This differs from the disc brake which uses the force applied by brake pads on each side of a rotating disc to slow the speed of a revolving wheel. Although (as reported by Gohring and von Glasner, 1990) discs brakes exhibit significant advantages to drum brakes, the majority of air-braked vehicles are reportedly (> 90%) equipped with cam-actuated brakes.

Brake Standards

FEDERAL SAFETY STANDARDS have been developed by government to establish mandatory performance and equipment requirements for the manufacture of motor vehicles. Original Equipment Manufacturers (OEM) consider and comply with safety standards during the design and production of new vehicles. This includes brake standards that have been developed and administered by regulators to ensure that air-braked vehicles can stop safely under normal and emergency conditions. The Federal Motor Vehicle Safety Standard 121 (CMVSS in Canada) applies to the manufacture of most heavy trucks, truck-tractors, trailers and buses equipped with air brake systems. The standard contains requirements for equipment and minimum brake retardation forces generated by each brake assembly from dynamometer tests. As a rule, OEM's ensure that newly-manufactured air-braked vehicles will not only meet, but more than exceed minimum braking performance requirements.

The braking performance of in-use vehicles that operate within Canada are regulated by each province. This differs from air-braked vehicles involved in interstate commerce in the U.S. that are regulated by the Federal Motor Carrier Safety Regulations (FMCSR). The braking performance and stopping distance test requirements from 32 km/h (20 mph) for in-use vehicles that operate in British Columbia are similar to those contained in Part 393.52 of the FMCSR (Table 1).

Table 1

Braking Performance Requirements from 32 km/h (20 mph) for In-Use Air-Braked Vehicles (FMCSR)

Type of Vehicle	Minimum Brake Force (% of GVW)	Minimum Dec. Rate (m/sec^2)	Maximum Stop Distance m (feet)
All single unit vehicles over 4,545 kg (except tractors) and combination of 2 vehicles in driveaway or towaway operation	43.5	4.26	10.7 (35')
All other vehicles and combination of vehicles	43.5	4.26	12.2m (40')

Stopping distance requirements from 97 km/h (60 mph) were re-instated by the U.S. National Highway Traffic Safety Administration (NHTSA) on 10 March 1995. The requirements became effective in the U.S. on 1 March 1997 for truck-tractors and on 1 March 1998 for other single-unit vehicles. A comparison of stopping distance requirements indicate that even with well-maintained service (foundation) brakes that are burnished and fully adjusted, air-braked vehicles require considerably more distance to stop than hydraulically-braked vehicles. Stopping distance requirements for truck-tractors are met while coupled to an unbraked flatbed (control) trailer. The difference between the stopping distance of hydraulically-braked vehicles compared to air-braked vehicles is further increased as the need for brake maintenance arises (Table 2). This was highlighted by Heusser (1991) who reported that calculated values of deceleration rates of air-braked vehicles could significantly lower (~50%) as a function of brake adjustment.

Table 2

Stopping Distance Requirements from 97 km/h (60 mph) for Air-Braked Vehicles Compared to Hydraulically-Braked Vehicles (FMVSS)

Type of Vehicle	Type of Brake System (FMVSS)	Service (Foundation) Brakes	
		Empty	Loaded
Buses	Air (121)	85m (280')	85m (280')
Trucks	Air (121)	102m (335')	94m (310')
Tractors	Air (121)	102m (335')	108m (355')
Cars	Hydraulic (135)*	70m (230')	70m (230')

VOLUNTARY STANDARDS associated with the performance and maintenance of air-braked vehicles have been developed by industry stakeholders. The Society of Automotive Engineers (SAE), The Maintenance Council (TMC), and the Truck Trailer Manufacturers Association (TTMA) have established standards and recommended practices with respect to the design, specifications, installation, maintenance, and testing of air-braked vehicles and related components (Table 3).

Table 3

Industry Standards / Recommended Practices for the Performance and Maintenance of Air-Braked Vehicles

Organization	Contribution
SAE	- Standards, Recommended Practices and Information Reports
TMC	- Recommended Maintenance Practices
	- Recommended Engineering Practices
TTMA	- Recommended Practices, Technical Bulletins

Brake Performance

Several studies have been conducted to examine the limitations that affect the performance capabilities of air-braked vehicles. Radlinski et al (1982) concluded that a substantial improvement in the braking performance of air-braked vehicles could be achieved if the adjustment of service (foundation) brakes were better maintained. Hargadine and Klein (1983) found that the braking performance of tractor-trailer configurations had deteriorated between 1974 and 1983, and that brake maintenance was still a problem with air-braked vehicles. Radlinski (1987) reported that there was a large gap between the performance of passenger cars and heavy trucks. Flick (1988) found from full scale tests, dynamometer testing, and computer simulation that the stopping distance of an air-braked (5-axle) vehicle could increase by about 50 percent when the service (foundation) brakes were at re-adjustment limits and operating at high temperatures (600° F). A heavy truck safety plan prepared by NHTSA (1991) indicated that research was being pursued to improve the stopping distance and controllability of heavy trucks. Heusser (1991) indicated that a predictive relationship exists between the extension of the applied pushrod stroke of brake chambers (adjustment) and corresponding reduction in the deceleration rate of air-braked vehicles.

Brake Design

Trends in brake design for air-braked vehicles have regularly been reported. Long (1959) reported that the re-design of the S-Cam brake was expected to improve air actuation and reduce friction of cam followers. Long felt that the use of water to cool service (foundation) brakes and a device that could prevent wheels from locking would be obvious advantages in the controllability and safety of commercial vehicles. Koenig and Kreider (1976) postulated that there would be three significant technological changes to air brake system components during the 1980's - (a) new compressor design to provide higher outputs with improved efficiency, (b) new parking brake to provide comparable performance to spring brakes but with less complexity and improved reliability, and (c) improved braking performance of trucks, truck-tractors and trailers with the adaptation of air disc brakes. McCallum and Tolan (1983) concluded that the S-cam brake still had a lot to offer because it is simple and can be made robust and reliable at a low cost. Oppenheimer (1990) reported that equipping air-braked vehicles with electro-pneumatic braking systems may simplify installation of air brake systems, reduce brake response times, and provide shorter stopping distances. Marwitz et al (1995) predicted that the performance of air-braked vehicles could be further improved with (a) disc brakes

* Stopping tests from speed of 100 km/h

on all wheels, and (b) the use of electro-pneumatic brake systems. More recently, it was suggested that, however innovative, intelligent transportation system (ITS) technologies should only be pursued after quality and reliability issues have been resolved.

BRAKE DESIGN ISSUES have developed and challenged engineers because of vehicle modification changes that have been made to improve the productivity of air-braked vehicles. This included efforts that were required to maintain traditional levels of braking performance with a downsized 15 X 5/8-inch cam-actuated brake (compared to the standard 16.5 X 7-inch brake) to accommodate lowered frame heights and low profile tires. Other vehicle modifications include, but were not limited, to (a) improved vehicle aerodynamics, (b) lower rolling resistance tires, and (c) fuel efficient diesel engines with less natural retardation. Cost savings expected from modifications that have been made to increase the freight-carrying capacity of Class 8 air-braked vehicles may (in some cases) have been offset by additional costs to maintain service (foundation) brakes. Questions have been raised about whether vehicle modifications have reduced the durability and increased the maintainability of service (foundation) brakes on air-braked vehicles.

Human Factor Issues

Driver error is often regarded as the primary contributing factor to crashes. Evans (1991) reported that road-user characteristics have been identified in multi-disciplinary post-crash investigations as factors in about 95 percent of crashes. Others, however, consider the emphasis placed on driver error as a factor in crashes as a gross over-simplification of the traffic safety problem. Woodson (1998) indicated that operator mistakes (regardless of application) may be encouraged as a function of design rather than merely an act due to carelessness, ignorance or lack of knowledge. Woodson regards human factors engineering as how compatible a product design is with a human's physical, mental and sensory-motor characteristics, and typical anticipatory and behavioural response expectations.

Wierwille and Peacock (1988) emphasized that no other system is more dependent on its operator than the automobile. This certainly applies to the standard of reasonable care expected of drivers that are not only required to safely operate air-braked vehicles, but also presumed to have the ability to make subjective assessments about whether maintenance-related braking problems exist, then, determine whether repairs are warranted before the vehicle is driven. Unlike drivers of hydraulically-braked vehicles that can become aware of when the "reserve" stroke of actuators (wheel cylinders) has decreased as a function of pedal height, drivers of air-braked vehicles cannot definitively determine whether the service (foundation) brakes are out-of-adjustment by applying the brake pedal. The inability of drivers to determine the eventual out-of-adjustment condition that will develop on air-braked vehicles by depressing the foot-operated brake pedal (more so with those equipped with manual slack adjusters or neglected and inoperative automatic brake adjusters) was explained by Williams and Knipling (1991).

The foot controlled master cylinder of hydraulically-braked vehicles has a fixed displacement. This differs from the foot-operated brake (treadle) valve that simply serves as a metering valve. Compared to a hydraulic brake system, the fixed pedal height of an air-braked vehicle does not change with the amount of pressurized air that is metered through the treadle valve. While the corresponding travel of the foot-operated brake pedal is greater than the treadle valve plunger travel, there is very little change in the movement of the pedal to alert drivers when making a light brake application on an air-braked vehicle if the service (foundation) brakes have become out-of-adjustment or whether another maintenance-related braking condition, that should be addressed without delay, has developed. Since most brake applications that are made by drivers to slow or stop air-braked vehicles (even those heavily laden) are generally light, it is conceivable that a driver of an air-braked vehicle may not become aware when (and to what degree) that a maintenance-related braking problem has reduced his ability to maintain control of the vehicle should an unexpected situation arise that required him to stop in a short distance or have to completely rely on the service (foundation) brakes to safely descend a steep grade.

Thoms (1983) reported that drivers make use of visual information and experience to estimate how much pressure should be applied to the brake pedal to achieve a pre-determined deceleration. The plunger travel of the treadle valve is diminutive when the foot-operated brake pedal of an air-braked vehicle is applied. Figure 1 illustrates the non-linear displacement of the treadle valve plunger travel as application pressure rises (E-6 Bendix).

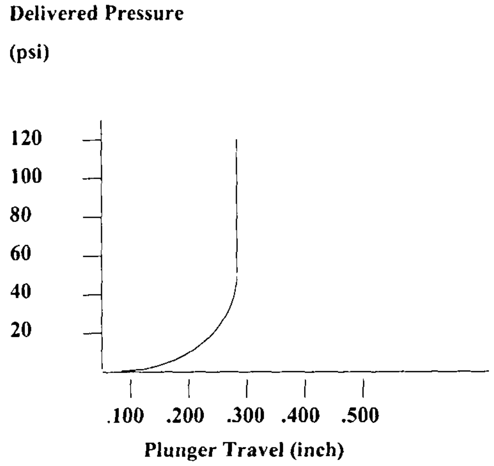

Figure 1 - Treadle Valve Plunger Travel vs. Delivered Pressure (psi)

Brake Maintenance

The braking performance of air-braked vehicles is very sensitive and dependent on brake maintenance. Moore (1954) felt that the wide spread between passenger cars and loaded commercial vehicles from the same speed could be narrowed considerably with adequate maintenance, and by the proper selection of engineered components on air-braked vehicles. Tauss (1958) surmised that the brake maintenance in some major fleets was a deplorable situation. Tauss further indicated that newspapers in 1957 were raising the issue of truck safety to the attention of motorists with headlines that read - "Defective Brakes and Deadly Trucks" (Philadelphia Inquirer). Based on a synthesis of information on the braking performance of air-braked vehicles, Radlinski (1987) reported that (a) U.S. air-braked vehicles did not perform as well as cars, (b) performance of air-braked vehicles could degrade significantly from the design-intent level if proper maintenance was not performed, and (c) the brake maintenance situation in the U.S. left something to be desired. The maladjustment of service (foundation) brakes has long been recognized as a problem. The torque output of air-braked vehicles is sensitive to the displacement of the applied pushrod stroke of brake chambers (adjustment). A rise in brake temperatures can further reduce brake torque and increase the stopping distance of air-braked vehicles.

The installation of automatic slack adjusters (ASA) on air-braked vehicles (factory-installed in the U.S. since 20 October 1994) was anticipated to reduce the number of air-braked vehicles found with service (foundation) brakes beyond re-adjustment limits. However, just as brake maintenance can affect the braking performance of air-braked vehicles, so too can brake maintenance directly affect the ability of ASA's to maintain proper brake adjustment and brake balance. The efficacy of ASA's can be affected by worn S-cam bushings, loose brake chambers, or inaccurate wheel bearing adjustment. Heusser (1992) revealed that the average pushrod stroke of type 30 brake chambers did not differ greatly between air-braked vehicles that were equipped with automatic slack adjusters (1.62 inch average stroke) and manual slack adjusters (1.68 inch average stroke).

A report by NHTSA (1995) that outlined a new agenda for the 21st century, indicated that 54 percent of defects noted on about 1.6 million air-braked vehicles inspected in 1992 were brake system related. These data indicated that 68 percent of defects involved out-of-adjustment brakes, and, on average nearly 1 of every 10 in-use heavy vehicles is operating with at least one significant non-adjustment-related brake system defect. According to the report, many of these maintenance-related braking problems (e.g. cracked brake drums, chafed or worn air lines, leaking chamber diaphragms) remain undetected simply because drivers were unaware that these latent, potentially hazardous conditions were present.

The stopping capability of air-braked vehicles can also be reduced if the applied pushrod stroke (and corresponding reserve stroke) of brake chambers is forfeited. This may occur from excessive clearance that develops with use or because incorrect repairs were performed that restricted the available pushrod stroke of brake chambers (e.g. worn splines on S-camshaft). No matter how the available pushrod stroke of brake chambers is forfeited, it reduces the reserve braking capacity of air-braked vehicles.

Another undetected maintenance-related braking problem that could significantly degrade the braking performance of air-braked vehicles was discovered in 1997 by the National Transportation Safety Board (NTSB) during the investigation of a truck-car crash. The NTSB attributed the cause of the crash to faulty brake maintenance. A notice was issued to alert the trucking industry that certain dual-systems on air-braked vehicles may have air lines to the foot-operated brake pedal that are reversed, and low-air warning switches that do not function. Despite the best of intentions and actions taken to conduct daily pre-trip inspections or perform periodic inspections, maintenance-related braking problems on air-braked vehicles can be overlooked by drivers and trained journeyman heavy duty mechanics. A basis for uniformity on the maintenance of service (foundation) brakes for air-braked vehicles has been fulfilled in part by the development of recommended practices.

Faulty Brakes (Enforcement)

Out-of-service criteria for air-braked vehicles was established by the Commercial Vehicle Alliance (CVSA) to assist enforcement officials determine what constitutes an unsafe vehicle-related or driver-related condition. Air-braked vehicles that fail to meet minimum requirements are placed out-of-service until repairs have been performed. CVSA is an association of state, provincial and federal officials responsible for the administration and enforcement of motor carrier safety laws in the United States, Canada and Mexico. The North American uniform out-of-service criteria is the guideline that is used by certified CVSA inspectors to determine whether the service (foundation) brakes on air-braked vehicles are considered defective and should be repaired. Air-braked vehicles are placed out-of-service when 20 percent or more of the service (foundation) brakes are defective or when certain out-of-service conditions on the brakes mounted on the steering axle are found (Table 4).

Table 4
Defective Brake Conditions

- absence of effective braking action
- missing / broken mechanical components
- loose brake components
- audible air leak at brake chamber
- applied pushrod stroke @ 90-100 reservoir pressure beyond re-adjustment limit
- defective lining (e.g. cracked, oil-soaked, thickness, missing)
- missing brake on any axle required to have brakes
- inoperable breakaway braking system (trailer)
- non-manufactured holes/cracks on spring section of brake chamber
- external cracks on brake drum
- portion of drum or rotor (discs) missing or about to dislodge
- defective air line (e.g. bulge, leak, improper splice, broken, crimped)
- inoperative or missing defective low pressure warning device
- unacceptable air loss rate
- inoperable or missing tractor protection valve
- insecure air reservoir
- defective air compressor (e.g. loose, cracked pulley / brackets)

A study was conducted by Fancher et al (1995) to examine 2,146 brake inspections performed by the National Transportation Safety Board. Based on analyses of these data, recommendations were made to change the brake adjustment criteria to reduce the percentage of "false positives" during roadside inspections of air-braked vehicles. This prompted CVSA in 1996 to revise the out-of-service criteria for air-braked vehicles. The change allows the displacement of the applied pushrod stroke of brake chambers (with 90-100psi of reservoir pressure) to extend even further before the service (foundation) brakes are required to be re-adjusted. This essentially permits air-braked vehicles, sensitive and dependent on maintenance, to operate with even less limited reserve braking capacity before pushrods can "bottom-out" in brake chambers. The stroked-out condition of brake chambers is often found when air-braked vehicles are inspected after being involved in downhill runaway events. It remains to be seen whether the change (regarded by some as a liberalized plan) will influence the frequency of crashes that arise because of the sensitivity of air-braked vehicles to maintenance (e.g. maladjusted brakes).

Maintenance-Related Braking Problems

Johnson (1946) reported that brake troubles have been present ever since transport vehicles have been around. Furthermore, that a relatively minor degree of foresight and preventative maintenance could prevent crashes caused by faulty brakes. Johnson concluded that " ... the slaughter on our highways ..." could be averted if service (foundation) brakes were maintained. The condition of service (foundation) brakes can be evaluated by reviewing the results of roadside inspections or post-crash inspections of air-braked vehicles.

ROADSIDE INSPECTIONS are conducted in most every jurisdiction in North America. From a review of the Motor Carrier Management Information System, Moses and Savage (1994) suggest that on a rough rule-of-thumb basis, a truck will, on average, be inspected every five years. Data from these inspections have often been reviewed to assess the mechanical fitness of air-braked vehicles. Limpert and Andrews (1987) concluded that as many as 41 percent of heavy vehicles that operate on highways in the U.S. may be unsafe due to defective brakes. The United States General Accounting Office (1990) reported that the out-of-service of air-braked vehicles remained fairly constant (mean 35%) from 1984 to 1989. From roadside inspection results obtained from the Bureau of Motor Carrier Safety for 1966, 1973 and 1983-84, Clarke et al (1991) reported that the proportion of air-braked vehicles that were placed out-of-service for brake-related deficiencies had remained relatively constant (mean = 64.8%). A 17-month study by the NTSB (1992) found that (a) 46 percent of 1,520 air-braked vehicles inspected had maladjusted brakes, (b) 15 percent of automatic slack adjusters were beyond re-adjustment limits, (c) available data do not permit the magnitude of brake-related deficiencies to be readily evaluated, (d) maintenance-related braking problems are associated with more crashes than statistics currently reveal, (e) drivers fail to comprehend the importance of well-maintained service (foundation) brakes, and (f) air-braked vehicles with marginal performance with cool brakes could lose braking effectiveness when brake temperatures rise. From the analysis of inspection data of 1520 five-axle heavy combination vehicles, Heusser (1992) found that brake-related defects were more likely to be found on older (rather than late) model air-braked vehicles. Seiff (1994) reported that 45 percent of the out-of-service violations recorded by CVSA in 1992 were brake violations. Maintenance-related braking problems were cited as the most frequent violation that resulted in why air-braked vehicles were placed out-of-service in 1995 and 1996.

POST-CRASH INSPECTIONS are arranged for some but not all crashes involving air-braked vehicles. This is generally done to determine the condition of the service (foundation) brakes of air-braked vehicles to resolve questions about the circumstances that may have lead to serious crashes. Accident statistics based on police-reported data make it difficult to determine to what extent maintenance-related braking problems contribute to crashes that involve air-braked vehicles. That may be because brake-related deficiencies - similar to driver-related factors like drowsiness - are not always apparent to enforcement officials that attend crash scenes. In-depth investigations have revealed otherwise (Table 5). Jones and Stein (1988) found that 56 percent of 734 large trucks involved in 676 crashes in Washington State had brake defects. Maintenance-related braking problems was a factor associated with a significant number of the 189 heavy truck crashes (> 10,000 pounds) with tow-away damage that were investigated in 1988 by the National Transportation Safety Board. A task force under the direction of the California Highway Patrol (CHP) conducted an analysis of truck-involved and truck at-fault crashes that occurred since truck safety began to deteriorate and crash involvement increased. The task force found that although crashes caused by faulty brakes had steadily declined, brake defects represented a significant proportion (mean = 63%) of the mechanical contributors that were related to truck at-fault fatal and injury crashes that occurred in California between 1978 and 1989.

Table 5

Estimated Crash Involvement of Air-Braked Vehicles due to Maintenance-Related Braking Problems

Source	Ratio	Findings
- Jones & Stein (1989)	56%	Brake defects in 676 tractor-trailer crashes
- CHP (1991)	63% (mean)	Brake defects related to truck at-fault & injury crashes (1978-89)
- TIFA (1993)	55%	Brake system identified as vehicle-related factor in fatal truck-involved crash
Clarke et al (1991)	30-36.4%	Annual number of brake-related crashes

From a review of crashes that occurred because of (a) deficient brakes, (b) downgrade runaways, (c) unable to stop in time, and (d) brake-induced instability, Clarke et al (1991) estimated that upward of 30.0 to 36.4 percent of the annual number of crashes involving air-braked combination vehicles could be brake-related. Vehicle-related factors listed in the Trucks Involved in Fatal Accident (TIFA) database were reviewed for 1993. The TIFA dataset includes virtually all the variables from the public version of the Fatal Accident Reporting System (FARS). The combination of FARS accident level variables with the physical detail of the TIFA survey is noted to produce the most detailed account of fatal truck crash data available. An analysis of vehicle-related factors (variable 162) from the 1993 TIFA dataset indicated that the codes for the brake system accounted for over one-half (55%) of the overall number of all "assigned" codes that described a particular component or system on heavy trucks (e.g. brakes, tires, steering). Vaughan (1993) concluded that the role of defects in crashes is grossly underestimated, and that the brake system is by far the largest source of those defects. The findings of an in-depth investigation of a fatal car-truck crash reported by the author (1997) found that maintenance-related braking problems may not always be detected even when a post-crash inspection of an air-braked vehicle is performed by a certified vehicle inspector. Calculations were performed by Moses and Savage (1997) to determine the upper bound (11%) and mid-range (6%) estimates of crash reduction from roadside inspections due to faulty brakes.

Brake Improvements

Pro-active measures have been taken to improve the braking performance and reduce the sensitivity of air-braked vehicles to maintenance. Atkin and Bennet (1964) anticipated steady improvements would be made in the safe operation of air-braked vehicles with the installation of split systems, antilock brake systems and increased use of retarders. A study by Murphy et al (1971) found that significant upgrade in the maximum braking performance of air-braked vehicles could be achieved by (a) better brake balance, (b) faster response times, (c) brake effectiveness that fully utilized the tire-road interface, and (d) advanced brake control systems that would allow rapid brake applications without creating vehicle instability while travelling on slippery surfaces. A test program sponsored by the Insurance Corporation of British Columbia and conducted by MacInnis (1986) to demonstrate the stopping behaviour of bobtail truck-tractors found that the overall brake deceleration substantially improved (almost double) when air pressure to the steer-axle brakes was increased to near maximum. From a series of tests of simulated emergency maneuvers Radlinski and Flick (1987) concluded that most drivers of air-braked combination vehicles with single trailers would be more likely to stop in a shorter distance and not lose control of an air-braked vehicle if truck-tractors were equipped with (as opposed to without) full operational service (foundation) brakes on steering axles.

Additional measures that could be taken to further improve the performance of air-braked vehicles were identified and proposed by Clarke and Radlinski (1991). This included design changes to enhance brake effectiveness, stability and control, and brake balance and compatibility of air-braked vehicles (Table 6). The Maintenance Council has developed a recommended practice (RP 628-1) for brake lining classification. The RP is intended to promote the dissemination of information to compare the performance of aftermarket brake linings on 16.5 X 7-inch brakes which have been tested to the original equipment dynamometer test procedure stipulated in FMVSS 121.

Air disc brakes are noted for providing superior stopping capability. Thompson (1994) predicted that the demand for air disc brakes would escalate for heavy vehicles in the European market. Yet concerns about compatibility and the additional cost of air disc brakes compared to drum brakes has reportedly restricted the wide-spread adaptation of disc brakes on air-braked vehicles in North America. Concerns about compatibility may be addressed with the adoption of a requirement that truck-tractors and other single unit vehicles sold in the U.S. since 1 March 1997 and 1 March 1998 respectively be factory-equipped with antilock brake systems. This may prompt further interest and expand (similar to Europe) the number of air-braked vehicles in North America that, in the future, will be equipped with air disc brakes

Table 6

Methods Proposed in 1991 to Improve the Braking System Effectiveness, Stability and Compatibility of Air-Braked Vehicles (NHTSA)

Proposed (adopted)
• disc brakes • higher-friction tires • long stroke brake chambers • automatic slack adjusters (1994) • antilock brake systems (1997/1998) • higher capacity steering axle brakes • stroke indicators on exposed pushrods (1994) • eliminate use of automatic front-wheel limiting valves • stopping distance performance requirements (1995) • truck-tractor bobtail proportioning valves • determine torque rating of aftermarket brake linings (TMC, 1997) • performance testing, rating, marking/labeling pneumatic valves • compatible tractor / trailer brake timing requirements (1991) • supplement use of service (foundation) brakes with retarders

The introduction of electronically controlled brake systems (EBS) technology has been considered to be the next advancement to further improve the braking performance of air-braked vehicles. Wrede and Decker (1992) predicted that the control and actuation of the service (foundation) brakes on air-braked vehicles would be electronically combined in the form of "brake management". Decker and Wrede (1994) also warned that incompatibility between systems could arise if effort is not taken to standardize the development of brake-by-wire systems. Lindermann et al (1997) regard the outlook for electronically controlled brake systems (EBS) as the basis for future safety improvements in the operation of air-braked vehicles. Hecker et al (1997) demonstrated that the control of a solo truck-tractor and laden tractor-trailer combination was considerably improved, even under reduced and varying road surface friction, with the use of an electronic brake system. Electronically controlled brakes (ELB) are apparently factory-installed (standard feature) on air-braked heavy trucks that are manufactured by a European manufacturer.

Finally, manufacturers have made product improvements to the S-cam brake assembly. Some of these changes have eliminated sources of component wear that could result in the forfeiture of available pushrod stroke of air-braked vehicles (e.g. upgraded camshaft bushings). Heavy duty return springs have also been introduced with long-life brake packages to assist automatic slack adjusters properly adjust service (foundation) brakes. Although not required, truck-tractors are often factory-equipped with bobtail proportioning valves to ensure that stopping distance requirements can be achieved. A marketing brochure from a major brake equipment supplier indicated that it is committed to making " ... truck brake problems a thing of the past".

Brake Inspections

Compliance measures have been instituted to serve as safeguards to reduce the probability of air-braked vehicles from becoming involved in brake-induced crashes. The *primary* safeguards to prevent the potential crash involvement of air-braked vehicles are mainly based on subjective assessments of brake system components from visual inspections performed by humans. This action is required to ensure that the condition of air brake systems will allow air-braked vehicles to be safely driven. These safeguards include (a) an obligation in most jurisdictions for truck owners to arrange periodic inspections on air-braked vehicles at least every 12 months, (b) drivers to perform daily pre-trip inspections, and (c) enforcement officials to routinely inspect air-braked vehicles at roadside inspections.

Drivers of air-braked vehicles are required to perform daily pre-trip inspections to satisfy themselves that the vehicle is road-worthy. Part of the inspection includes a visual check of the adjustment and condition of the service (foundation) brakes. Knowledge to perform this duty is acquired from training courses to obtain a higher classification of license or endorsement to drive air-braked vehicles. The inability of drivers to detect defective brake conditions or recognize the importance of maintaining service (foundation) brakes within re-adjustment limits when pre-trip inspections are performed can (usually without their knowledge) significantly reduce their ability to control the speed and direction of air-braked vehicles. Drivers may lapse in their duty to identify maintenance-related braking problems on air-braked vehicles for a variety of reasons, including (a) limited mechanical aptitude, (b) indolence or lack of interest, (c) incorrect assumptions about the actual condition of the brake system, (d) operational demands that compete with available time to perform a thorough check of the brake system, or (e) learning barrier that restricts the ability to fully comprehend technical information about brake systems.

There are multiple other reasons why drivers may not determine whether the service (foundation) brakes are properly adjusted. This includes falsely believing that the adjustment of service (foundation) brakes can be checked by walking around an air-braked vehicle with the (spring) parking brakes applied and observing the extent that exposed pushrods are extended from brake chambers. Alternatively, drivers have been known to believe that the adjustment of service (foundation) brakes on air-braked vehicles can be checked while seated in the comfort of the cab compartment by merely observing the reservoir gauge to determine whether a given amount of pressure drops after the foot-operated brake pedal is fully depressed.

A cursory review of data collected in 1998 during a focused enforcement inspection campaign of construction trucks indicates that drivers of air-braked vehicles (despite having completed daily pre-trip inspections) may not be fully aware of the condition of the service (foundation) brakes, and moreover, the implications that surround the sensitivity of air-braked vehicles to maintenance. Laurie (1938) pointed out that drivers daily reports on the operation of large trucks often provide sufficient advanced warning to notify mechanics about impending failures.

If a maintenance-related braking problem (as depicted in Appendix A) is not identified by a driver, it may continue to be present until the air-braked vehicle is next scheduled for maintenance or a periodic inspection. The problem may still remain undetected if a trained journeyman heavy duty mechanic at a certified inspection facility is not able to detect the defective brake condition, or does not correctly perform the necessary repairs to fully rectify the problem. Should this occur, there is a possibility that the problem may be identified if the air-braked vehicle, by chance, is targeted for a "random" roadside inspection by enforcement officials. Air-braked vehicles found with maintenance-related braking problems can be placed out-of-service when inspected by certified CVSA inspectors.

Maintenance-related braking problems may be more readily identified with the deployment of performance-based brake inspection testers. A research program sponsored by the Federal Highway Administration was initiated in 1993 to evaluate the merits of using performance-based technologies to inspect air-braked vehicles at roadside inspections. Data collected and analyzed from one year of field tests indicate that performance-based testers, particularly the roller brake dynamometer, showed good correlations with CVSA inspection and appear to be immediately useful as screening devices. Performance-based regulations must be developed, however, before performance-based testers can be used as an enforcement tool. As with other forms of intervention to apprehend unsafe vehicles before crashes occur, there are certain limitations to performance-based testers. These include the understanding that only a chance encounter with enforcement officials will prevent air-braked vehicles with faulty brakes from being stopped, then, subsequently placed out-of-service *before* potentially becoming involved in brake-induced crashes.

Brake Warnings

Federal Motor Vehicle Safety Standard (FMVSS) 121 requires that air-braked vehicles be equipped with a continuous visible or audible warning in the cab compartment to readily alert drivers when reservoir pressure drops below 60psi (Table 7). The standard also requires that drivers of air-braked vehicles be provided with a gauge that illustrates the amount of pressure in the reservoir system.

Table 7

Cab Display Requirements for Air-Braked Vehicles (FMVSS 121)

- gauge/s to illustrate service reservoir system air pressure
- audible / visible continuous warning when service reservoir pressure < 60psi (413 kPa)
- indicator lamp to activate when malfunction affects ABS on power unit
- indicator lamp to activate when malfunction affects ABS on towed air-braked vehicle (effective on 1 March 2,001)

Additionally, truck-tractors manufactured on or after 1 March 1997 and each single unit vehicle manufactured on or after 1 March 1998 in the U.S. must be equipped with an indicator lamp (mounted in front or in clear view of drivers) that activates whenever a malfunction affects the generation or transmission of responses or control signals in the antilock brake system. Indicator lamps must remain illuminated whenever malfunctions exist in antilock brake systems while the ignition switch is in the 'on' position. After 1 March 2,001, newly-manufactured air-braked vehicles in the U.S. equipped to tow another air-braked vehicle must also be equipped with an electrical circuit that is capable of transmitting malfunction signals from the antilock brake systems of one or more towed vehicles.

There is no current requirement that air-braked vehicles be equipped with a cab-display device to readily alert drivers about maintenance-related braking problems that have degraded the braking performance or reduced the reserve braking capacity of the service (foundation) brakes. These problems are generally the same brake-related deficiencies that historically (and continue to be) discovered when roadside inspections or post-crash inspections are conducted on air-braked vehicles.

Vehicle-Based Warning Devices / Monitoring Systems

Vehicle-based warning devices are usually installed on motor vehicles to provide drivers with an advanced notice about the need to take action. Merker (1966) reported the engineering details of the Sentry Signal Warning System that was developed to provide advantages of both the gauge and warning light. In experiments with drivers to evaluate driver information systems for cars of the future, Green (1996) found that drivers know the brake system is important and would respond as desired to a brake warning. Late model passenger vehicles are equipped with a multitude of warnings lights to both remind drivers (e.g. parking brake applied, service due) or to readily alert drivers about conditions that need immediate attention (e.g. low oil pressure or brake fluid). Some warnings are designed with a safety factor to allow drivers to operate vehicles to the nearest authorized service centre for inspection (e.g. SRS, check engine). Lerner et al prepared definitions to determine when warnings should be issued to prompt the immediate need for drivers to respond to an imminent crash avoidance situation or cautionary crash avoidance situation.

Vehicle-based monitoring systems are being explored to monitor the status of vehicle systems and condition of drivers. Information generated by vehicle-based monitoring systems may assist drivers make informed decisions about whether action is warranted to circumvent crash involvement. Over 20 years ago, Forman and Lemeshewsky (1975) indicated that although it would be desirable to monitor the status of brakes to avoid the consequences associated with dangerous brake failures, on-board monitoring was limited in scope. One such limitation was the transfer of data between the seven-pin electrical connector (six circuits plus one ground) that supplies power between the tractor and trailer of air-braked vehicles. This can now be accomplished by several possibilities including (but not limited to) communication signal multiplexing, voltage enhancements, radio/telemetry communication linkages, additional electrical circuits, and wiring system upgrades.

An intelligent power and high speed communications link was developed between the tractor and trailer by the Truck Multiplexing (TruckMux™) project using the standard SAE J1067 seven-wire cable and J560 connector. Wissing et al (1998) reported that the TruckMux™ prototype outfitted to a tractor-trailer was capable of handling over 70 million J1939 messages without a single failure. NHTSA (1995) reported that on-board brake system performance monitoring systems offer many potential advantages including providing drivers of air-braked vehicles with advanced notice that brake maintenance or repairs are required. The system approach to design a digital message center that could display warning messages (including maintenance-related information about the brake system) to operators of air-braked vehicles was explained by Rodriguez et al (1997).

A tire monitor system (TMS) has been developed (and seemingly became available in April 1998) to provide a cab-display warning to inform drivers of air-braked vehicles when the tire inflation pressure has dropped more than 10 percent of fleet-specified pressure. Sensors mounted within tires (each with their own frequency) use valve stems as antennas to transmit data to the cab compartment. Similarly, new generation [smart] sensors may permit the development of vehicle-based monitoring brake systems that can provide information to drivers about the status of air-brake systems by measuring and monitoring brake torque, temperature, acceleration or the linear angle of applied pushrods.

Depending on the objective, different approaches may be taken to develop vehicle-based brake monitoring systems for air-braked vehicles. Whichever approach is taken, design issues will need to be addressed and challenges resolved. With any type of system that may be entirely relied upon by drivers to make informed decisions, this includes questions that surround the correct interpretation of data, reliability of electronic systems, and human factor issues with regard to providing real-time information to drivers. Additionally, there are questions about the cost-benefit and standardization of advanced systems integrated into air-braked vehicles, that in the future, will likely be equipped with electronically controlled braking systems (EBS). In terms of driver acceptance of vehicle-based monitoring systems, a survey of 152 drivers in Great Britain (1998) found that 89 percent of truck drivers would like a wakefulness monitor that sounds an audible alarm.

Low-Cost Cab-Display Brake Fault Indicator Lamp

The concept of a low-cost cab-display brake fault indicator lamp (BFIL) is proposed to address "known" maintenance-related braking problems that arise because of the sensitivity of air-braked vehicles to maintenance. (Appendix B). Unlike the complexities that may accompany the development and installation of more sophisticated vehicle-based monitoring systems that potentially could influence drivers to become complacent and abstain from performing daily checks of air brake systems, a BFIL would be intended to "assist" drivers make informed decisions about whether brake repairs are warranted before air-braked vehicles are placed into service or descend steep grades. Similar to other indicator lamps (e.g. ABS malfunction, check engine) the illumination of the BFIL would be easy to interpret by drivers and the integrity (and collected faults) of a BFIL could be confirmed when periodic inspections were performed. Much like data recorded by electronic engines, decisions could be made by truck owners to determine what information would be captured and stored by a BFIL. The specific details with respect to the design and development of a BFIL are beyond the scope of this paper.

Further research would provide an opportunity to resolve questions about equipping air-braked vehicles with a low-cost cab-display brake fault indicator lamp. For example:

- could the image of the trucking industry be bolstered, and truck safety concerns of road users addressed, by equipping air-braked vehicles with a BFIL?
- is there a strong market demand for the installation of a BFIL in air-braked vehicles?

- would the widespread installation of a BFIL in air-braked vehicles be instrumental in reducing the out-of-service rate of air-braked vehicles?
- should an initiative to equip air-braked vehicles with a BFIL be industry-driven or regulated?
- what role can industry take to standardize the installation of a BFIL in air-braked vehicles?
- would enforcement officials have an interest to access data captured by a BFIL?
- would a BFIL increase the reliability of service (foundation) brakes by raising the awareness of drivers to conditions that are sensitive to maintenance?
- what level of activation error could be tolerated by the integration of a BFIL in air-braked vehicles?
- what are the product liability implications should a BFIL malfunction?

DISCUSSION

Clarke et al (1987) reported that with the exception of the steering axle, most air-braked vehicles are capable of generating sufficient brake torque to lock (or nearly lock) all wheels on all road surfaces regardless of loading conditions. This however, assumes that the service (foundation) brakes are adequately maintained and that someone will be vigilant on a daily basis to ensure that the applied pushrod stroke of each brake chamber is maintained within re-adjustment limits. Even with service (foundation) brakes properly maintained, air-braked vehicles take considerably longer to stop than hydraulically-braked vehicles. This disparity is further aggravated when brake-related maintenance (including adjustment) is overlooked. Continuous intervention is required to preserve the braking capacity of the service (foundation) brakes and compensate for the degradation in the stopping capability of air-braked vehicles as brake components wear. The sensitivity of air-braked vehicles to maintenance has long been recognized as a safety issue. Although several conditions associated with the service (foundation) brakes can be regarded as maintenance-related braking problems (e.g. cracked drums, oil-soaked linings, audible air leaks), the most common problem, by far, remains the excessive applied pushrod stroke of brake chambers (adjustment). Left unresolved, maintenance-related braking problems can seriously affect the ability of drivers to maintain control of air-braked vehicles.

There has been considerable debate about whether there is a causal link between maintenance-related braking problems of air-braked vehicles and crashes. The limited amount of quantitative crash-related data available may explain why a direct link between maintenance-related braking problems and crashes involving air-braked vehicles may not have been definitively established. Despite this finding, serious crashes with tragic outcomes have, and continue, to occur. Perhaps most notably are downhill runaway events that render drivers of air-braked vehicles with little, and in some situations, absolutely no ability to control descent speed. In most instances crash-involved drivers of air brake vehicles (including bus drivers) were not likely acutely cognizant, through knowledge gained from training courses or after performing pre-trip inspections, that a maintenance-related braking problem existed, and moreover, had grossly deteriorated the stopping capability and reserve braking capacity of the service (foundation) brakes.

A false sense of security may be present with respect to safeguards that have been imposed to ensure that maintenance-related braking problems are identified before diminished braking performance leads to the crash involvement of air-braked vehicles. Considerable emphasis is placed (and assumptions made) that someone (usually the driver) will accurately determine whether an air-braked vehicle has a maintenance-related braking problem before it is placed into service. Currently, this can only properly be done through observation or physical action while lying on the ground and crawling around in dim light conditions that exist (regardless of time of day) underneath air-braked vehicles. Visibility restrictions, access constraints, design limitations, and performance that continues to be reliant on maintenance, still require that this same procedure be taken even with air-braked vehicles equipped with stroke indicators and automatic brake adjusters.

The completion of daily pre-trip inspections by drivers does not guarantee that air-braked vehicles will not later (even that same day) be involved in crashes due, partly or entirely, to maintenance-related braking problems. To believe otherwise assumes that drivers of air-braked vehicles are (a) keenly aware about the limited reserve braking capacity of air-braked vehicles compared to hydraulically-braked vehicles, (b) cognizant that maintenance-related braking problems that affect braking performance and reduced braking capacity cannot readily be detected by observing gauges in the cab compartment or with a light brake application, (c) have the mechanical aptitude to know what constitutes a maintenance-related braking problem serious enough to require immediate attention, or (d) have the authority or wherewithal to make arrangements to resolve maintenance-related braking problems before air-braked vehicles are placed into service. Regardless of the reason why drivers either abstain from inspecting the condition and adjustment of service (foundation) brakes or are unable to detect maintenance-related braking problems, there is unquestionably reason for concern when the most relied upon and dependent safeguard to identify brake faults on air-braked vehicles appears inadequate. The same dependence to identify operational deficiencies of "critical" components to maintain control is not imposed on drivers that drive hydraulically-braked vehicles, nor, operators of other modes of transportation (e.g. air, marine, rail).

Maintenance-related braking problems may also be identified by trained journeyman heavy duty mechanics when air-braked vehicles are next scheduled for routine maintenance, periodic inspections, or by chance encounter with enforcement officials at roadside inspections. This, however, assumes that journeyman heavy duty mechanics will (a) not inadvertently overlook maintenance-related braking problems, (b) always perform proper repairs, and (c) will detect and resolve brake-related deficiencies before air-braked vehicles are involved in brake-induced crashes. In short, visual inspections of the brake systems on air-braked vehicles provides considerable room for interpretation by humans (drivers or mechanics) about whether air-braked vehicles are (or are not) safe to drive. The new millennium is expected to introduce continuous rapid development of low-maintenance air-braked vehicles and more outsourcing of maintenance. Will this assist to resolve or exacerbate safety concerns associated with the sensitivity of air-braked vehicles to maintenance?

Manufacturers have taken steps through design to address the sensitivity of air-braked vehicles to maintenance. Additionally, minimum standards were established to test and license drivers (e.g. CDL endorsements / restrictions) and advancements have been made in the design of brake-related components to address the sensitivity and reliability of air-braked vehicles (e.g. long stroke chambers, automatic brake adjusters). Although it may be premature at this time to know just what effect brake improvements introduced in recent years will have in the future, there continues to be an unacceptable number of air-braked vehicles routinely placed out-of-service at roadside inspections because of maintenance-related braking problems. In terms of a duty of ordinary and reasonable care, Johnson and Eidson (1995) indicated that manufacturers are responsible for (a) the design and production of products, (b) keeping track of advanced discoveries and scientific information associated with the safety of its product, and (c) providing warnings when sound engineering practices cannot effectively eliminate all known hazards.

The only current requirement for air-braked vehicles to be equipped with a continuous audible or visible warning device is to alert drivers when supply (reservoir) system pressure drops below 60psi. Yet it is doubtful that there have been many (certainly fewer than those because of maladjusted brakes) air-braked vehicles involved in serious crashes because of a catastrophic loss of pressure in the supply (reservoir) pressure. Drivers cannot become aware while seated in the cab compartment when the braking performance or reserve braking capacity of air-braked vehicles has been compromised by maintenance-related braking problems. A low-cost cab-display brake fault indicator lamp may be an effective method to prevent costly mistakes that inadvertently and regrettably can be made because of the inability of drivers (for whatever reason) to detect maintenance-related braking problems on air-braked vehicles before serious crashes occur.

For the safety of all road users, should the duty of care associated with detecting conditions that degrade the braking performance and limit the reserve braking capacity of air-braked vehicles continue to be solely dependent on traditional and conventional means - the ability of drivers to detect maintenance-related braking problems when daily pre-trip inspections are conducted? Or should consideration be given to determine whether advancements in electronic systems may now allow the opportunity for air-braked vehicles to be equipped with a reliable low-cost cab-display brake fault indicator lamp that could in the future (along with inspections of brake components) "assist" drivers become aware of maintenance-related braking problems *before* air-braked vehicles are placed into service or descend steep grades?

SUMMARY AND CONCLUSIONS

The sensitivity of air-braked vehicles to maintenance has been a safety issue for a long time. Maintenance-related braking problems can significantly diminish braking performance and reduce the limited reserve braking capacity of air-braked vehicles. Left undetected, brake-related deficiencies can further increase the disparity between the distance required for air-braked vehicles compared to hydraulically-braked vehicles to safely stop. Manufacturers have been instrumental in gains that have been achieved to advance the performance and reliability of air brake systems. Considerable effort has been devoted to optimize the braking performance of air-braked vehicles and address brake maintenance issues. While air brake systems have been improved, maintenance-related braking problems still prevail and the principle reason why air-braked vehicles are placed out-of-service at roadside inspections.

On a day-to-day basis, drivers are the *primary* safeguard for detecting maintenance-related braking problems on air-braked vehicles. Despite having been trained, drivers as a group are generally limited in their knowledge and understanding about the design limitations, maintenance requirements, and operational demands that affect the braking performance and reserve braking capacity of air-braked vehicles. Drivers of air-braked vehicles may often abstain or inadvertently overlook maintenance-related braking problems when daily pre-trip inspections are conducted, or use inaccurate methods to check the adjustment of service (foundation) brakes on air-braked vehicles.

Similar to driver-related factors, maintenance-related braking problems are not always easily discernible to enforcement officials that attend crashes involving air-braked vehicles. The prevalence of maintenance-related braking problems as a probable cause of crashes involving air-braked vehicles is considered to be under-reported.

Advancements in electronic systems have now made it possible to develop vehicle-based monitoring systems and display messages in the cab compartment of air-braked vehicles. The concept of equipping air-braked vehicles with a low-cost cab-display brake fault indicator lamp (BFIL) may reduce the out-of-service rate of air-braked vehicles inspected at roadside inspections by assisting drivers make informed decisions about whether brake repairs are warranted. A BFIL is not intended to abdicate the duty of drivers to perform daily pre-trip and enroute inspections of air brake systems, but to *enhance* the safety of air-braked vehicles. Conceptually, this would be done by supplementing information from visual inspections of air brake systems to assist drivers become keenly aware of whether "anticipated" maintenance-related braking problems are present (those historically and routinely discovered at roadside inspections) so that, if necessary, repairs can be arranged *before* air-braked vehicles are placed into service or descend steep grades.

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The conclusions reached, and opinions expressed, in this paper are solely the responsibility of the author and do not necessarily represent the official policy of the Insurance Corporation of British Columbia.

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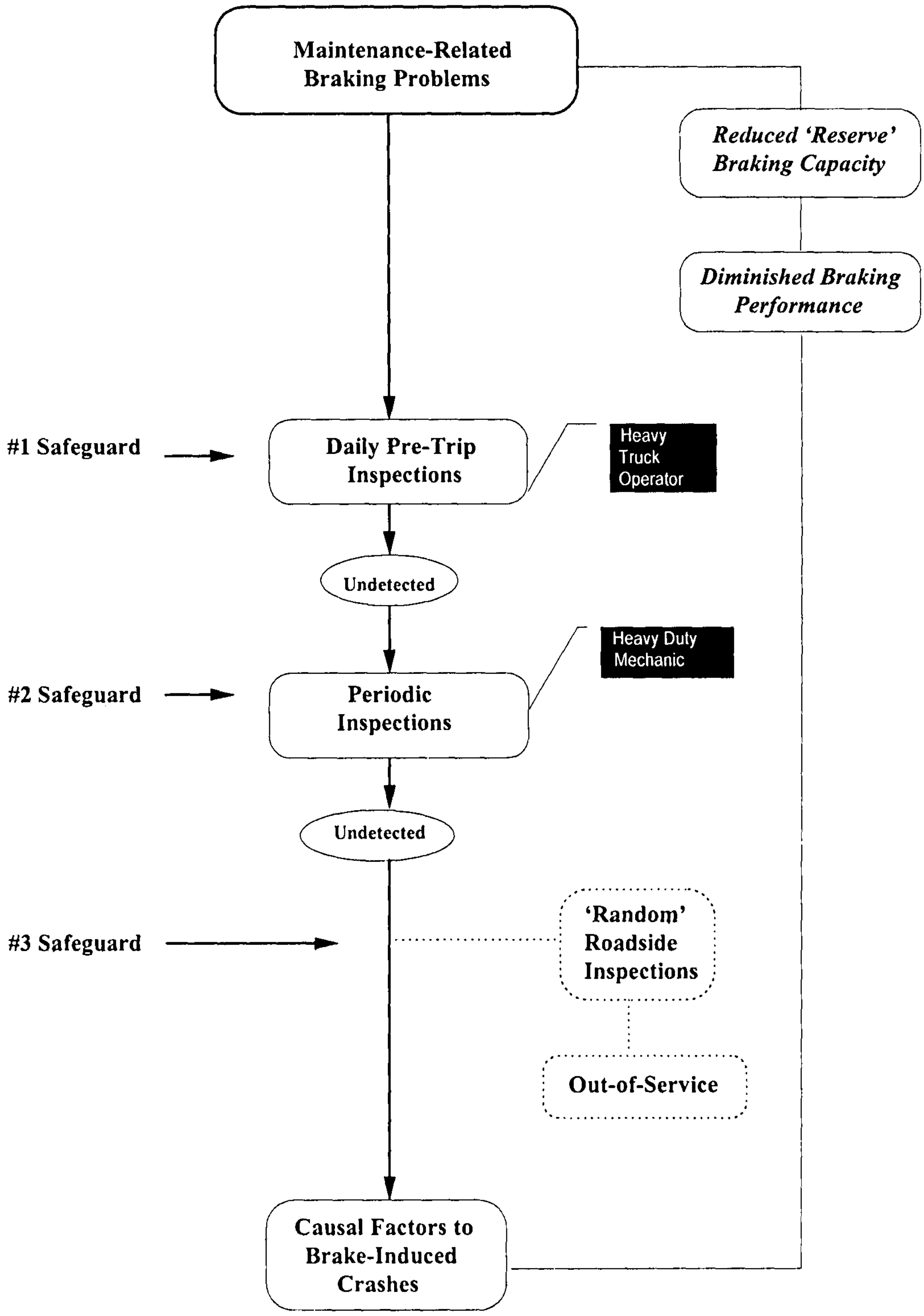
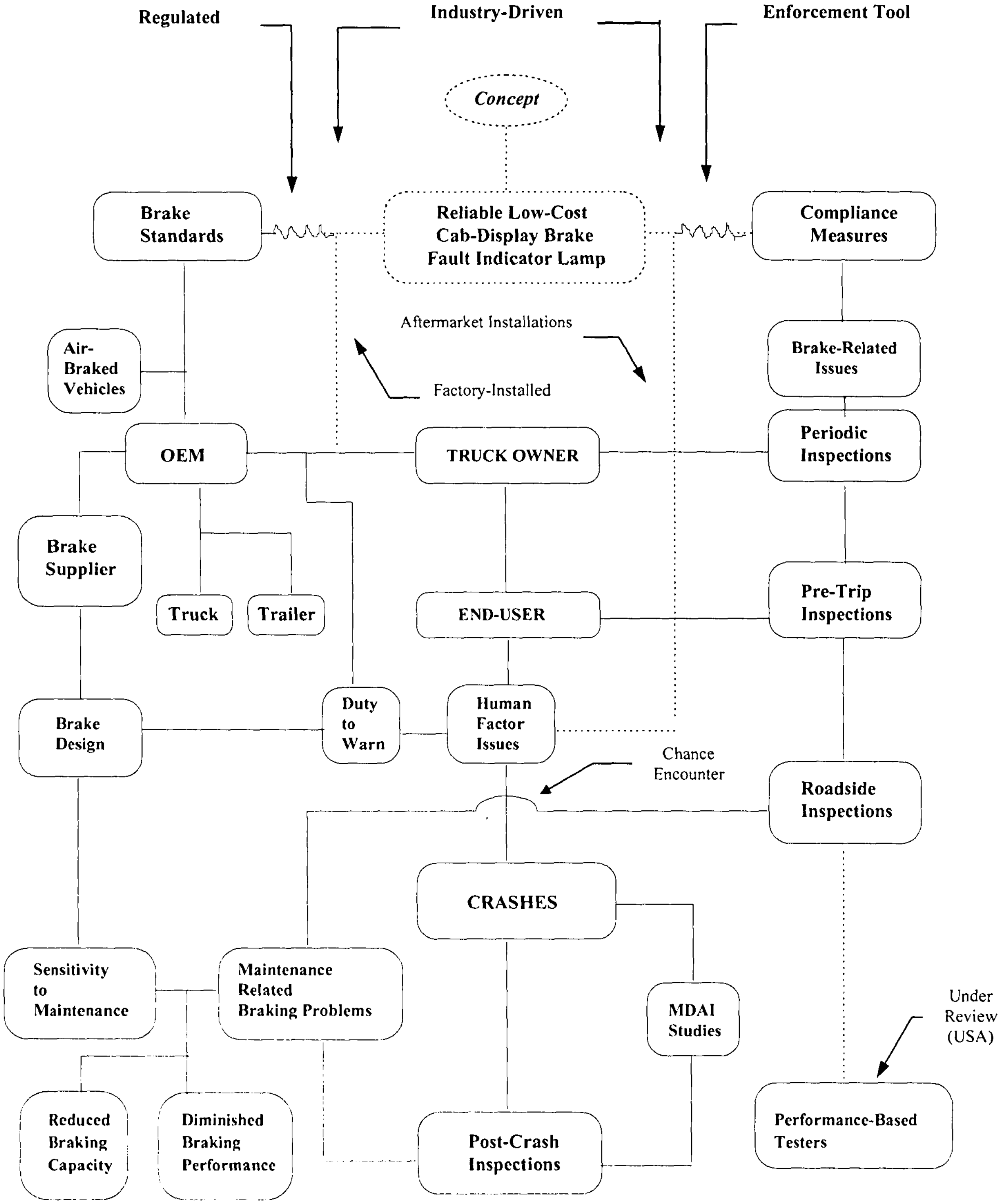
Appendix A

PRIMARY SAFEGUARDS TO PREVENT BRAKE-INDUCED CRASHES INVOLVING AIR-BRAKED VEHICLES



Appendix B

CONCEPTUAL INTEGRATION OF A RELIABLE LOW-COST CAB-DISPLAY BRAKE FAULT INDICATOR LAMP FOR AIR-BRAKED VEHICLES



CRITERIA FOR THE EVALUATION OF CHILD DETECTION AIDS AT SCHOOL BUS STOPS

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Paper Number 98-S4-P-22

ABSTRACT

Transport Canada, in cooperation with the SAAQ (Quebec Automobile Insurance Corporation) and Transports Québec (MTQ), and with the support of Groupe Cartier and Les Consultants Génicom, has completed the first phase of a study whose final objective is to develop an evaluation grid for school bus safety aids. Phase I was specifically aimed at identifying and weighting criteria to be used to evaluate child detection aids. The aids considered improve a driver's chance of detecting school children while they are getting on and off the bus and thus increase the children's safety.

After identifying the school bus problem, reviewing the main technologies available, conducting a study of the driver's duties, and analysing the risks of school bus accidents, a number of criteria were selected to evaluate the aids under consideration.

Twenty-one main criteria in five major categories were identified. The categories are the reduction/elimination of the risks of an accident (safety criteria), the impact on the driver's duties and the interface with the children (ergonomic criteria), the cost of the aid and the school bus service (economic criteria), the noise and visual distractions (environmental criteria), and the aid's performance and technical reliability (technical criteria). These criteria have been incorporated into a preliminary evaluation grid. The grid will be validated in Phase II of the project.

INTRODUCTION

Background

In Quebec, approximately 700 000 children use school bus services daily and some 10 000 drivers travel almost 1 million kilometres each day. Considering the scale of this activity, school buses are by far the safest way to travel compared to other modes of transportation.

Nevertheless, each year several children are victims of school bus accidents. Between 1982 and 1991, there were 183 victims, all school-age children; 12 died and 35 were seriously injured. All of these accidents occurred while the children were getting on or off a bus or while the bus was pulling up or moving away from the bus stop.

In Canada, between 1986 and 1995, there were 33 deaths and 520 injuries resulting from children being struck by a school bus at a bus stop.

In light of these circumstances, a number of companies, inventors, and others concerned with school transportation have developed a large number of devices over the years to improve the safety of school children.

The aids considered improve a driver's chance of detecting school children in the driver's blind spots while the children are getting on and off the bus, and thus increase the children's safety.

School Bus Driver Visibility

In 1995, Transport Canada, in cooperation with MTQ, conducted an exhaustive study on drivers' field of view, both direct and reflected, for all bus designs and mirror configurations. The study succeeded in establishing a new requirement for school bus mirrors, and an updated Canada Motor Vehicle Safety Standard (CMVSS) no. 111 (Mirrors) took effect in November 1997 (1). All school buses manufactured in or imported into Canada after that date will have to be fitted with two external mirror systems. The B system (see Figure 1) consists of two cross-view convex mirrors that enable the driver to see a child in front of the vehicle or on the sides as far as a point rearward of the service door. The A system consists of a convex and flat mirror system installed on each side of the vehicle that provides a view rearward of each side of the vehicle extending to the horizon. The improved standard prescribes performance criteria requiring the installation of mirrors that provide the driver not only with a full field of view but also with a clear view of objects located in blind spots.

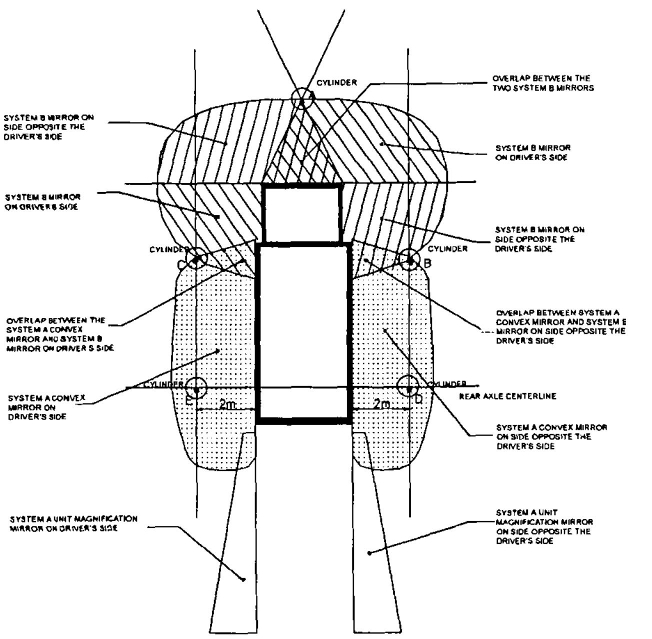

Figure 1. Field of view provided by the new school bus mirrors required by Transport Canada MVSS no. 111

The advent of new mirror systems will greatly improve drivers' visibility, but that alone will not eliminate the problem. Factors such as poor luminosity, poor contrast between the child and its surroundings, or a poor-quality reflective surface will diminish their effectiveness. In addition, drivers will not be able to detect the presence of a child unless they look in their mirrors and look for long enough to make out the image reflected in them. A minimum fixation time is required to make out an object appearing in a mirror. Is there any solution, then? Many advocate mandatory use of flat-nosed buses. Although such vehicles unquestionably offer better direct visibility, the blind-spot problem still remains. Should we, as an adjunct to the new mirror systems, require the addition of auxiliary safety devices, such as retractable barriers, infrared or microwave sensors, camera systems, and alarms? What is the effectiveness, performance, and reliability of these devices? What are their effects on the driver or on the child?

Study Objective

This study is the first phase of a project aimed at developing an evaluation grid for child detection devices (2).

The specific objective of this study was to define and weigh the criteria that are to become an integral part of the evaluation grid for child detection aids at school bus stops.

APPROACH

Conducting this study involved:

- identifying the overall problem of school bus safety in Quebec. Quebec was selected as the reference school transportation system for the study, because it was convenient and because it is representative of a Canadian system;
- reviewing the available devices and those under development that could be applied to improve child detection;
- conducting an investigation of a school bus driver's duties;
- analysing the risks involved when school children get on and off buses;
- determining, defining, and weighting criteria that should be included in the evaluation of safety devices, based on these investigations;
- proposing an approach to make the evaluation criteria operational and formulating recommendations for implementation of the project.

RESULTS

Review of Detection Aids

The purpose of external aids to protect children around school buses is to ensure their safety when the buses arrive at and depart from bus stops, as well as throughout embarkment and disembarkment. The aids include crossing control signal arms, rear-view mirrors, video cameras, external speakers, front and side aprons, and mechanical/ electronic detectors.

They can be classified as active, reactive, or passive. These categories can in turn be subdivided, according to whether the aids are preventive or corrective.

In 1996, in parallel to a major Quebec Coroner's inquest into school bus safety, MTQ mandated researchers at the Université du Québec at Trois-Rivières (UQTR) to evaluate the effectiveness of various safety devices in aiding the detection of children in the danger zones around a school bus (see Figure 2) (3).

This study concluded that a few devices had the potential of reducing the accident risk and recommended that these devices be improved and evaluated in-service for a limited period of time. One element of uncertainty that was not fully explored in the study was the device/driver interface. Our study aims at addressing this issue.

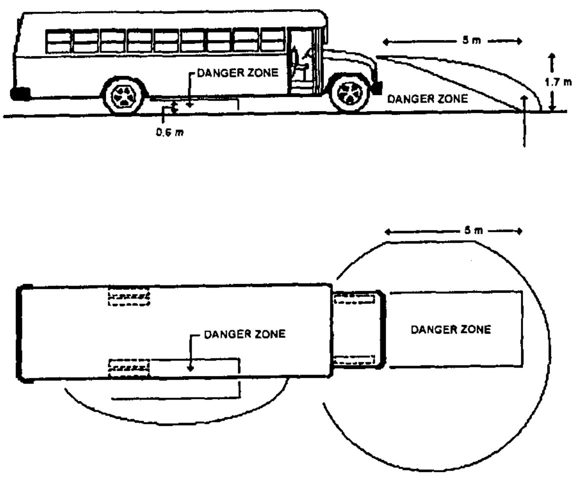

Figure 2. Danger zones around a school bus - UQTR study

Investigation of a Bus Driver's Duties

The main purpose of this investigation was to assess the demands on a driver when he or she approaches a stop, while the children are getting on and off the bus, and when the driver is pulling away, and to determine the variables that could affect these demands. The results are based on a literature review, observations of drivers, and issues raised during three focus group discussion sessions held with drivers and other school transportation stakeholders.

The data gathered showed that driving a school bus is highly demanding and that the number and type of variables involved differ according to the context in which the activity occurs (e.g., several children, high noise level, heavy traffic, etc.). A number of variables related to the school children, roads, type of bus, etc., were also shown to have an impact on the driver's activities. This information was useful in developing the fault tree derived from the risk analysis of school bus accidents.

Risk Analysis

The purpose of the accident risk analysis was to identify and rank in terms of probability the real and possible causes of a specific category of accidents - that is, when a bus hits a child.

The methodology used to gather information consisted of three components: an analysis of accident statistics and reports; driver monitoring and focus group discussions; and creation of incident scenarios via the development of a fault tree.

Analysis of Accident Statistics - The analysis of statistics and accident files provided data on the seriousness of the injuries, the victims' age and sex, the initial and main points of impact, and the causes and circumstances of accidents that occurred while the buses were stopped, loading/ unloading, and when they were pulling away. The typical accident scenario is as follows: In late afternoon, a six-year-old girl crosses the street in front of the school bus on her way home; the bus starts up again, hits the girl with the front of the bus, and then crushes her under a back wheel.

The observations of the driver's duties carried out as part of the ergonomic study also helped to identify the risk factors involved in a bus hitting a child.

Development of a Fault Tree - The fault tree analysis showed the dynamics of a "bus hits child" accident in the form of a tree-like structure representing various combinations and sequences of undesirable events that could lead to an accident. From a tip of a branch, an accident scenario can be constructed. As an illustration, Figure 3 presents the final parts of a sequence of events and/or circumstances leading logically to an accident. In the study a total of 114 events/circumstances were inventoried.

Assigning Probability of Occurrence - Using the information from accident statistics combined with that obtained through consultations with bus drivers on their perceptions of the risks, it was possible to estimate the probability of events that could lead to a bus hitting a child (i.e., the top event of the fault tree).

As an illustration, Table 1 presents a partial list of events/circumstances (only those close to the top of the fault tree) with their relative probability of occurrence, based on the driver's perception of the risk, accident statistics, a synthesis of those two probabilities slightly adjusted by the analyst, and finally the calculated top event probability.

The probability of occurrence of the "bus hits child" being caused by event X is determined by the multiplication of the probability of all the events/circumstances between the event X and the top event in the branch. With this information, it was possible to determine the relative importance of various risk factors, to help determine and weight criteria for the evaluation of detection aids.

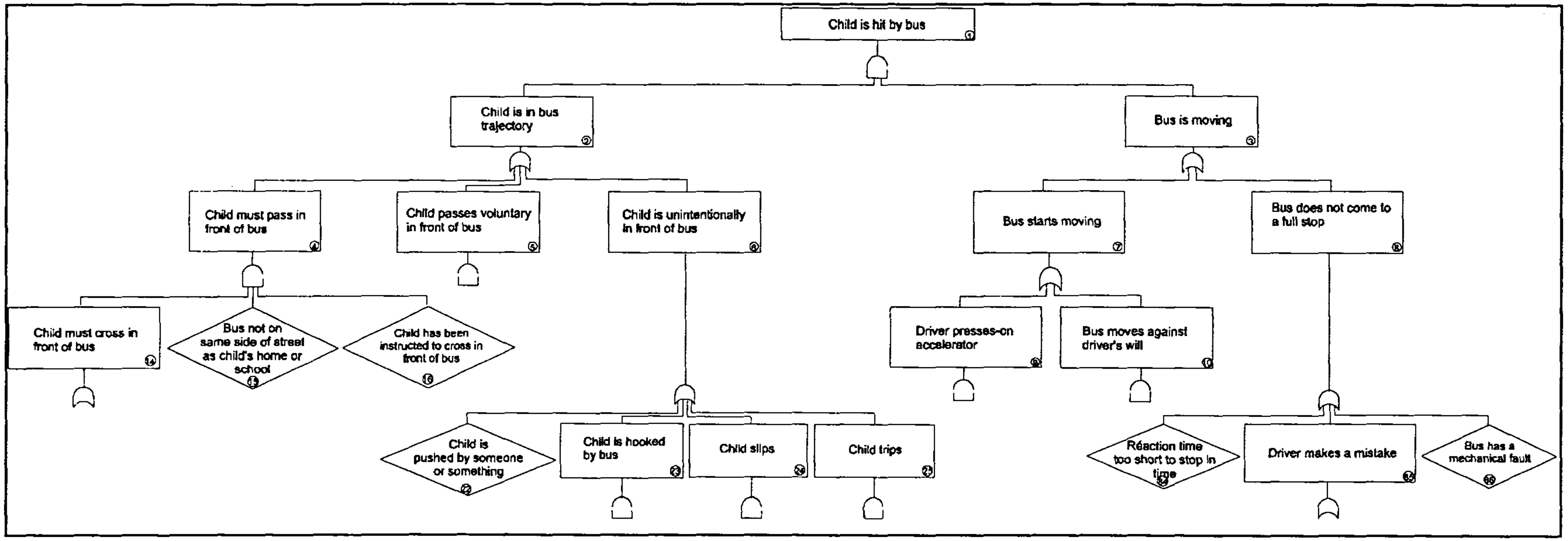

Figure 3. Partial presentation of the fault tree chart depicting the undesirable events/circumstances leading to an accident "bus hits child"

Table 1
Partial Table of Undesirable Events Probability

Event no. (*)	Previous Level Probability(%) Driver's Perception of Risk (std. dev.)	Accident Statistics	Synthesis	Top Event Probability
1	-	-	-	-
2			100	**100**
3			100	**100**
4	21(21.38)	54	50	**50**
5	54(25.15)	13	20	**20**
6	26(21.07)	33	30	**30**
7	51(25.95)	87	80	**80**
8	49(25.90)	13	20	**20**
9	81(24.33)	90	85	**68**
10	19(24.33)	10	15	**12**
14			100	**35**
15			100	**50**
16			100	**50**
22	31(17.81)	20	20	**6**
23	16(19.65)	20	15	**4.5**
24	29(16.39)	50	45	**13.5**
25	23(15.41)	10	20	**6**
84	50(16.23)		50	**10**
85	38(18.48)		40	**8**
86	20(29.31)		10	**2**
...	...	...	...	**...**

(*) Event no. presented in Figure 3

Device Evaluation Criteria

To identify the criteria pertinent to the evaluation of safety devices, the impact of implementing a device was analysed. The analysis identified various aspects where the impact was likely to be felt the most: the elimination of risk (safety), the driver's duties and the interface with the child (ergonomics), the cost of school transportation (economics), noise and visual distractions (environment), and the performance of the device itself (technical). Table 2 presents the main criteria in each of the categories, and their relative weight.

Each of these aspects constitutes a major category of criteria identified as being part of the evaluation of school bus safety devices.

Criteria in the "safety" category were identified and weighted by calculating the probability of undesirable events occurring on the fault tree developed during the risk analysis. This category of criteria evaluates how a device can decrease the risk of an accident occurring.

Table 2
Proposed Weighted Criteria for Evaluation of Detection Aid Safety Devices

CRITERIA CATEGORIES/ Criteria	Weighting
SAFETY	**50%**
Type of action (one of the following)	/100
. Preventing a child's presence	100
. Detecting a child's presence	95
. Helping a driver see the child	70
. Helping a driver see the signals	20
x Danger Zone Coverage	/100
. Location of regions covered	% (*)
. Proportion of regions covered	% (*)
. Time of action	% (*)
ERGONOMICS	**25%**
	/100
. Impact on the driver's duties	70
. Quality of the device/child interface	30
TECHNICAL	**15%**
	/100
. Compliance with standards and regulations	"Go/no go"
. Device performance	60
. Device reliability	30
. Device flexibility	10
ECONOMICS	**8%**
	/100
. Total cost of device	40
. Useful service life of device	40
. Stage of development	20
ENVIRONMENT	**2%**
	/100
. Noise produced	70
. Visual impact	30

(*) Individual weight not yet assigned

The ergonomic criteria were identified and weighted on the basis of information acquired during the ergonomic study and reflect the consultant's experience in this area. These criteria deal essentially with the relationships between the devices and the driver and between the devices and the children.

Technical and economic criteria were identified and weighted using similar studies previously carried out on either school bus safety devices or new technologies. Finally, environmental criteria were defined to ensure that the devices did not have a major impact in terms of visual distraction or noise.

Once the criteria are identified and weighted, it is relatively easy to organize them within an evaluation tool. An initial qualitative grid was thus developed, although it still must be validated.

Proposed Action Plan for Phase II of the Project

The process of validating the evaluation criteria and preliminary evaluation grid will consist of five main activities:

- training a validation committee made up of private and public stakeholders working in the school transportation field;
- holding facilitated sessions using the Delphi technique to get the stakeholders' opinions and agreement on the initial evaluation grid;
- reviewing the evaluation tool;
- using the evaluation grid, analysing the results obtained, and comparing them with those obtained from other evaluations/tests performed on safety devices;
- carrying out a final review of the grid according to the test results.

CONCLUSION

The study activities so far completed have led to the definition and relative weighting of 21 evaluation criteria grouped under five categories. These criteria have been grouped into a preliminary evaluation grid that must be validated in Phase II.

The study has also led to the following conclusions:

- a typical "bus hit child" accident occurs in late afternoon, involves a six-year-old girl crossing in front of a bus after leaving the bus to go home. She is hit by the front of the bus and run over by a back wheel;
- the most critical period is after school on the return trip, when several school children disembark at one stop and take several different directions, walking or running away from the bus;
- January, February, and March are the most accident prone months across Canada, except for Quebec.
- A detection aid device would be more effective if it acts on events/circumstances close to the top of the fault tree.

ACKNOWLEDGEMENTS

The authors would like to thank the members of the study steering committee - representatives from MTQ, SAAQ, the Transportation Coordinator Committee of the Quebec School Board Association, ASTE, ATEQ, APAC and Transport Canada - for their guidance and support. Contributions from the bus drivers and transportation safety officers who participated in the focus group discussions are also acknowledged.

The views expressed in this paper are those of the authors alone and should not be interpreted otherwise.

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LARGE SCALE EXPERIMENT OF CONTOUR MARKING FOR TRUCKS

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Paper Number 98-S4-W-23

1 INTRODUCTION

During the last 10 years several large scale experiments were made on behalf of introducing a contour marking for trucks for better conspicuity. The results comparing the accident rates of marked and unmarked trucks always showed a reduction of the number of accidents. This was the reason for preparing a new ECE-Draft Regulation:

Uniform provisions concerning the approval to retroreflective marking of heavy and long vehicles and their trailers as an annex to the agreement:

Concerning the adoption of uniform conditions of approval and reciprocal recognition of approval for motor vehicle equipment and parts. Within this Draft Regulation several requirements were made on behalf of

- geometrical dimensions
- coefficients of retroreflection
- chromaticity co-ordinates

and others.

In a large scale experiment restricted to Germany it was allowed by only special permission to equip trucks and trailers with logos, graphics, letters, and characters of different material types and colours. The geometrical data and the coefficients of retroreflection of the marking of trucks and trailers were measured during the procedure of giving the special permission for installation of the markings.

2 MEASUREMENTS

The coefficient of retroreflection was measured by a special retrometer in the geometry:

$$\alpha = 20', \beta_2 = 5°.$$

The data is given in $R'/cd \cdot m^{-2} \cdot lx^{-1}$ in the following descriptions abbreviated to R'/U. No colour-measurements were made because of the lack of a portable equipment giving reproducible results.

The coefficient of retroreflection was measured following the below described procedure for the contour marking:

Driver's cabin:	1 measuring area
Side of the truck/trailer:	1 measuring area at the front, the middle, and the rear of the vehicle body
Rear of the truck/trailer:	1 measuring area at the left, middle, and right part of the vehicle body.

The measurements were carried out at the horizontal part of the lower contour.

The measurements for the logos, distinctive marks, letters, and characters were carried out in a typical area of the marking. Always three single measurements were made within every single area, the linear average value was calculated. During the course of the measurements the retrometer was calibrated to standard-materials.

3 REQUIREMENTS AFTER THE DRAFT REGULATION

The Draft Regulation differs between 3 material classes:

Class C:	materials for contour marking
Class D:	materials for logos/distinctive marks and others
Class E:	materials for logos/distinctive marks and others for extended areas $A > 2m^2$

The photometric requirements for a measuring geometry $\alpha = 20'$, $\beta_2 = 5°$ for these three types are

Class C:	white:	$R' \geq 450U$,
	yellow:	$R' \geq 300U$
Class D:	any colour	$R' \leq 150U$
	area $A \leq 2m^2$	
Class E:	any colour	$R' \leq 50U$
	area $A > 2m^2$	

For lettering and characters the requirements are

- number of letters N $\leq$ 15
- height of letters H = 30...100cm.

There are several other requirements which are not discussed here because it was not within the task for this large scale experiment.

4 RESULTS - GEOMETRICAL REQUIREMENTS

4.1 Numbers of Letters and Characters

In figure 1 the frequency distribution f of the numbers of letters and/or characters is plotted.

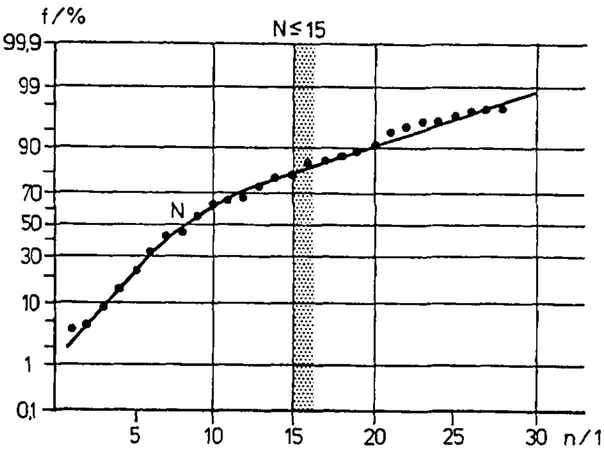

Fig. 1: Frequency distribution f of the numbers n of letters and/or characters within contour markings
N $\leq$ 15: Maximum limit for the number of letters and/or characters

These results represent the lettering of 344 different trucks and trailers. The borderline N $\leq$ 15 shows the requirement after the Draft Regulation. Roughly 80% of the lettering are fulfilling this requirement.

4.2 Thickness of Lines and Width of Lettering

Figure 2 shows the frequency distribution f of the width (W) of letters and the thickness (T) of lines of letters.

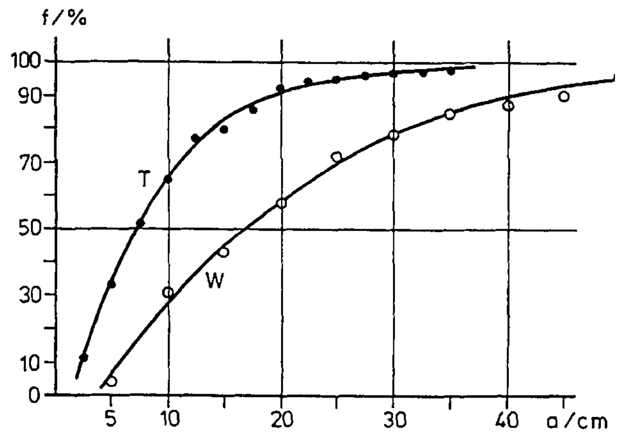

Fig. 2: Frequency distribution f of dimensions of letters and/or characters
T: Thickness of lines
W: Width of letters and/or characters

For 80% of the lettering the results are

width: W $\leq$ 31cm

thickness of line T $\leq$ 14cm.

4.3 Height of Lettering

For the height of lettering the requirements are

$$30\text{cm} \leq H \leq 100\text{cm}.$$

According to figure 3 in which the frequency distribution f for the lettering height is plotted

45% of lettering are smaller than H = 30cm

8% of lettering are larger than H = 100cm.

Therefore roughly 53% of the lettering are not performing this requirement.

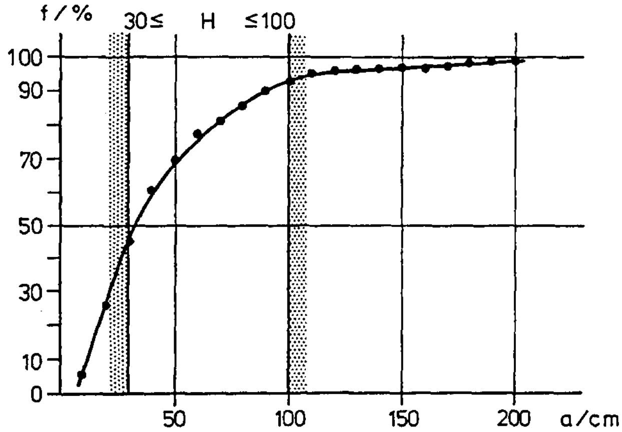

Fig. 3: *Frequency distribution f of heights a of letters and/or characters*
30 ≤ H ≤ 100: *Limits for the height of letters and/or characters*

4.4 Area of Logos or Distinctive Marks

In the requirements the class of used material is depending on the size of the logo, distinctive mark etc. For areas A ≤ 2 m² class D materials are permitted, for larger areas the class E material should be used. In figure 4 the frequency distribution of the height (H) and width (W) of logos or distinctive marks is shown.

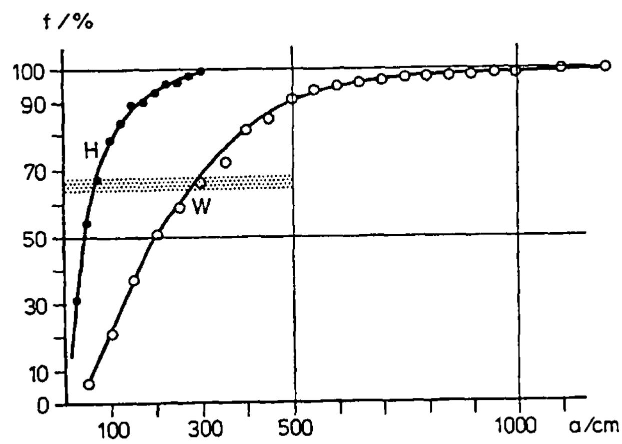

Fig. 4: *Frequency distribution f of widths W and heights H of logos or distinctive marks*

The dotted area represents in approximation A ≈ 2 m². Based on these results one can expect that ≈ 70% of the logos or distinctive marks will fulfil the requirement A ≤ 2 m² and can consist of material class D. This value is only an estimation because the effective area was not measured but only the all over size. So the value of f ≈ 70% is even higher.

5 RESULTS - PHOTOMETRIC REQUIREMENTS

5.1 Contour Marking

In the figures 5 and 6 the photometric measuring results for contour markings are plotted for different situations. In figure 5 the frequency distribution f for clean rear contour marking of retroreflective material type 3 is shown.

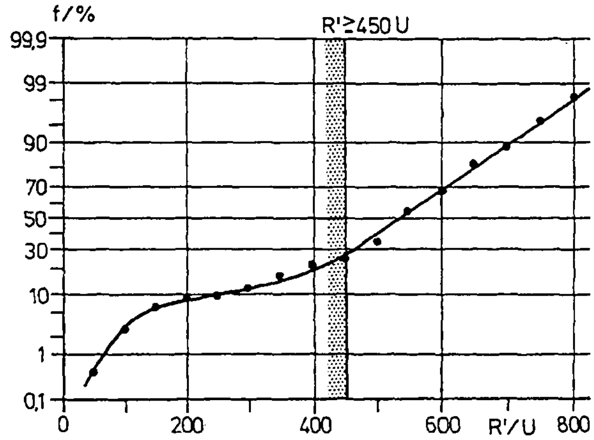

Fig. 5: *Frequency distribution f of the coefficients of retroreflection R' of contour markings at the rear of trucks and trailers*
R' ≥ 450U: *Minimum requirement (class C) for the coefficient of retroreflection R' for white materials*

The dotted borderline shows the minimum photometric requirement R' = 450U. The contour marking was measured after the area for measuring had been cleaned carefully. The results show that f ≈ 27% of the contour markings are not fulfilling the photometric requirements.

For different areas the results measured are shown in figure 6.

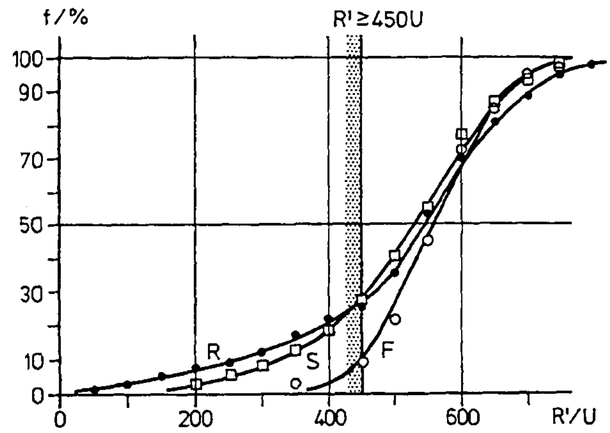

Fig. 6: *Frequency distribution f of the coefficient of retroreflection R' of contour markings at different places of trucks and trailers*

F:	*Side of driver's cab*
S:	*Side of the truck or trailer*
R:	*Rear of the truck or trailer*
R' ≥ 450U:	*Minimum requirement for the coefficient of retroreflection R' for white materials for contour marking (class C)*

Again the frequency distributions f for the photometric values R' for contour markings of clean material of type 3 are shown. The results for side marking (S) and rear marking (R) are differing not too much whilst the results gained from the contour marking of driver's cabin (F) are different. The material mounted at the driver's cabin seemed to be stressed less than at other positions.

Roughly f = 27% of rear and side contour markings are not fulfilling the minimum photometric requirements of R' ≥ 450U for white materials. For materials mounted at driver's cabin this value is reduced to f ≈ 10%.

5.2 Reducing of Photometric Performance by Dirt

During all measurements the photometric data were gained first for dirty marking and then after cleaning for clean marking.

The influence of dirt can be shown in figure 7 for contour marking, and in figure 8 for logos or distinctive marks.

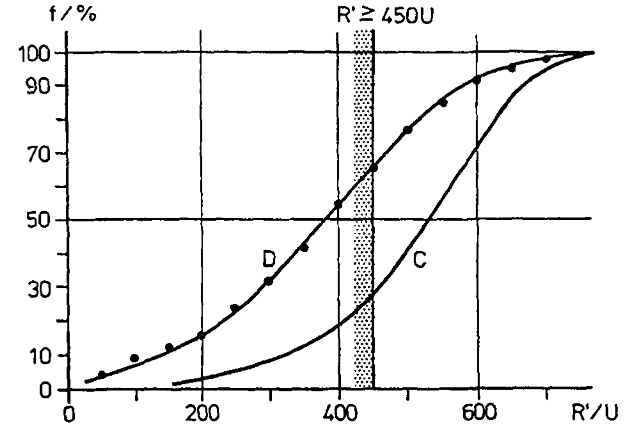

Fig. 7: *Frequency distribution f of the coefficient of retroreflection R' of clean (C) and dirty (D) contour markings at the side of trucks and trailers*

D:	*Dirty contour marking*
C:	*Contour marking after cleaning*
R' ≥ 450U:	*Minimum requirement for the coefficient of retroreflection for white materials for contour marking (class C)*

In figure 7 the results of figure 6 are plotted (C) adding the results for dirty (D) contour markings. These results were found for contour marking of material type 3 at the side of the truck or trailer. The dotted borderline shows the minimum requirement of photometric performance for contour markings. For the value f = 50% the reduction of photometric performance by dirt is about ΔR' ≈ 30%.

In figure 8 similar to figure 7 the frequency distribution f is shown for the coefficient of retroreflection R' for clean (C) and dirty (D) logos or distinctive marks of white material of type 1.

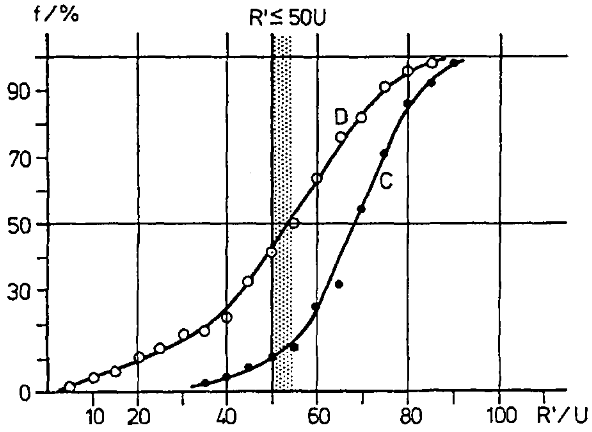

Fig. 8: *Frequency distribution f of the coefficient of retroreflection R' of clean (C) and dirty (D) logos or distinctive marks at the side of trucks or trailers*

D:	*Dirty logo or distinctive mark*
C:	*Logo or distinctive mark after cleaning*
R' ≤ 50U:	*Maximum for the coefficient of retroreflection R' for logos or distinctive marks of any colour and of class E materials*

The dotted borderline shows the maximum for the coefficient of retroreflection R' for material of class E, the borderline of class D (R' ≤ 150U) is not plotted. For clean materials only f = 10% are fulfilling the requirements for class E in contrary to class D where 100% of the materials are performing the maximum value of R' ≤ 150U. The reduction of the photometric performance by dirt is for f = 50% nearly ΔR' ≈ 25%.

5.3 Contour Marking and Colour of Materials

During the large scale experiment, for the contour marking different types of materials and colours were used. In figure 9 the coefficient of retroreflection R' is plotted for different colours of clean (C) and dirty (D) materials of type 1.

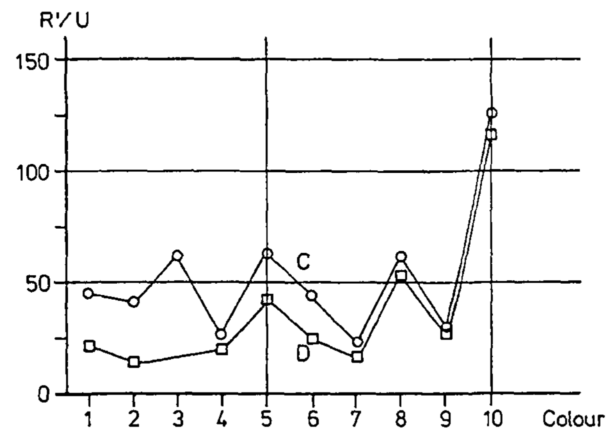

Fig. 9: *Mean values of the coefficient of retroreflection R' of clean (C) and dirty (D) contour markings of type 1 material with different colours*

1:	*yellow*	*6:*	*white/yellow*
2:	*gold*	*7:*	*red*
3:	*orange*	*8:*	*silver*
4:	*black*	*9:*	*green*
5:	*white*	*10:*	*pink*
D:	*Dirty contour marking*		
C:	*Contour marking after cleaning*		

None of those materials fulfil the minimum requirement of R' ≥ 450U (white) or R' ≥ 300U (yellow). In addition in figure 10 the results for the materials of type 2 and type 3 are shown.

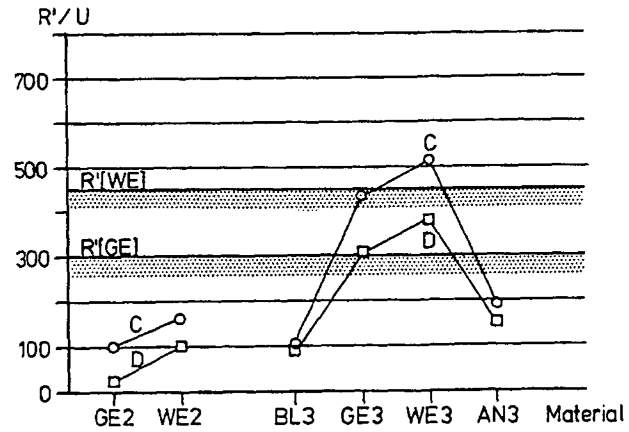

Fig. 10: Mean values of the coefficient of retroreflection R' of clean (C) and dirty (D) contour markings of different type of material and of different colour

GE2:	*yellow*	*type 2*
WE2:	*white*	*type 2*
BL3:	*blue*	*type 3*
GE3:	*yellow*	*type 3*
WE3:	*white*	*type 3*
AN3:	*anthracite*	*type 3*
R'(WE):	*Minimum requirement for the coefficient of retroreflection R' for white materials for contour marking (class C)*	
R'(GE):	*Minimum requirement for the coefficient of retroreflection R' for yellow materials for contour marking (class C)*	

Only the materials: type 3 - white and type 3 - yellow are performing the minimum photometric requirements (dotted borderlines) for contour marking (class C).

5.4 Logos/Distinctive Marks and Colours of Materials

For clean logos or clean distinctive marks the mean values of the coefficient of retroreflection R' are shown in figure 11.

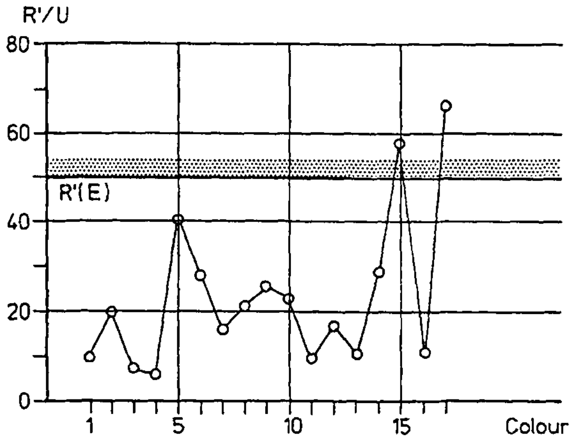

Fig. 11: Mean values of the coefficient of retroreflection R' of clean logos or distinctive marks of different colours

1:	*blue*	*9:*	*light green*
2:	*brown*	*10:*	*orange*
3:	*dark blue*	*11:*	*red*
4:	*dark green*	*12:*	*pink*
5:	*yellow*	*13:*	*red/violet*
6:	*gold*	*14:*	*black*
7:	*green*	*15:*	*silver*
8:	*light blue*	*16:*	*violet*
		17:	*white*

R'(E): Maximum for the coefficient of retroreflection R' for logos or distinctive marks of class E (areas $A>2m^2$)

The dotted borderline R'(E) describes the maximum value for the coefficient of retroreflection for materials class E R' ≤ 50U. Except the materials of the colours white or yellow all the other materials perform the class E-requirement, they can be used without size limitation. The materials with the colour white or yellow have to be restricted to sizes A ≤ 2 m2.

The influence of dirt layer on material for logos or distinctive marks can be derived from figure 12 where the mean values of the coefficient of retroreflection for dirty (R'(D)) and clean (R'(C)) materials are plotted for the different colours as in figure 11.

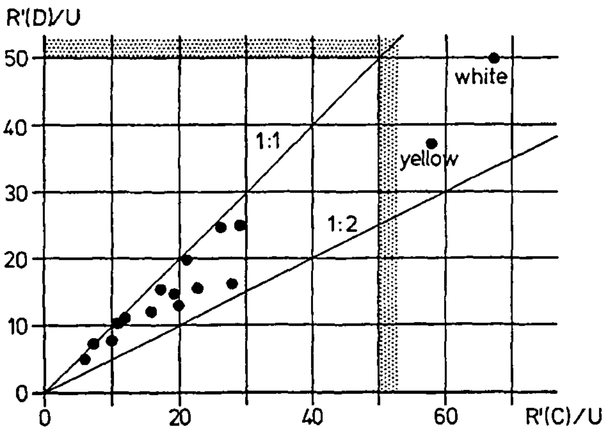

Fig. 12: *Mean values of the coefficient of retroreflection R' of clean materials (R'(C)) and dirty materials (R'(D)) of logos or distinctive marks of different colours*
1:1, 1:2: *Ratio of the values of coefficient of retroreflection before (R'(D)) and after cleaning (R'(C))*

The dotted borderline describes the performance limits for the class E-material. Again the colours white and yellow are not fulfilling these requirements. The reduction of the coefficients of retroreflection R' of materials in use by dirt is roughly between 10% and 50%.

6 CONCLUSIONS

The performance requirements for geometric and photometric values as described in the Draft Regulation for

- Retroreflective Markings -

can be fulfilled by materials available today for the contour marking as for logos, distinctive marks, letters and characters.

There are some reductions in the numbers of letters and characters necessary. Also a reduction of the limits of heights of letters and characters should be strived for.

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Technical Session 5

Advanced Air Bag Technology

Chairperson: W. Thomas Hollowell, National Highway Traffic Safety Administration, United States

THE INFLUENCE OF EUROPEAN AIR BAGS ON CRASH INJURY OUTCOMES

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Pete Thomas
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Loughborough University
United Kingdom
Paper Number 98-S5-O-01

ABSTRACT

The UK Co-operative Crash Injury Study currently includes data on 205 seat belted drivers from frontal impacts in which an air bag deployed; of these, 142 suffered some degree of injury. To detect the influence of frontal air bags, the distribution of injury over the body regions of these drivers was compared to that of a much larger group from vehicles without air bags. The injured drivers from air bag vehicles showed relatively fewer head injuries, especially fractures, and relatively more arm injuries. No abnormal types of injury or circumstances of injury were identified for the air bag group. Air bags generally appear to deploy at vehicle impact severities that pose a statistical risk of significant head injury, and also in a proportion of lower severity impacts. As a group, the air bag equipped vehicles were larger, more modern, and more often fitted with seat belt pretensioners than the non air bag vehicles, with an older and more male driving population.

INTRODUCTION

Motor vehicle manufacturers have tended to customise air bag characteristics differently for the North American and European markets, particularly with regard to deployment threshold, inflation rate and air bag volume. This has arisen in response to different regulatory requirements, consumer preferences, advocacy group pressures and legal considerations. Additionally, seat belt use and the size, mass, and structural properties of the car fleets diverge considerably. The effectiveness of air bags in North America has been extensively studied by several authors [Backaitis and Roberts (1987), Huelke and Moore (1993), Crandall et al (1994), Libertiny (1995), Dalmotas et al (1996)]. However it has not been possible to assume that the benefits and problems associated with air bags in North America are being replicated on the roads of Europe.

Australian studies have also addressed how air bags influence injury outcome. Fildes et al (1996) presented results which suggested that head, face, chest , abdomen and pelvis injuries were reduced in Holden Commodore cars fitted with air bags, using 63 air bag cases and 85 non air bag cases. The Commodore air bag has a higher deployment threshold, lower deployment speed and faster venting than many US air bags because it was designed for belted occupants. In these respects it has similarities to European systems. However, the size of the vehicle and the 65 litre driver bag do not compare well with European vehicle and air bag sizes.

Some results of European studies are available. In Germany, Otte (1995) compared 31 belted occupants with air bag deployment to 1483 belted occupants without air bags. He noted a lower overall injury severity in the air bag cases but a higher incidence of cervical spine strain. Morris et al (1996) investigated driver injury patterns in 97 European and Japanese cars with air bag deployment and mixed belt use. He concluded that air bags appeared to be improving injury outcome for the head but also suggested that cervical spine strain rates were not decreasing. The study also showed that, for the air bag cases, the most common site of moderate to serious injury (AIS 2+) was the lower limb followed by the upper limb. Langwieder et al (1996) compared a sample of 188 drivers with deployed air bags (mostly belted) to German insurance data for non air bag cars. He reported that AIS 2+ injuries in air bag cars occurred predominantly to the lower and upper extremities rather than to the head or chest, concluding that driver air bags lead to a substantial reduction in head injuries.

To date, the evaluation of air bag effectiveness in Europe has been based on a relatively low number of cases of air bag deployment. This remains a constraint. However a clearer picture is beginning to emerge as the number of relevant accidents that are systematically investigated and documented begins to accelerate. The findings presented in this paper are based on the latest release of results from the UK Co-operative Crash Injury Study (CCIS), which is a major source of in-depth crash investigation data in Europe.

The CCIS study has been funded by the British government and a consortium of motor manufacturers since its inception in 1983. It is managed by the Transport Research Laboratory. Teams from Loughborough

University, Birmingham University, and the Vehicle Inspectorate examine approximately 1600 vehicles per year. The three groups use the same data collection forms and methods, and the case studies are combined into a single computer database. This whole database contains anonymous information on over 13000 vehicles, 21000 occupants and 68000 injuries.

Crashed vehicles from regional catchment areas around England are admitted to the sample depending on police assessment of accident severity. Accidents where an occupant from any vehicle dies, is admitted to hospital as an inpatient, or requires medical treatment are classified as fatal, serious, and slight accidents respectively. When an accident is selected, CCIS attempts to include all vehicles involved, provided the vehicle in which injury occurred is no more than seven years old. Currently CCIS succeeds in obtaining almost all eligible fatal accidents, about 80% of eligible serious accidents, and a quota (25%) of slight accidents. These criteria have varied over the period of data collection relevant to this paper, but not dramatically. The weighting of the sample is therefore linked to the severity of occupant injury.

This connection between injury level and admission to the sample means that it is not completely straightforward to demonstrate the effectiveness of air bags in mitigating (or aggravating) injury. One approach might be to compare the level of injury of occupants from air bag equipped vehicles to that of occupants from non air bag vehicles. This may work if the two groups are selected at random, on vehicle impact severity, or some other injury-independent basis. However in the CCIS sample someone in the accident is required to be fatally, seriously, or slightly injured–the selection of *all* occupants is consequently biased towards injury cases. This distorts the perceived effectiveness of the air bag in mitigating or aggravating occupant injury.

The approach adopted in this paper is to look for differences in the pattern of injury between the two groups, specifically in the distribution of injury over body regions. The air bag's intended function is to protect the head. If it succeeded perfectly in this respect (which is impossible) the CCIS sample would still contain slightly, seriously, and fatally injured occupants from air bag deployed vehicles, but these subjects would have no head injuries. The extent to which the air bag actually works should be reflected in a shift away from head injuries among *injured* occupants from air bag vehicles–relatively less head injuries and, by the same token, relatively more injuries to other regions of the body.

The introduction of air bags has coincided with other developments in vehicle safety: among these are seat belt pretensioners and the design of vehicle body structure for a variety of crash tests with instrumented dummies. No attempt is made in this paper to distinguish the separate contributions of the various coexisting safety features. This would place excessive load on limited data. The comparisons made here are between air bag equipped vehicles, with all their accompanying secondary safety features, and non air bag vehicles, with all their secondary safety characteristics.

OVERVIEW OF CCIS DATABASE 1992-98

Air bag equipped vehicles first appeared in the CCIS sample during phase IV of the project which started in mid 1992. The collection of data for phase V is due to end in mid 1998. The results presented in this paper are drawn from these two phases–this includes all air bag equipped vehicles documented to March 1998. Although weighting factors can be applied to the CCIS data to undo the sampling bias in favour of more severe injury cases, the analysis here is directly descriptive of the sample.

Table 1.
CCIS 1992-98:
Maximum Occupant Injury Severity per Vehicle

Injury Severity	Vehicles	
Fatal	218	4%
Serious	1370	22%
Slight	2665	43%
Uninjured	1434	23%
Unknown	514	8%
Total	6201	100%

There are details on 6201 vehicles. The maximum level of injury within each vehicle is shown in Table 1. Slight injury cases make up almost half of the sample; fatal and serious injury cases together are about one quarter, as are non-injury cases.

Table 2.
CCIS 1992-98: Accident Type

Accident Type	Vehicles	
Front	3380	55%
Side	1512	24%
Rear	415	7%
Rollover	743	12%
Other	151	2%
Total	6201	100%

Frontal impacts make up over half of the sample, as Table 2 shows. This is where the effectiveness of (frontal) air bags should manifest itself.

Table 3.
CCIS 1992-98: Air Bags

Air bag	Vehicles	
Not fitted	5651	91%
Deployed	312	5%
Not deployed	238	4%
Total	6201	100%

The presence of air bags is shown in Table 3. A large majority of vehicles were not fitted with air bags, and many air bags were not triggered by impact. This left 5% with air bags fitted and deployed.

Table 4.
CCIS 1992-98: Seat Belt Use

Seat belt	Front occupants	
Used	5746	71%
Not used	844	10%
Not known	1516	19%
Total	8106	100%

Details are available on 8106 drivers and front passengers from the 6201 vehicles. Over 70% of these occupants had seat belt use confirmed by physical evidence collected at the vehicle examination. Taking account of the unknown cases, it is likely that over 80% were wearing seat belts. This usage rate is high enough to warrant focussing on the effectiveness of air bags in their intended role in Europe as supplementary restraint systems, used in conjunction with seat belts.

FRONTAL IMPACTS WITH BELTED DRIVERS

With a high rate of seat belt use and the intended role of European air bags as supplements to conventional restraints, drivers known to have not worn their seat belts were excluded from the examination of air bag effectiveness. Occupants who were fully ejected from the vehicle or burnt by fire were also excluded.

It is not uncommon for crashed vehicles to make contact with more than one object during an accident. Here impact type is defined by the *most severe* impact, as assessed by the accident investigators. (There is usually no difference between the most severe vehicle impact and the vehicle impact that results in the most severe injury; where there is, the investigators are required to take injury consequences into account.) If the impact was to the front of the car, and the direction of impact force was within 45 degrees of head on (11 o'clock to 1 o'clock), and the car at no stage rolled over, the impact was defined as a frontal. Of the 3380 frontal impact vehicles mentioned in Table 2, 2711 met these definitional requirements, as shown in table 5.

Table 5. Air Bags

Air bag	Vehicles
Not fitted	2445
Deployed	205
Not deployed	61
Total	2711

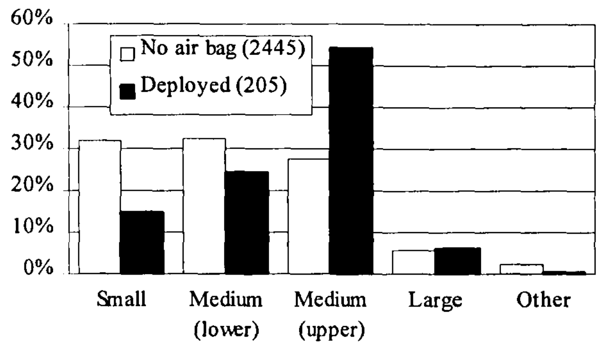

Figure 1. Vehicle size category.

The distribution of vehicle size is shown in Figure 1. Air bag vehicles in the sample tend to be larger than those without air bags: only 39% were categorised as small or lower medium compared to 64% of non air bag vehicles. This probably reflects the phased introduction of air bags into the European fleet via upmarket models.

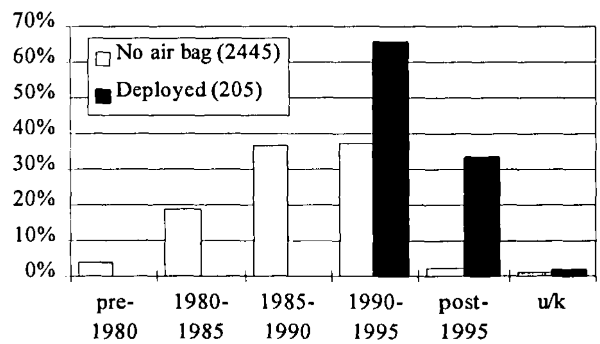

Figure 2. Vehicle year of first registration.

The year of first registration is shown in Figure 2. Vehicles equipped with air bags tend to be newer than vehicles in the comparison group: all vehicles with air bags date from 1990-95, compared to 40% of those without air bags.

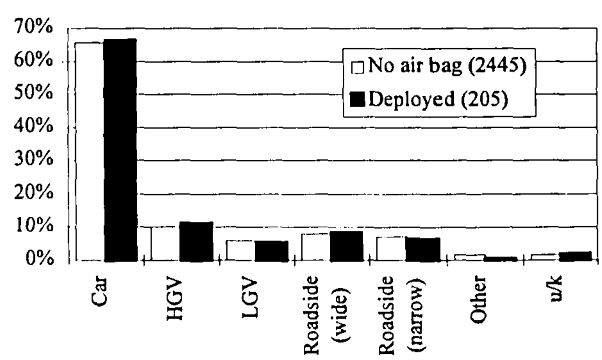

Figure 3. Collision partner (object struck).

The collision partners of the vehicles are shown in Figure 3. Car to car impacts predominate; collisions with heavy goods vehicles (HGV) or light goods vehicles (LGV) are about as frequent as with fixed roadside objects. The distribution is very similar between the air bag and non air bag groups.

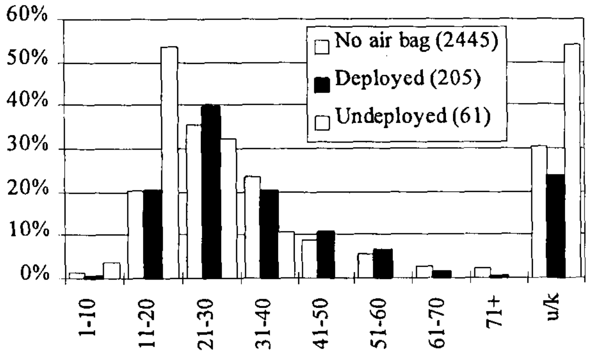

Figure 4. Impact severity–Equivalent Test Speed (km/h).

One measure of impact severity available on the CCIS database is Equivalent Test Speed (ETS), which may be described as the speed with which a vehicle would need to strike a rigid barrier to cause the observed amount of damage. ETS was calculated from vehicle damage (crush profiles) using Crash3–a standard accident reconstruction computer program. There is a close correspondence between the speeds calculated for vehicles without air bags and vehicles with deployed air bags. Where ETS is known, approximately 60% of both groups fall into the 21-40 km/h band with the remaining 40% split equally above and below. In contrast, the vehicles with undeployed air bags peak in the lower range of 11-20 km/h with nothing above 40 km/h.

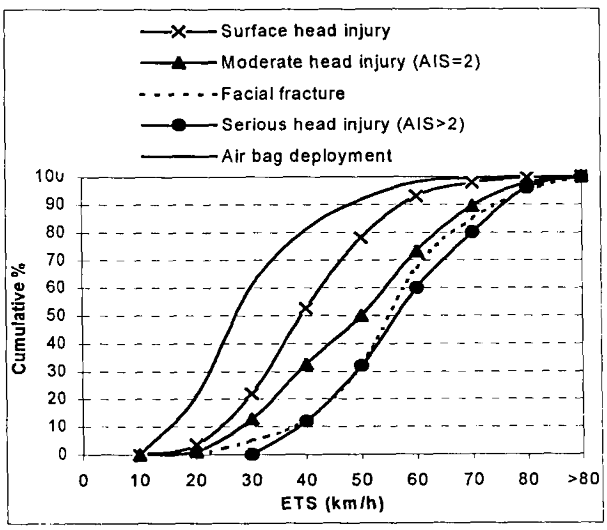

Figure 5. Equivalent Test Speed for air bag deployment and belted drivers with head injury from steering wheel contact in non air bag cars.

In Figure 5 the distribution of ETS for air bag deployments is shown plotted with the ETS distributions for belted drivers who sustained head injury from steering wheel contact in cars not equipped with air bags (Frampton, 1997). There are indications that some air bags may be deploying where the risk of moderate to serious head injury is minimal. One fifth of air bags deployed below 20 km/h where virtually no head injury was sustained from steering wheel contact.

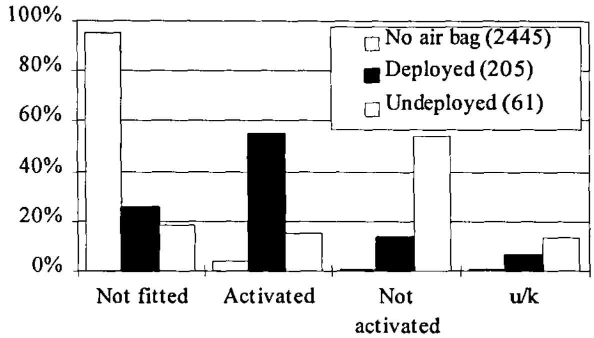

Figure 6. Seat belt pretensioners.

Seat belt pretensioners tend to accompany air bags, and they tend to activate when air bags deploy. Only 5% of non air bag vehicles in the sample were fitted with pretensioners, compared to around 70% of air bag equipped vehicles, as Figure 6 indicates. However where seat belt pretensioners were fitted, the activation rate was 82%, 80%, and 21% for the no air bag, deployed air bag, and undeployed air bag groups respectively.

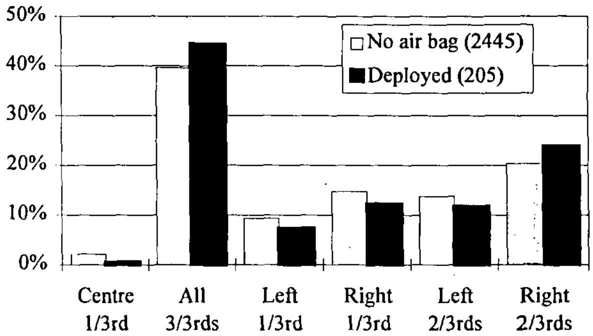

Figure 7. Zone of direct contact on vehicle front end.

Figure 7 shows which thirds of the vehicles' front end came into contact with the object struck. The region of direct contact (partly or wholly) encompassed all three thirds of the front end in 40-45% of cases, and the left or right two thirds of the front end in about 35% of cases. The distribution of contact zones is similar for the air bag and non air bag groups.

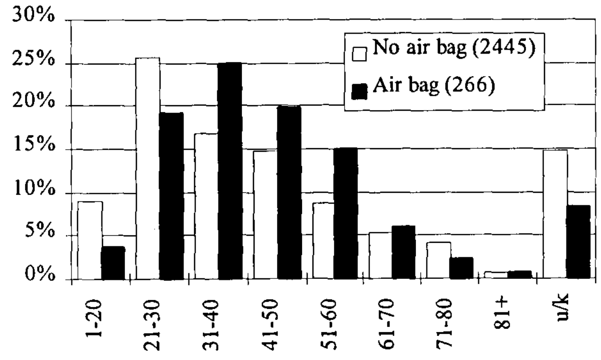

Figure 8. Driver age (years)

Figure 8 shows driver age for vehicles with and without air bags. Drivers of air bag equipped vehicles seem to be older. The modal, or most frequent, age group is 21-30 years for non air bag cars, but 31-40 years for the air bag equipped group.

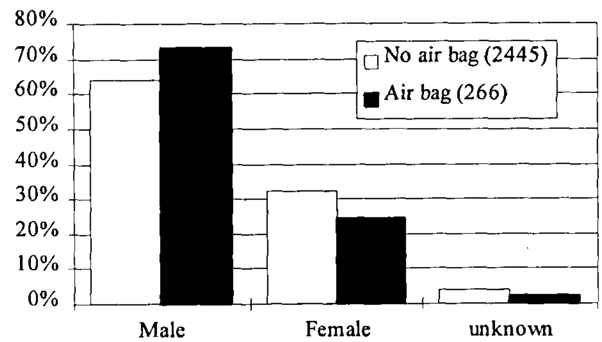

Figure 9. Driver sex.

Figure 9 shows that the proportion of male drivers–already high–is slightly higher for air bag equipped vehicles: 70-75%, compared to around 65% for non air bag vehicles.

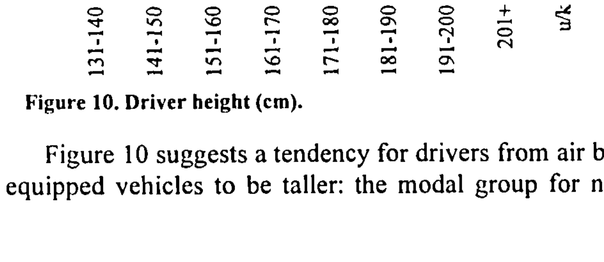

Figure 10. Driver height (cm).

Figure 10 suggests a tendency for drivers from air bag equipped vehicles to be taller: the modal group for non equipped vehicles is 161-170 cm, compared to 171-180 cm for air bag equipped vehicles. This may be a consequence of the higher proportion of males in air bag equipped vehicles. The height of many drivers is not known.

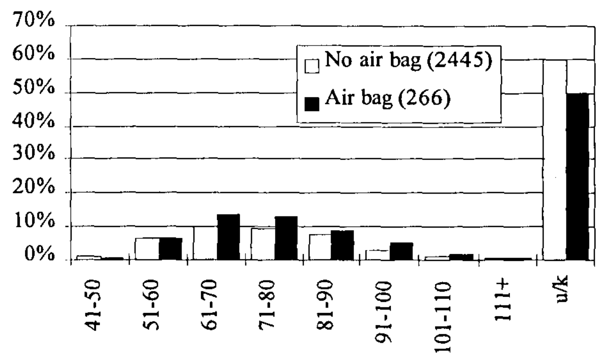

Figure 11. Driver weight (kg).

Figure 11 indicates no clear differences in the distribution of occupant weight. The weight of many drivers is not known.

INJURY PATTERNS OF BELTED DRIVERS IN FRONTAL IMPACTS

As already mentioned, the approach taken in this paper is to detect the influence of air bag on crash injury outcomes by comparing groups of *injured* occupants from air bag and non air bag vehicles. Air bags are designed to improve protection of the head–if this were their only effect, drivers with air bags would incur the same non-head injuries but enjoy a lower incidence or severity of head injury. Therefore among injured drivers from air bag vehicles, there would be a reduction in the ratio of head injuries to non-head injuries, as represented in Figure 12. This is the same thing as a rise in the ratio of non-head injuries to head injuries. In interpreting the 'location of injury' histograms in this section, it should be borne in mind that an increased proportion of non-head injuries does not necessarily imply a reduced level of protection of the chest, abdomen, legs, and so on.

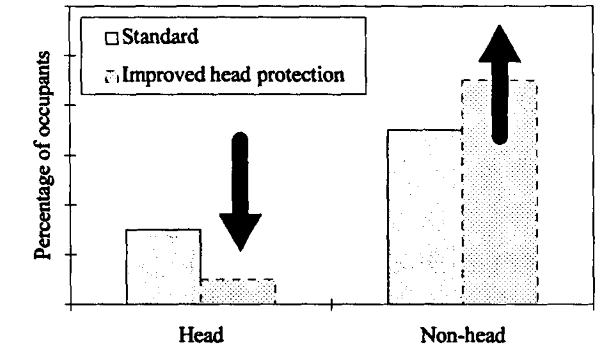

Figure 12. Schematic of how improved head protection may alter the ratio of head to non-head injuries in an injured population.

MAIS distributions and 'location of injury' charts are presented for a number of injured driver populations in this section. The point of showing (similar) MAIS distributions for the air bag and non air bag groups is to support the inference that differences in injury patterns arise from the influence of the air bag, since there would be little validity in drawing this conclusion if air bag fatalities were being compared to non air bag slight injury cases, or vice-versa. The selection of subgroups is intended to identify where the effect of air bags, if present, is most pronounced.

Table 6. Driver MAIS injury severity

	Air bag not fitted	Air bag deployed	Air bag undeployed
Not injured	862	63	32
MAIS 1	992	99	24
MAIS 2	367	28	5
MAIS 3	137	9	0
MAIS 4	35	2	0
MAIS 5	34	3	0
MAIS 6	18	1	0
Total	2445	205	61

The distribution of MAIS injury severity for drivers from frontal impacts is shown in Table 6. Uninjured drivers cannot contribute to the investigation of injury patterns, and the number of injured drivers from the undeployed group is rather low to sustain analysis. This leaves 1583 and 142 injured drivers from the non air bag and air bag deployed groups respectively as the main basis for analysis. Figure 13 shows that the distribution of maximum injury severity for the two groups is quite similar: 63-70% MAIS 1, 20-23% MAIS 2, and 11-14% MAIS 3-6.

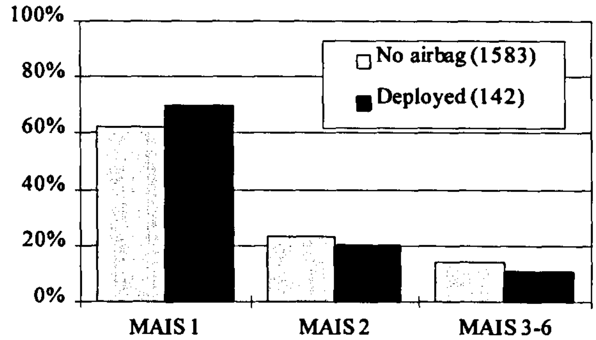

Figure 13. Maximum injury severity.

The location on the body of each driver's most severe injury is shown in Figure 14. Where an occupant had more than one body region with equally severe injuries, the body regions were weighted accordingly. For example, if an occupant had injuries of MAIS level to the chest and legs, the MAIS location was assigned 0.5 to the chest and 0.5 to the legs; similarly, if injuries of MAIS severity occurred in three regions, each region was assigned 0.33.

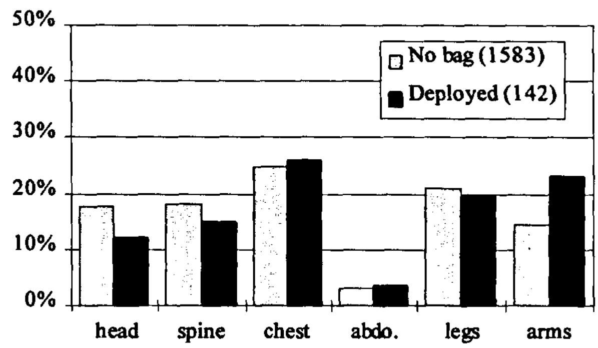

Figure 14. Location of most severe injury.

The most severe injury was only occasionally abdominal–about 3% of occupants. The chest was the most common individual site, at around 25%; the other four regions took shares around the 15-20% range. Drivers from air bag deployed vehicles had their most severe injury less often to the head and more often to the arms.

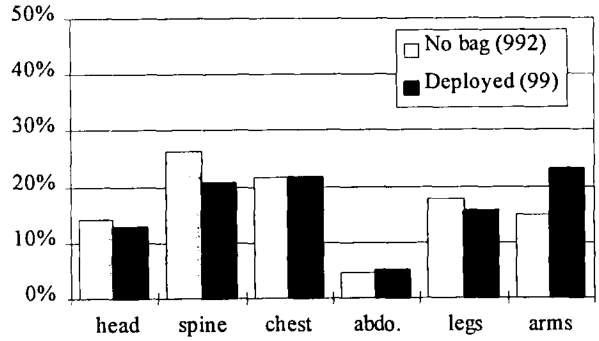

Figure 15. Location of most severe injury for MAIS 1 drivers.

Among MAIS 1 occupants, Figure 15 suggests a shift towards proportionally more arm injury and away from spinal (and neck) injury for the air bag group. The types of injury alluded to in this chart are mainly superficial bruises, abrasions and lacerations, except for the spine, which is mainly whiplash (muscle strain).

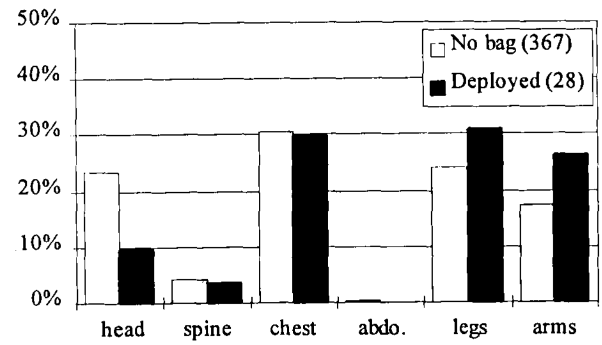

Figure 16. Location of most severe injury for MAIS 2 drivers.

Among MAIS 2 occupants, few occupants had their most severe injury located in the spine or abdomen. Figure 16 suggests a shift away from head injury among drivers from air bag vehicles.

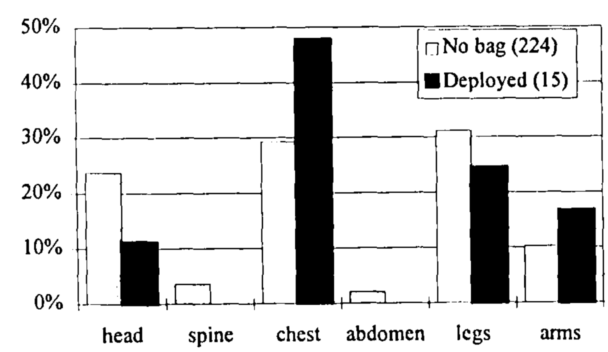

Figure 17. Location of most severe injury for MAIS 3-6 drivers.

Among MAIS 3-6 occupants, Figure 17 also suggests a shift away from head injury, in this case mainly towards the chest. With only 15 drivers from air bag deployed vehicles in this category, these results are liable to be erratic.

Figure 13 to Figure 17. Two trends emerge for drivers from air bag deployed vehicles: the head is less often the location of the most severe injury, particularly at the MAIS 2 and MAIS 3-6 levels; and the arms are more often the location of the most severe injury. At the higher injury severity levels, the incidence of the head being the most severely injured region is less than half, 10% compared to 23%; for the arms at all severities, the incidence is 23% compared to 15%. These results are consistent with the mitigation of head injury and the aggravation of arm injury in air bag deployed vehicles. At MAIS 1 level, the spine (and neck) is a common site of injury and there is a lower incidence among the air bag deployed group. This result should be interpreted with caution, since air bags tend not to deploy at the lowest impact severities when MAIS 1 outcomes and reports of whiplash are quite common. The air bag group is therefore probably understocked with these cases compared to the non air bag group (cf. Figure 4). Whiplash is discussed separately in connection with Table 7 below. A second result that should be interpreted with caution is the relatively high incidence the chest as the location of the most severe injury among the air bag group at the MAIS 3-6 level. The sample size supporting this result is low and other results in this paper do not support the conjecture that air bags are detrimental to the chest.

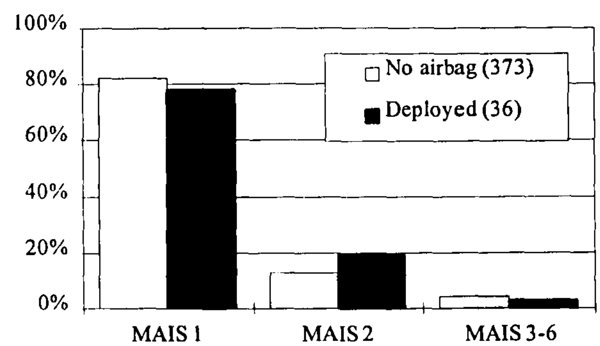

Figure 18. Distribution of MAIS for drivers with injury to one body region only.

About one quarter of drivers had injury to only one body region: 373 from non air bag group vehicles and 36 from air bag vehicles. The distribution of MAIS for these occupants is shown is Figure 18. The two groups were generally lightly injured, with around 80% MAIS 1 and less than 5% MAIS 3-6.

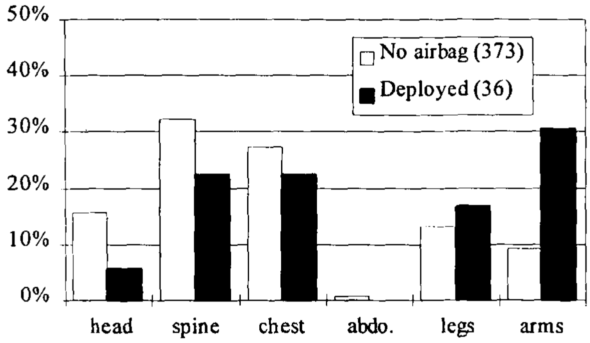

Figure 19. Location of injury for drivers with injury to one body region only.

Figure 19 shows where drivers with only one injured body region were injured. The most marked difference between the two groups of occupants is in the region of the arms: 31% for the air bag group compared to 9% for the non air bag group. This suggests that drivers of air bag deployed vehicles are specifically vulnerable to localised arm injuries, under circumstances when they may otherwise have been uninjured. The difference in spinal and neck injury is the whiplash phenomenon discussed above.

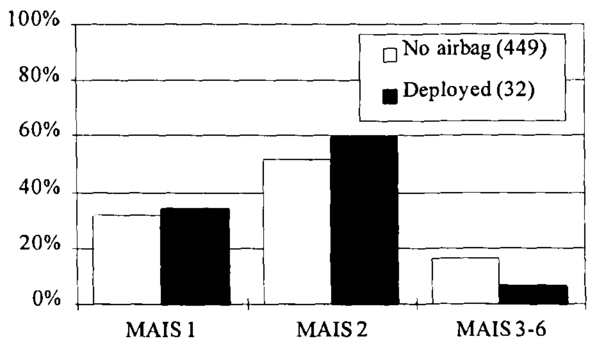

Figure 20. Distribution of MAIS for drivers with skeletal or internal injury to one body region.

Figure 20 shows the distribution of MAIS for drivers with injury to the skeletal system (mainly fractures) or internal organs in exactly one body region. There are 449 drivers from non air bag vehicles and 32 drivers from air bag deployed vehicles in this category. Lesions of the skin, brief loss of consciousness, and whiplash (muscle strain) are the main common types of injury not considered here. This group tends to be drawn from the intermediate range of injury severity. The distribution of MAIS for the two groups is similar, with over half having injury at MAIS 2 level. The MAIS 1 level injuries are mostly bone fractures.

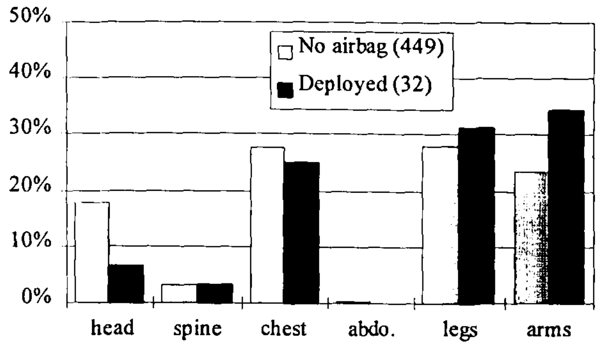

Figure 21. Location of injury for drivers with skeletal or internal injury to one body region.

Figure 21 shows where the skeletal or internal injury was located for these groups. The difference between the two groups is greatest in the region of the head and arm, indicating that the air bag influences injuries of this nature. The incidence of head injury is lower among drivers from air bag vehicles (6% compared to 18%) but arm injury is higher (34% compared to 23%).

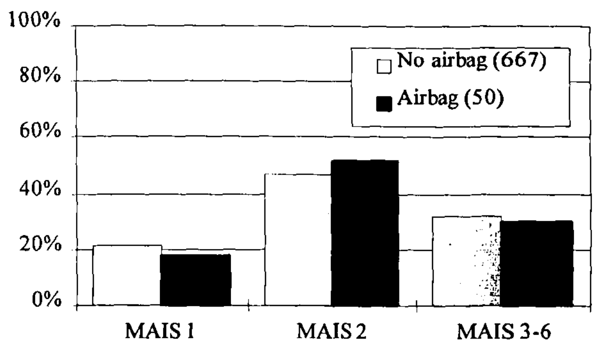

Figure 22. Distribution of MAIS for drivers with skeletal injury.

Over one quarter of injured drivers suffered skeletal injury (mainly fractures): 677 from non air bag vehicles and 50 from air bag vehicles. The distribution of MAIS for these occupants is shown in Figure 22 and is similar for the two groups. This subpopulation includes most injured drivers with MAIS 2 or MAIS 3-6 injuries (90%) but only a minority of MAIS 1 drivers (10-15%).

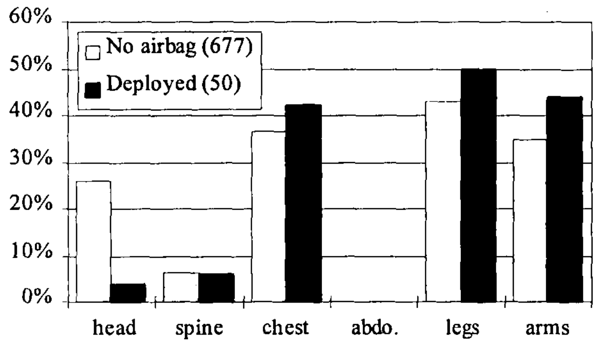

Figure 23. Location of skeletal injury.

Figure 23 shows where skeletal injuries occurred. The totals add up to more than 100% because occupants could have fractures to more than one body region. The abdomen was defined to include no bony structures and therefore registers zero. A distinctly lower proportion of drivers from air bag vehicles had fractures to the face or skull compared to drivers from non air bag vehicles (4% compared to 26%). This reduction is balanced by an even spread of increased incidence to the arms, legs, and chest (5-10%). This result strongly indicates that air bags provide protection against head fractures.

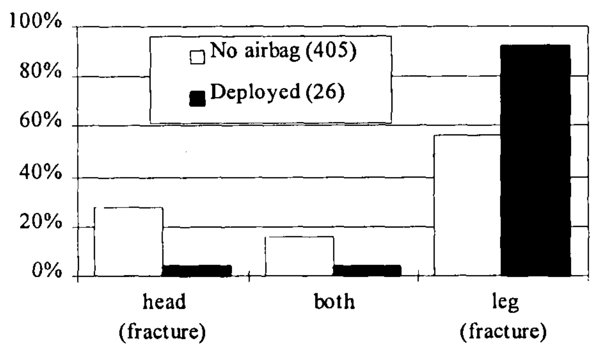

Figure 24. Ratio of occupants with head fractures and leg fractures.

In elaboration of Figure 23, Figure 24 shows the overlap between head and leg fractures for the 405 drivers from non air bag vehicles and the 26 drivers from air bag vehicles who had these injuries. Among the non air bag group, 28% had a head fracture but no leg fracture; 56% had a leg fracture but no head fracture; and 16% had both head and leg fractures. These proportions are markedly different for drivers of air bag deployed vehicles, with a shift away from head fractures, albeit on low numbers-there is only one air bag driver in the 'head (fracture)' and 'both' categories. This change of balance is repeated for head and chest fractures shown in Figure 25.

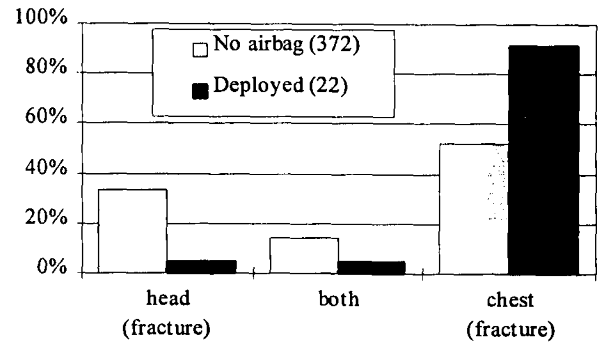

Figure 25. Ratio of occupants with head fractures and chest fractures.

The relationship between head, chest and leg fractures suggests a strong shift away from the head for drivers from air bag vehicles. These occupants were in impacts serious enough to cause leg and chest fractures but did not incur the higher ratio of facial and skull fractures experienced by the non air bag group.

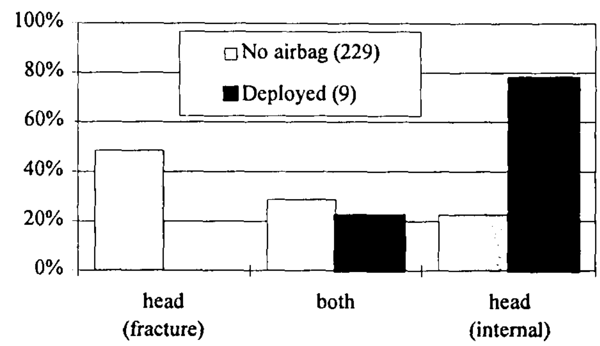

Figure 26. Ratio of occupants with head fractures and internal head injury.

Figure 26 shows the overlap between head fractures and internal head injuries (excluding brief loss of consciousness, amnesia, and other AIS 1-2 head injuries.) None of the 9 drivers from air bag deployed vehicles in this category incurred a head fracture without brain injury, in contrast to close to half of the non air bag group. This early result suggests that air bag equipped vehicles are more protective against head fractures than internal head (brain) injury. It should be noted that the number of occupants from air bag vehicles available to support this conjecture is low, only nine, and the result is therefore tentative.

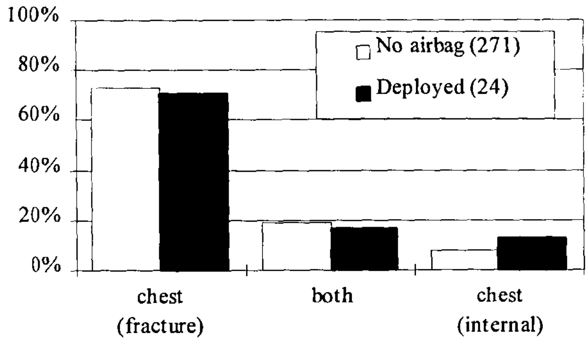

Figure 27. Ratio of occupants with chest fractures and internal chest injury.

Figure 27 shows the overlap between chest fractures and internal chest injuries. There is essentially no difference between the air bag and non air bag groups. This implies that air bags have an equal influence on the skeleton and internal organs of the chest, unlike the head. For seat belted drivers, based on the trends apparent in the data so far, it is probably a neutral influence.

Table 7. Brief loss of consciousness and whiplash.

	Air bag not fitted (1583)		Air bag deployed (142)		Air bag not deployed (29)	
Brief LOC	141	9%	5	4%	3	10%
Whiplash	599	38%	48	34%	17	59%

Brief loss of consciousness and whiplash were excluded from several analyses above. Table 7 shows a lower incidence of brief LOC among injured occupants from air bag vehicles than among those from non air bag vehicles: 4% compared to 9%. The incidence of whiplash among injured occupants from air bag and non air bag vehicles is 34% and 38% respectively. The high whiplash result for drivers from vehicles with undeployed air bag probably arises from an association between low impact severity and a high level of reported whiplash. If the two air bag groups are aggregated, there is no difference in the incidence of whiplash in air bag and non air bag vehicles (38%).

DISCUSSION

The results presented in the preceding sections cover various aspects of collision circumstances, vehicles, occupants, and injuries relevant to an assessment of air bag effectiveness. Vehicles with air bags in the CCIS sample are larger, more modern, and more often fitted with seat belt pretensioners than vehicles without air bags, and there appears to be a higher quotient of older males in the air bag equipped cars. On the other hand, the severity of impact (ETS), the objects struck, and the degree of frontal offset are very similar between the two groups. The differences associated with air bags–vehicle age, size, pretensioners etc.–are undoubtedly relevant to injury outcomes, but how important compared to air bags is difficult to say. With a relatively low sample size, there is little option but to acknowledge that any differences in injury outcomes are a collective effect of all these factors.

The strongest finding noted in the tables and charts above is an apparently dramatic drop in the proportion of injured drivers from air bag deployed vehicles with facial or skull fractures. This is based on 50 drivers with skeletal injury (in any body region). With the number of relevant cases in the CCIS database rapidly growing, however, we retain an open mind on the robustness of this phenomenon. Interestingly, the first nine drivers from air bag deployed vehicles in the database with head fractures or significant brain injury showed no fractures without brain injury, unlike half of the non air bag comparison group. If air bags provide equal protection to the skeleton and brain, the proportion of fractures to brain injuries should remain steady. This result therefore raises the possibility that European SRS air bags are providing a greater benefit for the bony facial structures and cranium than for the brain, although it should be added that results for the whole head (skeleton and internal organs) also look positive.

A second consistent trend to emerge from the analysis is that drivers from air bag deployed vehicles have arm injuries more often than the law of averages would seem to dictate. In particular, there is a substantially higher proportion of drivers with injuries *only* to the arms among the air bag group. Although these are mainly minor AIS 1 lesions, the trend apparently persists into the higher levels of injury severity. It would of course be no surprise if the arms were vulnerable to injury, because of their close proximity to the steering wheel and inflating air bag during impact. No clear, consistent trends indicating an influence of the air bag on other body regions were identified.

A review of injuries specifically attributed to the air bag in the CCIS database revealed almost entirely bruises, abrasions, strains, and sprains, mainly to the face and arms. It is difficult, however, for anyone to judge in each individual case whether these common, minor injuries are introduced by the air bag or whether the air bag merely fails to prevent their occurrence, and they therefore have not been presented in detail. On the other hand, unusual injuries or exceptional circumstances of injury like those reported from North America would be noted by the crash investigators. Our examination of the CCIS database and a number of case files unearthed no such instances and we are not aware of opinion among the investigators that abnormal events are occurring with deployed air bags.

Finally there is every indication that air bags generally deploy at impact levels that pose a statistical risk of significant head injury.A proportion also deploy at low crash severities, below where head injury occurs in non air bag equipped vehicles. There may be good technical reasons for initiating deployment at low crash severities to ensure the air bag always deploys at the threshold where head injury begins to occur.

Future work on the effectiveness of SRS air bag systems could profitably focus on head and arm injuries, particularly the relationship between facial fractures, skull fractures, and brain injury. As more data becomes available, it would be helpful to account for the separate influence of vehicle mass and other safety features associated with air bags in the European fleet. With a different method of analysis, the CCIS database may also support an assessment of the 'absolute' effectiveness of air bags in mitigating (or aggravating) occupant injury–this would be an assessment of the proportion of injuries prevented in real accidents by air bags.

CONCLUSIONS

Based on the data collected by the UK Co-operative Crash Injury Study, which currently includes details on over 140 seat belted drivers injured in frontal impacts with deployed air bags:

(1) Air bag deployment is associated with larger, more modern cars, seat belt pretensioners, and an older, more male driving population.

(2) Air bags generally appear to deploy in impacts that pose a statistical risk of significant head injury–when they are needed–and also in less severe impacts.

(3) Compared to injured drivers from non air bag vehicles, injured drivers from air bag deployed vehicles incur proportionally less head injuries and proportionally more arm injuries. The favourable head injury result arises most directly from a reduction in fractures. No clear, consistent trends indicating an influence of the air bag on the spine, chest, abdomen, or legs have been identified.

(4) No specific, exceptional types of injury or circumstances of injury associated with air bags have been identified.

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The views expressed in this paper are entirely those of the authors. The results and review of past work in the first half of the paper originate mainly from the research of R. Frampton; responsibility for the results in the second half and the overall co-ordination of the paper lies mainly with J. Lenard.

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INJURIES IN PRIMARY AND SUPPLEMENTARY AIRBAG SYSTEMS

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Abstract

In this study, an attempt was made to compare injury rates to restrained occupants in airbag deployed and non-airbag deployed vehicles in four different countries. Analyses were conducted both on "raw" data-sets and also with assumptions that injuries to the lower limbs are unaffected through interaction with a deploying airbag.
This study reveals problems with comparing data from more than one country and highlights a requirement for a harmonised global approach to accident data collection particularly with a corresponding growth in vehicle export markets.

Introduction

In terms of the history of vehicle safety, the driver airbag, a device designed to control forces and deceleration to the human body during a traffic crash is a relatively new addition to the vehicle, despite being conceptualised in the 1950's.

In North America, prototype airbags first became available in the 1970's but not until the mid-1980's were they mass-produced for fitment in passenger cars. Such airbags were designed to be used as 'primary' restraint systems; that is, they were designed to provide a baseline of protection to those occupants who do not wear seat belts and to add protection to those who do use belts.

Elsewhere, airbags became available somewhat later than in North America. Generally they took the form of supplementary restraint systems (SRS's) which provide optimum protection to the restrained occupant in a frontal crash.

Because of relatively high seat-belt wearing rates in Europe and Australia, airbag systems tend to be designed differently to those in USA (Fildes et al, 1996). The airbag deployment threshold is usually set higher (around 25 km/h, depending on the manufacturer and crash circumstances) so that the airbag deploys only when a crash is of such severity that the seat-belts alone can not afford complete protection. The rate at which the airbag inflates also tends to be lower. This means that different airbag systems are used in these vehicles when compared with the more aggressive systems developed for unrestrained occupants in North America.

In terms of providing optimal crash protection, it has been suggested that the combination of seat belts and airbags provides the most effective restraint system (Williams & Lund, 1988). Although the development and testing of airbags is achieved in laboratory studies under rigorously controlled crash-tests, a true assessment of the injury-reduction capability of such systems can only be determined from studies of real-world crashes in which the airbag has deployed. Such studies have revealed mixed fortunes; studies of larger more aggressive airbag systems in North America, (where the belt usage rate is in the region of 60%) have raised some issues with deployments (Huelke et al, 1994; Huelke and Reed, 1996a & 1996b; Dalmotas et al, 1996) while in other countries where the restraint use is high, the benefits of less aggressive systems are apparent (Langwieder et al, 1996, Fildes et al 1996).

However, in parallel with these individual country-specific analyses of airbag effectiveness, there is an increasing trend towards global trade and importation or exportation of vehicles (Thomas & Otte; 1996). Consequently, manufacturers find it advantageous to minimise the design variation necessary to sell their products internationally. Such manufacturers also aim to reduce injuries sustained in their vehicles and can gain a marketing advantage in being able to demonstrate the safety of their products. Therefore it is necessary to provide the commercial car industry with in-depth feedback on field-studies of airbag performance. Optimally, research should be able to provide governments and industry with comparisons of airbag performance in differing countries. This would provide evaluations of product capability and would aid identification of factors that contribute to overall product effectiveness in each country. However, in practice, the process of providing data that is comparable across research organisations is difficult to achieve because of differences in interpretation of procedural guidelines, sampling considerations, resources and customer-driven specifications. In this study, we provide a case-example in which a comparison of injury outcomes across countries was undertaken.

Method

Data were obtained from recent retrospective studies of vehicle crashes and occupant injuries in the USA (NASS database), Australia (CVF database), Canada (PCS and the ADS databases) and Germany (GDV database). These databases involved a combination of person-entry and vehicle-entry criteria (tow-away crashes) at varying levels of crash severity. Vehicles in each study were inspected a few days after the collision in panel shops and/or recovery yards. Injury information was obtained either from the occupant themselves or from hospital or coronial records. Injuries were rated according to the Abbreviated Injury Scale 1985 or 1990 editions.

All vehicles were involved in a frontal impact in which the principal direction of force (PDoF) applied to the front of the vehicle was between 2 and 10 o'clock. Seat belt use in each study was determined retrospectively at the time of inspection based on the available evidence of seat belt loading, such as markings on the webbing, buckle and/or tongue, or from distortion of the D-ring or B-pillar cladding.

Data were collected on seat belt use, airbag fitment and deployment, impact direction, vehicle damage, occupant injuries and contacts. Crash severity (delta-V) was estimated from damage profiles using the CRASH 3 program (NHTSA, 1986) for the USA and Australia or from more detailed calculations in Germany (delta-V was not available in the Canadian database).

Only a limited number of analyses were possible at this time due to possible confounding influences and time and resource constraints available. Given the focus on assessing airbag benefits in this paper, only data for drivers in frontal crashes who wore their seat belts in vehicles with or without airbags were analysed. Representatives in each country undertook the analysis of their own database and these findings were collated at the Monash University Accident Research Centre in Melbourne, Australia.

Results

Raw Data Analysis

An initial analysis was undertaken of the data set analyses immediately available in each of the four countries and these findings are presented in Tables 1-2 and Figure 1.

These results show that for the US, Australia and Canada, airbags led to a reduction in AIS 2+ injuries in most body regions. For Germany, it was only possible to examine injury differences to the head, chest, abdomen and lower limbs from this database which showed airbag benefits for the head and abdomen but dis-benefits to the chest and lower limbs.

Table 1 *Probability of injury by country for drivers with seat belt restraints alone.*

Unadjusted Injury Risk - AIS 2+				
Body Region	USA	Australia	Canada	Germany
Head	2.0%	12.9%	7.6%	9.5%
Face	0.6%	2.4%	3.7%	
Neck	0.1%	3.5%	0.6%	
Chest	1.7%	14.1%	5.7%	3.5%
Abdo/pelv	0.5%	2.4%	2.1%	3.0%
Spine	0.1%	1.2%	1.3%	
U. limb	1.9%	7.1%	5.3%	
L. limb	1.6%	4.7%	6.6%	8.5%

Table 2 *Probability of injury by country for drivers with seat belt and airbag restraints.*

Unadjusted Injury Risk - AIS 2+				
Body Region	USA	Australia	Canada	Germany
Head	1.0%	4.8%	2.9%	5.4%
Face	0.2%	-	0.3%	
Neck	0.1%	-	0.0%	
Chest	1.2%	6.3%	1.4%	8.1%
Abdo/pelv	0.2%	-	0.6%	2.7%
Spine	0.1%	3.2%	0.6%	
U. limb	2.6%	4.8%	2.3%	
L. limb	3.5%	4.8%	1.7%	10.1%

It is possible that the German results can, in part, be explained by an over-representation in the sample of older drivers. Apart from the German results, this suggests that airbags are a benefit in reducing severe injuries in the areas where improvements are expected, notably the head, face, chest and abdominal regions. Some aspects of these findings need to be discussed.

First, the size of effect was quite varied across all countries. For example, the US head and chest reduction was relatively small compared to all others and especially so for Australia. This may reflect differences in airbag performance between countries where the design criteria were known to be different. In Australia and Germany, for instance, airbags are designed for a restrained population, whereas North American airbags are designed to be used with an unrestrained population and therefore deploy at lower thresholds and are more aggressive. However, there are other possible explanations for this also. It is understood that the NASS sample in the US includes non-deployed airbag cases in the seat belt restrained category in these data, thus the seat belt-only sample could have been of lower crash severity overall which might help explain this difference.

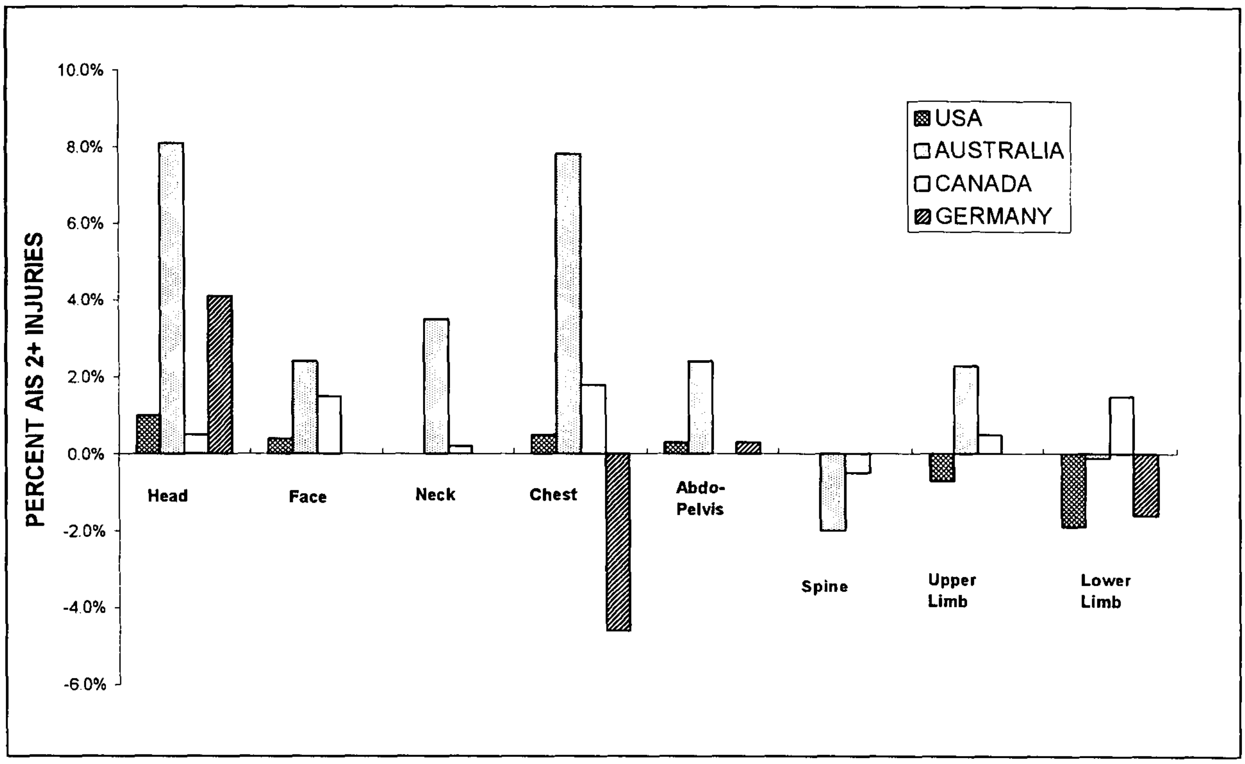

Figure 1 *Difference in percent of injuries for drivers with seat belt only and seat belt and airbag restraints.*

In three of the four countries, lower limb injuries were more frequent in the airbag sample than the seat belt only sample which was unexpected as airbags should have little influence on these injuries. This further suggests that the two samples in some of these countries were not of similar crash severity and therefore, these findings may be quite biased. Furthermore, it became apparent that not all samples had similar entrance criteria. In the USA and Australia for example, both samples were vehicle based with a tow-away threshold. In Canada and Germany, at least on of the samples was injury based where an occupant needed to be injured for inclusion.

In Australia, it was known that the crash severity distributions between samples were quite similar which is reflected in the comparatively similar lower limb results in this country. Unfortunately, though, at this time, it was not possible to control accurately for delta-V in the analyses of the other countries. One way in which these severity differences might be alleviated would be to assume that there should be no difference in lower limb injuries between the samples in each country and to adjust all other injuries by equating lower limb injuries between the two samples. This was only possible though for intra-countries and for samples involving vehicle entrance criteria, hence these adjustments were confined to the USA and Australian samples only.

Table 3 *Probability of Injury by Country for the* *adjusted seat belt only data*

Unadjusted Injury Risk - AIS 2+		
Body Region	USA	Australia
Head	4.4%	13.2%
Face	1.3%	2.5%
Neck	0.2%	3.6%
Chest	3.7%	14.4%
Abdo/pelv	1.1%	2.5%
Spine	0.2%	1.2%
Upper limb	4.2%	7.3%
Lower limb	3.5%	4.8%

NB: Data were adjusted by equating lower limb injury %s with the seat belt and airbag distributions and then weighting all other body region %s accordingly.

Adjusted Data Analysis

Table 3 shows the seat belt only sample results from Table 1 re-adjusted to equate with the same frequency of lower limb injuries as in the seat belt and airbag sample in Table 2 for each of the four countries. The different injury outcomes when subtracting the original airbag findings from the adjusted seat belt only sample are shown in Figure 2 below.

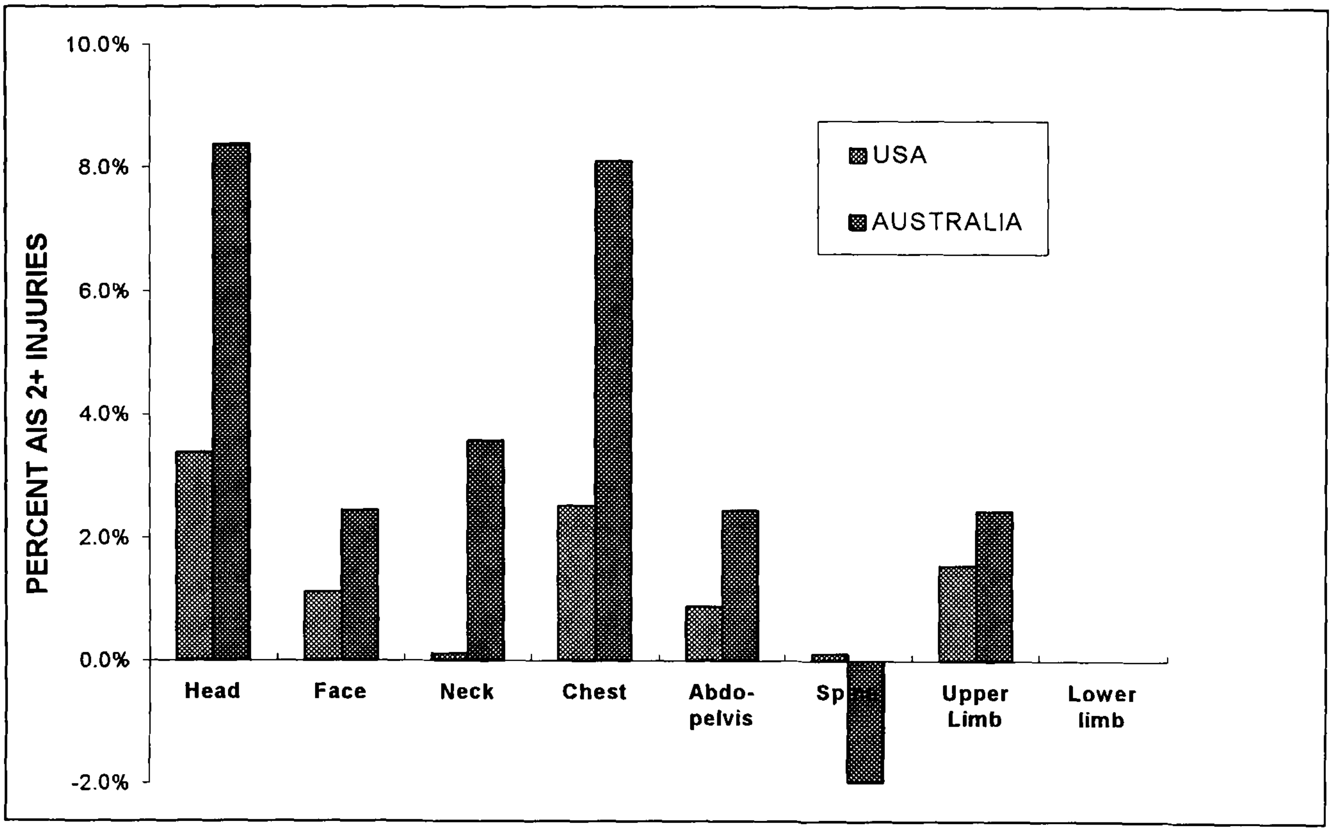

Figure 2; *Difference in percent of injuries for drivers with the adjusted seat belt only and the original seat belt and airbag restraints.*

The adjusted results show substantial increases in injury reductions for US airbags after adjustment, although still less than that reported for Australia for head, neck, chest, upper limb and abdominal injury benefits. This can be explained by the fact that airbags in the USA have a much lower deployment threshold than in Australia and thus it would be expected that overall more injuries would be apparent for the higher deployment (higher crash severity) population of cars. Thus, even with this adjustment, the two samples were still substantially different in other ways that could not be controlled for in this preliminary analysis.

The apparent increase in spinal injuries in the Australian airbag sample has been previously reported in Fildes et al (1996) and is probably a function of the small sample of cases available for this analysis. As noted earlier, this needs to be monitored closely in future analyses.

Discussion

This comparative analysis of airbag performance across countries has demonstrated the difficulty of undertaking these analyses without the ability to control adequately for all possible extraneous influences in these data sets. Given greater resources and more time, it would be possible to obtain the four data sets and to undertake an analysis with more control of the possible confounding factors such as crash type and severity, vehicle mass and so on. Unfortunately, this was not possible at this stage.

Even so, this analysis demonstrates that airbags do reduce occupant injury in all of the four countries examined here. In particular, there were reductions in life threatening injuries to the head, chest (except for Germany) and to the abdomen and pelvic regions. These results are especially important for guidance to designers and authorities as countries move towards harmonisation and optimising the benefits of this new safety technology.

While it seemed appropriate to equate the USA and Australian samples on the basis of similar severe lower limb injury results, the legitimacy of this procedure is not fully understood. For example, seat belt wearing status is not always reliable as seat belt loading evidence can be difficult to find on occasions. This is particularly so for the airbag sample as these devices can often alleviate belt loading in many minor severity crashes. Of more importance, though, is the consequence of applying a constant weighting factor to all body region injuries equivalent to the lower limb injury differences between the two samples.

Without more definitive evidence, it is not possible to judge what effect this had on the effectiveness figures and therefore these findings need to be treated with a degree of caution.

The Need for Harmonised Databases

This analysis has illustrated the benefits of both primary and supplementary restraint airbags as well as potential problems in attempting to compare safety performance of vehicles across countries. More precision with these results would have been possible had greater control been possible over some of the extraneous influences when undertaking these analysis. While this was partly a resource issue, there were still a number of fundamental differences in the data collection methods that would always be a source of contamination in these results.

It is clear that the only way to evaluate safety performance unambiguously using real world injury data is by the establishment of harmonised data collection methods and databases between countries. A number of key variables need to be included such as crash type, crash severity, injury coding, seat belt wearing, airbag deployment, and so on to permit comparative analyses to be undertaken. Also, the data collection methods and entrance criteria must also be consistent to be sure that the findings are meaningful and reliable.

It is understood that the European Commission have a committee who are working towards the establishment of a harmonised data collection procedure in Europe, the so called Community European Road Accident database system (CARE). Currently, there is a committee formed by the European Union to examine the feasibility of such a database and what information should be contained on it. It is still very much in the formative stages of the project and a 10 year time-line has been established for its possible introduction. There is, at present, a long standing OECD database (IRTAD) containing details on fatalities within Europe and CARE which may provide supplementary injury information.

The degree to which development and implementation of this data collection procedure and database would suffice the needs identified here would be worthwhile establishing. As this committee efforts seems to be aimed at harmonised mass data records, there may not be sufficient detail included to provide the degree of control required for these analyses. If this is the case, there would be considerable merit in the formation of a harmonised procedure for in-depth crash investigation procedures. This would provide at least two benefits.

1. It would provide manufacturers and government authorities with the data necessary to compare in-vehicle safety performance internationally.
2. It would enable countries to share their data and thus permit more powerful analyses using well controlled and detail information not currently available.

As this study has shown, at present, it is not straightforward process to combine data from several sources to derive a composite data-set with which in turn to empirically answer research questions. Therefore any degree of harmonisation between crash injury studies may have considerable benefits if an acceptable approach to the method of harmonisation can be found.

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AIR BAG COLLISION PERFORMANCE IN A RESTRAINED OCCUPANT POPULATION

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ABSTRACT

For the past five years, the Road Safety and Motor Vehicle Regulation Directorate of Transport Canada has conducted studies of motor vehicle collisions which have resulted in air bag deployments. Canada enjoys high usage of seat belts and, consequently, the vast majority of occupants in the crashes under study were fully restrained. This provided an opportunity to evaluate the effectiveness of air bags as supplemental restraint systems. Results from this process demonstrated that thresholds set by manufacturers for air bag deployment were generally lower than necessary to protect fully restrained occupants. Furthermore, the major drawback of first generation air bags was their aggressivity which often gave rise to air bag-induced injuries to belted occupants. Now, many 1998 vehicles have been equipped with "depowered" air bags. The present paper provides a brief overview of the collision experience with air bags in Canada, and presents some preliminary results from in-depth studies of real world crashes involving second generation air bags.

INTRODUCTION

With the advent of widespread availability of supplementary air bags in Canadian vehicles, Transport Canada initiated a study of real world crashes in which air bags deployed. Starting in October, 1993, eight university-based research teams conducted in-depth collision investigations on convenience samples of such incidents, focusing on crash severity and occupant injury mechanisms (Dalmotas, 1995a).

The air bag study has taken place in three distinct phases. Initially, any air bag deployment crash was included in the study, irrespective of occupant injury outcome. In Phase II of the study, the criteria for inclusion required that an occupant protected by an air bag which deployed in a crash was transported to hospital for examination and/or treatment.

Phase III of the study was recently initiated. The focus of the study has shifted to collisions involving late model vehicles in an attempt to capture incidents involving depowered air bag systems. In Phase III of the study, any crash involving air bag deployment in vehicles less than 3 years in age is captured, these cases being once again independent of injury outcome.

PHASE I AND PHASE II STUDY RESULTS

The initial phase of the air bag study took place between October, 1993 and May, 1995. During this period, a total of 409 air bag crashes were documented. Driver restraint use in the case vehicles was 93% (380). Twenty-three percent (95) of vehicles experienced deployment of passenger air bags, with 36 right front passengers present, 89% (32) of whom were belted.

The second phase of the study was conducted during the period June, 1995 through August, 1997. A total of 309 cases were identified in which an occupant protected by an air bag was transported to hospital following the crash. Seat belt usage by drivers was 87% (268). Sixty-one percent (190) of the vehicles were equipped with dual air bags. There were 92 right front passengers present where passenger bags deployed, 93% (86) of whom were restrained.

Summary information for these two initial phases of the study, providing seat belt usage rates, injury severity and body region, and collision severity, is provided in Tables 1 through 4. As might be expected, given the different case selection criteria, there was a distinct shift towards higher crash severities and greater degrees of injury between Phase I and Phase II of the study. In Phase I, about 75% of case vehicles had estimated barrier speeds (EBS) of 25 km/h or less, compared to about 53% for Phase II. The injury rate for front seat occupants in Phase I was about 65% compared to 92% for Phase II. Face, upper extremity, and lower extremity were the most common injury locations, with an increased percentage of lower extremity injuries and a decreased percentage of facial injuries in Phase II.

Detailed commentary on the results of our earlier field accident investigations, including many case studies, have been reported previously in the literature (e.g. Dalmotas, 1996). The highlights of our findings were as follows:

- Supplementary air bags, in combination with manual seat belts, reduce serious head and facial injuries in high severity crashes.
- There is an increased risk of injury in low severity collisions, especially to the upper extremities and face, over that which would be expected for belted occupants in equivalent crash situations.

Table 1.
Occupants Involved in Air Bag Deployment Crashes

Air Bag Study	Phase I		Phase II		Phase III	
	Driver	Passenger	Driver	Passenger	Driver	Passenger
Total number of cases	409	409	309	309	84	84
Deployments	409	95 (23%)	309	190 (61%)	84	79 (94%)
Front occupants with air bags	409	36 (38%)	309	92 (48%)	84	21 (25%)
Belted front occupants with air bags	380 (93%)	32 (89%)	268 (87%)	86 (93%)	78 (93%)	18 (86%)

Table 2.
Injury Severity for Belted Occupants Involved in Air Bag Deployment Crashes

	Phase I		Phase II		Phase III	
MAIS	Driver	Passenger	Driver	Passenger	Driver	Passenger
0	134 (35%	12 (38%)	22 (8%)	8 (9%)	27 (35%)	4 (22%)
1	217 (57%)	18 (56%)	174 (65%)	55 (65%)	45 (58%)	12 (67%)
2	20 (5%)	1 (3%)	43 (16%)	11 (13%)	3 (4%)	2 (11%)
3	6 (2%)	1 (3%)	15 (6%)	6 (7%)	1 (1%)	-
4	3 (1%)	-	7 (3%)	1 (1%)	1 (1%)	-
5	-	-	4 (2%)	2 (2%)	1 (1%)	-
6	-		2 (1%)	2 (2%)	-	-

Table 3.
Injury Frequency by Body Region for Belted Occupants in Air Bag Deployment Crashes

	Phase I		Phase II		Phase III	
Body region	Driver	Passenger	Driver	Passenger	Driver	Passenger
Head	26 (4%)	-	39 (5%)	12 (5%)	3 (2%)	1 (3%)
Face	166 (26%)	25 (46%)	163 (19%)	74 (29%)	20 (14%)	14 (38%)
Neck	15 (2%)	-	16 (2%)	8 (3%)	-	-
Thorax	67 (11%)	6 (11%)	119 (14%)	35 (14%)	18 (13%)	5 (14%)
Abdomen	19 (3%)	3 (6%)	28 (3%)	13 (5%)	5 (3%)	-
Spine	42 (7%)	-	20 (2%)	10 (4%)	6 (4%)	2 (5%)
Upper Extremities	184 (29%)	10 (19%)	238 (28%)	46 (18%)	57 (40%)	8 (22%)
Lower Extremities	119 (19%)	10 (19%)	215 (26%)	61 (24%)	35 (24%)	7 (19%)

Table 4.
Equivalent Barrier Speeds (EBS) of Case Vehicles

EBS (km/h)	Phase I	Phase II	Phase III
0-15	75 (21%)	24 (9%)	11 (15%)
16-20	117 (33%)	66 (25%)	27 (36%)
21-25	75 (21%)	51 (19%)	21 (28%)
26-30	39 (11%)	47 (18%)	9 (12%)
31-35	27 (8%)	26 (10%)	2 (3%)
36-40	8 (2%)	20 (8%)	1 (1%)
>40	18 (5%)	31 (12%)	4 (5%)

- Females show a higher rate of air bag induced injury in low speed collisions than males, especially with respect to the upper extremities.
- Air bag deployment thresholds are too low for optimal protection of belted occupants.
- Air bag deployment characteristics are overly aggressive for optimal protection of fully restrained occupants.

Of particular concern from the results of our early field studies was a number of cases of air bag induced fatal injuries resulting to occupants involved in minor frontal collisions. Three such cases, involving two drivers and one right front passenger, have been reported previously in the literature (Dalmotas, 1995b; McClafferty, 1997; German, 1997). Since the publication of these cases, two additional driver fatalities have been identified. These two cases are briefly reviewed below:

ACR3-1919: A 1996 Lexus ES300 was travelling southbound on a snow and ice covered residential street. The driver failed to negotiate a left curve and ran off the road to the right. The vehicle travelled across the lawn of a residence, striking a small sapling, breaking through two wooden fences, and finally impacting the corner of a garage (12FLEW1). The latter impact resulted in the deployment of both front air bags.

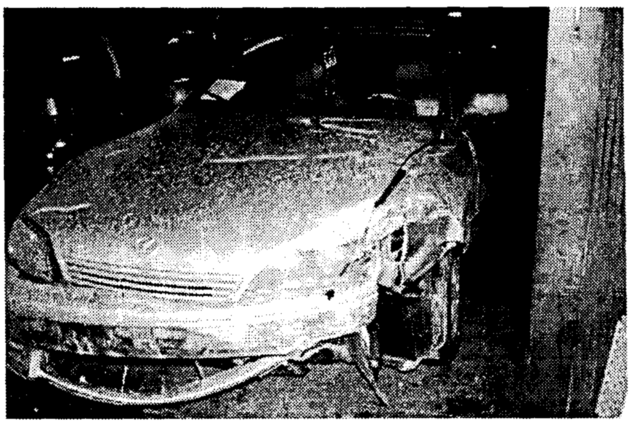

Figure 1. 1996 Lexus ES300.

The driver of the Lexus (44 years, female, 157 cm, 53 kg) was using the available three-point seat belt system. The investigating police officer indicated that the driver's seat was positioned close to the steering wheel. Subsequent detailed examination of the air bag assembly identified cosmetic transfers on both the air bag cover and fabric. These witness marks indicated that the driver's head was in extremely close proximity to the air bag module at the time of deployment.

The driver was unresponsive at the collision scene. She was transported to hospital where attempts at resuscitation were unsuccessful. No autopsy was conducted. The cause of death was stated as closed head injury. Other recorded injuries were contusions to the face, chest, and upper right arm, and a burn to the middle and index fingers of the left hand.

ASF2-1505: A 1992 Ford Tempo was travelling southbound along a two-lane, undivided rural highway. The road was wet as there was light precipitation. A vehicle ahead of the Tempo braked. The Tempo's driver also braked, but lost directional control. The car crossed the centre line and entered the east ditch. The front of the Tempo struck the back slope of the ditch (12FDEW1) at which point the driver's air bag deployed.

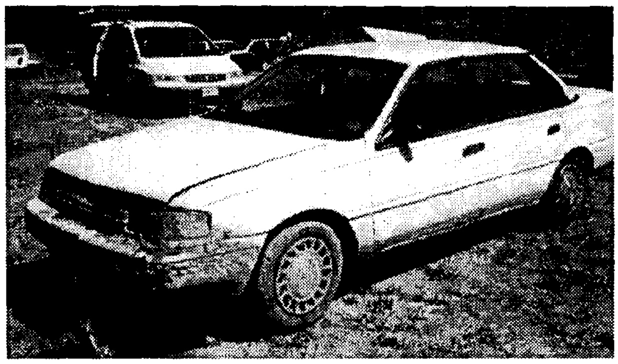

Figure 2. 1992 Ford Tempo.

The driver (79 years, female, 155 cm, 77 kg) was fully restrained with her seat in the forward of middle position. Emergency medical personnel arrived within 15 minutes of the collision. The driver was coherent and complaining of chest pain. She was removed from the vehicle and transported to hospital. Later the same day, medical complications arose and the driver was transported to a trauma centre where she died early the next morning. The driver sustained a comminuted fracture of the left lateral mass of C1, multiple bilateral rib fractures, a lacerated aorta, a fractured sternum, minor contusions, lacerations and abrasions to the face, chest and extremities.

PHASE III STUDY RESULTS

The third phase of the study was commenced in September, 1997. To date a total of 84 cases have been investigated. Summary data for this current phase of the study are included in Tables 1 through 4.

It is interesting to note that in the 84 collisions studied, 94% (79) case vehicles were equipped with dual air bags. This underscores the increasing availability of supplementary air bags in the vehicle fleet.

At the present time, the small number of cases with depowered air bags and the number of vehicle occupants in this latest phase of the air bag study precludes drawing any firm conclusions as to the effectiveness of recent air bag designs. Furthermore, in reviewing the data presented in the tables, one must consider that included is a mix of 1996-97 model year vehicles with first generation air bags, and 1998 model vehicles, most of which were equipped with depowered air bag systems.

Given the very limited data which are currently available it is instructive to extract the subset of 1998 model year vehicles which are known to have been equipped with second generation air bags. Amongst the cases in the current study were 17 vehicles of model year 1998. Ten of these vehicles were determined to have been equipped with depowered air bags. The following case studies highlight the findings with respect to these latter vehicles:

ACR4-1108: A 1998 Ford Contour was turning left out of a parking lot. The Contour's driver observed a vehicle approaching from her left, but believed she had sufficient time to complete the turn. The driver of the oncoming 1990 Oldsmobile Ciera braked but was unable to avoid a collision. The front of the Ciera (12FYEW1) struck the left rear quarter panel of the Contour (09LZEW2). Both front air bags in the Contour deployed.

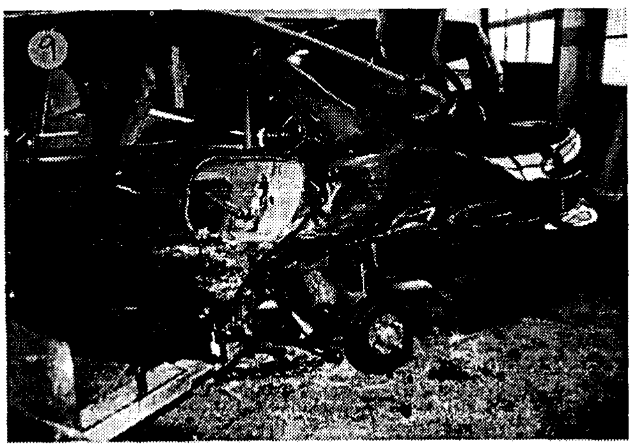

Figure 3. 1998 Ford Contour

The Contour's driver (54 years, female, 157 cm, 54 kg) was fully restrained, with her seat adjusted to the forward of middle position. The driver sustained contusions over the hips and left shoulder as a result of seat belt loading, a contusion to the right elbow from contact by the deploying air bag, and a contusion to the left knee from contact with the door interior (MAIS 1).

ACR4-1117: The case vehicle, a 1998 Dodge Neon, was travelling northbound on a two-lane, undivided, urban collector in foggy conditions. The car came up to a Y-intersection where its right front end struck a utility pole in the gore area. The pole penetrated completely through the vehicle's structure (01FRAW9). The front portion of the vehicle continued ahead and rolled down an embankment; the rear portion remained close to the pole.

The driver (25 years, male, 180 cm, 99 kg) was belted and seated fully rearward. Both front air bags in the case vehicle deployed. The driver was fatally injured in the crash. He suffered an open skull fracture, right haemothorax, a fracture to the right humerus, and fractures to both lower legs (MAIS 5).

Figure 4. 1998 Dodge Neon

ACR4-1308: A 1998 Acura 1.6 EL was travelling westbound along an urban street at night. The driver slowed down as she approached an intersection, as the traffic light was red. At the same time, a 1978 John Deere snow plow was heading northbound on the intersecting street. The driver of the snow plow intended to turn right at the intersection but, due to the slippery road, the vehicle rotated 180 degrees clockwise, and its left rear wheel struck the front of the Acura (12FDEW1). Both front air bags in the Acura deployed in the impact.

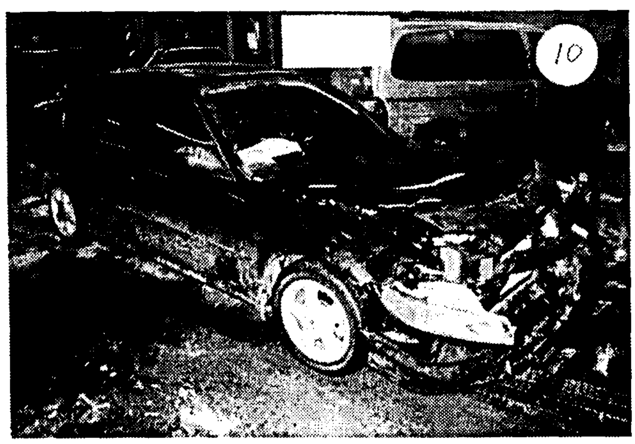

Figure 5. 1998 Acura 1.6 EL

The fully restrained driver of the Acura (20 years, female, 160 cm, 53 kg) had her seat adjusted in the forward of middle position. She received a sprained left shoulder (MAIS 1) due to seat belt loading. She also complained of pain to the chest, neck, back, both hands and chest.

The fully restrained, right front passenger in the Acura (22 years, male, 178 cm, 75 kg) had his seat adjusted rearward of middle. He sustained a contusion to his right hip due to seat belt loading (MAIS 1). Following the crash, this occupant fell to the ground, possibly losing consciousness for several seconds. He received a facial contusion as a result of striking the ground.

ACR4-1309: At the end of an afternoon, a 1998 Pontiac Sunfire was travelling southbound along a four-lane undivided city street. The Sunfire's driver was alcohol impaired and allowed his vehicle to travel into the northbound passing lane. The driver of an oncoming 1990 Chevrolet Cavalier swerved to the left, trying to avoid a collision; however, the right front corner of the Sunfire sideswiped the right side of the Cavalier. As a result of this impact, both the Sunfire's front air bags deployed. As the Sunfire continued past the Cavalier, it came into a head-on crash with a 1991 Ford F-350 pickup truck which had been following the Cavalier. This impact resulted in extensive crush to the front structure of Sunfire, and overriding of the front bumper (12FDEA4).

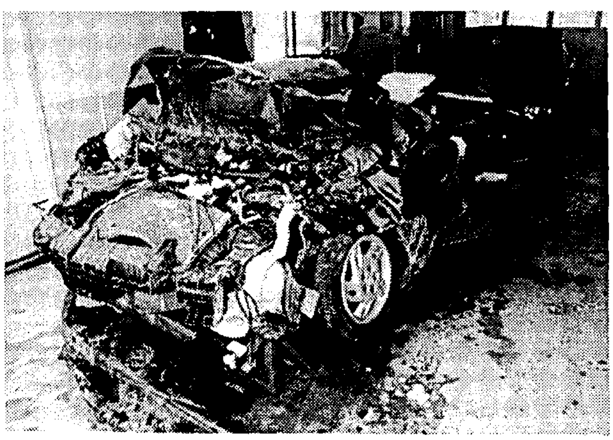

Figure 6. 1998 Pontiac Sunfire

The driver of the Sunfire (38 years, male, 191 cm, 90 kg) was fully restrained and was sitting in the rearward of middle position. He sustained fatal injuries (MAIS 5) in the collision with the pickup truck, as a result of major loading to his chest by his vehicle's steering wheel, which was severely deformed. He suffered multiple bilateral rib fractures, lacerations to the heart and vena cava with haemo-mediastinum, and multiple lacerations to the liver with haemo-peritoneum. He also sustained a contusion to the scalp and lacerations to the right knee.

ACR4-1506: The driver of a 1998 Ford Explorer was attempting to turn left at an intersection with a busy arterial roadway. In his haste to complete the turning manoeuvre he cut the corner too sharply and the left front end of his vehicle struck a utility pole at the edge of the median (12FLEN1).

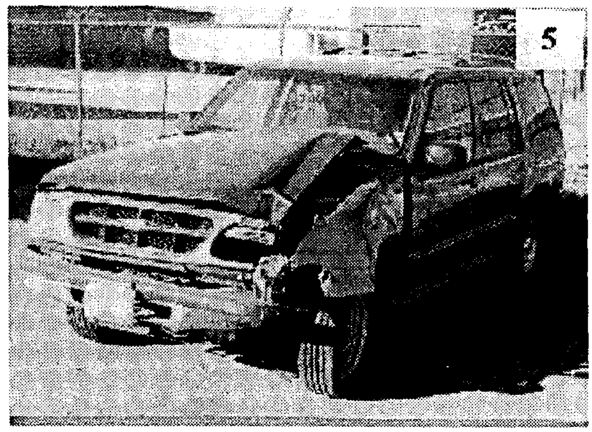

Figure 7. 1998 Ford Explorer

The driver (29 years, male, 180 cm, 73 kg) was fully restrained with his seat positioned rearward of middle. Both air bags in the utility vehicle deployed. The driver was uninjured (MAIS 0).

ACR4-1508: A 1998 Jeep Grand Cherokee was travelling southbound on an urban arterial at night. Snow was falling and the road was wet with icy sections. The vehicle entered a moderate downgrade at which point the driver lost directional control. The Cherokee rotated clockwise through 360 degrees and its front bumper struck (11FDEW2) a retaining wall on the west side of the road. Both air bags in the vehicle deployed in the impact.

Figure 8. 1998 Jeep Grand Cherokee

The driver (26 years, male, 188 cm, 91 kg) was accompanied by a right front passenger (33 years, female, 173 cm, 68 kg). Both occupants were fully restrained. The driver's seat was fully rearward, while the passenger's seat was in the middle position.

Both occupants braced prior to impact with the wall. The driver was uninjured (MAIS 0). The passenger, sustained abrasions to both thighs from contact by the air bag (MAIS 1). She also complained of numbness to the left nostril and of lower back pain.

ACR4-1512: A 1998 Ford Mustang was travelling southbound along a four-lane undivided road. The roadway was snow covered and rain was falling. While attempting to turn left into a private driveway the driver lost directional control. The vehicle mounted the east curb where its front end struck a group of small trees and metal posts (12FDEW2).

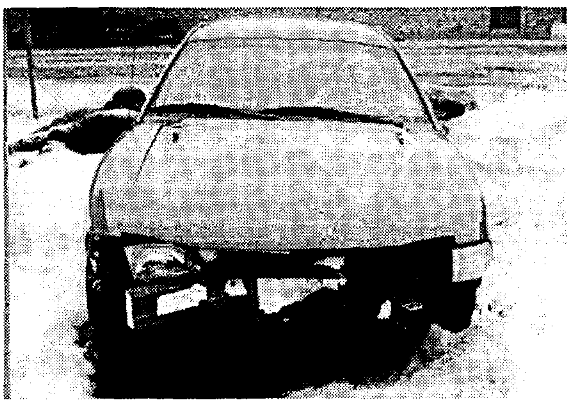

Figure 9. 1998 Ford Mustang

The driver (46 years, male, 178 cm, 70 kg) was fully restrained with his seat in the middle position. He complained of soreness to his neck and back (MAIS 0).

ACR4-1513: A 1988 Acura Legend was travelling westbound in the driving lane of a freeway and was being followed by the case vehicle, a 1998 Chevrolet Cavalier. The road was congested and, as the Acura approached an entrance ramp, traffic ahead slowed to a stop.

Figure 10. 1998 Chevrolet Cavalier

The Acura's driver brought his vehicle to a halt. The driver of the Cavalier braked, but the front of his vehicle (12FDEW1) struck the rear of the Acura (06BDLW1).

The fully restrained driver (40 years, male, 170 cm, 65 kg) of the Cavalier had his seat adjusted close to the middle position. Both front air bags deployed. The driver was uninjured (MAIS 0).

ACR4-1516: A 1998 Honda Civic was travelling northbound along an urban collector road and was in the process of passing a stationary transit bus. A 1991 Toyota Previa entered the roadway from a private driveway just ahead of the bus. The right front end of the Civic (01FZEW1) struck the left front corner of the Previa (10LFEW1).

Figure 11. 1998 Honda Civic

The Civic's driver (22 years, male, 188 cm, 77 kg) was belted with his seat in the rearward of middle position. He braked prior to impact and held on tightly to the steering wheel. He complained of soreness to his nose as a result of contact by the air bag but no specific injury was documented (MAIS 0).

The right front passenger (23 years, female, 163 cm, 57 kg) in the Civic was belted with her seat fully rearward. She sustained multiple facial abrasions as a result of contact with the air bag (MAIS 1).

ACR4-1607: The case vehicle, a 1998 Dodge Neon, was travelling along a two-lane, undivided, rural arterial. As the Neon approached an oncoming GMC pickup truck, a small utility trailer being towed by the truck began to jacknife. The trailer hitch released, the safety chains failed, and the trailer became airborne across the roadway. The driver of the Neon braked, but the trailer struck the left front wheel and fender of the vehicle (12FLHN6). The impact resulted in the deployment of both front air bags in the Neon.

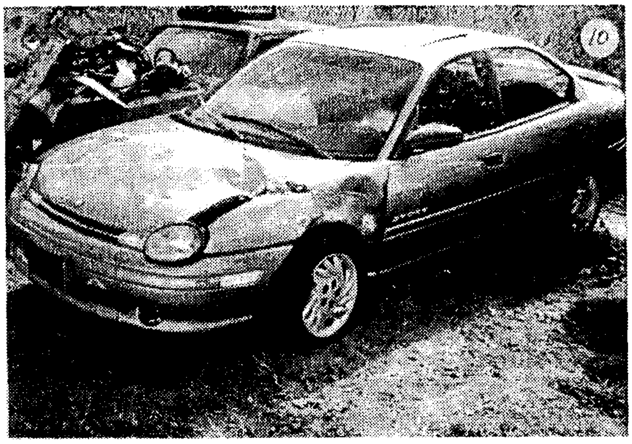

Figure 12. 1998 Dodge Neon

The driver of the Neon (44 years, female, 173 cm, 86 kg) was belted with the seat adjusted rearward of middle. She received contusions to two fingers on the left hand due to contact by the air bag (MAIS 1). She also reported redness to her face, and apparent fading of her hearing in the right ear immediately post-crash.

ACR4-1612: A 1998 Chevrolet Cavalier was travelling northbound in the curb lane of a four-lane urban arterial. A pickup truck which was overtaking the Cavalier moved abruptly into the curb lane.

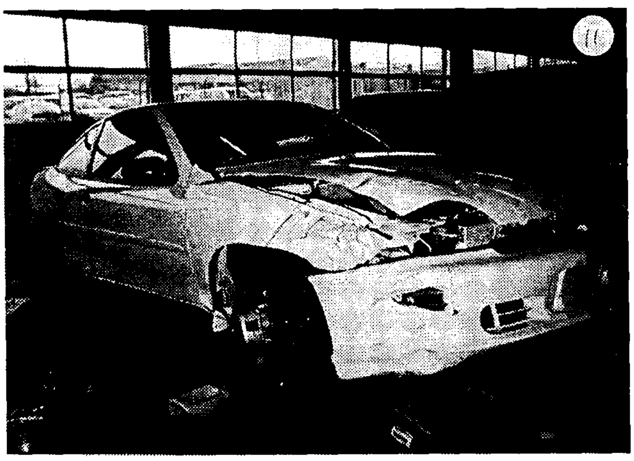

Figure 13. 1998 Chevrolet Cavalier

The driver of the Cavalier steered to the right to avoid a hitting the truck. The front of the Cavalier (12FREE3) struck a wooden utility pole which caused both front air bags to deploy.

The Cavalier's driver (16 years, female, 165 cm, 52 kg) was fully restrained and was uninjured (MAIS 0).

CONCLUSIONS

In the early stages of our study, the benefits of supplementary air bags were demonstrated, largely through a reduction in the incidence of serious head injuries in high severity crashes. Nevertheless, a number of drawbacks with early air bag system designs were also identified. In particular, there was an elevated risk of injury in minor to moderate collisions. Whereas most such injuries were minor, occasionally severe and even fatal injuries were experienced in low severity crashes.

In particular, some of the injury patterns were not normally seen for belted occupants in equivalent collision situations. Another unusual feature of air bag/occupant interactions was an elevated risk of injury to females. This has resulted in Canada pursuing a possible regulation using 5th percentile dummies with the seats in the fully forward position (Dalmotas, 1996).

The data resulting from the Canadian study have been analyzed and published on a continuing basis. The results of the research have been utilized in promoting effective use of occupant restraint systems, both seat belts and child restraints, while taking into account the availability of supplementary air bags.

Guidelines by which motor vehicle occupants might minimize the risk of air bag induced injury were published by Transport Canada and widely distributed. These included: ensuring that a seat belt was always correctly used; adjusting the occupant's seat to be as far rearward as practicable; placing children under the age of 12 years in the rear seat, secured by an appropriate occupant restraint system; and never placing a rear-facing infant carrier in a right front passenger seat where an air bag was installed.

The study data have also been shared with the automobile manufacturers and air bag suppliers. In September, 1996 the Minister of Transport wrote to the vehicle manufacturers asking them to work urgently with Transport Canada to improve air bag collision performance. In November of the same year, the domestic manufacturers announced that they would introduce less aggressive air bags in Canadian vehicles, improve labelling, and proactively notify customers of safety issues related to air bag systems. This announcement was quickly followed by similar action on the part of vehicle importers. As a result, second generation air bags have been installed in many Canadian vehicles, commencing in the 1998 model year. These new air bags have less powerful deployment characteristics than earlier systems, through a combination of system redesign, and/or the use of less propellant.

While the number of crashes involving depowered air bag systems which have been investigated to date remains small, the preliminary results are encouraging. Two drivers were fatally injured; however, both instances resulted from the nature and severity of the collisions, rather than being influenced by the depowering of the air bags. One case involved destruction of the structural integrity of the vehicle. The other saw the driver's air bag deploy in an initial, rather minor impact, such that it was unavailable to him for a subsequent severe head-on crash. The remaining incidents were all collisions of minor severity. In these non-fatal crashes, there were a total of 12 front seat occupants (9 drivers and 3 right front passengers). All 12 occupants were belted. Eight individuals (7 drivers and 1 passenger) were uninjured, while the remaining 4 occupants (2 drivers and 2 passengers) received minor contusions or abrasions due to contact with the air bag.

Despite, the introduction of second generation air bags into new vehicles in Canada, concern remained with respect to certain occupants of vehicles in the existing fleet. This was particularly the case for a small group of occupants who, for various reasons, were unable to follow the safety precautions suggested by Transport Canada with respect to minimizing the risk of air bag induced injury. The Minister again contacted automobile manufacturers and requested that they take steps to deal with such consumers. Agreement was reached between the federal government, the governments of the provinces and territories, and the automobile manufacturers, on a national programme for air bag deactivation. This programme was announced by the Minister in February, 1998.

Situations where individuals are deemed to be at risk are: children in rear-facing infant carriers which must be installed in the right front passenger seat, i.e. in pickup trucks and sports cars; children who must occupy the right front passenger seat, as is sometimes the case in car pools; drivers who are unable to attain a seating position with at least 25 cm of clearance between their chest and the steering wheel; and occupants having a specific medical problem requiring deactivation of the air bag.

The deactivation process is one of informed consent, where concerned individuals are provided safety information indicating both the benefits and drawbacks of air bag systems, and underscoring the implications of deactivating the air bag. Individuals who believe that they would benefit from deactivation complete a form certifying that they fit into one of the categories of individuals at risk and that they fully understand the consequences of deactivating the air bag. The completed form is returned to the government which reviews the information provided and returns the form, acknowledging its proper completion. The consumer may then take this form to a vehicle service centre to have the deactivation procedure performed. Finally, the servicing technician completes the form, indicating the manner in which deactivation was performed, and returns the form to the government for retention.

It is anticipated that most air bag deactivations will be accomplished through the installation of a manual cut-off switch with telltale warning lights. This method is preferred as it allows the air bag to be temporarily deactivated for a specific individual at risk, while retaining the option for readily enabling the air bag system should another occupant desire the supplementary protection which the air bag offers.

Transport Canada's study of the real world collision performance of air bag systems continues, as does our effort to improve air bag design through a programme of crash testing and research. As more knowledge and expertise is developed, air bag systems will become more intelligent. It is hoped that advanced technologies will address the safety issues associated with these systems.

ACKNOWLEDGMENTS AND DISCLAIMER

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The conclusions reached, and opinions expressed, in this paper are solely the responsibility of the authors. Unless otherwise stated, they do not necessarily represent the official policy of Transport Canada.

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DRIVER STATURE INJURIES AND AIRBAG DEPLOYMENT CRASHES? -- ANALYSIS OF UMTRI CRASH INVESTIGATIONS--

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Paper Number 98-S5-O-05

ABSTRACT

At the University of Michigan Transportation Research Institute (UMTRI), 776 crashes involving steering wheel airbag deployments have been investigated in detail (as of 1/1/98). A subset of only the frontal crashes, in which the steering wheel airbag deployed, and driver stature was known, was formed (646 drivers). The vast majority of all drivers were lap-shoulder belted. Of these drivers, 70% sustained no injuries or an AIS-1 level injury. In these 646 crashes there were 203 "short" stature drivers, 165 cm or less in height (32% of all drivers). Of the shorter drivers there were 40 MAIS-2 level injuries and 15 who survived with an MAIS injury level of 3, 4, or 5. These higher level injuries were usually found in only one body area. Details of the injury locations and contacts are presented. Data on the taller drivers (443) were similarly tabulated. Of the taller drivers (≥ 168 cm), 74% had a MAIS-0 or 1 level injury. Of taller drivers with the MAIS-3, 4 or 5 injuries, the majority (70%) had such injuries unrelated to the deployment of the airbag. Of all the MAIS-2+ injured drivers, short or tall, 57% had such injuries unrelated to airbag deployments. The lower extremity was the body area most often involved, followed by the brain and upper extremity injuries.

INTRODUCTION

Recently concern has been raised about the short driver exposed to steering wheel airbag deployments. NHTSA has reported that there are about 40 drivers who sustained fatal or serious injuries in airbag deployment crashes. These were mostly females, 65 inches in stature (164 cm), or less and were in minor to moderate severity airbag deployment crashes. A review of the UMTRI crash investigations, wherein the steering wheel airbag deployed, was conducted in order to determine the frequency of injury and injury severity in the short driver population, and to compare these findings with the "taller" drivers in the UMTRI series.

MATERIALS AND METHODS

As of 1/1/98 UMTRI personnel have investigated 776 crashes in which the steering wheel airbag deployed. In this series there were 130 non-frontal crashes, or cases with unknown driver stature. These were omitted, leaving 646 crashes for review. Of these 646 drivers, 203 (31%) are the shorter drivers whose stature was 165 cm or less. All of these drivers were females, except one, and the majority were belt restrained (86%). These cases were individually reviewed to determine the location of the body areas of AIS-2 or greater injury severity, and to identify the object(s) contacted to cause these injuries. The data on each driver set were divided into two groups, those drivers with their highest injury level of MAIS-2, and those with an MAIS-3, 4, or 5 level injury who survived. The same review was carried out for the drivers who were 168 cm or taller.

RESULTS

The Shorter Drivers

Of the 203 drivers exposed to airbag deployments, most (70%) had an MAIS-0 or 1 level injury severity (Table 1). These injuries were noted to the face, upper extremity, thorax and abdomen. They include abrasions, contusions, and muscle strains to one or more body areas. In general, most were due to the lower instrument panel, floor, toepan (lower extremity injuries), restraint webbing (torso injuries) or airbag (face and forearms).

Of the 40 drivers who had an MAIS-2 injury, 20% of all the short drivers, the injuries were primarily located in one of three body regions-the lower or upper extremity, or the brain (Table 2). There were three drivers with two body areas involved, each with an AIS-2 level injury, and one driver with three AIS-2 level body areas involved. Half of the short drivers did not have the MAIS-2 injury from airbag contact or due to airbag deployment. These injuries were primarily located in the lower extremity (Table 2). Injuries of AIS-2 in short drivers, related to airbag deployments, were primarily located in the forearm (fractures), or the brain (unconscious less than one hour).

Of the 203 short drivers, 7% (15 drivers) survived with MAIS-3, 4 or 5 level injury (Table 3). Six drivers had these injuries in the lower extremity. Of the 15 drivers, 13 had AIS-3+ injuries from sources unrelated to airbag deployment.

A subset of the short drivers was created, using those drivers 160 cm or less (Table 1). Of these 91 drivers (all females), 21 (23%) had an MAIS-2 level injury and nine (10%) had MAIS-3, 4 or 5 level injuries. Two-thirds (64%) had only AIS-0 or 1 level injuries (Table 1). In Tables 2 and 5 these drivers are separately presented in parentheses.

The shortest of drivers fair well in airbag deployments. Of the shortest drivers stature is not related to injury severity (Table 3) Note that of the very short drivers (≤ 154 cm), AIS-2 or 3 level injuries are infrequent. Of the 20 shortest drivers (≤ 160 cm) with an MAIS-2 level injury, 10 had these AIS-2 level injuries unrelated to airbag deployment. (Table 4) There were 25 body regions injured at the MAIS-2 level in these 20 drivers. The majority of these were unrelated to the airbag deployment (16). Of the AIS-2 injuries in this group of 21 drivers that were related to the airbag deployment, four were to the upper extremity, and five to the brain.

Of the 91 shortest drivers there were only nine at the MAIS-3 or 4 level involving one of three body regions--the lower extremity (5), chest (3) and the upper extremity (1) (Table 6). Five were due to contact with the floor, pedals, or with the instrument panel. Two others were injured by steering wheel contact. Only two of the nine drivers had airbag related injuries.

There were six short drivers who were killed (Table 7). Five sustained a cervico-cranial dislocation or upper cervical fracture-dislocation with spinal cord or the spinal cord/brainstem junction disruption. Four of the six were in severe crashes and had significant injuries other than in the cervical area. One died in a relatively minor crash.

Table 1
The MAIS of Drivers in Frontal Airbag Crashes

Stature

	≤160 cm		161-165 cm		All ≤165 cm		≥ 168 cm	
MAIS	No	%	No	%	No	%	No	%
0-1	59	64	83	75	142	70	326	74
2	20	23	20	17	40	20	68	14
3+	9	10	6	5	15	7	42	9
Died	3	3	3	3	6	3	7	2
Total	91	100	112	100	203	100	443	100

Table 2
MAIS-2 Level Injuries of Drivers ≤165 cm in Stature $^{\Theta}$

Body Regions

Source of Injury	**Lower Extrem**	**Upper Extrem**	**Brain**	**Neck**	**Abd**	**Brain/LX**	**Brain/ UX/LX**	**UX/ Neck**	**UX/ LX**
Floor/Pedals	10* (5)								
Instrument Panel	2* (1)	(2)							
Door Interior	1*								
3-Point Restraint		1*			(1)*				
Airbag		(1)	6 (5)	1			1	1	
Side Glass		(1)							
Wshd/Sunvisor/Roof		4	4* (1)						
Steering Wheel		(1)*							
Door Int/Inst. Panel						(1)			(1)*
Total	13* (6)	10 (5)	11 (6)	1	(1)	(1)	1	1	(1)

BODY REGION:
Abd=Abdomen
LX=Lower Extremity
UX=Upper Extremity

$^{\Theta}$In parentheses ( ) are drivers ≤ 160 cm in stature
*Injuries unrelated to airbag deployments

Table 3
The Shortest Drivers (≤ 160 cm)
Stature & Injury Severity
MAIS

Stature (cm)	**0-1**	**2**	**3 or 4**	**Died**	**Total**
160	20	9	2	1	32
158	2				2
157	18	6	3	1	28
155	8	3	3	1	14
154	1				1
153	1				1
152	7	1	1		10
151	1				1
150	1	1			2
Total	59	20	9	3	91

Table 4
The Shortest Drivers (≤ 160 cm)
MAIS-2 Body Regions & Sources of Injury by Stature

Body Regions

Source of Injury	**Lower Extremity**	**Upper Extremity**	**Brain**	**Abd**	**Brain/ LX**	**UX/ LX**
Floor/Pedals	160, 160, 157, 155, 155					
Instrument Panel	160	***157, 157***				
3-Point Restraint				***150***		
Airbag		***160***	***160, 160, 160, 157, 157***			
Side Glass		***160***				
Wshd/Sunvisor/Roof			160			
Steering Wheel		152				
Door Int/Inst. Panel					157	***155***

Bold italics=related to airbag deployment

Table 5
MAIS- 3, or 4 Injuries of Drivers Who Survived (≤ 165 cm in Stature) $^{\Theta}$

Body Regions

Source of Injury	**Lower Extremity**	**Brain**	**Chest**	**UX**	**Chest/ Abd**	**LX/ LX**
Floor/Pedals	2* (2)					
Instrument Panel	3* (3)	1*		(1)		
Airbag			1 (1)			
Roof		1, 1*				
Steering Wheel			3* (2)			
Instrument Panel/Side Panel						1*
3 Point Restraint					1*	
Total	5* (5)	3	4 (3)	(1)	1	1

$^{\Theta}$In parentheses ( ) are drivers ≤ 160 cm in stature
*Injuries unrelated to airbag deployments
There were only 3 AIS-4 injuries in this group. All were 162 or 163 cm in height.

Table 6
The Shortest Drivers (≤ 160 cm)
MAIS- 3, or 4 Body Regions & Sources of Injury by Stature

Body Regions

Source of Injury	**Lower Extremity**	**Chest**	**UX**
Floor/Pedals	157, 157		
Instrument Panel	157, 157, 152		
Airbag		***157***	***160***
Steering Wheel		157, 160	

Bold italics=related to airbag deployment

The Taller Drivers

In the series of 646 drivers exposed to airbag deployment, there were 443 taller drivers (≥168 cm). Of these, 74% sustained injuries of an MAIS-0 or 1 (Table 1). Of the tall drivers, 14% had an MAIS-2 level injury. As with the shorter drivers, there were more lower extremity injuries that are unrelated to airbag deployment (Table 5). Additionally, there were a number of these tall drivers, 15 of 68, with an AIS-2 upper extremity injury as their most severe injury. Also, the brain ranked in the top three body areas with an AIS-2 injury in these taller drivers. These three body areas, lower and upper extremity and brain accounted for the majority of the body areas with an AIS-2 level injury. In the taller drivers there were 11 individuals who had multiple body areas (two or more) that were involved, each with an AIS-2 level injury.

Table 7

Short Drivers Who Died

Body Areas	No.
Brain	1 (1)
Neck	5 (2)
Total*	6 (3)ϕ

*All airbag related

ϕ In parenthesis ( ) are drivers ≤160 cm in stature

Table 8

MAIS-2 Level Injuries of Tall Drivers*

Body Regions

Source of Injury	Lower Extremity	Upper Extremity	Brain	Chest	Eye	Face	Lumbar Spine
Floor/Pedals	8*						
Instrument Panel	7*	2 1*					
Door	4*	1*					
3-Point Restraint				6*			
A-Pillar			1				
Airbag		6	3	1	2	1	
Side Glass			1				
Sunvisor/Header			2				
Steering Wheel		2*					
Seat Back			1*				
Console	2*	1*					
Exterior to Car				1*			
Unknown		1*					
Miscellaneous		1*				1*	
Induced							1
Total	21*	15	8	8	2	2	1

*Injuries unrelated to airbag deployment

Additionally 11 drivers had two or more body areas injured at the AIS-2 level:

*Neck/Lumbar Spine	rear passenger	*Brain/Chest	header/steering wheel
*LX/LX(x2)	inst panel/floor	*UX/LX	inst panel/floor
*Chest/LX	3-point restraint/inst panel	Brain/Face/LX	airbag/airbag/floor
*Skull/Face/Chest	steering wheel	UX/Abdomen	airbag/steering wheel
*UX/Chest	steering wheel/3-point restraint	Brain/LX	airbag/inst panel

In Table 8, the sources of these AIS-2 level injuries of the 68 tall drivers are shown. Those injuries, unrelated to the airbag deployment, are shown with an asterisk. There are 21 lower extremity injured drivers whose injuries were unrelated to airbag deployment. Of the upper extremity AIS-2 injuries, seven contacted structures within the car, contacts unrelated to the deploying airbag. This is also true for one of the individuals with an AIS-2 brain injury. In addition, seven of the drivers with multiple body areas injured at the AIS-2 level had their injuries unrelated to airbag deployment. Thus, of the 68 tall drivers with a AIS-2 level injury, 45 (66%) had AIS-2 injuries unrelated to the airbag deployments.

The taller drivers with more serious injuries of AIS-3, 4, or 5 (42 drivers) had a distribution fairly widely through the different body areas (Table 9). The lower extremity and chest are the areas that predominate, with the chest being more frequently severely injured than, for example, the upper extremity. At these higher levels of injury severity, there are but few combinations of body areas at the AIS-3 level, only four of the 42 drivers. In Table 9 the sources of the injury of the various body areas of the tall drivers who survived at the MAIS-3, 4, 5 level are indicated. Again, many of the injuries are unrelated to the airbag deployment. Of these 42 drivers, 29 (69%) had these more severe injuries from impacts unrelated to airbag deployments.

Of the seven tall drivers who died, all were in severe crashes, (car, tree, semi-trailers) or were over 70 years of age. One driver was lying on the steering wheel at impact having passed out due to drugs and alcohol (Table 10).

Table 9

MAIS-3, 4 or 5 Level Injuries of Tall Drivers Who Survived*

Body Regions

Source of Injury	LX	Chest	Brain	UX	Abd.	Neck	Face	Brain/ Chest	UX/ LX	Chest/ LX	LX/ LX
Instrument Panel	10*			3			1			1*	
Airbag		1		3		1		1			
Header, A-pillar			1			1					
Steering Wheel		2*									
3-Point Restraint		5*			2*						
Roof, Roof Side Rail			5*	1							
Console	1*										
Door/IP									1*		
Floor-Pedals	1*										
IP/Floor											1*
Total	12*	8	6	7	2*	2	1	1	1*	1	1*

*Injuries unrelated to airbag deployments. In this table there are 9 drivers with AIS-4 or 5.

Table 10

Tall Drivers Who Died

Body Areas	No
Brain	2
Chest	4
Brain & Chest	1
Total*	7

*one chest and the brain/chest fatalities were airbag related

DISCUSSION

Airbags are reducing fatalities, moderate and serious injuries. In frontal impacts (12 o'clock) the fatality reduction is 31%[1]. Moderate head injuries, with a combination of the 3-point restraint and airbag, are reduced by 83% and serious head injuries are reduced by 75% with the belt/airbag combination. Belts and bags reduce moderate chest injury by 59% and serious chest injuries by 66%.

Malliaris, et al reviewed the 1988-92 NASS/CDS file and identified 350 drivers with lap-shoulder belts and airbag deployments[1]. Their analysis indicated a higher frequency of AIS-1 level injury than in our data (83% vs. 72%) and had the same frequency of AIS-2 level injuries. However, data were not presented on driver stature and injury severity.

The majority of all drivers, tall and short, have but minor injuries. Short drivers have a higher frequency of AIS-2 level injuries than do the taller drivers, but about the same frequency of MAIS-3, 4 or 5 level injuries. Half of the MAIS-2 level injuries of short drivers are unrelated to airbag deployments whereas two-thirds of the MAIS-2 injuries in the tall driver group were not airbag related. The majority of the more severe injuries (MAIS-3+) to short drivers were not related to the airbag as was found in the tall driver group. The shortest of drivers (≤160 cm) do not appear to be at a higher risk in frontal airbag crashes than those 161 cm or taller, except possibly in the lower extremity. One-third of the shortest drivers had an MAIS-3 or greater injury level in the lower extremity. Most of the shortest driver's MAIS-2 level injuries were unrelated to airbag deployment. Short drivers of 161-165 cm in height have an injury severity distribution nearly identical to the tall drivers (≥ 168 cm).

Brain injury accounts for about 30-35% of the AIS-2 injuries to all drivers in this study. As described in the AIS dictionary, any loss of consciousness for less than an hour, amnesia or lethargic, stuporous or obtunded on admission to the hospital, or on initial observation at the scene, places the patient at the AIS-2 level.[2] However, the majority of these drivers studied are concussed for much less than one hour and did not have any long-term cerebral dysfunction.

In all drivers, the lower extremity is the body area most commonly involved in AIS-2+ injuries and these are sustained on the lower instrument panel, on the floor or foot pedals. The leading cause of the upper extremity fractures is the flinging of the extremity onto interior structures by the deploying airbag .

An interesting finding is the lack of AIS-2+ injuries, to the abdomen and thoraco-lumbar spine, body regions which are noted to be injured in lap-shoulder belted drivers without airbags in frontal crashes.

In the tall driver series the lower extremity, brain and upper extremity injuries predominate, as was noted in the short driver group. Chest injuries were also noted in the taller driver group. Of the 22 upper extremity injuries of AIS-2 or 3 in the tall drivers, 15 were related to the airbag deployment.

Taller drivers have slightly higher frequency of the more severe injuries (MAIS-3+) and are more prone to having two or even three body regions injured, at the AIS-2 level, than noted in the short drivers.

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ASSESSMENT OF ADVANCED AIR BAG TECHNOLOGY AND LESS AGGRESSIVE AIR BAG DESIGNS THROUGH PERFORMANCE TESTING

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ABSTRACT

On March 19, 1997, the National Highway Traffic Safety Administration (NHTSA) published a Final Rule amending FMVSS No. 208 to allow manufacturers to de-power air bags in their passenger vehicles. This is considered an interim solution to the problems associated with aggressive air bag deployments. Consequently, the amended rule has a sunset provision that removes the amendment, with the addition of "advanced" air bag requirements to be developed in the future.

As part of the process to develop test procedures, a study was conducted to test the capabilities of advanced air bag technologies, and evaluate less-aggressive air bags designed for a belted market in Australia. Testing consisted of static air bag deployments and dynamic HYGE sled and crash testing using Hybrid III adult and child dummies.

Advanced systems testing indicate that Multi-stage inflation can tailor bag deployments for the crash severity. However, it was still challenging for the platform tested to meet IARV's when child dummies were out-of-position (OOP) relative to the air bag. The Holden air bag used in Commodore VS and VR models in Australia passed an FMVSS No. 208 full-frontal rigid barrier crash test with unbelted dummies, although lack of knee bolsters caused the dummies to submarine somewhat on the driver-side. OOP results were moderately aggressive on the driver-side and very aggressive on the passenger-side with the 3 and 6 year old dummies.

BACKGROUND

FMVSS No. 208[1] is the frontal impact protection regulation in the United States. Until March of 1997, this standard required air bags to automatically deploy in a 30 mph frontal barrier crash test with two belted or unbelted H-III 50th percentile male dummies. After a number of cases in which the air bag deployment forces resulted in a serious to fatal injury, the National Highway Traffic Safety Administration (NHTSA) began a comprehensive investigation to understand the causes of these fatalities.

Initial studies into the crashes revealed one prevalent characteristic that was common to almost all the cases. Each occupant, driver or passenger, was in close proximity to the air bag module when it deployed. Reasons for these out-of-position (OOP) occupants were different for the driver and child passenger. Driver fatalities were predominantly of small-stature adults, who due to their stature, were seated close to the steering wheel. Child passenger fatalities were split into two groups. The first were infants in rear-facing child seats that were in the right-front passenger seat. The back of the child seat was very close to the module when it deployed. The second child passenger fatality scenario involved un- restrained children who were thrown into the instrument panel during pre-impact braking. Then, as the crash occurred the bag deployed with the child on or very close to the air bag module.

The NHTSA began to investigate the options available to quickly avert additional fatalities. A public education campaign was initiated to inform parents of the dangers to children riding in the front seat with a passenger air bag and advised them to correctly restrain their children in the back seat. To address driver fatalities, recommendations were developed for how far to sit from the air bag module. Inasmuch as education alone was not expected to eliminate the problem, a test program conducted at NHTSA's research lab, the Vehicle Research and Test Center (VRTC), was conducted to examine the effects of an air bag deployment to out-of-position (OOP) occupants. It was discovered that reducing the air bag inflator output, without any other changes, reduced the loads applied to OOP child and adult dummies. There was, however, a corresponding increase in injury measurements on full-size dummies in sled tests that simulated the FMVSS No. 208 full frontal barrier crash test. Therefore, NHTSA began investigating ways to allow air bag "de-powering".

In response to agency inquiries on de-powering, auto manufacturers claimed that to "de-power" their air bags, FMVSS No. 208 would need to be amended. The American Association of Automobile Manufacturers (AAMA) proposed a sled test that simulates a car-to-car crash in a lower severity impact than the frontal barrier test. Consequently, the reduced severity crash would require less occupant restraint and manufacturers would be able to reduce the inflator output. The requirement to change FMVSS No. 208 to allow the auto manufacturers to de-power their air bags hinged on the industry's claim that the then current barrier test required overly aggressive and large air bags, particularly on the passenger-side, where children would be seated. The agency determined that a temporary change to the standard to allow air bags to be de-powered and reduce the risk of air bag induced fatalities, outweighed the risks put upon occupants in high speed crashes. A sunset provision was added to the regulatory amendment that removes the sled test option on September 1, 2001. At that time, there would be new regulatory requirements to introduce advanced air bags that should prevent harm to OOP occupants and meet the FMVSS 208 barrier crash test with unbelted dummies.

Advanced Systems Development and Testing

Air bag suppliers and automobile manufacturers have been developing and researching a variety of technologies to improve air bag performance, and reduce the potential of inflation-induced injuries from aggressive air bag deployment. Some of the advanced technologies may provide more information about the crash and have the capability to tailor or suppress the air bag restraint response to the individual occupant. The general categories of information provided by advanced technologies include: occupant safety belt use, occupant position relative to the air bag module, occupant size/mass, and the crash severity. This information can be used to make a more informed decision on the type of air bag deployment scheme to employ. Other advanced systems make use of less technical alternatives such as compartmented air bags, advanced fold patterns, controlled venting systems, and lower inflation onset rates to reduce aggressiveness while maintaining full occupant protection.

One of the emerging near-term technologies that could be ready for production in 1998[2] is multi-stage air bag inflators. Multi-stage air bag inflators have the potential of providing a low level, a high level, and a range of mid-level inflations. These levels are achieved by either firing only the primary stage of deployment, firing the primary and secondary stages simultaneously, or by firing the secondary stage at a specified time after the firing of the primary stage. Different multi stage air bag inflator technologies are under development by the industry. Some design strategies utilize a compressed gas inflator with two separate initiators; other designs consist of packaging two separate pyrotechnic charges a single inflator. In conjunction with the multi stage air bag inflator technology, a sensor mechanism and the associated control logic are required to make effective use of the different inflation levels.

A test series was conducted to examine an advanced air bag system utilizing a multi-stage inflator and advanced single-point sensor. The advanced system was provided through cooperation with TRW Inc. Dynamic sled and crash tests were conducted to examine the performance characteristics of the system in a moderate to high crash severity environment. An additional set of tests were performed on the driver and passenger air bag to test the aggressiveness of the air bag system with OOP occupants. The objectives of the tests were:

1. Assess the potential to meet Injury Assessment Reference Values (IARV's) when an occupant is OOP as well as protect occupants in high speed crashes.

2. Examine test procedures for testing OOP dummies for repeatability.

Australian Air Bag Development

The wearing rate for seatbelts in Australia is currently greater than 95% for front seat occupants and greater than 80% for rear seats. This is a result of legislation introduced in Australian states in 1970/71 which produced a rapid reduction in road deaths. The high seatbelt wearing rate allowed Australia to implement a frontal crash test standard using restrained dummies. The technical requirements of Australian Design Rule 69 (Frontal Crash Protection) are the same as those of US FMVSS No. 208, except the dummies are restrained with the vehicle's seatbelts. This has allowed manufacturers to optimize restraint systems for the restrained occupants, resulting in less aggressive air bags, with a higher deployment threshold.

One such vehicle, whose air bags are designed for the restrained occupant is the Holden Commodore. The Commodore is one of Australia's two best selling cars, with its market rival the Ford Falcon being of similar size and mass. Approximately 50% of VR and VS model Commodores were sold with the optional air bag. Initially the air bag rate was much higher for private vehicles than for fleet cars (which make up about 70% of sales in this vehicle category), however the acceptance of the value of air bags in the fleet market has increased over time to the point that air bags are now standard across the current Commodore model range.

A test series was conducted with the VS Holden Commodore Vehicle. The testing was conducted in conjunction with the Australian Federal Office of Road Safety (FORS) at the Autoliv test facility outside of Melbourne, Australia. One crash test and a series of static OOP tests were conducted with the child and small female dummies. The objectives were:

1. Assess the performance of the Holden Commodore air bag in a frontal barrier crash test with two unbelted 50^{th} percentile adult male H-III dummies.

2. Determine the aggressiveness of the Holden air bag to OOP occupants.

TEST METHODOLOGY

Characteristics of Air Bag Systems Tested

Platform 1 Multi-stage air bag inflator - A multi-stage inflator was tested on a vehicle platform (referred to as Platform 1) to experimentally evaluate the performance of such devices. The advanced air bag system comprised of a compressed gas container with dual-squibs. By varying the firing time of the squibs, the inflation gas rise rate and peak pressure, when measured in a tank test, could be varied. Firing of only one squib was referred to as a first-stage air bag deployment. Firing of the second squib, a pre-determined time after the first was referred to as a multi-stage deployment. Multi-stage deployment increased the inflator output for more severe crash conditions. The closer the second firing to the first, the higher the inflator output. In the tests reported here, there were three firing sequences: First stage only deployment (low-level inflation), multi stage deployment with a 5 ms delay between squib firings (high-level inflation), and multi-stage deployment with a 20 ms delay between squib firings (mid-level inflation). Table 1 illustrates the tank test output for the driver and passenger air bag with the 3 firing sequences. A single point advanced air bag sensor with the multi-stage driver and passenger inflators was also evaluated in a crash test to examine the complete advanced air bag system. For this particular vehicle platform, a distributed sensor system was more desirable, but time limitations restricted testing to off-the-shelf equipment that was modified through adjustments of the signal processing software (crash sensor algorithm).

Table 1.
Multi-stage Inflator 60 l Tank
Curve Characteristics

Deployment Stage	Driver Side (kpa x kpa/ms)	Passenger Side (kpa x kpa/ms)
Primary	100 x 5	320 x 8
Primary + 20 ms Delay	130x5	500 x 9
Primary + 5 ms Delay	160 x 8	560 x 17

Out-of-position aggressiveness from the lowest level of deployment, and moderate and high speed performance with adult dummies as the inflation rise rate and peak pressure were increased, were evaluated with a combination of static OOP tests, sled tests, and crash tests.

Holden Commodore VR vehicle - The Holden Commodore is produced by General Motors' Holden Australia. While it was developed as a European vehicle, the Commodore has been extensively modified for Australian manufacture and possesses a unique floorpan, drivetrain configuration, suspension design and therefore crash pulse. The Commodore's air bag systems are optimized for restrained occupants.

A driver's side air bag was available as an option on Commodores from the VR model (1993), with a passenger side air bag being made available on the VS series (1995). Apart from the passenger air bag, crash performance of VR and VS models would be very similar. VR and VS Commodores are also fitted with ELR seatbelts with webbing grabbers.

The Driver's side air bag in the Commodore is a full sized (65 liter) bag, however the inflator is designed to be as non-aggressive as possible. The bag produces a peak inflation pressure of 300 kPa in a 1 cubic foot tank test. The air bag has two 45 mm vents and 275 mm tethers to prevent "bag slap" for the restrained occupant. The passenger air bag is 120 liters in size and is also tuned for restrained occupants. The bag produces 240 kPa in a 100 liter tank test. There are two 30 mm vents and tethers to control the deployment pattern.

The Commodore has also been the subject of a real-world crash study with a collection of VS and VR models with air bags, and a number of earlier VN and VP models (no air bags) as a control group. The initial study, reported at the 1996 ESV conference [3], covered a total of 178 crashed vehicles, with 64 fitted with air bags and the remaining vehicles consisting of 54 baseline (VN & VP models) and 60 non-air bag (VR & VS without the optional air bag/s).

The driver data showed a significant decrease in head injuries, particularly of AIS 2 and above, as well as a decrease in face and neck injuries. Chest injuries were almost halved, with very significant reductions at AIS 2+ and AIS 3+. There was a slight increase in AIS 1 injuries to the upper extremities, with lower extremity injury rates being fairly similar between the air bag and non-air bag vehicles. There was however an apparent increase in the number of spinal injuries in air bag cars at AIS 1 and 2, though the number of injuries were fairly small in both vehicle types.

Overall the study reported a significant reduction in the Probability of injury and mean harm for Holden Commodores fitted with air bags.

Test Matrix

To fully test the ability of an advanced air bag system to prevent harm to OOP occupants while continuing to protect adults in higher speed impacts, a large matrix of tests would be necessary. Figure 1 illustrates a matrix of conditions that could be used to determine the conditions necessary to evaluate air bag and sensor performance when designing to protect a variety of crash and occupant conditions. Generally, a large number of these conditions would be evaluated through crash testing, sled testing, static air bag deployments, and computer simulations to prove the reliability of the system. Sensors that measure the crash severity, occupant size, occupant position, and belt use, can determine the appropriate inflation level.

Testing all the conditions in the matrix was not practicable in this test program. However, a subset of conditions were addressed to determine the general benefits and drawbacks of this particular system. Figure 2 shows the subset of tests conducted with the advanced air bag system for Platform 1. This matrix shows the static OOP tests and sled tests simulating the conditions in the matrix. Vehicle pulses at those conditions shown were provided from actual crash tests or computer simulations with Platform 1. Air bag firing times for sled tests represent the desired firing time of the sensor for that particular crash scenario using the "5 inch/30 ms" rule-of-thumb. The firing times of the first and second stage are listed in pairs. The first is the time into the crash where the first squib fires, the second is the time into the crash where the second squib fires. Consequently a 12,32 represents a 20ms delay between firing the two squibs. All static tests were conducted with the deployment of only the first stage (Firing of the primary squib). Several repeat tests were also conducted to evaluate the repeatability of the positioning procedure.

The testing with the Australian system was limited to static OOP testing and to a 30 mph full-frontal barrier crash test to examine the characteristics of an air bag system designed for a belted population when tested to the full-frontal barrier crash test in FMVSS No. 208 with unbelted 50th percentile male dummies.

Out-of-position Static Tests - The same OOP test procedures were used for Platform 1 and the Holden air bag.

The 3 and 6 year old H-III dummies were positioned to measure the aggressiveness of the air bag. Two dummy positions were developed based on the ISO 10982[4] procedures for OOP testing. Figure 3 illustrates a 3 year old dummy seated in position 1 and position 2. Position 1 sets the dummy's chest against the air bag module with a vertical spine. The dummy is then raised until the dummy's head is within 10 mm of the w/s, or the mid-sternum of the chest is in the same horizontal plane as the geometric centerline of the air bag module cover. Position 2 puts the dummy on the edge of the seat and bends the torso forward at the hip until contact with the forward structure of the vehicle. The procedure for the six-year old is the same. Figure 4 shows the six year old seated in position 2 on Platform 1.

The 5th percentile female was used to test the aggressiveness of the driver-side air bag. The dummy was placed in two positions in close proximity to the air bag. Position 1 and position 2 were based on ISO DTR 10982 test procedures for testing OOP occupants. Position 1 places the head and neck of the dummy in close proximity of the air bag module. Position 2 places the chest against the air bag module. In each

Belt-Use	Crash Mode	Delta V (mph)	3 YO OOP		6 YO OOP		5^{th} Driver OOP		5^{th} Driver	50^{th} Driver	5^{th} Pass.	50^{th} Pass.
			OOP 1	OOP 2	OOP 1	OOP 2	OOP 1	OOP 2				
Properly Belted*	Full Front	20										
		30										
	Pole	20										
		30										
Unbelted	Static	0										
	Full Front	20										
		30										
	Pole	20										
		30										

Figure 1. Matrix of Conditions to fully evaluate air bag performance.

Belt-Use	Crash Mode	Delta V (mph)	3 YO OOP		6 YO OOP		3YO Prox.		5^{th} Driver OOP		5^{th} D	50^{th} D	5^{th} P	50^{th} P
			OOP 1	OOP 2	OOP 1	OOP 2	8" Back	4" Back	OOP 1	OOP 2				
Proper Belted*	Full Front	20												
		30									×		×	×
	Pole	20												
		30												
Un-belted	Static	0	Static	Static	Static	Static	Static	Static	Static	Static				
	Full Front	20												
		30									✓×	×	✓	✓×
	Pole	20									☆◇			☆N
		30												

Figure 2 - Testing conducted with Platform 1 air bag system.

✓ - multi-stage deployment; 12 ms and 17 ms
× - multi-stage deployment; 12 ms and 32 ms
◇ - multi-stage deployment; 57 ms and 77 ms
☆ - single stage deployment; 57 ms
N - no deployment

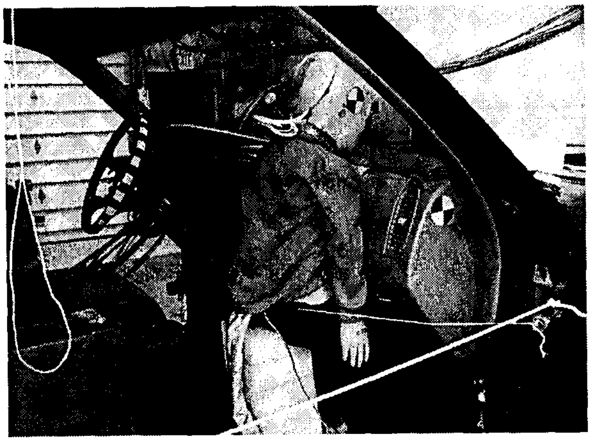

Figure 3a. Three year old, Position 1

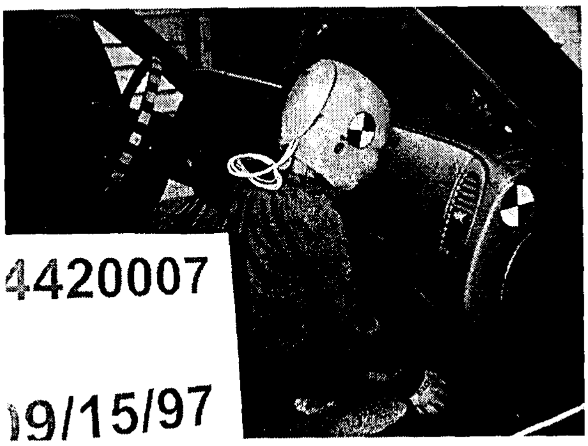

Figure 3b. Three year old, Position 2

Figure 4. Six year old - Position 2

case, the dummy spine was maintained at the same angle as the steering wheel.

__Sled Tests__ - Sled tests were not conducted with the Holden air bag. A series of sled tests were conducted with the platform 1 air bag in a test buck at the Transportation Research Center (TRC) sled facility. Dummy size and simulated crash conditions are shown in Figure 2. A combination of firing sequences with the multi-stage inflator were also examined. The testing consisted of a sled simulation of a 48 k/hr (30 mph) crash pulse into a rigid barrier and a 32 k/hr (20 mph) center-pole crash. Each condition was tested with the 5^{th} female and 50^{th} male H-III dummies, belted and unbelted, with three combinations of the multi-stage squib firing.

__Crash Tests__ - Platform 1 was tested at 40 km/h (25 mph) into an 305 mm (12") pole, offset 234 mm (9.2") to the left of the vehicle centerline. The offset position was chosen as the softest spot into the front of the vehicle (between the rail and the engine block) to test the sensor's ability to fire the air bag on-time and at the appropriate inflation level. A single-point sensor was used to detect the impact severity and fire the air bags. A 5^{th} percentile female dummy was placed in the driver seat and a 6 year old H-III was placed in the passenger seat. The test was recorded by 12 cameras, each at 1000 frames per second.

In order to determine the effectiveness of the Commodore's de-powered air bags in protecting un-belted occupants a vehicle was tested to the US FMVSS 208 standard. The vehicle selected was a 1993 VS Commodore with driver and passenger air bag. The Commodore's restraint system was not designed to cope with unrestrained occupants and therefore no knee bolsters are fitted on the vehicle. The test was conducted at the Autoliv Australia crash test facility. The test was at 48.7 km/h (30.2 mph) into a rigid concrete barrier (with a plywood face). 50^{th} percentile Hybrid III dummies were positioned in both driver and passenger seats. The test was recorded by 7 film cameras, including overall and close-up views on both sides, plus frontal, overhead and underside views. The camera frame rate was 1000 frames per second (3000 frames for side close-ups).

Injury Assessment Reference Values (IARV's)

Head Injury Criteria (HIC), resultant chest g's, neck criteria (Nij), chest deflection, and chest viscous criterion (V*C) were recorded and/or calculated for each test. The following table lists the injury thresholds associated with each measure. All threshold values have been developed to represent a similar risk of AIS 3+ injury.

Table 2.
Injury Threshold and Critical Values.

Injury Criteria	Threshold Measurement			
	3 year old	6 year old	5th female	50th male
HIC	900	1000	1000	1000
Chest g's	51	65	60	60
Chest Compress (mm)	28	31	41	50
V*C (m/s)	1	1	1	1
Max Nij	1	1	1	1
Fzn	2500	3000	3200	3600
Myn*	90/30	140/40	210/60	410/125

* - Flexion/Extension

Nij is a relatively new measure that is a normalized resultant of neck forces and moments. Neck axial forces are combined with the neck moment calculated about the occipital condyle using the following equation:

$$N_{ij} = \frac{F_z}{F_{zn}} + \frac{M_y}{M_{yn}}$$

where,
Fz = Upper Neck Axial Force (N),
My = Moment about Occipital Condyle (N-m),
Fzn = Axial Force Critical Value (N), and
Myn = Moment Critical Value (N).

Critical values are not compared with the individual neck injury measures, they are only used in calculating Nij.

V*C is the chest compression velocity times the chest compression divided by the chest depth. The V*C is calculated by taking the chest potentiometer and differentiating to get the chest velocity. The measured compression is then divided by the chest depth and multiplied by the calculated chest compression velocity. The result is multiplied by 1.3 to make the measurement relative to external chest compression.

Each injury measure was taken during interaction with the air bag deployment. Impacts after the dummy moves away from the air bag and strikes the seat back were not considered in any of the injury measures recorded.

PERFORMANCE TEST RESULTS

Platform 1 (Advanced Air Bag)

Static tests were conducted on a 5th female driver, and 3 year old and 6 year old Hybrid III passenger dummies. The test setups were described in the Test Methodology. The test results are summarized below.

Static OOP Test Results - HIC and chest g's were very low in the OOP tests with the 5th female H-III driver (Table 3). Chest compression was 34 mm in position 2 (chest on the air bag module). V*C marginally failed. Nij, the neck injury criteria were well below the threshold value of 1.0 in both positions.

Based on these results, it appeared that with a first-stage deployment of the multi-stage air bag, the 5th female could meet injury threshold values with only small improvements in the advanced air bag to reduce the V*C measurement.

A test series on the passenger-side was also conducted using the 3 year old H-III dummy. Table 4 shows the results of a proximity study when the 3 year old dummy was moved back along the longitudinal axis of the vehicle. Position 1 was used as the baseline test and two additional tests were performed with the dummy in the same geometric orientation, but backed off the instrument panel by 100 mm (4 inches) and 200 mm (8 inches). As expected, injury measures declined as the dummy was moved away from the air bag as it deployed.

V*C calculations were questionable because of anomalous readings in the chest pot for the first two positions. However in the 200 mm back position, V*C was still over 1 m/s. Nij was reduced from 4.38 to 1.65, to 0.23, at position 1, position 1-100 mm back, and position 1-200 mm back, respectively. Figure 5 shows the reduction in Nij as the dummy was moved back. It appears that at approximately 150 mm (6 inches), the Nij goes below 1.0. This type of information is useful for air bag system designers who may set up "risk zones" that would suppress the air bag once an occupant entered. In this case to prevent Nij from exceeding 1.0, the risk zone could not be any closer than 150 mm to the instrument panel. Therefore,

Table 3
5[Th] Female Static OOP Driver Tests.

Injury values	Units	Test condition			
		Pos. 2	Pos. 2	Average Pos. 2*	Pos. 1
HIC 36		13	13	13	11
Head Resultant	g	17	17	17	46
Chest resultant	g	25	24	25	15
Chest compression	mm	34	31	32	13
V*C	m/s	1.21	0.86	1.04	0.19
Neck shear	N	277	267	272	390
Neck tension	N	539	418	479	1163
Neck compression	N	32	73	53	57
Flexion Moment about Occipital Condoyle	N-m	20	23	22	2
Extension Moment about Occipital Condoyle	N-m	25	25	25	33
Max N_{ij}		0.55	0.52	0.53	0.68

* The Average column has the average of the results of the two ISO 2 tests.

Table 4
3 Year Old Proximity Tests.

Injury values	Units	Test condition		
		Pos. 1	**Pos. 1 (4"back)**	**Pos. 1 (8"back)**
HIC 36		273	91	13
Head Resultant	g	140	77	40
Chest resultant	g	103	89	43
Chest compression	mm	"questionable data"		23
V*C	m/s	"questionable data"		1.20
Neck shear	N	2432	397	336
Neck tension	N	3415	2435	586
Neck compression	N	1	1	85
Flexion Moment about Occipital Condoyle	N-m	10	6	9
Extension Moment about Occipital Condoyle	N-m	92	24	5
Max N_{ij}		4.38	1.65	0.23

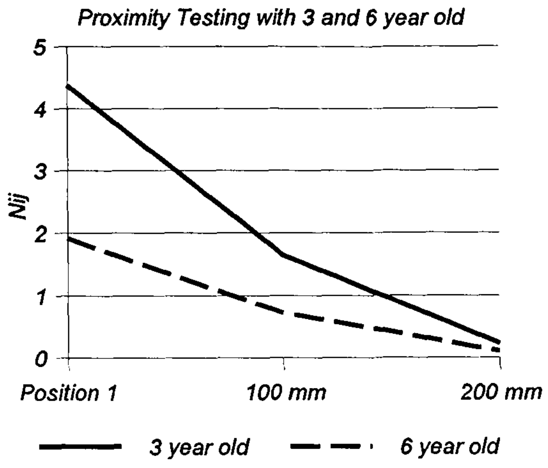

Figure 5. Proximity results for 3 and 6 year old. Six year old 100 and 200 mm results are extrapolated.

a suppression system, working in conjunction with the multi-stage inflator here, may still suppress the air bag deployment when the occupant enters within 150 mm (6 inches) of the instrument panel. These risk zones would be dependent on the aggressiveness of individual air bag systems in vehicles.

Position 2 was tested three times to examine the repeatability of the test procedures (Table 5). It appeared that HIC, chest g's and neck measurements were repeatable. Some discrepancies were found, again, in the chest potentiometer readings which affected the V*C calculation. Only one of the three test gave reliable V*C results.

When looking at the 3 year old tests as a whole, it is apparent that the first-stage deployment of the multi-stage inflator was not low enough to pass IARV's when the dummy was on the instrument panel. Clearance of at least 150 mm (6 inches) appeared to be necessary in position 1 while less clearance may be possible for position 2.

A similar test matrix was used when testing the OOP 6 year old, except no proximity study was done (Table 6). The Nij calculated for the 6 year old tests was less than half that of the 3 year old. Consequently, if the relative difference between the 6 year old and 3 year old Nij is the same at 100 mm and 200 mm, the point where Nij crosses over the 1.0 level is approximately 80 mm (Figure 5).

In the repeatability tests for position 2, Nij, HIC, and chest g's were in close agreement. However, as was seen in the 3 year old, chest V*C and compression were not very repeatable. The combination method of calculating V*C eliminates differentiation of the chest pot and makes the V*C calculation more stable.

<u>**Sled Test Results**</u> - A series of sled tests as outlined in Figure 2 was conducted with the advanced air bag system on a Platform 1 sled-test buck. Table 7 summarizes the test results for the severe impact test simulation with a 5 ms delay in firing the second squib. The sled test simulated a full frontal rigid barrier impact at 30 mph. The unbelted 5th female driver and passenger passed all the IARV's except the driver chest compression and driver and passenger Nij. The 50th male driver and passenger met all the IARV's in Table 2.

Another test series was conducted using a softer air bag (20 ms delay in firing second squib) with the belted and unbelted 5th female and 50th male (Table 8). For the 5th female driver, the belted occupant failed Nij, chest g's, chest compression, and chest V*C. The unbelted only failed chest compression by a marginal level. The 5th female, belted passenger passed all injury criteria. The 50th male unbelted driver failed chest g's. Both 50th male unbelted passengers also failed chest g's. The belted male passenger passed all the injury criteria. Consequently, it appears that along with crash severity, belt-use would also be a good discriminator on what inflator level to fire.

It can be surmised from Figure 6 that occupant size is also an important factor in discriminating the inflator level needed. Figure 6 is a bar chart comparing the injury response on unrestrained 5th and 50th male dummies with the high and mid-level inflation. The IARV's were normalized by their threshold value. For the 5th driver and 50th passenger, HIC and chest g's increased as the delay in firing the second squib increased from 5 to 20 ms. V*C for the 5th driver also increased, but the V*C on the 50th male was very low in both firing sequences. The Nij, however, decreased as the delay in the second squib firing increased. Subsequently, the unrestrained 5th female did not require the high-level needed by the 50th male in this simulated crash condition.

One final sled test series was conducted in a simulated 32 km/h (20 mph) center-pole impact. Here the time-to-fire was 57 ms into the crash. The sled series tested conditions with a 20 ms delay in firing the squib and a primary deployment only. The 5th female was tested on the driver side with the primary only and unbelted (Table 9). In this case the restraint was sufficient to pass the injury reference values. The 5th female driver was also tested with the second squib firing 20 ms after the first. In this case the air bag provided more restraint than was necessary and

Table 5
3 Year Old Repeatability Tests.

Injury values	Units	Test condition		
		ISO 2	ISO 2	ISO 2
HIC 36		555	516	468
Head Resultant	g	161	186	137
Chest resultant	g	128	125	127
Chest compression	mm	**	**	49
V*C	m/s	**	**	5.80
Neck shear	N	962	955	948
Neck tension	N	3736	4097	3838
Neck compression	N	1	1	1
Flexion Moment about Occipital Condoyle	N-m	39	39	38
Extension Moment about Occipital Condoyle	N-m	21	32	36
Max N_{ij}		1.50	2.20	2.17

Table 6
6 Year Old Tests.

Injury values	Units	Test condition			
		ISO 2	ISO 2	ISO 2	ISO 1
HIC 36		276	245	268	86
Head Resultant	g	126	119	112	91
Chest resultant	g	47	45	50	114
Chest compression	mm	32	42	46	51
V*C	m/s	2.02	3.96	6.00	5.46
Neck shear	N	1540	1505	1557	1463
Neck tension	N	3566	3479	3646	3462
Neck compression	N	186	165	194	48
Flexion Moment about Occipital Condoyle	N-m	55	58	58	3
Extension Moment about Occipital Condoyle	N-m	21	13	12	56
Max N_{ij}		1.55	1.53	1.59	1.92

Table 7
30 mph Bag fire times 12, 17.

Injury values	Units	Dummies				
		5th Female Driver Unbelted	5th Female Passenger Unbelted	50th Male Driver Unbelted**	50th Male Passenger Unbelted	50th Male Passenger Unbelted (R)
HIC 36		218	514	191	304	295
Head Resultant	g	52	77	ND	55	52
Chest resultant	g	52	53	45	48	44
Chest compression	mm	43	13	41	15	13
V*C	m/s	0.23	0.03	ND	0.03	0.04
Neck shear	N	-651	-482	383	1972	1745
Neck tension	N	1555	1977	2184	398	460
Neck compression	N	38	37	71	925	717
Flexion Moment Occipital Condoyle	N-m	7	5	23	ND	95
Extension Moment Occipital Condoyle	N-m	38	56	42	ND	20
Max Nii		1.10	1.27	ND	ND	0.43

NA - Sternal Instrumentation not available in 50th male
** - TRW Data, 0 ms delay
ND - No Data

Table 8
Full Frontal, 30 mph Bag fire times 12, 32.

Injury values	Units	Dummies						
		5th Female Driver Unbelted	5th Female Driver Belted	5th Female Passenger Belted	50th Male Driver Unbelted	50th Male Passenger Unbelted	50th Male Passenger Unbelted (R)	50th Male Passenger Belted
HIC 36		495	640	1135	524	668	654	828
Head Resultant	g	55	69	101	60	72	81	83
Chest resultant	g	57	67	55	69	63	62	51
Chest compression	mm	43	46	24	43	15	13	29
V*C	m/s	0.30	0.32	0.30	0.17	0.04	0.03	0.06
Neck shear	N	-289	-777	451	1260	2334	1910	-308
Neck tension	N	1544	1700	1597	1876	523	850	1548
Neck compression	N	71	31	34	172	571	1520	67
Flexion Moment Occipital Condoyle	N-m	4	6	8	29	121	83	8
Extension Moment Occipital Condoyle	N-m	20	36	19	6	9	45	26
Max Nii		0.75	1.08	0.78	0.58	0.30	0.45	0.61

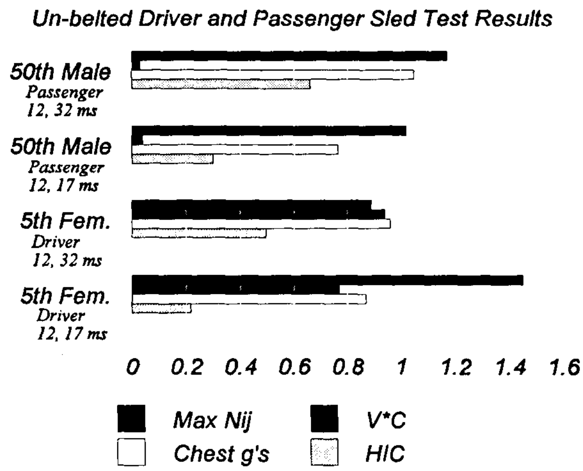

Figure 6. 48 km/h Sled Test Results.

Table 9
20 mph Delayed bag deployment, (Simulated center-pole impact).

Injury values	Dummies	5th Female Driver Unbelted	50th Male Passenger Unbelted	5th Female Driver Unbelted	50th Male Passenger Unbelted
	Bag fire times Primary, Secondary (ms)	57, none	57, none	57, 77	none, none (i.e. No Bag)
	Units				
HIC 36		189	164	288	486
Head Resultant	g	53	37	61	78
Chest resultant	g	27	39	33	37
Chest compression	mm	22	7	24	32
V*C	m/s	0.27	0.00	0.10	0.10
Neck shear	N	-303	937	-545	-776
Neck tension	N	1370	963	1788	1312
Neck compression	N	62	1226	59	1817
Flexion Moment Occipital Condoyle	N-m	1	20	0	2
Extension Moment Occipital Condoyle	N-m	30	15	40	152
Max Nij		0.74	0.29	0.93	1.21

increased HIC, chest g's, chest compression, and Nij. Nij was .93 in this case. Testing on the passenger side was conducted with the 50th male dummy. The unbelted male was first tested with the first-stage deployment only. All the injury criteria were met. The air bag was then cut-off and the test re-run. For this scenario, the 50th male passed the injury criteria again, except for Nij. Consequently, an unbelted 50th percentile male still needs an air bag to meet the IARV's at this crash condition. It is important to understand the effect of inflation levels at this speed range, since it is the range of transition from no deployment, low-level deployment and mid-level deployment.

Crash Test Results - A systems test was conducted with the multi-stage inflator and a single-point advanced sensor used to determine the time-to-fire (TTF) and the firing sequence. The test was a 40 km/h (25 mph) test into a 205 mm (12 inch) pole. The pole impact was situated such that it hit the softest part of the vehicle front-end. This was a very stringent test of the sensor's capability to fire on-time, and with the correct inflation level. The vehicle peak g's at the rear deck was 29.6 and occurred 86.80 milliseconds into the crash. The sensors fired the air bag 74 milliseconds after impact, and fired the first stage of the inflator only. The results from the dummy readings are shown in Table 10. The 5th female driver failed chest compression and V*C, but passed all the other criteria. Compression was high from the chest impact with the lower portion of the steering wheel rim before the air bag deployed.

The 6 year old failed chest g's, chest compression, and V*C. The bag trajectory carried the bag around the back of the dummy. The air bag then forced the dummy into the I/P, causing high chest loads. The load cell data from the neck shear force and neck moment went open during the test. The data collected before the channels went open indicate that the Nij would have been well over 1.0. An earlier deployment of the bag would have helped reduce these loads.

Holden Commodore (De-powered air bag)

OOP Test Results - The 5th female H-III dummy was utilized and tested in Position #1 (chin on module) and Position #2 (Chest on module). The steering column was adjusted to its lowest position and retracted fully forward towards the front of the vehicle. The steering column was replaced after each test. In position 2, the windshield prevented the head from being placed on top of the steering wheel. In that case, the dummy was placed as high as possible until there was approximately 10 mm between the top of the dummy's head and windshield.

Results are summarized in Table 11. A repeat of position one was performed due to data and film collection difficulties. The driver-side air bag was not aggressive to the OOP 5th female driver. Head and chest responses were well below the IARV's. Neck response was also well below the Nij threshold.

The results of the OOP testing of the 3 year old were very typical of U.S. air bags tested for aggressiveness (Table 12). Every critical value was exceeded in position 1. Nij was over 500 percent of the IARV. HIC was over 150 percent of its threshold value.

While most results were lower in position 2 than in position 1, the neck extension in position 2 was 113 N-m, compared to 48 N-m in position 1. Six year old test results are also summarized in Table 12. As was seen in the 3 year old responses, most the injury criteria and critical values for the head and neck were exceeded in either position 1 or position 2. Chest compression and V*C IARV's were not exceeded in either case. The combo method for calculating V*C was not available because the 6 year old dummy was not fitted with sternal accelerometers. In position 1, Nij was over 300 percent of the IARV. HIC in position 2 was exceeded due to the head impact from the air bag module cover.

Crash Test Results

Test results of the FMVSS No. 208 test are shown in Table 13. The injury criteria were met on the driver and passenger test, although there was significant submarining of the dummy on the driver-side due to lack of knee bolsters in the Commodore. The omission of knee bolsters is a result of the Commodore design optimizing restraints for belted occupants.

Driver-side HIC was well within the 80% safety margin usually used by the auto industry. Chest g's were at 54 g's which would pass FMVSS No. 208, but may not be an accepted margin of safety for some vehicle manufacturers. Chest deflection was very high at 72.5 mm, with a 76.2 mm limit in FMVSS No. 208. Femur loads were also quite high at nearly 90% of the threshold value. Although V*C was not a requirement, it was recorded and reported as 1.7 m/s. This is a V*C measure failure when compared to the 1 m/s threshold.

Passenger results were typical of FMVSS No. 208 results for US vehicles. HIC was 571, chest g's were 46.6, and chest deflection was 13.2 mm.

In conclusion, while the driver-side results for OOP testing were very benign, the FMVSS No. 208 results were marginal, although it passed the criteria. Conversely, the OOP results on the passenger-side were

Table 10
Frontal Impact 40 km/h (25 mph) into 305 mm (12 inch) Pole.

Injury values	Units	5th Female Driver	6 YO seated forward
HIC 36		35	665
Head Resultant	g	51	195
Chest resultant	g	53	105
Chest compression	mm	46	35
V*C	m/s	1.33	1.45
Neck shear	N	-611	**
Neck tension	N	315	4964
Neck compression	N	1576	4262
Flexion Moment about Occipital Condoyle	N-m	7	190**
Extension Moment about Occipital Condoyle	N-m	5	7
Max Nij		0.58	**

** - Data channel went open during test

Table 11
5th female driver OOP test results.

Dummy Position		Position 1	Position 1	Position 2
HIC (36ms)		14	20	28
Head Res.	g	51	39	19
Chest Res.	g	39	13	26
Chest (3ms)	g	20	11	20
Chest Comp.	mm	6.3	9.2	21
V*C	m/s	.02	.03	.37
Neck Shear	N	460	220	230
Neck Tension	N	**	1010	830
Neck Compression	N	**	10	10
Ext.Moment about occipital condyle	N-m	14	12	14
Flxn. Moment about occipital condyle	N-m	2	3	16
Max Nij		**	.41	.38

** - Fz channel went open during test

Table 12
H-III 3YO and 6YO passenger OOP test results.

		3 YO		6 YO	
Dummy Position	**Units**	**Position 1**	**Position 2**	**Position 1**	**Position 2**
HIC (36ms)		1464	1428	766	1444
Head Res.	g	265	188	204	195
Chest Res.	g	101	44	64	58
Chest Comp.	mm	44.0	5.9	24.7	2.8
V*C	m/s	1.43	.08	.36	.01
Shear	N	2840	990	2000	1600
Tension	N	6310	3280	7110	3270
Compression	N	0	0	0	0
Ext. Moment about occipital condyle	N-m	48	113	83	75
Flxn.. Moment about occipital condyle	N-m	8	0	19	2
Max Nij		5.55	2.53	2.91	2.66

Table 13
208 Crash Test Results with Holden Commodore.

Injury Measures	US FMVSS No 208 Injury Thresholds	Driver Results	Passenger Results
HIC	1000	609	571
Chest G's	60 g's	53.8	46.6
Chest Deflection	76.2 mm	72.5	13.2
Max. Femur Load	10 kN	8.97	7.76
V*C	no requirement	1.7	0.0

SUMMARY AND CONCLUSIONS

This paper examined an advanced air bag system with multi-stage air bags and single-point sensor. The performance was tested using child dummies in OOP conditions and sled and crash tests in high speed belted and unbelted conditions using the 5th and 50th Hybrid III Dummies. In another test series, an air bag system designed for the Australian market was tested to determine how well a de-powered air bag performed with occupants OOP and in the FMVSS No. 208 full frontal barrier crash test with unbelted 50th percentile male dummies. The following conclusions were derived from these tests.

Conclusions of Testing with Advanced Air Bag

- The lowest level inflation of the multi-stage inflator could not meet IARV's for the OOP 3 and 6 year old dummies.
- 3 year old dummy readings passed the neck Nij criteria at 150 mm from the I/P. Interpolation of the 6 year old test results suggest Nij could be passed at approximately 80 mm from the I/P
- The advanced multi-stage inflator successfully restrained 5th and 50th dummies in a 30 mph sled test using variable outputs of the inflator. Sensors to determine occupant size and belt-use would work well with a multi-stage inflator system that tailors the output for a particular situation.
- Output of both stages met all injury criteria for the 50th male in 20, and 30 mph crash simulations.
- Output of both stages met all injury criteria except chest g's and chest compression for the 5th female in 20, and 30 mph crash simulations.
- A crash sensor successfully detected a soft-pulse crash and deployed only the first stage of the air bag.
- Bag fire time was late and contributed to deploying the air bag after the 6 year old was severely OOP. Further development is necessary to improve sensor timing, although the sensor in this program was not the optimal one of choice.

Conclusions of Testing with Holden air bag

- Driver 50th percentile male dummy marginally passed 208 crash test requirements.
- Driver air bag performed well in static OOP tests. Results were similar to OOP testing with U.S. de-powered driver air bags.
- Passenger air bag performed well in the crash test and 50th percentile male dummy passed all FMVSS No. 208 requirements by a comfortable margin of safety.
- Passenger air bag did not perform well in static OOP tests. Bag performance was similar to full-powered bag in US. Consequently, it appears that the passenger air bag is similar to bags designed in US for unbelted 208 barrier crash test.

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ASSESSMENTS OF AIR BAG PERFORMANCE BASED ON THE 5TH PERCENTILE FEMALE HYBRID III CRASH TEST DUMMY

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ABSTRACT

Historically, assessments of frontal crash safety have been based primarily on the measured responses of 50[th] percentile male dummies in relatively high speed vehicle crashes against a rigid flat barrier. Under such test conditions, the ability of supplementary airbag systems to greatly reduce head injury potential is clearly evident in crash tests performed by Transport Canada and others. However, significant segments of the driving population travel routinely with their seats positioned ahead of the nominal mid-position used in 50[th] percentile male dummy tests. Moreover, most frontal impacts can be expected to produce softer vehicle deceleration signatures than those produced in flat rigid wall tests. The necessity of broadening the range of regulated crash conditions to which vehicles fitted with airbag systems are subjected is highlighted in crash tests performed by Transport Canada using 5[th] percentile female Hybrid III tests, with seats placed in their most forward positions. The neck loads observed in these tests far exceeded commonly referenced injury assessment values. The magnitudes of the neck loads were influenced not only by the aggressiveness of the airbag system, but also by the timing of the deployment of the airbag. The neck loads observed in low speed offset frontal crash tests often exceeded those observed in high-speed, rigid-wall tests, as a result of the timing of airbag deployment.

INTRODUCTION

The fitment of supplementary airbag systems is not mandatory in Canada. In the formulation of occupant protection standards governing occupant protection in frontal crashes, emphasis in Canada continues to be placed on regulating total system performance, rather than the specification of hardware. The technical requirements of Canada Motor Safety Vehicle Standard (CMVSS) 208 have been revised recently to reflect performance levels achievable with current technology. The revised performance requirements have only been satisfied consistently by vehicles fitted with supplementary airbag systems [1,2]. Given the highly integrated nature of the automobile industry in North America, it is anticipated that most, if not all, new passenger-carrying vehicles sold in Canada will be fitted with supplementary airbag systems. Though no test with an unbelted dummy is specified in Canada, it is reasonable to expect that the design of most airbags fitted in Canada will continue to be strongly influenced by US regulatory requirements, which continue to emphasize the protection of unbelted occupants.

One major shortcoming of both Canadian and US regulatory requirements is that each front outboard seating position is tested with a dummy of 50th percentile male dimensions in one well-defined seating posture. Consequently, the performance levels achieved in the test may not be indicative of the levels of protection likely to be afforded to occupants of different stature. Of particular concern are possible adverse airbag-occupant interactions if the seat is located forward of the mid seat position. There is evidence from laboratory testing that the proximity of an occupant to the airbag module has a strong influence on the response of the neck and the chest [3,4].

FIELD PERFORMANCE

In order to gain an understanding of the field performance of supplementary airbag systems in Canada, Transport Canada, in the fall of 1993, initiated a directed study devoted to documenting the injury experience of occupants involved in crashes resulting in the deployment of an airbag system. The data collection methodology adopted for this study is similar to that used in the Fully Restrained Occupant Study (FROS) where the emphasis was on evaluating the collision performance of three-point seat belt systems [5]. The Air Cushion Restraint Study (ACRS) utilizes the resources of university-based collision investigation teams located across Canada. Each participating team is assigned a defined area of operation and case selection criteria. The study and findings are described in detail in previous publications [6,7,8].

Available Canadian evidence suggests that, as expected, airbags are highly effective in preventing serious or fatal head injury and facial fracture in high severity crashes, but that these gains are offset by bag-induced injuries in low severity crashes, when deployment is unwarranted if the belt system is being used. Female drivers are the most adversely affected in low-severity crashes.

The Canadian experience with airbags is consistent with the findings of a number of US studies. The introduction of the airbag has produced a variety of new injury mechanisms, such as facial injuries from "bag slap", upper extremity fractures, either directly from the deploying airbag module or from arm flailing, and thermal burns to the face and arms [9, 10, 11]. Among adults, most of the bag-induced injuries are minor in severity (AIS 1) as measured by the Abbreviated Injury Scale (AIS) [12]. However, upper extremity fractures rated AIS 2 or AIS 3 are not uncommon [13]. In the 1996 Report to Congress, NHTSA noted that the risk of serious (AIS 3) upper extremity injury to a belted driver may increase by some 40 percent with airbags [14]. Others have estimated that the risk of upper extremity injury among belted drivers may be increased by as much as a factor of 4 given airbag deployment [15]. Several studies have noted that the incidence of bag-induced upper extremity injury, particularly of upper extremity fracture, is far higher among female drivers than male drivers [8, 16,17]. The majority of the bag-induced arm fractures among belted female drivers occur in relatively low speed impacts [8].

In terms of overall fatality risk, the initial findings, at least for adults, are encouraging. Without exception, the effectiveness studies completed to date have shown that airbags reduce the risk of fatal injury among both drivers and adult passengers by some 11-14 percent, with the prevailing rates of seat belt usage in the US [18, 19, 20, 21].

Available evidence also suggests that airbags increase the overall risk of fatal injury among children under the age of 10 by some 21 percent [21]. In the US, NHTSA is investigating collisions involving airbag-related fatal or seriously injured occupants under its Special Crash Investigations (SCI) programme. Over 55 child deaths, directly attributable to airbag deployments, have been recorded to date under this programme. The vast majority of these deaths occurred in crashes of relatively minor severity. This death toll prompted NHTSA to relax the unbelted test requirements associated with FMVSS 208 in order to facilitate the rapid introduction of "depowered" airbag systems into the US.

At the time of writing, the SCI database also contained a total of 43 airbag-related adult fatalities. Of the 13 belted drivers represented in the database, 10 (77%) were females. All ten female victims were under 165 cm in height. The majority sustained fatal neck and/or head trauma. All three belted male drivers sustained fatal chest trauma. Of the 21 unbelted drivers represented in the database, 16 (76%) were females. The majority of unbelted drivers, both males and females, sustained fatal chest trauma.

A monitoring programme, similar to the SCI, has also been implemented in Canada. To date, only one child death directly attributable to an airbag deployment is known to have occurred in Canada. At least four adult deaths directly attributable to an airbag deployment in a relatively low speed impact are known to have occurred in Canada. Three of the cases involved belted female drivers. The remaining case involved an unbelted male driver.

While most case studies of airbag-related deaths involve low to moderate speed collisions, it is important to recognize that the energy released by an airbag is independent of collision severity. As such, fatal bag-related injury can occur at all collision severities. With increasing collision severity, however, the injury outcome, in the absence of airbag deployment, becomes increasingly uncertain. Consequently, counts of airbag fatalities are limited to lower speed crashes where, in the absence of deployment, the occupant would have been expected to survive the crash.

JOINT TC/NHTSA CRASH TEST PROGRAMME

Based on an examination of the available data on the field performance of airbag systems in Canada, in 1996 Transport Canada implemented a major research programme to evaluate testing protocols which could be incorporated in Canada Motor Vehicle Safety Standard (CMVSS 208) to minimize the risk of bag-induced injury to belted occupants of short stature in frontal collisions. The crash test dummy selected for the programme was the 5th percentile Hybrid III female. In addition to representing a small adult, it has the advantage of representing, in size, a 12- to 13-year old child. Given the current recommendation in Canada, that all children aged 12 years or less, travel in a rear seat whenever possible, the 5th percentile female Hybrid III is an ideal dummy for the purposes of regulating front seat passenger-side protection.

Two series of full-scale vehicle crash tests were conducted as part of the programme. The first series involved 48 km/h rigid barrier crash tests with the seats in the full forward position. The second series of tests involved low-speed, offset-frontal crashes, utilizing the deformable barrier face and vehicle alignment protocols defined in Europe under Directive 96/79/EC. As in the rigid barrier tests, the 5th percentile Hybrid III was tested with the seat in the fully forward position.

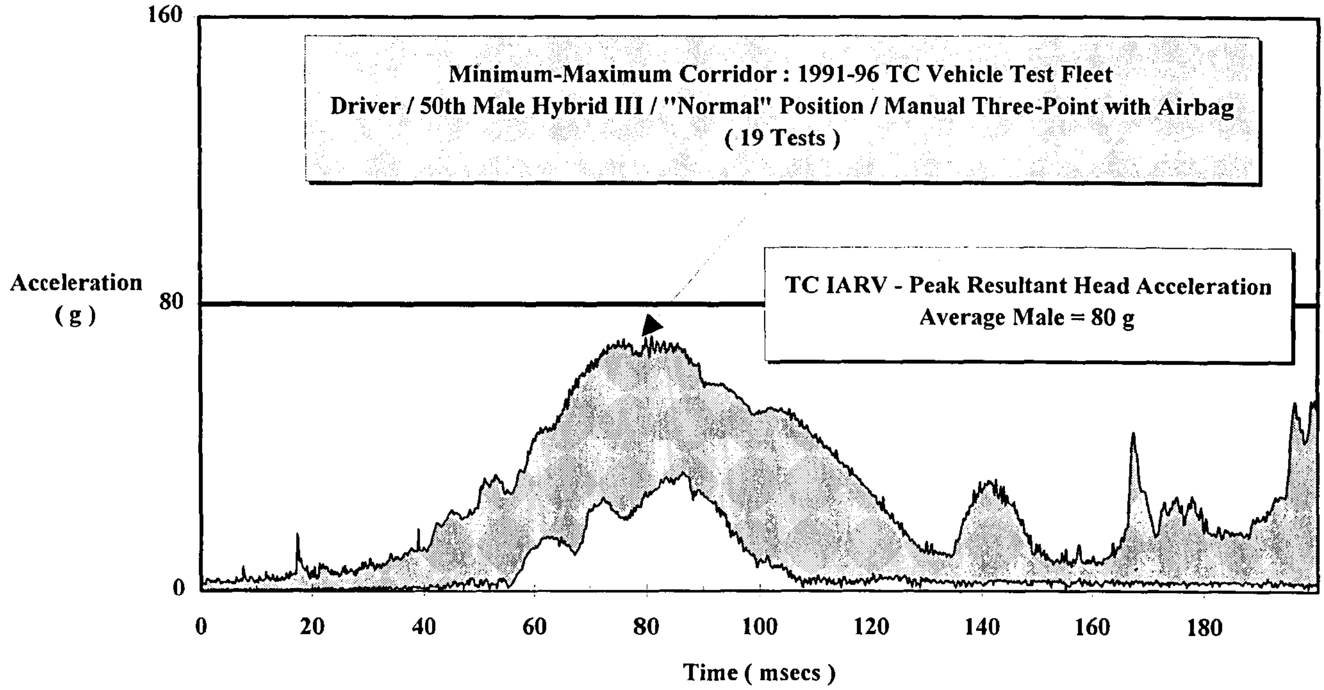

Figure 1. Range of Resultant Head Acceleration Responses Measured in 48 km/h Rigid Barrier Tests of First Generation Airbag with 50th Percentile Male Hybrid III (Driver Side).

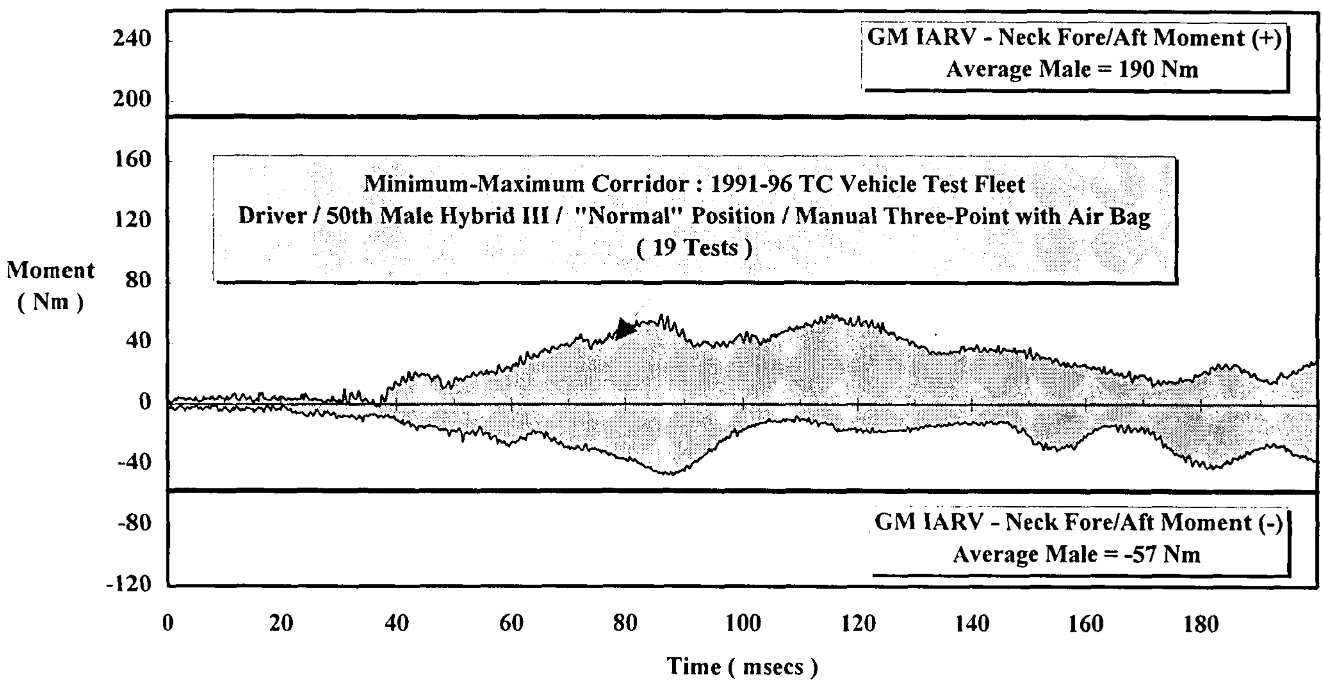

Figure 2. Range of Neck Extension Moment Responses Measured in 48 km/h Rigid Barrier Tests of First Generation Airbag Systems with 50th Percentile Male Hybrid III (Driver Side).

As part of a joint research agreement between Transport Canada and the NHTSA, the programme was expanded to include a representative sample of both first- and second-generation airbag systems and vehicles of different size classes. A total of 72 full-scale vehicle crash tests, utilizing one or two 5th percentile Hybrid III dummies, have been performed to date, generating a database of 124 individual 5th percentile Hybrid III dummy tests.

Baseline Responses - Mid-Size Male Hybrid III

In interpreting the results obtained in the tests with the 5th percentile female Hybrid III, it is informative to first consider the dummy responses typically measured in 48 km/h rigid barrier tests using the 50th percentile male Hybrid III dummy. The resultant acceleration-time histories of the head measured on the driver side in airbag tests with the dummy belted in 19 tests conducted by Transport Canada are presented in Figure 1. The fore/aft neck moment-time histories associated with the same tests are presented in Figure 2.

In a rigid barrier crash, the vehicle deceleration pulse generally produces deployment of the airbag early in the crash, typically within 15 to 25 milliseconds of the first contact with the barrier. This, in combination with the clearance between the steering wheel module and dummy, normally provided when the seat is in the mid-position, allows the airbag to inflate fully, prior to dummy contact. Under such circumstances, head and neck kinematics are well controlled and excessive forward flexion or rearward extension of the neck is avoided. In all 19 tests, the peak resultant head acceleration values were less than Transport Canada's Injury Assessment Reference Value (IARV) of 80 g [2]. Similarly, the peak fore/aft neck moments were all well below the IARV values of 190 Nm in flexion and 57 Nm in extension, derived by General Motors [22]. Although not presented, all peak neck shear forces and peak axial forces measured in this series of tests were also well below GM IARV values. Consequently, the tests would predict negligible risk of injury of the head or neck under the conditions represented. The near absence of bag-related fatalities among belted male drivers from head or neck trauma would support this conclusion.

5th Percentile Female Hybrid III Results

<u>Rigid Frontal Barrier Tests</u> - Driver-side response data generated with the 5th percentile female dummy are available for a total of 34 48 km/h rigid frontal barrier crash tests, in which the vehicle was equipped with a driver-side airbag and the bag deployed. The peak dummy response values and calculated injury indices

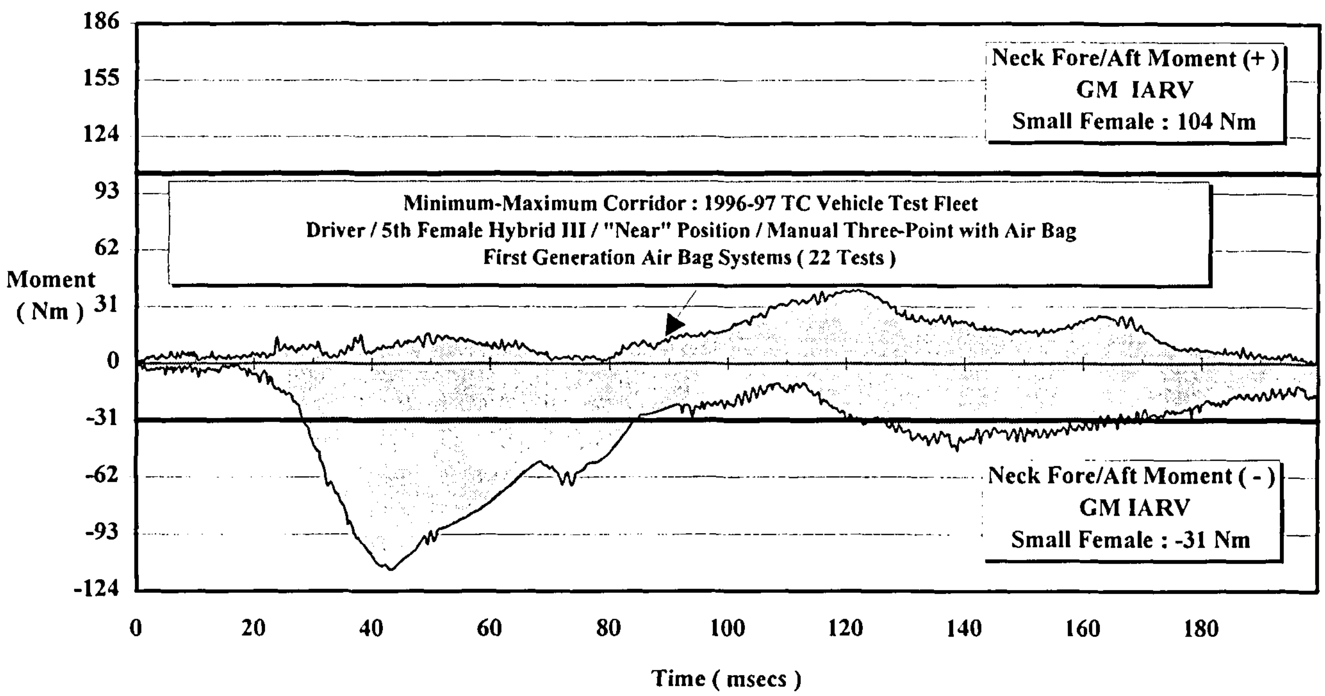

Figure 3. Range of Neck Extension Moment Responses Measured in 48 km/h Rigid Barrier Tests of First Generation Airbag Systems with 5th Percentile Female Hybrid III (Driver Side).

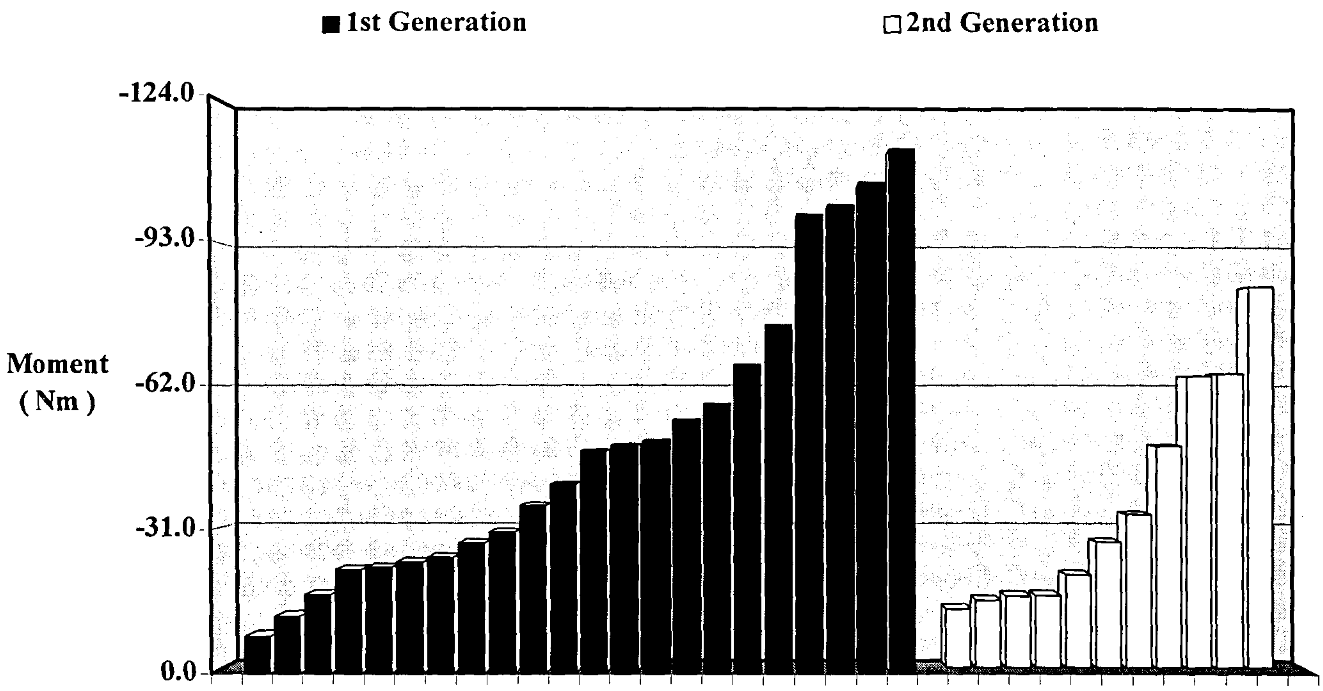

Figure 4. Peak Driver Neck Extension Moments Measured in 48 km/h Rigid Barrier Tests with 5th Percentile Female Hybrid III as a Function Air Bag Grouping.

obtained in this series of airbag tests are summarized in Appendix A1 for drivers, and Appendix A2 for front right passengers.

Given the imprecise nature of the term "depowered", the term "second-generation" is used in the present paper to denote vehicle models redesigned for model year 1998 to take advantage of the amendments to FMVSS 208 introduced to facilitate "depowering" of airbag systems in the US. The term "first-generation" is used to describe all pre-1998 airbag systems and 1998 airbag systems not yet redesigned at the time of vehicle purchase. It should be noted that the changes made to many 1998 vehicle models were not necessarily limited to reductions in the power output of the airbag module. Other components of the airbag system were frequently changed as well and, in some cases, the seat belt systems were redesigned. It should be also noted that six pre-1998 vehicles were modified by Transport Canada to reflect 1998 design changes to the airbag system and seat belt assemblies (if applicable). These vehicles are included in the second-generation airbag totals.

As most bag-related deaths in the case of belted female drivers are associated with neck trauma, the discussions below focus primarily on the fore/aft neck extension moments measured on the dummy. The range of neck responses observed in the first generation test series in rigid barrier tests with the 5th percentile female dummy in the driver's position is depicted in Figure 3.

The close proximity of the small dummy to the steering wheel results in the dummy interacting with the airbag while it is still expanding. This typically results in the head being forced upwards and rearwards as the bag continues to expand under the chin producing an extension-tension neck response. Maximum extension of the neck is generally observed some 40 to 50 milliseconds into the crash.

Complete driver neck response data are available for 22 of the 23 tests with first generation systems and 11 tests with second generation systems. A comparison of the peak neck extension moments observed in these tests is presented in Figure 4. As can be seen, both series of tests generated a wide range of peak values. In contrast to the results obtained using a mid-size male dummy, exceedances of the GM neck extension IARV for a small female (31 Nm) were common in this series of tests. The IARV was exceeded in 13 of 22 (59%) of the first-generation tests and in 5 of 11 (45%) of the second-generation tests. Peak values exceeding three times the IARV were observed in 4 (18%) of the first generation tests, the highest neck extension moment value being

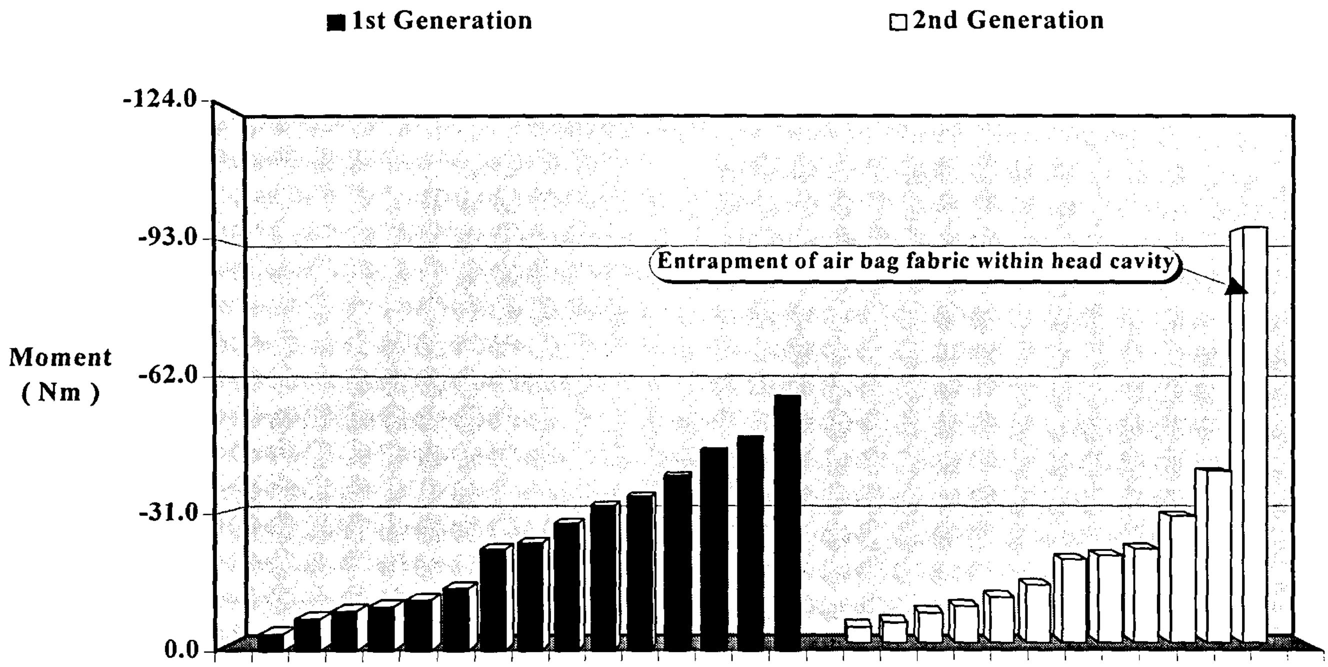

Figure 5. Peak Front Right Passenger Neck Extension Moments Measured in 48 km/h Rigid Barrier Tests with 5th Percentile Female Hybrid III as a Function Airbag Grouping.

113 Nm. The highest neck extension moment observed in the second generation tests was 84 Nm. The average peak neck extension moment observed in the second-generation test series was some 26% lower than the mean value observed in the first generation series of tests (36.6 Nm vs. 49.4 Nm).

The corresponding data for the passenger tests are presented in Figure 5. Passenger head and neck kinematics were far more complex than for the driver. Depending on the vehicle and design of the airbag system, the neck experienced either axial tension or compression accompanied by either forward flexion or rearward extension, with all possible combinations represented. In tests involving first-generation systems, exceedance of any neck IARV was observed only when the loading conditions produced a tension-extension response. The extension IARV was exceed in 6 out of 15 (40%) of the tests. However the maximum extension moment was only 58 Nm, less than half the maximum value recorded on a 5th-percentile driver. The extension IARV was exceed in 2 of 12 of the second-generation tests. In one of these, however, the airbag fabric very clearly penetrated the head cavity, despite the use of a protective neck shield. The neck response data for this test are therefore highly suspect. Excluding this test, the mean neck extension moment for the second generation test series was 16.3 Nm, or 38% less than the mean value of 26.1 Nm observed in the first-generation test series.

Offset Frontal Deformable Barrier Tests - The vast majority of tests conducted with the European offset deformable barrier face were conducted with a nominal impact speed of 40 km/h. This speed was selected since early testing indicated that the associated impact severity was sufficient to trigger the deployment of most, if not all, current airbag systems, while still representing a collision environment which is relatively innocuous to a belted individual, including belted occupants who travel with the seat fully forward. All tests were performed with a 40% vehicle offset to the barrier face as defined in Directive 96/79/EC. The driver- and passenger-side data generated by this series of 40 km/h tests are summarized in Appendices A.3 and A.4, respectively.

Complete neck response data for the driver's position in this series of 40 km/h impacts are available for 12 first-generation and 12 second-generation tests. The peak neck extension moments are presented in Figure 6. It is interesting to note that, despite the fact that the 40 km/h offset deformable barrier test condition is far less severe than the 48 km/h rigid barrier test condition, the offset tests produced higher peak neck response values.

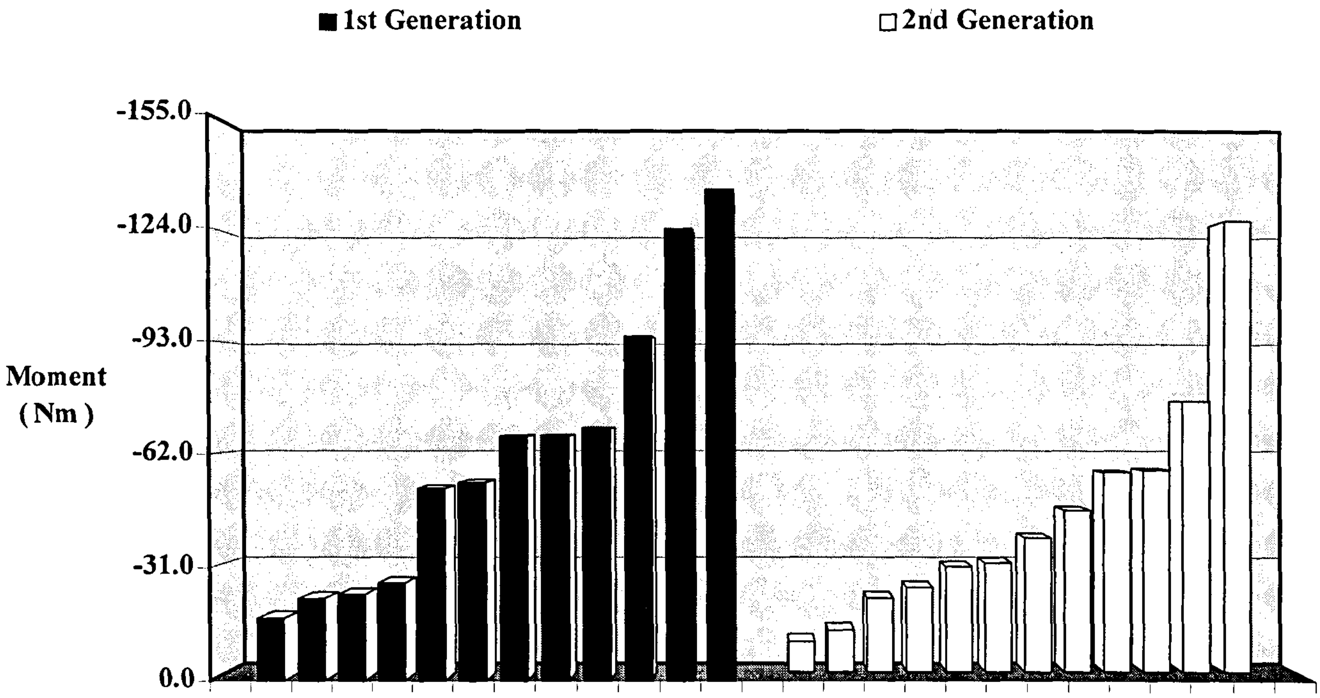

Figure 6. Peak Driver Neck Extension Moments Measured in 40 km/h Offset Frontal Deformable Barrier Tests with 5th Percentile Female Hybrid III as a Function Airbag Grouping.

The highest peak neck extension value observed in the first-generation test series was 134 Nm, while the corresponding highest peak value observed in the second generation test series was 127 Nm. Notwithstanding the similarity in maximum values, the mean peak neck extension moment observed in the second-generation test series was 36.3 Nm, a value approximately 42% lower that of the mean value of 62.7 Nm observed in the first generation test series.

Figure 7. Delayed Deployment (1st Generation Airbag)

The elevated neck moment values observed in the offset tests can be attributed to the timing of the airbag deployments. These occurred as late as 110 milliseconds into the crash. In a number of instances the initial clearance between the dummy and the delay in firing of the bag resulted in the dummies head being in contact with the airbag module at time of deployment (Figure 7).

The neck extension IARV was exceeded by the driver in 8 of 12 (67%) of the first-generation tests and in 6 of 12 (50%) of the second-generation tests. However, while peak neck extension values exceeding twice the IARV value were observed in 6 of 12 first-generation tests (50%), this was the case for only 2 of 12 (17%) of the second generation tests. That difference accounts for the much lower mean neck extension value noted above for the latter series of tests.

In the second generation test series, the influence of late bag deployment on neck response was far less pronounced than in the first generation test series. Indeed, the second lowest peak neck extension moment was recorded in the test which produced the latest airbag

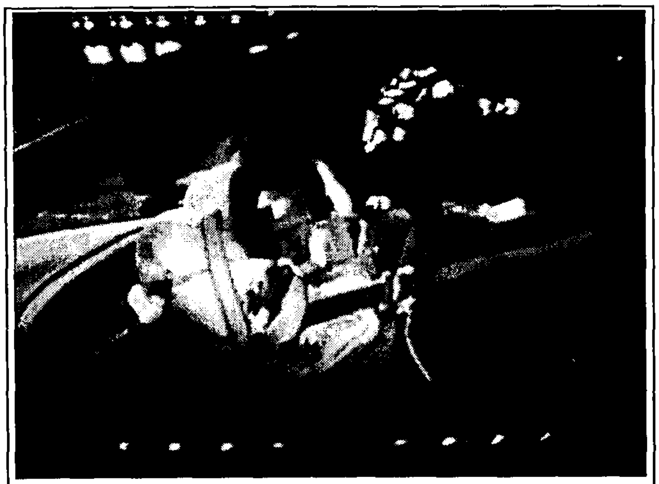

Figure 8. Delayed Deployment (2nd Generation Airbag)

deployment in the second-generation test series. At the time of deployment, the head was already in contact with the module. The tear pattern of the module cover and steering wheel design, in combination with the reduced power level of the airbag module, resulted in the airbag deploying laterally and sufficiently behind the steering wheel rim so that very little impact energy was transferred to the head (Figure 8). The peak driver neck extension moment observed in this test was 12 Nm.

Neck response data for the passengers in this series of 40 km/h impacts are available for 7 first-generation tests and 13 second-generation tests. The neck extension IARV was exceeded by the passenger in 4 of 7 (57%) first-generation tests and in 2 of 13 (15%) second-generation tests. The mean neck extension moment for the second-generation test series was 13.9 Nm, approximately 57% less than the mean value of 32.6 Nm observed in the first-generation test series.

The magnitude of the passenger neck moments was strongly influenced by the timing of the airbag deployment. This was true for both first and second generation vehicles. The highest neck moment observed in the second-generation test series was 58 Nm and was produced by the test associated with latest deployment (107 ms). The same vehicle model was also represented in the first-generation test fleet. The 1997 version of the same vehicle model produced a peak neck extension value of only 22 Nm. The much lower value likely reflects the earlier time of airbag deployment (34 ms).

Specialty Tests - As part of the above offset test series, a number of selected vehicle models were also tested at different impact severities. These tests were

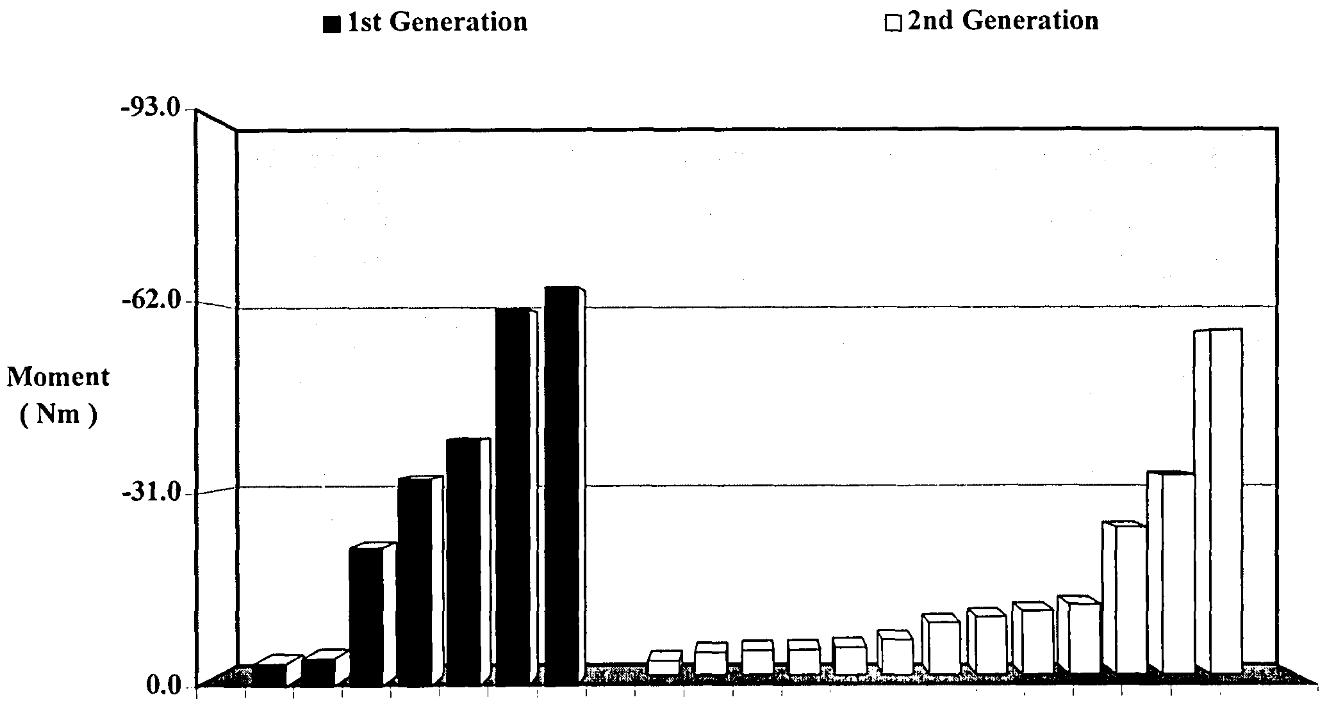

Figure 9. Peak Front Right Passenger Neck Extension Moments Measured in 40 km/h Offset Frontal Deformable Barrier Tests with 5th Percentile Female Hybrid III as a Function Airbag Grouping.

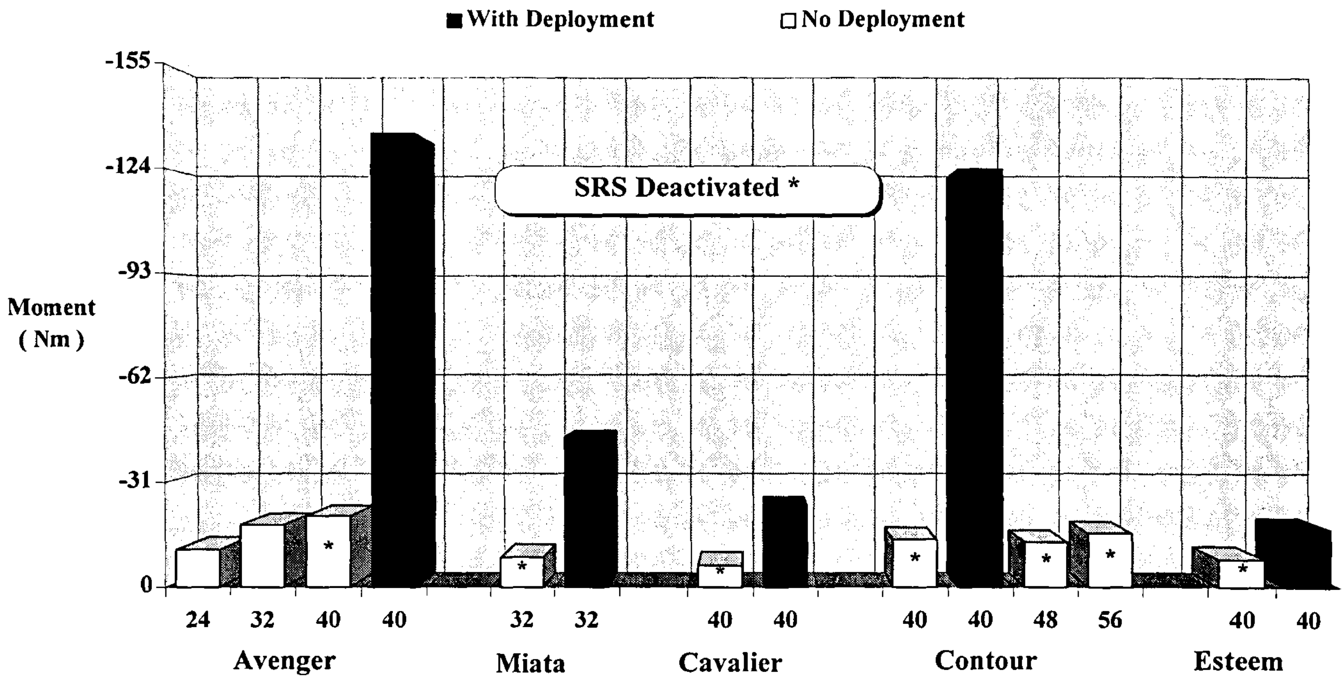

Figure 10. Peak Driver Neck Extension Moments Measured in Offset Frontal Deformable Barrier Tests with 5th Percentile Female Hybrid III as a Function Impact Speed and Airbag Deployment.

performed initially to establish the collision severity at which the airbag system would deploy in an offset deformable barrier test. In addition, it was intended to quantify the effects of deactivation, on the responses measured on a belted 5th percentile female Hybrid III, with the seat in the fully forward position, at collision severities at or just above the deployment threshold. Seven tests were performed with deactivated airbags. For one vehicle model, two additional tests, one at 48 km/h and one at 56 km/h, were performed with the airbag system deactivated. A detailed breakdown of the dummy responses measured in this series of tests is provided in Appendix A.5. The peak driver neck extension moments observed in this series of tests, are presented in Figure 10.

From the data presented, it can be observed that the peak neck moments obtained with airbag deployment always exceeded those which were obtained when the airbag system was deactivated. Indeed, in none of the tests performed with the airbag system deactivated was any commonly referenced IARV or regulated injury index exceeded. These results suggest that current airbag deployment thresholds are set too low, at least for belted drivers.

The above results also highlight the requirement for a low-speed test procedure to ensure that airbag systems are not only optimized for belted occupants but also that their performance is assessed over a range of different collision severities. In Figure 11, curves of vehicle deceleration versus time, typically observed in high-speed tests against rigid barriers, are compared with those observed in 40 km/h offset frontal deformable barrier tests with a 40% vehicle offset. Whereas the rigid wall test can be seen to produce very high vehicle decelerations very early in the crash sequence, the offset condition produces a "soft" deceleration pulse with peak decelerations relatively late in the collision. As can also be seen, the profile of the crash pulse in the offset test shows good agreement with generic sled pulses used to represent a typical collision.

The late deceleration peaks produced in the offset test often trigger airbag deployment. Under such situations, very high neck loads can be produced by the bag, whereas, in the absence of airbag deployment, the same occupant would be riding down the collision safely. With the advent of airbag systems, it can be seen that the relevance of the high speed rigid wall test has been greatly reduced.

Paired-Vehicle Comparisons - Many vehicle models represented in the first-generation test series differed from those in the second-generation series. The subset of vehicle models that was represented in both series of tests was examined separately, to see if these tests of paired vehicles showed any trends which differed from those observed in the main programme. The results for the paired vehicles are presented in Figures 12 and 13 for rigid- and offset-barrier tests, respectively.

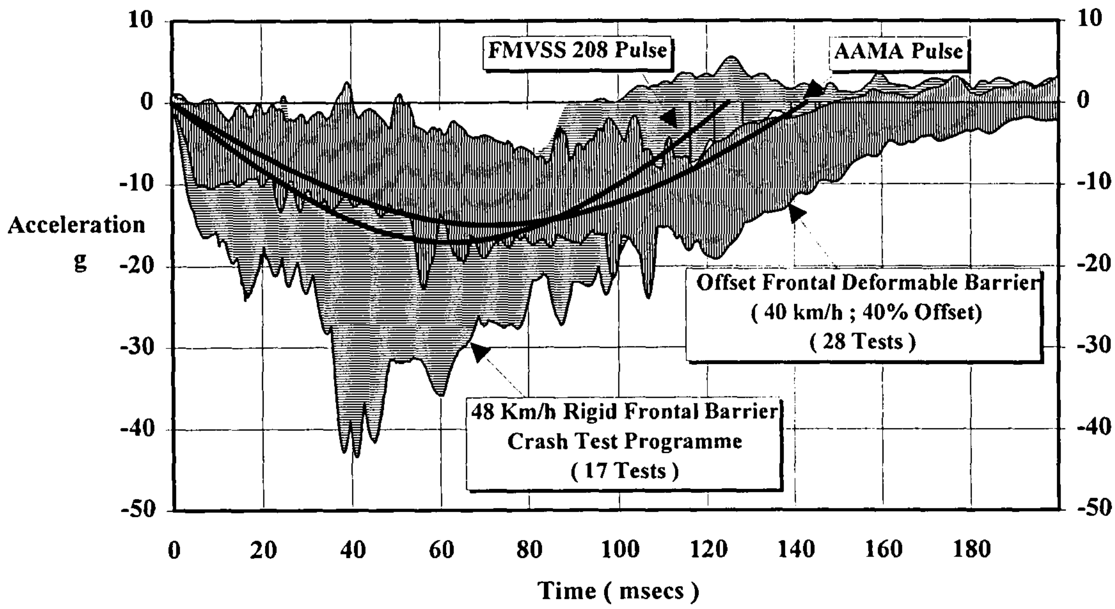

Figure 11. Comparison of Crash Pulses

From the results presented, it can be seen that the tests of paired vehicles produced trends similar to those noted in earlier discussions. The second-generation tests produced lower peak driver neck extensions, with the largest differences being observed in the offset tests. Given that the offset test is more representative of real-world crashes, this suggests that the magnitude of the benefits likely to be achieved with "depowering" could be greater than predicted on the basis of rigid barrier test data. Further support for this observation can be found in a comparison of the peak neck extension values, observed in static tests of one of the vehicle models represented in the paired-vehicle subset. Those results are presented in Figure 14.

In that series of static airbag tests, a 5th percentile female Hybrid III driver was subjected to a series of four separate airbag deployments. The baseline test was done with the seat in the fully forward position and the seat back in the most upright position. The dummy was then pivoted forward until the head was in contact with the module and retested. Additional tests were performed at two intermediate positions. The fifth static test took the form of an ISO-type "chin on hub" out-of-position test. As would be expected, the maximum neck extension moments increased with increasing proximity of the dummy to the airbag module. In tests where the dummy is in close proximity to the module, the reductions in peak neck loads achieved with second-generation airbag modules show much closer agreement with those predicted by the offset tests than with those predicted by the rigid barrier tests. It is also interesting to note that, while static out-of-position tests are frequently regarded to represent a "worst-case" scenario, even the "chin on hub" test produced a peak neck extension value that was lower than that observed in the full-scale vehicle offset test.

DISCUSSION

Low speed offset frontal crash testing, using belted 5th-percentile dummies in the fully forward seat position, overcomes two serious deficiencies which exist in current regulatory practices. The first deficiency is the absence of any requirements explicitly addressing the frontal protection requirements of drivers of short stature who, by necessity, often sit close to the steering assembly. In addition, current regulatory practices fail to ensure that optimum benefits are achieved over the range of collision severities represented in the field. Rigid wall tests, in themselves, provide little assurance that timely deployment of the airbag will be achieved in the "softer" collisions which account for the majority of real frontal crashes. The low-speed offset test should not be viewed as a substitute for the high speed barrier test. Rather, it

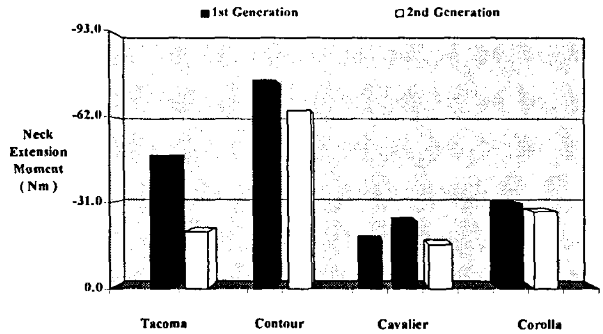

Figure 12. Peak Driver Neck Extension Moment : 1st Generation vs. 2nd Generation Systems (48 km/h Rigid Barrier).

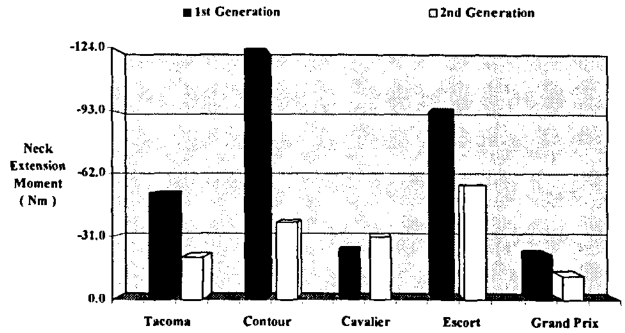

Figure 13. Peak Driver Neck Extension Moment : 1st Generation vs. 2nd Generation Systems (40 km/h Offset Frontal).

should be viewed as a means of broadening the relevance of frontal protection standards to encompass a wider range of occupants sizes and collision severities. An added advantage of the low speed offset frontal test, as described in the present paper, is that it makes use of testing hardware already in widespread use around the world.

The findings of the present study suggest that changes in airbag design introduced in most 1998 models should help to reduce the incidence of serious or fatal bag-related injury among both drivers and right-front passengers. Further improvements in sensor technology are required, however, with respect both to the discrimination of collision severity and the assurance of timely airbag deployment. The frequency of late or delayed deployments observed in the present test programme suggests the need for additional, satellite crash sensors in the forward portions of the vehicle.

Not all aspects of the testing hardware or procedures developed or employed in the offset testing protocol have been finalized. Issues yet to be resolved completely include the design of the neck shield, and finalization of the dummy positioning procedure. Once these two issues are resolved, repeatability trials will be performed.

DISCLAIMER

The conclusions reached and opinions expressed in this paper are solely the responsibility of the author. Unless otherwise stated, they do not necessarily represent the official policy of Transport Canada.

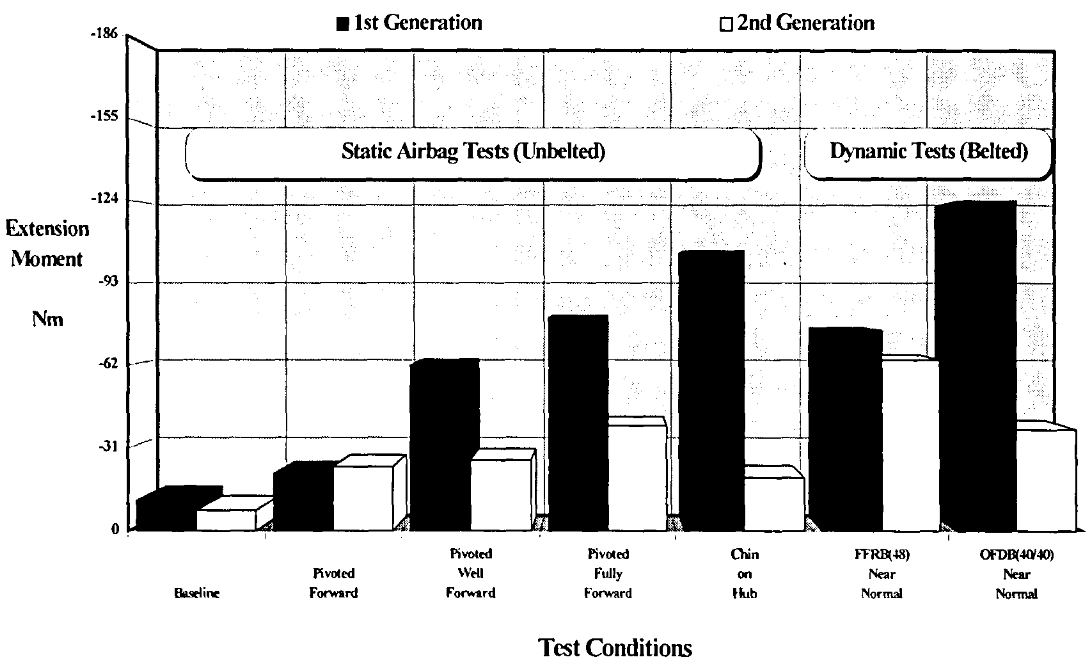

Figure 14. Peak Driver Neck Extension Moment as a Function of Test Condition.

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Appendix A.1 - 48 km/h Full Frontal Rigid Barrier Crash Test Series / 5th Percentile Female Hybrid III ATD / Driver Side Results

Full Frontal Rigid Barrier Crash Test Series		Head Response	Neck Response		Chest Response		
		SAE 1000	SAE 1000	SAE 600	SAE 600 / SAE 180	SAE 600 / SAE 180 / SAE 60	SAE 600 / SAE 180
TC Test Number / Test Vehicle		Resultant Head No Clip Acc. (g) / HIC (15 ms)	Axial Force Positive/Negative (N)	Calculated Occipital Moment Positive/Negative (Nm)	Mid-Sternum Deflection (mm)	Mid-Sternum VC (m/s)	Resultant Chest No Clip Acc. (g)
First-Generation Test / Air Bag Deployment							
TC96-101D	1996 Toyota Tacoma	**97.6** / 700	2802 / -1768	8 / -48	#N/A / -41.4	#N/A / #N/A / 0.000	81.0 / #N/A
TC96-102D	1996 Dodge Avenger	58.4 / 283	2710 / -454	7 / -101	#N/A / -29.7	#N/A / #N/A / 0.265	38.3 / #N/A
TC96-103D	1996 Mazda MPV	**104.0** / 268	2612 / -327	11 / -99	#N/A / -22.7	#N/A / #N/A / 0.164	40.2 / #N/A
TC96-112D	1996 Merc Mystique	67.1 / 307	2593 / -387	11 / -75	#N/A / -24.4	#N/A / #N/A / 0.210	48.0 / #N/A
TC96-114D	1996 Chev Cavalier	52.7 / 181	1857 / -603	13 / -17	#N/A / -21.2	#N/A / #N/A / 0.090	46.4 / #N/A
TC96-115D	1996 Suzuki Esteem	61.9 / 309	1980 / -1006	14 / -36	#N/A / -30.6	#N/A / #N/A / 0.269	49.5 / #N/A
TC96-122D	1996 Mazda Miata	39.8 / 54	1793 / -549	32 / -49	#N/A / -42.3	#N/A / #N/A / 0.337	49.3 / #N/A
TC96-151D	1996 Toyota Corolla	50.1 / 154	1638 / -432	10 / -31	#N/A / -21.7	#N/A / #N/A / 0.075	39.8 / #N/A
TC97-101D	1997 GM Venture	65.6 / 334	2120 / -276	#N/A / #N/A ND	#N/A / -34.7	#N/A / #N/A / 0.363	50.4 / #N/A
TC97-102D	1997 Jeep TJ	48.6 / 209	1669 / -333	16 / -25	#N/A / -48.2	#N/A / #N/A / 0.518	41.2 / #N/A
TC97-103D	1997 Hyundai Tiburon	41.3 / 75	1844 / -521	40 / -105	#N/A / -33.8	#N/A / #N/A / 0.256	48.6 / #N/A
TC97-104D	1997 Ford F150 PU	**129.7** / 313	1812 / -803	26 / -28	#N/A / -35.1	#N/A / #N/A / 0.267	80.5 / #N/A
TC97-105D	1997 Saturn SL	42.7 / 149	1593 / -403	17 / -12	#N/A / -34.7	#N/A / #N/A / 0.367	36.8 / #N/A
TC97-106D	1997 Suzuki X90	58.6 / 290	2514 / -1051	11 / -66	#N/A / -35.2	#N/A / #N/A / 0.226	59.6 / #N/A
TC97-107D	1997 Dodge Dakota	47.5 / 106	1736 / -720	8 / -41	#N/A / -40.4	#N/A / #N/A / 0.323	48.2 / #N/A
TC97-110D	1997 Chev Cavalier	50.7 / 138	1469 / -521	19 / -24	#N/A / -29.4	#N/A / #N/A / 0.311	38.7 / #N/A
TC97-134D	1997 Toyota Rav4	65.8 / 403	2491 / -800	31 / -58	#N/A / -39.4	#N/A / #N/A / 0.367	61.5 / #N/A
TC97-153D	1997 Cherolet Malibu	48.8 / 194	2047 / -736	6 / -50	#N/A / -23.2	#N/A / #N/A / 0.123	115.7 / #N/A
TC97-161D	1997 Pontiac Grand Prix	47.7 / 165	1262 / -86	11 / -23	-17.0 / #N/A	0.074 / 0.054 / 0.051	#N/A / 32.7
TC97-162D	1997 Toyota Camry CE	53.9 / 208	1895 / -233	10 / -113	-30.7 / #N/A	0.393 / 0.333 / 0.318	#N/A / 43.3
TC97-164D	1997 Volkswagen Jetta GL	37.2 / 93	1250 / -35	28 / -23	-21.0 / #N/A	0.200 / 0.182 / 0.146	#N/A / 52.9
TC97-165D	1997 Ford Escort LX	52.0 / 178	1902 / -255	2 / -55	-23.7 / #N/A	0.171 / 0.132 / 0.121	#N/A / 59.2
TC98-105D	1998 Plymouth Voyager	52.9 / 255	1567 / -368	12 / -8	-43.0 / #N/A	0.659 / 0.509 / 0.509	#N/A / 46.7
Second-Generation Test / Air Bag Deployment							
TC97-201D	1996 Merc Mystique [M]	69.9 / 366	2385 / -178	16 / -64	-31.5 / #N/A	0.507 / 0.421 / 0.411	#N/A / 46.8
TC97-203D	1997 Chev Cavalier [M]	44.1 / 113	1446 / -181	14 / -16	-18.6 / #N/A	0.218 / 0.190 / 0.162	#N/A / 42.1
TC98-102D	1998 Nissan Altima	45.4 / 141	1481 / -169	13 / -16	-21.5 / #N/A	0.155 / 0.140 / 0.127	#N/A / 42.9
TC98-103D	1998 Honda Accord	50.4 / 225	1647 / -329	2 / -49	-32.3 / #N/A	0.351 / 0.305 / 0.299	#N/A / 48.4
TC98-106D	1998 Ford Explorer 2WD	48.2 / 154	2179 / -276	13 / -65	-39.8 / #N/A	0.850 / 0.727 / 0.701	#N/A / 61.4
TC98-107D	1998 Nissan Sentra	47.5 / 199	1363 / -7	4 / -15	-20.3 / #N/A	0.133 / 0.117 / 0.099	#N/A / 38.1
TC98-108D	1998 Dodge Neon	67.8 / 354	1996 / -339	8 / -13	-29.0 / #N/A	0.358 / 0.295 / 0.288	#N/A / 50.4
TC98-111D	1998 Mazda 626	52.4 / 220	2150 / -663	4 / -84	-23.9 / #N/A	0.185 / 0.132 / #N/A	#N/A / 49.3
TC98-112D	1998 Nissan Frontier	65.9 / 436	1626 / -435	12 / -34	-40.7 / #N/A	0.509 / 0.413 / #N/A	#N/A / 48.2
TC98-201D	1998 Toyota Corolla VE	60.5 / 324	1957 / -355	5 / -28	-18.3 / #N/A	0.189 / 0.110 / 0.097	#N/A / 37.9
TC98-205D	1998 Toyota Tacoma PU	87.7 / 545	2730 / -436	10 / -20	-42.5 / #N/A	0.700 / 0.488 / 0.448	#N/A / 62.1

Notes :

M - Vehicle modified to reflect 1998 design changes.

ND - No data. Transducer or data acquisition failure/malfunction.

Appendix A.2 - 48 km/h Full Frontal Rigid Barrier Crash Test Series / 5th Percentile Female Hybrid III ATD / Front Right Passenger Side Results

Full Frontal Rigid Barrier Crash Test Series		Head Response	Neck Response		Chest Response		
		SAE 1000	SAE 1000	SAE 600	SAE 600 / SAE 180	SAE 600 / SAE 180 / SAE 60	SAE 600 / SAE 180
TC Test Number	Test Vehicle	Resultant Head No Clip Acc. (g) / HIC (15 ms)	Axial Force Positive/Negative (N)	Calculated Occipital Moment Positive/Negative (Nm)	Mid-Sternum Deflection (mm)	Mid-Sternum VC (m/s)	Resultant Chest No Clip Acc. (g)
First-Generation Test / Air Bag Deployment							
TC97-165P	1997 Ford Escort LX	48.5 / 197	2015 / -83	31 / -58	-32.5 / #N/A	0.274 / 0.209 / 0.203	#N/A / 45.7
TC97-164P	1997 Volkswagen Jetta GL	49.1 / 160	1849 / -293	17 / -40	-37.4 / #N/A	0.450 / 0.381 / 0.376	#N/A / 49.7
TC97-162P	1997 Toyota Camry CE	89.6 / 108	273 / -1694	78 / -7	-19.3 / #N/A	0.105 / 0.072 / 0.067	#N/A / 33.5
TC97-161P	1997 Pontiac Grand Prix	58.1 / 204	1638 / -88	8 / -45	-21.0 / #N/A	0.169 / 0.125 / 0.119	#N/A / 44.5
TC97-153P	1997 Cherolet Malibu	54.9 / 236	587 / -1190	57 / -23	#N/A / -15.1	#N/A / #N/A / 0.083	47.2 / #N/A
TC97-134P	1997 Toyota Rav4	152.8 / 564	2961 / -1536	4 / -33	#N/A / -33.1	#N/A / #N/A / 0.312	80.1 / #N/A
TC97-110P	1997 Chev Cavalier	62.2 / 343	1263 / -708	26 / -14	#N/A / -21.8	#N/A / #N/A / 0.128	50.9 / #N/A
TC97-107P	1997 Dodge Dakota	34.2 / 86	1596 / -432	33 / -48	#N/A / -33.0	#N/A / #N/A / 0.313	42.1 / #N/A
TC97-106P	1997 Suzuki X90	65.3 / 133	2019 / -362	43 / -35	#N/A / -36.4	#N/A / #N/A / 0.256	56.9 / #N/A
TC97-105P	1997 Saturn SL	49.9 / 205	1815 / -397	24 / -11	#N/A / -30.1	#N/A / #N/A / 0.140	47.6 / #N/A
TC97-104P	1997 Ford F150 PU	46.7 / 180	1124 / -406	30 / -4	#N/A / -34.4	#N/A / #N/A / 0.304	59.7 / #N/A
TC97-103P	1997 Hyundai Tiburon	53.4 / 267	990 / -495	25 / -10	#N/A / -26.6	#N/A / #N/A / 0.204	63.5 / #N/A
TC97-102P	1997 Jeep TJ	43.0 / 166	1552 / -273	13 / -29	#N/A / -38.1	#N/A / #N/A / 0.345	41.0 / #N/A
TC97-101P	1997 GM Venture	53.6 / 193	2003 / -394	35 / -24	#N/A / -26.5	#N/A / #N/A / 0.179	95.5 / #N/A
TC96-124P	1996 Dodge Caravan	72.6 / 87	812 / -793	98 / -9	#N/A / -26.0	#N/A / #N/A / 0.152	46.5 / #N/A
Second-Generation Test / Air Bag Deployment							
TC97-201P	1996 Merc Mystique [M]	62.0 / 384	757 / -725	47 / -4	-16.2 / #N/A	0.076 / 0.066 / 0.063	#N/A / 52.9
TC97-203P	1997 Chev Cavalier [M]	59.6 / 285	1764 / -416	27 / -8	-14.4 / #N/A	0.080 / 0.061 / 0.059	#N/A / 58.8
TC98-102P	1998 Nissan Altima	65.0 / 296	197 / -1342	74 / -11	-11.9 / #N/A	0.063 / 0.047 / 0.046	#N/A / 39.8
TC98-103P	1998 Honda Accord	56.3 / 269	1057 / -241	14 / -22	-23.1 / #N/A	0.190 / 0.174 / 0.156	#N/A / 44.6
TC98-105P	1998 Plymouth Voyager	63.6 / 318	1477 / -459	37 / -19	-30.6 / #N/A	0.340 / 0.270 / 0.254	#N/A / 51.9
TC98-106P	1998 Ford Explorer 2WD	43.8 / 155	1249 / -585	22 / -14	-21.2 / #N/A	0.156 / 0.113 / 0.103	#N/A / 46.7
TC98-107P	1998 Nissan Sentra	51.7 / 244	1066 / -292	29 / -20	-27.1 / #N/A	0.242 / 0.208 / 0.193	#N/A / 45.3
TC98-108P	1998 Dodge Neon	59.0 / 303	519 / -729	47 / -7	-19.9 / #N/A	0.132 / 0.087 / 0.078	#N/A / 48.7
TC98-111P	1998 Mazda 626	61.7 / 262	2783 / -222 S2	18 / -96 S2	-27.9 / #N/A	0.294 / 0.208 / #N/A	#N/A / 48.8
TC98-112P	1998 Nissan Frontier	70.7 / 356	1050 / -2126	45 / -30	-43.9 / #N/A	0.665 / 0.602 / #N/A	#N/A / 56.2
TC98-201P	1998 Toyota Corolla VE	88.0 / 559	578 / -1904	29 / -5	-19.0 / #N/A	0.062 / 0.050 / 0.048	#N/A / 47.4
TC98-205P	1998 Toyota Tacoma PU	59.0 / 300	1447 / -374	37 / -40	-35.8 / #N/A	0.417 / 0.344 / 0.342	#N/A / 66.9

Notes :

M - Vehicle modified to reflect 1998 design changes.

ND - No data. Transducer or data acquisition failure/malfunction.

S2 - Peak value suspect. Penetration of airbag fabric into head cavity.

Appendix A.3 - Offset Frontal Deformable Barrier Crash Test Series / 5th Percentile Female Hybrid III ATD / Driver Side Results

Offset Frontal Deformable Barrier Crash Test Series		Head Response	Neck Response		Chest Response		
		SAE 1000	SAE 1000	SAE 600	SAE 600 / SAE 180	SAE 600 / SAE 180 / SAE 60	SAE 600 / SAE 180
TC Test Number / Test Vehicle		Resultant Head No Clip Acc. (g) / HIC (15 ms)	Axial Force Positive/Negative (N)	Calculated Occipital Moment Positive/Negative (Nm)	Mid-Sternum Deflection (mm)	Mid-Sternum VC (m/s)	Resultant Chest No Clip Acc. (g)
40 km/h ; 40% Offset Frontal Test - First-Generation Test / Air Bag Deployment							
TC94-022D	1994 Dodge Caravan	53.9 / 226	1009 / -32	19 / -67	-25.0 / #N/A	0.200 / #N/A / 0.158	#N/A / 21.3
TC95-206D	1995 Ford Contour	74.5 / 367	2752 / -505	17 / -124	#N/A / -22.4	#N/A / #N/A / 0.170	42.4 / #N/A
TC96-002D	1996 Suzuki Esteem	42.5 / 85	1225 / -229	19 / -17	#N/A / -23.1	#N/A / #N/A / 0.174	28.2 / #N/A
TC96-021D	1996 Toyota Tacoma	93.2 / 648	3044 / -705	20 / -53	#N/A / -23.1	#N/A / #N/A / 0.072	29.7 / #N/A
TC96-024D	1996Chev Lumina LS	71.7 / 240	2676 / -308	5 / -67	#N/A / -33.9	#N/A / #N/A / 0.569	58.6 / #N/A
TC96-025D	1996 Chev Cavalier	47.6 / 112	1330 / -270	23 / -24	#N/A / -21.9	#N/A / #N/A / 0.169	20.6 / #N/A
TC96-211D	1996 Dodge Avenger	82.9 / 338	4583 / -644 S	11 / -134 S1	#N/A / -37.6	#N/A / 0.057 / 0.252	77.8 / #N/A
TC97-205D	1997 Pontiac Grand Prix	27.5 / 52	693 / -115	11 / -23	-9.7 / #N/A	0.035 / 0.062 / 0.021	#N/A / 17.9
TC97-206D	1997 Toyota Camry	90.5 / 293	1763 / -4	2 / -54	-30.3 / #N/A	0.266 / 0.076 / 0.217	#N/A / 32.2
TC97-208D	1997 VW Jetta	38.0 / 19	832 / -230	22 / -27	-14.7 / #N/A	0.081 / 0.188 / 0.045	#N/A / 22.4
TC97-209D	1997 Ford Escort	45.7 / 138	755 / -25	19 / -94	-16.6 / #N/A	0.113 / 0.118 / 0.091	#N/A / 22.0
TC98-207D	1998 Dodge Caravan	31.6 / 66	1184 / -37	1 / -69	-21.8 / #N/A	0.136 / #N/A / 0.104	#N/A / 24.0
40 km/h ; 40% Offset Frontal Test - Second-Generation Test / Air Bag Deployment							
TC97-200D	1997 Merc Mystique [M]	50.9 / 187	896 / -81	18 / -38	-24.3 / #N/A	0.265 / 0.127 / 0.210	#N/A / 25.7
TC97-204D	1997 Chev Cavalier [M]	48.4 / 193	825 / -41	8 / -31	-12.5 / #N/A	0.056 / 0.106 / 0.048	#N/A / 21.4
TC98-101D	1998 Toyota Corolla	44.2 / 145	1370 / -70	21 / -24	-13.6 / #N/A	0.103 / 0.220 / 0.046	#N/A / 26.6
TC98-109D	1998 Toyota Tacoma	62.5 / 311	1535 / -412	15 / -21	-20.4 / #N/A	0.173 / 0.491 / 0.103	#N/A / 28.6
TC98-202D	1998 Nissan Altima	45.0 / 96	1499 / -68	16 / -57	-18.6 / #N/A	0.120 / 0.181 / 0.098	#N/A / 16.6
TC98-203D	1998 Ford Escort	41.0 / 87	1478 / -6	35 / -56	-14.1 / #N/A	0.079 / 0.383 / 0.060	#N/A / 18.1
TC98-204D	1998 Ford F150	29.4 / 27	646 / -39	15 / -9	-17.1 / #N/A	0.094 / #N/A / 0.067	#N/A / 21.0
TC98-206D	1998 Ford Explorer 2WD	62.3 / 183	2573 / -57	1 / -30	-24.3 / #N/A	0.249 / #N/A / 0.167	#N/A / 27.7
TC98-208D	1998 Dodge Neon	77.1 / 486	2829 / -117	0 / -127	-26.1 / #N/A	0.334 / #N/A / 0.169	#N/A / 38.7
TC98-209D	1998 Honda Accord	81.7 / 402	3495 / -603	2 / -77	-27.6 / #N/A	0.764 / #N/A / 0.374	#N/A / 41.1
TC98-210D	1998 Nissan Sentra	64.0 / 325	2246 / -589	39 / -46	-17.5 / #N/A	0.235 / #N/A / 0.151	#N/A / 29.8
TC98-211D	1998 Pontiac Grand Prix SE	57.1 / 131	2090 / -22	22 / -12	-27.3 / #N/A	0.466 / #N/A / 0.306	#N/A / 33.9

Notes :

- M - Vehicle modified to reflect 1998 design changes.
- ND - No data. Transducer or data acquisition failure/malfunction.
- S - Full-scale setting of transducer exceeded.
- S1 - Peak value suspect. Full-scale setting for x-axis neck shear force exceeded.

Appendix A.4 - Offset Frontal Deformable Barrier Crash Test Series / 5th Percentile Female Hybrid III ATD / Front Right Passenger Side Results

Offset Frontal Deformable Barrier Crash Test Series		Head Response	Neck Response		Chest Response		
		SAE 1000	SAE 1000	SAE 600	SAE 600 / SAE 180	SAE 600 / SAE 180 / SAE 60	SAE 600 / SAE 180
TC Test Number / Test Vehicle		Resultant Head No Clip Acc. (g) / HIC (15 ms)	Axial Force Positive/Negative (N)	Calculated Occipital Moment Positive/Negative (Nm)	Mid-Sternum Deflection (mm)	Mid-Sternum VC (m/s)	Resultant Chest No Clip Acc. (g)
First-Generation Test / Air Bag Deployment / "Near' Position							
TC94-022P	1994 Dodge Caravan	82.2 / 202	482 / -527	84 / -4	-9.6 / #N/A	0.048 / 0.033 / 0.031	#N/A / 30.8
TC96-024P	1996Chev Lumina LS	128.9 / 378	3507 / -289	23 / -61	#N/A / -14.7	#N/A / #N/A / 0.060	33.8 / #N/A
TC96-025P	1996 Chev Cavalier	74.8 / 22	435 / -235	43 / -4	#N/A / -13.3	#N/A / #N/A / 0.045	21.4 / #N/A
TC97-205P	1997 Pontiac Grand Prix	44.7 / 98	1125 / -208	31 / -22	-8.0 / #N/A	0.031 / 0.024 / 0.020	#N/A / 35.2
TC97-206P	1997 Toyota Camry	210.7 / 1640	2950 / -4050	58 / -64	-9.4 / #N/A	0.087 / 0.061 / 0.047	#N/A / 35.1
TC97-208P	1997 VW Jetta	25.7 / 36	1104 / -105	14 / -33	-11.7 / #N/A	0.038 / 0.028 / 0.026	#N/A / 24.4
TC97-209P	1997 Ford Escort	27.6 / 45	1231 / -29	19 / -40	-8.5 / #N/A	0.028 / 0.026 / 0.022	#N/A / 22.7
Second-Generation Test / "Near" Position							
TC97-200P	1997 Merc Mystique [M]	29.8 / 63	489 / -241	32 / -4	-8.6 / #N/A	0.020 / 0.016 / 0.015	#N/A / 23.0
TC97-204P	1997 Chev Cavalier [M]	44.9 / 63	599 / -527	18 / -4	-8.2 / #N/A	0.020 / 0.015 / 0.013	#N/A / 19.1
TC98-101P	1998 Toyota Corolla	67.3 / 373	1901 / -1872	66 / -9	-18.0 / #N/A	0.057 / 0.046 / 0.042	#N/A / 32.4
TC98-109P	1998 Toyota Tacoma	45.8 / 101	1650 / -108	4 / -25	-23.3 / #N/A	0.309 / 0.256 / 0.214	#N/A / 40.8
TC98-202P	1998 Nissan Altima	46.6 / 124	35 / -1948	91 / -4	-5.7 / #N/A	0.020 / 0.016 / 0.015	#N/A / 24.4
TC98-203P	1998 Ford Escort	29.6 / 12	276 / -565	41 / -2	-12.3 / #N/A	0.022 / 0.018 / 0.015	#N/A / 15.7
TC98-204P	1998 Ford F150	24.3 / 19	631 / -83	13 / -5	-16.9 / #N/A	0.079 / 0.066 / 0.061	#N/A / 23.5
TC98-206P	1998 Ford Explorer 2WD	100.3 / 83	1028 / -1300	67 / -12	-9.6 / #N/A	0.057 / 0.049 / 0.039	#N/A / 28.4
TC98-207P	1998 Dodge Caravan	38.9 / 117	961 / -41	19 / -6	-18.6 / #N/A	0.098 / 0.075 / 0.061	#N/A / 22.0
TC98-208P	1998 Dodge Neon	184.7 / 200	1142 / -83	30 / -11	-15.0 / #N/A	0.074 / 0.057 / 0.056	#N/A / 37.1
TC98-209P	1998 Honda Accord	61.4 / 297	546 / -1311	32 / -33	-13.4 / #N/A	0.043 / 0.034 / 0.031	#N/A / 21.4
TC98-210P	1998 Nissan Sentra	53.2 / 119	791 / -8	24 / -10	-15.0 / #N/A	0.051 / 0.035 / 0.029	#N/A / 18.4
TC98-211P	1998 Pontiac Grand Prix SE	112.1 / 365	2315 / -18	36 / -58	-16.8 / #N/A	0.041 / 0.031 / 0.028	#N/A / 21.5

Notes :

M - Vehicle modified to reflect 1998 design changes.

Appendix A.5 - Other (Special) Tests / 5th Percentile Female Hybrid III ATD

Special Test Series	Head Response SAE 1000	Neck Response SAE 1000	Neck Response SAE 600	Chest Response SAE 600 / SAE 180	Chest Response SAE 600 / SAE 180 / SAE 60	Chest Response SAE 600 / SAE 180
TC Test Number / Test Vehicle	Resultant Head No Clip Acc. (g) / HIC (15 ms)	Axial Force Positive/Negative (N)	Calculated Occipital Moment Positive/Negative (Nm)	Mid-Sternum Deflection (mm)	Mid-Sternum VC (m/s)	Resultant Chest No Clip Acc. (g)
48 Km/h Frontal Barrier Crash Test Series						
Driver Side : No Air Bag System Fitted / Air Bag Fitted - No Air Bag Deployment (Not triggered or suppressed)						
TC96-125D 1996 Ford Taurus [N1]	111.3 / 698	2447 / -816	14 / -30	#N/A / -39.6	#N/A / #N/A / 0.264	51.9 / #N/A
TC97-108D 1997 Hyundai Elantra	109.9 / 384	2399 / -308	28 / -40	#N/A / -52.7	#N/A / #N/A / 0.643	64.0 / #N/A
Passenger Side : No Air Bag System Fitted / Air Bag Fitted - No Air Bag Deployment (Not triggered or suppressed)						
TC97-108P 1997 Hyundai Elantra	59.1 / 338	2047 / -162	70 / -28	#N/A / -31.0	#N/A / #N/A / 0.192	66.2 / #N/A
Offset Frontal Deformable Barrier Crash Test Series						
Driver Side : 24 km/h ; 40% Offset Test - No Air Bag System Fitted / Air Bag Fitted - No Air Bag Deployment (Not triggered or suppressed)						
TC96-204D 1996 Dodge Avenger	62.7 / 206	644 / -597	18 / -11	#N/A / -7.9	#N/A / 0.228 / 0.010	20.2 / #N/A
Driver Side : 32 km/h ; 40% Offset Frontal Test - First-Generation Test / Air Bag Deployment						
TC95-021D 1995 Mazda Miata	116.3 / 490	4170 / -425	15 / -45	#N/A / -25.9	#N/A / #N/A / 0.204	97.7 / #N/A
Driver Side : 32 km/h ; 40% Offset Test - No Air Bag System Fitted / Air Bag Fitted - No Air Bag Deployment (Not triggered or suppressed)						
TC95-127D 1996 Mazda Miata	46.2 / 115	809 / -501	24 / -9	#N/A / -12.2	#N/A / #N/A / 0.018	17.1 / #N/A
TC96-202D 1996 Dodge Avenger	55.5 / 179	790 / -470	10 / -18	#N/A / -9.9	#N/A / 0.500 / 0.014	19.7 / #N/A
Driver Side 40 km/h ; 40% Offset Test - No Air Bag System Fitted / Air Bag Fitted - No Air Bag Deployment (Not triggered or suppressed)						
TC96-205D 1996 Suzuki Esteem	49.2 / 191	892 / -279	14 / -8	#N/A / -22.9	#N/A / 0.223 / 0.055	23.6 / #N/A
TC96-207D 1996 Chev Cavalier	52.6 / 131	978 / -235	33 / -7	#N/A / -20.0	#N/A / 0.053 / 0.033	21.5 / #N/A
TC96-209D 1996 Merc Mystique	45.1 / 135	978 / -355	16 / -14	#N/A / -20.6	#N/A / 0.028 / 0.091	28.8 / #N/A
TC96-210D 1996 Dodge Avenger	54.1 / 235	527 / -321	16 / -21	#N/A / -13.1	#N/A / 0.227 / 0.018	22.1 / #N/A
Driver Side : 48 km/h ; 40% Offset Test - No Air Bag System Fitted / Air Bag Fitted - No Air Bag Deployment (Not triggered or suppressed)						
TC95-002D 1995 Merc Mystique	48.5 / 205	488 / -29	15 / -13	-29.1 / #N/A	0.215 / #N/A / 0.164	#N/A / 32.2
Driver Side : 56 km/h ; 40% Offset Test - No Air Bag System Fitted / Air Bag Fitted - No Air Bag Deployment (Not triggered or suppressed)						
TC97-163D 1997 Merc Mystique	42.8 / 141	593 / -36	24 / -16	-34.1 / #N/A	0.255 / 0.057 / 0.215	#N/A / 31.2
Driver Side : 40% Offset Test - First-Generation Test / Specialty Test : Simulated Bracing Posture						
TC96-212D 1996 Dodge Avenger	68.8 / 258	3821 / -29	15 / -92	-37.7 / #N/A	0.547 / 0.103 / 0.409	#N/A / 45.5
Front Right Passenger Side : 40 km/h ; 40% Offset Test - No Air Bag System Fitted / Air Bag Fitted - No Air Bag Deployment (Not triggered or suppressed)						
TC96-021P 1996 Toyota Tacoma	26.8 / 45	816 / -317	32 / -6	#N/A / -24.1	#N/A / #N/A / 0.064	20.1 / #N/A
TC96-207P 1996 Chev Cavalier	24.1 / 35	866 / -229	33 / -8	#N/A / -22.6	#N/A / #N/A / 0.041	19.3 / #N/A
Front Right Passenger Side : 48 km/h ; 40% Offset Test - No Air Bag System Fitted / Air Bag Fitted - No Air Bag Deployment (Not triggered or suppressed)						
TC95-002P 1995 Merc Mystique	28.4 / 57	939 / -41	30 / -8	-11.9 / #N/A	0.038 / 0.024 / 0.022	#N/A / 26.2
Front Right Passenger Side : 56 km/h ; 40% Offset Test - No Air Bag System Fitted / Air Bag Fitted - No Air Bag Deployment (Not triggered or suppressed)						
TC97-163P 1997 Merc Mystique	91.0 / 353	1114 / -270	48 / -10	-14.1 / #N/A	0.044 / 0.030 / 0.029	#N/A / 31.9

Notes :

N1 - No deployment of driver-side airbag. Fault attributed to lack of adequate power in power supply substituted for original vehicle battery.

MEASURING AIRBAG INJURY RISK TO OUT-OF-POSITION OCCUPANTS

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ABSTRACT

Real-world crash experience has shown the need to reduce the risk of injury from inflating airbags to out-of-position occupants including small adult drivers. The small (5th percentile) female Hybrid III dummy positioned very close to the steering wheel/airbag assembly is the primary means currently available for assessing potential risk of severe chest and head/neck injury to out-of-position drivers. However, researchers have identified shortcomings with this dummy in reliably assessing potential interactions between the head/neck and the deploying airbag. Several noncrash airbag deployment tests in two late-model vehicles were conducted with a small female Hybrid III dummy. The dummy's spine had been modified to permit the upper torso to rotate forward without the buttocks leaving the driver seat in order to better simulate at-risk positions that a belted driver could achieve. Tests with the standard Hybrid III head and neck, even though supplemented with a foam neck shield as recommended by Melvin et al. (1993), confirmed non-biofidelic interaction between the dummy and deploying airbag. Several modifications to the dummy's head skin and neck shield were tested to determine whether any gave more repeatable and biofidelic results. None of the head skin/neck shield configurations tested was found to provide a reliably biofidelic indication of airbag inflation injury risk.

INTRODUCTION

More than 74 million cars and light trucks on U.S. roads are equipped with driver airbags, and all cars and most light trucks manufactured since the 1997 model year also have passenger airbags. Studies show that airbags have reduced deaths in frontal crashes by about 26 percent for belted drivers and by about 32 percent for unbelted drivers (Ferguson et al., 1995). Deaths in frontal crashes also have been reduced by about 14 percent for belted passengers and by about 23 percent for unbelted passengers (Braver et al., 1997). The National Highway Traffic Safety Administration (NHTSA) estimates that as of May 1998 airbags had saved nearly 3,000 lives in the United States (NHTSA, 1998). Thus, airbags are effective in reducing the risk of death and injury associated with many severe frontal car crashes.

Despite this overall effectiveness, real-world experience has shown that some out-of-position occupants are being injured and even killed by deploying airbags. As of May 1998, NHTSA attributed 99 deaths in low-severity crashes to airbag inflation energy. These deaths include 38 adult drivers, 4 adult passengers (a belted 98-year-old female, an unbelted 88-year-old female, an unbelted 57-year-old male, and an unbelted 66-year-old female), 44 children ages 1-11, and 13 infants (10 restrained in rear-facing infant seats and 3 seated on adult passengers' laps).

Two phases of airbag deployment have been associated with high, injury-causing forces: the punch-out phase and membrane-loading phase (Horsch et al., 1990). The punch-out phase occurs before or immediately after an airbag escapes from the module. If this escape is blocked by an unconscious driver slumped over the steering wheel, for example, the gas pressure inside the airbag becomes greater than normally required to break the module cover, and the resulting high force is concentrated on that part of the driver blocking the airbag's deployment path. Generally, the risk of injury from punch-out forces is significantly reduced with even a small separation between the occupant and airbag module. The membrane-loading phase occurs after the airbag is out of the module. The injury-causing forces result from a combination of the airbag's internal pressure and the tension forces arising from the inflating airbag wrapping around the occupant in its path. Membrane forces on an out-of-position occupant can be high even with some separation between the occupant and airbag module.

Drivers who must sit close to the steering wheel to drive, either because of short stature or medical reasons, compose one group potentially at risk of such injuries. Sixteen of the 38 adult drivers whose deaths have been attributed to airbags were 160 cm (63 inches) tall or shorter, and all but one with fatal neck injuries were women. Tests with dummies also indicate that smaller, more fragile drivers are at greater risk than larger drivers of injuries caused by the forces of deploying airbags (Melvin et al., 1993). Consequently, most current efforts to study airbag injury risk to out-of-position drivers use the small (5th percentile) female Hybrid III dummy and associated injury reference values.

Some researchers have identified problems associated with the Hybrid III dummy's design that make it difficult to accurately measure injury risk in tests in which an airbag is deployed at close range to the dummy (Horsch et al., 1990). The dummy's head and neck are different from those of a human in two important ways. First, the neck is much smaller in diameter than the segment of the population it is intended to represent. Second, there is a hollow area between the chin and neck that provides an unrealistically large reaction surface for airbag membrane loading (Figure 1). An inflating airbag, even while still folded, could push into this area and, as it expands, generate higher forces than could be generated for a human of the same size. Research indicates that a realistic contact surface in this area is critical to assuring biofidelic airbag loading (Melvin et al., 1993).

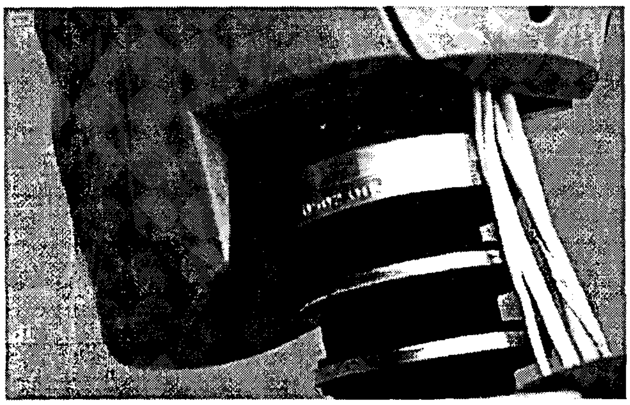

Figure 1. Standard Hybrid III Head and Neck.

The Insurance Institute for Highway Safety has completed a series of noncrash airbag deployment tests using the 5th percentile female Hybrid III dummy with various head and neck modifications to evaluate interactions between the dummy and airbag. Fourteen of the drivers killed by airbag deployments are believed to have been belted, indicating that belt use does not always protect such drivers from airbag inflation injury. Therefore, the dummy was modified to permit the upper torso to rotate forward without the buttocks leaving the driver seat to simulate positions a belted driver might achieve under some circumstances. The dummy's abdominal insert was removed, and the lumbar spine was replaced with a hinged joint with just enough friction to maintain the dummy's posture when not externally supported.

MEASUREMENT METHOD

The series of deployment tests reported in this study includes airbags from two different vehicle models: the 1996 Dodge Grand Caravan and 1996 Honda Accord. Each model was tested several times with the 5th percentile female Hybrid III dummy positioned in the driver seat with the lap/shoulder belt fastened. Vehicle adjustments were made appropriate for a small driver: steering wheel fully down, seat belt D-ring adjustment fully down, seat fully forward, etc. The dummy was leaned toward the steering wheel with the buttocks against the seat back. Two different out-of-position configurations were tested in each model: the dummy leaning forward enough to achieve a chest-to-steering wheel hub clearance of 12 cm and the dummy leaning forward as far as possible. In the latter condition, the dummy's forehead rested against the upper steering wheel rim, and the measured, horizontal clearance between the chest and steering wheel hub was 8 cm in the Honda Accord and 7 cm in the Dodge Grand Caravan.

Tests were conducted with the unmodified dummy and with the dummy modified using three different approaches to improving the biofidelity of head/neck and airbag interaction: standard head skin with a separate, molded foam neck shield; modified head skin and neck wrap; and modified head skin with integrated neck shield. Two different foam neck shields were used, and both wrapped around the neck and extended into the hollow area between the chin and neck. The first design, Molded Foam I (Figure 2), was a modified 50th percentile male Hybrid III dummy neck shield devised early in the Institute's testing because a shield for the 5th percentile female

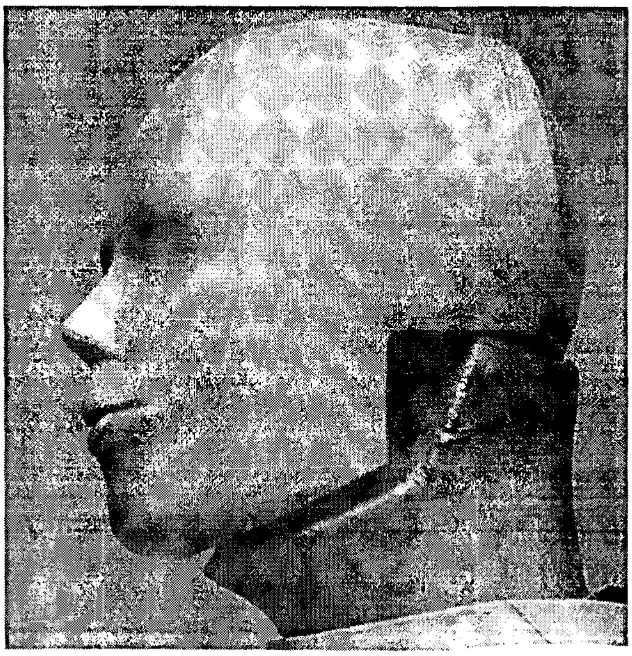

Figure 2. Standard Head Skin and Molded Foam I.

dummy was not commercially available. The 50th percentile neck shield had been developed originally in response to the Horsch et al. (1990) research on out-of-position airbag risk. The Institute's modification trimmed this larger shield to fit the small female dummy. Subsequent to the Institute's initial tests, a version of this foam neck shield, Molded Foam II (Figure 3), specifically designed to fit the geometry of the small female dummy, became available from Applied Safety Technologies Corporation (part no. V00279).

Figure 3. Standard Head Skin and Molded Foam II.

The other tested designs included modifications of the vinyl covering (skin) of the dummy's head and chin. Both were developed by the Society of Automotive Engineers Hybrid III Dummy Family Task Group and built by First Technology Safety Systems. The Modified Head Skin and Neck Wrap (Figure 4) added vinyl skin under the chin to partially cover the hollow area (chin strap) and extended the vinyl skin in the area of the tempero-mandibular joint rearward to cover the right-angle-shaped notch visible in the dummy's profile. This design also included a rectangular piece of 7-mm thick rubber foam wrapped around the neck and fixed with Velcro along the back of the neck.

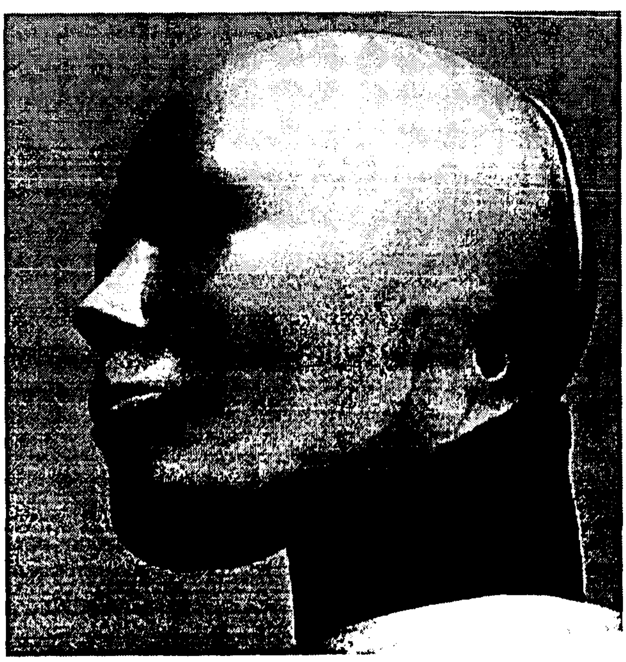

Figure 4. Modified Head Skin and Neck Wrap.

The modified vinyl head skin in the fourth design tested, Modified Head Skin and Integrated Neck Shield (Figure 5), was similar to the Modified Head Skin and Neck Wrap, but instead of wrapping the neck with foam, the vinyl skin was extended down from the posterior edge of the chin strap to provide a continuous surface from the top of the head to the top of the dummy's torso jacket.

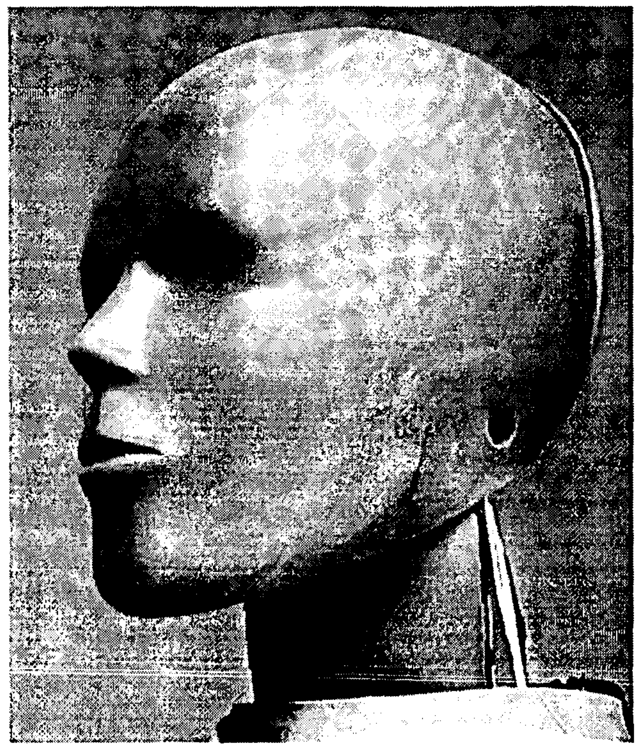

Figure 5. Modified Head Skin and Integrated Neck Shield.

Instrumentation for the airbag deployment tests measured three head accelerations, six upper neck loads, three chest accelerations, and chest compression. Compression of the neck produced positive axial forces; bending the neck to tip the head forward produced positive anterior-posterior (A-P) moments; and pushing the head forward while restraining the torso produced positive A-P shear forces. Neck flexion/extension bending moments were measured by the six-channel, through-the-head load cell at a point 17.78 mm above the dummy's occipital condyle. For comparison with injury reference values, the measured moments were translated to the occipital condyle (OC) location by adding the moment (in Nm) associated with the measured A-P shear force (in N) as follows:

$$\text{Occipital } M_{A\text{-}P} = M_{A\text{-}P} + [0.01778(F_{A\text{-}P})] \quad (1.)$$

High-speed and still photography were used to record airbag deployments. The vinyl skin in the area behind the chin on the standard head skin and on the upper surface of the chin strap on the modified head skin were colored with grease paint. If the airbag entered the hollow area between the chin and neck, the paint would transfer to the airbag fabric to indicate whether the airbag circumvented the neck and chin shields.

Dummy Neck Calibration

In addition to the airbag deployment tests, neck-pendulum calibration tests were conducted to determine whether the various head/neck modifications prevented the neck from meeting specified flexion and extension response characteristics (Society of Automotive Engineers Dummy Testing Equipment Subcommittee, 1994). These tests consisted of attaching the head and neck upside down to the end of a rigid-arm pendulum, swinging the assembly at a specified speed and stopping the pendulum arm, allowing the neck to bend under the force of the head's momentum. The calibrated response was defined by the measured neck bending moments and head rotation.

RESULTS

Neck Calibration Tests

Calibration tests were not performed with Molded Foam I. The head and neck equipped with Molded Foam II met the requirements for extension response for the 5th percentile female Hybrid III dummy, but the flexion response of this configuration (68.3 Nm) did not meet the maximum flexion bending moment requirements (69-84 Nm). The Modified Head Skin and Neck Wrap met all extension and flexion response requirements. The effects of the Modified Head Skin and Integrated Neck Shield on the specified head/neck response could not be determined with the pendulum tests because the interaction between the extended vinyl neck flap and the dummy's torso jacket could not be simulated.

Airbag Deployment Tests

In all tests, recorded head and chest accelerations as well as chest compressions were very low in comparison with reference values indicating injury risk. Therefore, these data are not presented further, and the comparison of dummy head/neck configurations focuses solely on neck injury measures. The injury assessment reference values (IARV) shown in the tables are based on General Motors' recommendation to NHTSA for use with the 50th percentile male Hybrid III dummy and were subsequently scaled to represent injury risk for small females (Backaitis and Mertz, 1994).

<u>Unmodified Dummy</u> Two 8-cm tests in the Honda Accord were conducted using the unmodified dummy (Table 1). Both tests produced maximum extension bending moments about twice the IARVs, and one test produced neck tension forces that exceeded the IARVs. In both tests, paint from behind the chin was transferred to both the front (away from the dummy) and rear (facing the dummy) panels of the airbag fabric, indicating the airbag entered the hollow space between the dummy's neck and chin. Clean sections of fabric between the colored areas indicated the deploying airbag still was folded when it contacted the painted surfaces.

Table 1
Tests with Unmodified Dummy

	Tension Force (kN)	A-P Shear Force (kN)	OC Extension Bending Moment (Nm)
IARV	2.2	±2.1	31
Honda Accord			
8 cm (KA98010)	2.3	2.0	66
8 cm (KA98011)	1.6	1.4	53

Data for the first Accord test (KA98010) is characteristic of dummy neck responses in all of this model's 8-cm tests (Figure 6). Analysis of the high-speed film showed the initial rapid tension pulse corresponded to the airbag cover flap slapping the dummy's chin as the airbag escaped the module. The longer duration tension pulse, shear force pulse, and neck extension bending moment pulse occurred as the inflating airbag wrapped around the dummy's head and neck. The neck loads peaked after the dummy began to move away from the steering wheel and then diminished to nearly zero while the dummy still was contacting the airbag. As the dummy moved away from the airbag, the film

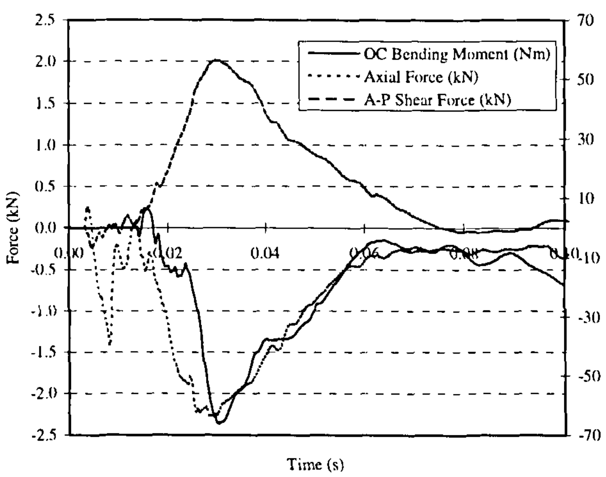

Figure 6. Standard Hybrid III head and neck response to noncrash airbag deployment in Honda Accord 8-cm test.

showed part of the airbag fabric pulled away from the tempero-mandibular notch behind the dummy's jaw.

Dummy with Molded Foam I Seven tests were conducted using the modified 50th percentile Hybrid III molded foam neck shield, five in the Honda Accord and two in the Dodge Grand Caravan (Table 2). The Accord's second and third 8-cm tests (KA98004 and KA98005) produced upper neck loads similar to those in the unmodified dummy tests, and the first 8-cm test (KA98002) exhibited even higher tension loading and exceptionally high positive shear loading. Consequently, the calculated extension bending moment for the occipital condyle was lower in the first test than in the second and third tests despite similar bending moments. In these three tests, paint from behind the dummy's chin was transferred to the airbag fabric, confirming the deploying airbag circumvented the foam neck shield. Paint patterns in these tests also were similar to those in the unmodified dummy tests, and high-speed film showed the airbag fabric pulled away from the tempero-mandibular notch behind the dummy's jaw as the dummy moved away from the airbag.

Table 2
Tests with Molded Foam I Neck Shield

	Tension Force (kN)	A-P Shear Force (kN)	OC Extension Bending Moment (Nm)
IARV	2.2	±2.1	31
Honda Accord			
8 cm (KA98002)	2.4	9.2	40
8 cm (KA98004)	1.9	1.8	64
8 cm (KA98005)	1.8	1.6	57
12 cm (KA97021)	1.1	6.3	37
12 cm (KA98003)	1.0	0.2	18
Dodge Grand Caravan			
7 cm (KA97004)	2.1	1.2	48
12 cm (KA97002)	1.3	0.8	49

Because the shear force in the Accord's first 8-cm test (KA98002) was exceptionally high, it was examined further. Only one difference between this test and the other two 8-cm tests was noted. The paint pattern in the first test was located farther to the right of the airbag's center than in the other two tests. Paint in the first test was located on both sides of the first crease to the right of the airbag's center, whereas paint in the other two tests was located between the centermost creases of the airbag folding pattern. This observation offers a possible explanation for the exceptionally high shear force recorded in the first test. The location of the paint pattern in the first test suggests the airbag was folded over on itself while behind the dummy's chin. The membrane tension forces generated as the fabric suddenly unfolded can be greater than would be predicted from airbag pressure multiplied by contact area (Patrick and Nyquist, 1972). Thus, the possibility that the fabric was folded more tightly in the chin cavity in the first test than in the other two tests may account for the high shear force recorded.

The Honda Accord's two 12-cm tests generally produced lower neck forces than this model's 8-cm tests. However, the first 12-cm test (KA97021) produced a peak extension bending moment slightly higher than the IARV and the second highest A-P shear force of any test using Molded Foam I. In the first test, paint was transferred to the center of the rear airbag panel, and the high-speed film showed the airbag fabric pulled away from between the dummy's chin and neck shield as the dummy moved away from the airbag. These observations indicate the airbag circumvented the neck shield. In doing so, the airbag probably folded back on itself as it pushed past the neck shield and into the space behind the jaw. When the internal airbag pressure increased, the fabric suddenly unfolded and membrane tension forces were generated, as was hypothesized to have happened in the Accord's first 8-cm test (KA98002).

Grease paint was not used in either of the Dodge Grand Caravan tests, so it is unknown whether the airbag circumvented the neck shield. In both tests, high-speed film showed the airbag contacted the dummy below the inferior edge of the neck shield and may have pushed the neck shield into the hollow area behind the chin. As the dummy moved away from the inflated airbag, the airbag fabric pulled away from the tempero-mandibular notch behind the dummy's jaw. Neck loads in the Grand Caravan's 7-cm test were similar to those in two of the Honda Accord's 8-cm tests (KA98004 and KA98005). Although most maximum neck loads were measured during the airbag's membrane-loading phase, the maximum tension force in the Grand Caravan's 7-cm test was recorded early when the airbag cover slapped the dummy's chin. The peak tension load measured during the membrane-loading phase in this test was 2.0 kN. In the Grand Caravan's 12-cm test, the maximum extension bending moment was higher than in both the Accord's 12-cm tests, and tension and A-P shear forces were about the same as those in one of the Accord's 12-cm test (KA98003).

Dummy with Molded Foam II Only two tests were conducted using the molded foam neck shield designed specifically for the 5th percentile female Hybrid III dummy (Table 3). The Honda Accord's 8-cm test produced peak neck loads similar to those in the unmodified dummy tests and to two of the Accord's 8-cm tests using Molded Foam I (KA98004 and KA98005). Although the maximum A-P shear force and extension bending moment were measured during the airbag's membrane-loading phase, the maximum tension force was recorded early in this test when the airbag cover slapped the dummy's chin. The peak tension load measured during the membrane-loading phase in this test was 1.6 kN. The high-speed film showed the airbag pulled against the dummy's vinyl skin at the posterior of the tempero-mandibular notch, but no paint was transferred to the airbag fabric. The absence of paint on the fabric indicated the airbag did not push between the foam and the dummy's chin.

The Dodge Grand Caravan's 7-cm test also produced neck loads similar to this model's 7-cm test using Molded Foam I. However, paint transferred to the airbag fabric in this test indicated the airbag circumvented the neck shield.

Table 3
Tests with Molded Foam II Neck Shield

	Tension Force (kN)	A-P Shear Force (kN)	OC Extension Bending Moment (Nm)
IARV	2.2	±2.1	31
Honda Accord 8 cm (KA98017)	1.8	1.4	56
Dodge Grand Caravan 7 cm (KA98018)	2.0	1.5	53

Dummy with Modified Head Skin and Neck Wrap

Five tests were conducted using this modification, three in the Honda Accord and two in the Dodge Grand Caravan (Table 4). The two Accord 8-cm tests produced neck tension and extension bending moment responses similar to those in this model's 8-cm tests using the foam neck shields. However, the high neck shear force in the first Accord 8-cm test using Molded Foam I (KA98002) was absent. In these two tests, some paint was transferred from the upper surface of the chin strap to the center of the rear airbag panel, and high-speed film showed the airbag pulled on the posterior edge of the chin strap as the dummy moved away from the airbag. The absence of paint on any other part of the airbag fabric could indicate that the transferred paint was from incidental contact rather than from the airbag inserting itself into the space behind the chin. No paint was transferred in the Accord's 12-cm test, and neck loads were well below IARVs.

Table 4
Tests with Modified Head Skin and Neck Wrap

	Tension Force (kN)	A-P Shear Force (kN)	OC Extension Bending Moment (Nm)
IARV	2.2	±2.1	31
Honda Accord 8 cm (KA98006) 8 cm (KA98007) 12 cm (KA98012)	 1.9 2.2 1.2	 1.4 1.4 -0.3	 52 53 17
Dodge Grand Caravan 7 cm (KA98016) 12 cm (KA98013)	 2.4 1.4	 2.6 1.7	 67 87

Although in the Accord's 8-cm tests the modified head skin and neck wrap seemed to resist airbag penetration into the hollow area between the dummy's chin and neck, this modification still allowed paint to be transferred to the airbag in both Dodge Grand Caravan tests. In the Grand Caravan's 7-cm test, paint was transferred to the front panel of the airbag, suggesting the airbag penetrated the hollow area early during deployment. Neck loads in both Grand Caravan tests were higher than in this model's 7-cm and 12-cm tests using the foam neck shields.

Modified Head Skin and Integrated Neck Shield

Only two 8-cm tests were conducted in the Honda Accord using this modification (Table 5). Maximum extension bending moments and A-P shear forces were considerably lower in these tests than in this model's 8-cm tests using any other dummy head/neck modification. The continuous surface presented by the head skin's integrated neck shield assured that the airbag could not insert itself into the hollow area between the dummy's chin and neck. However, high-speed film showed that the airbag pushed the integrated neck shield against the neck and may have restricted the rearward rotation of the head. If this restriction occurred, it suggests the possibility that some airbag deployment forces were carried by the neck shield and not registered by the neck load cell. Thus, the true airbag injury risk may have been masked. The lower A-P shear and tension forces recorded in these tests might be explained by this alternative loading mechanism rather than by the absence of airbag penetration into the hollow area behind the chin.

Table 5
Tests with Modified Head Skin and Integrated Neck Shield

	Tension Force (kN)	A-P Shear Force (kN)	OC Extension Bending Moment (Nm)
IARV	2.2	±2.1	31
Honda Accord 8 cm (KA98008) 8 cm (KA98009)	 1.5 1.4	 0.8 0.7	 33 33

DISCUSSION

Among the tested configurations of the 5th percentile female Hybrid III dummy's head and neck, only the continuous surface of the Modified Head Skin and Integrated Neck Shield assured that the airbag would not insert itself into the hollow area between the dummy's chin and neck. However, observation from high-speed film indicated that the airbag, pushing against the integrated shield, might itself produce erroneous neck load measurements to the extent that it hinders neck motion. Consequently, this modification did not meet one of the design criteria for an effective neck shield identified by Melvin et al. (1993). Based in part on film analysis and injury measures recorded in these tests, the Society of Automotive Engineers Hybrid III Dummy Family Task Group decided at its March 19, 1998 meeting not to recommend the integrated neck shield design for use in out-of-position airbag testing.

None of the other dummy modifications prevented the airbag from inserting itself into the hollow area between the dummy's chin and neck in either vehicle model. The Modified Head Skin and Neck Wrap seemed to fend off the Honda Accord's airbag, as did the Molded Foam II neck shield, but neither prevented the Dodge Grand Caravan's airbag from pushing into the space behind the dummy's chin. In fact, the Modified Head Skin and Neck Wrap produced the highest neck loads measured among all Dodge Grand Caravan tests. Thus, these Hybrid III head/neck configurations cannot be expected to provide reliable measures of airbag injury risk. It also is likely that airbags with different folding patterns and deployment paths will interact differently with various head/neck configurations, just as the Accord and Grand Caravan airbags interacted very differently with the Modified Head Skin and Neck Wrap.

Another difficulty revealed by these tests is that the neck extension bending moment is the measure most sensitive to airbag interaction. Neck extension bending moments exceeded published IARVs (Backaitis and Mertz, 1994) in all but three tests. However, the extension bending moment IARV describes the injury risk for a human neck extended rearward, as in a rear-end collision (Mertz and Patrick, 1971). None of the maximum extension bending moments in this series was measured at a time when the dummy's neck was extended rearward. Consequently, the meaning of neck bending moments is unclear because the heads/necks were not in position to suffer the injury on which the IARV is based. The fatal head/neck injuries to out-of-position drivers often involved basilar skull fractures, which typically are more associated with tension forces (Hopper et al., 1994). The implications of a high bending moment without neck extension are particularly obscure when the neck tension loads, which may provide a more direct indication of this kind of injury, are relatively low in comparison to the IARV.

Other interpretations of neck force measurements yield somewhat different implications. According to Mertz et al. (1997), the 2.2 kN tension force IARV may understate neck injury risk. The injury risk relationships developed by the authors, which were based on airbag tests with pigs and 3-year-old child dummies, indicate that the 2.2 kN tension force represents a 50 percent risk of a neck injury rated 3 or greater on the Abbreviated Injury Scale (AIS). A 10 percent risk of an AIS ≥ 3 injury would be associated with tension forces of about 1.9 kN or neck bending moments of 50 Nm. Thus, according to this alternate analysis of neck forces, the neck tension and bending moments recorded in this series indicate more similar risks of serious head/neck injury, and the greater sensitivity of the neck tension force seems more relevant to real-world head/neck injury experience. Nevertheless, this discussion indicates the need to further consider the issue of injury thresholds in out-of-position tests.

CONCLUSIONS

None of the dummy head/neck configurations, except the Modified Head Skin with Integrated Neck Shield, was completely effective at preventing the airbag from inserting itself into the space behind the dummy's neck, and the integrated neck shield currently is unacceptable because it cannot be determined whether the shield itself provides an alternative load path that is unmeasured. Consideration of test results from both vehicle models suggests that a well fitting, foam neck shield might have the best potential to meet the needs of out-of-position airbag testing. Molded Foam II in the Honda Accord tests prevented the airbag from entering the hollow area between the dummy's chin and neck, and in the Molded Foam I tests with the Dodge Grand Caravan the airbag pushed into the space under the neck shield instead of penetrating the space behind the dummy's neck. The Institute is investigating a subsequent configuration that combines the modified head skin with the molded foam neck shield, bonding the neck shield to the top of the chin strap of the modified head skin. However, at this time there does not appear to be a head/neck configuration of the 5th percentile female Hybrid III dummy that can reliably provide a biofidelic indication of airbag inflation injury risk to out-of-position drivers.

ACKNOWLEDGMENTS

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ASSESSMENT OF FOREARM INJURY DUE TO A DEPLOYING DRIVER-SIDE AIR BAG

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INTRODUCTION

Since their introduction, air bags have been shown to save lives and reduce the risk of injury. [1] Early reports stated that injuries related to deployment of an air bag were minor and infrequent. [2] As the number of cars equipped with air bags increases, more data is becoming available and more reports of injuries caused by air bag deployment are appearing in the literature. Air bags have been designed to fully inflate before the occupant contacts it, typically within 50 milliseconds of vehicle impact.[2] Occupants who are either out of position or in close proximity to the air bag module at the time of deployment have sustained severe injuries. Because of growing concern with regard to the position of drivers in relation to the air bag module, it is important that the mechanisms of injury associated with air bag deployment be assessed.

A Canadian study of crashes in which an air bag deployed found that the upper limb is the most frequent site of injury to drivers. [3] While seldom life threatening, upper limb injuries can cause significant disability. Injury to the median nerve, tendon rupture, vascular injuries and other soft tissue damage may occur as a complication of fracture or as a separate event. Long term complications can include arthritis and joint instability. [4] Friedman et al., Huelke et al., and Smock et al. [5, 6, 7] describe upper limb injuries, including abrasions lacerations, contusions and burns, which they attribute to deployment of a driver's side air bag. They also report fractures of the humerus, radius, ulna, and metacarpals.

Taylor et al. conducted a search of the National Automotive Sampling System (NASS) data base. They reviewed 65 cases in which an air bag deployed and an upper limb injury of greater than or equal to level 2 on the Abbreviated Injury Scale (AIS 2) was reported. [8] In studying this data, they found that drivers restrained by a three point belt and an air bag had four times the incidence of upper limb injuries as did drivers using a three point belt alone. In addition, they identified three mechanisms by which an air bag can cause an upper limb injury. All of these mechanisms require that the hand or forearm be in close proximity to the air bag module when it deploys. One is a result of direct interaction between the forearm and the deploying air bag. The other two involve the forearm being flung upward or laterally and contacting the interior of the vehicle. These injuries were found in crashes where there was a change in velocity of less than 15 mph, as well as in high speed collisions.

Taylor et al. used the Research Arm Injury Device (RAID) to measure forces and moments generated by a deploying air bag impacting a driver's forearm. [8] The RAID is an aluminum tube with a joint at one end allowing rotation about two axes. At the other end is a concentrated mass representing the hand. The tube is instrumented with strain gauges and accelerometers. Using this device, they have measured moments far in excess of previously reported values of human tolerance. Although the RAID measurements were high, Bass, et.al., have shown that the measurements correlate to cadaver injuries under similar test conditions.[9]

Researchers at the National Highway Traffic Safety Administration (NHTSA) used an instrumented dummy to quantify the forces generated by a deploying air bag impacting a driver's forearm.[10,11] The forearm was positioned over different air bag module systems in various configurations and the loading during static deployment was measured. This data demonstrated the same trends as the RAID data, but higher accelerations and lower moments and wrist velocities were measured with the dummy. Both the RAID and the dummy were able to differentiate between aggressive and less aggressive air bags.

The question of how much force the forearm can withstand was addressed by Pintar and Yoganandan [12] using dynamic three-point bending tests. Fresh cadaver forearms were placed on simple supports resting on load cells with the supports contacting both the radius and the ulna. Each forearm was tested once with an impactor speed of either 3.3 m/s or 7.6 m/s. Fractures were produced on all specimens. The higher speed impacts produced more comminuted and more distal fractures. They suggested that a person with a lower forearm mass may have a decreased failure bending moment.

Researchers at the University of Virginia have addressed the forces generated by a deploying air bag impacting a driver's arm. They conducted three series of tests using human cadaver upper limbs disarticulated at the shoulder, some frozen and some embalmed. [13] In the first series, forces and bending moment in the steering wheel and humerus were the only data gathered. Forearm acceleration was added in the second series of tests. In the third series, strain gauges were added to assess forearm bending moments. They concluded that severe injury may result from contact with a deploying air bag but that increased bone strength may decrease the risk of injury.

At the University of Michigan Transportation Research Institute, researchers used unembalmed cadavers to investigate forearm interaction with a deploying drivers side air bag.[14] They varied the spacing between the forearm and the air bag module and found that increased spacing between the two greatly reduced the incidence of fracture. They also determined values for peak forearm velocity and bone mineral content that separated incidents of fracture and no fracture.

This study has examined forearm injury patterns produced by static deployment of a driver's side air bag. Attention was focused on the loadings that occur during the punchout phase of deployment because it has already been determined that the highest loadings occur during punchout[15] Loading patterns and the correlation of loadings and injuries were examined with the expectation that fractures would occur during punchout and that bending would be the mechanism of failure.

METHODS

The test fixture used was a rigid seat padded with stiff foam. The seat and seat back angles were fixed, but the seat could be moved forward or backward. The steering column was rigid but the height and angle could be adjusted. The supporting framework behind the seat was also padded with foam to protect the forearm from further injury following loading by the air bag. Two different air bags were chosen in conjunction with researchers in other laboratories. One is considered an aggressive air bag and the other is considered less aggressive. The designations "aggressive" and "less aggressive" were based on the tank pressures and the incidence of injury from field data. [8] The aggressive system is coded H-91 and has an inflater output of 350 kPa x 22 kPa/msec for a 28L tank. The less aggressive system is coded L-92 and has an inflater output of 319 x 12.

Paired tests were conducted with each subject so that an H-91 system was used on one forearm and an L-92 system was used on the other. Prior to the first test, a matrix was prepared which alternated whether each air bag was used on the right or left limb. Subjects were placed in the matrix in the order that they became available.

Four adult cadavers, 3 females and 1 male were used. They ranged in age from 68 to 89 years. Although the subject ages tended to be somewhat advanced, it was determined that these subjects were suitable for assessing arm injury due to air bag deployment since the Bone Mineral Density was typical for post-menopausal women. All cadavers were unembalmed and all instrumentation and testing was done within 60 hours of death. Prior to instrumentation and testing, the upper limbs were palpated and exercised through their range of motion to eliminate rigor mortis and to check for evidence of previous injury. Both forearms of each cadaver were placed in supination and the pre-test X-rays were taken. Anthropometric measurements of the upper limbs for each subject were recorded. The radius and ulna lengths were measured from the x-rays. Post-test x-rays of both forearms for each subject were taken immediately after testing. A summary of these measurements is recorded in Table 1.

Planar strain gauge rosettes were applied to the radius and ulna in order to qualify the strain patterns at or near any distal fracture sites. Since the majority of forearm fractures occur in the distal third of the radius, the site selected was just proximal to the distal metaphysis. This site maximized the possibility of measuring strains at or near the fracture site and minimized interference with other instrumentation. The posterior aspect of the forearm was chosen to minimize the possibility of destroying or dislodging the gauges on impact. A three gauge rectangular rosette, Micro-Measurement CEA-06-062UR-350, was chosen to define the principal strains.

The distal radius and ulna were exposed and a site on the posterior aspect of the bone was selected for gauge application as shown in Figure 1. Although the preferred site was the posterior aspect, a more medial or lateral site was necessary to provide a relatively flat area large enough to mount the gauge on some of the smaller bones. The periosteum was removed from the bone at the selected site. The bone was abraded with fine sandpaper, then degreased and dried with isopropyl alcohol. A catalyst was applied to the back of the gauge and it was bonded with cyanoacrylate. (M-bond 200) A few additional drops of cyanoacrylate were placed at the wiring solder joints for mechanical protection. A protective coating of microcrystaline wax

Table 1.
Subject Anthropometry

Subject Number	Sex	Age	Stature (cm)	Weight (kg)	Forearm Subcutaneous Tissue (mm)		Ulna Length (cm)		Radius Length (cm)	
					R	L	R	L	R	L
1	F	89	161	45	<1	<1	24.50	24.29	22.61	23.22
2	M	80	175	49.5	2	2	27.70	28.08	26.37	26.77
3	F	87	162	64.5	6	6	24.81	25.04	23.01	23.44
4	F	68	168	65.9	8	5	27.80	26.86	25.91	25.32

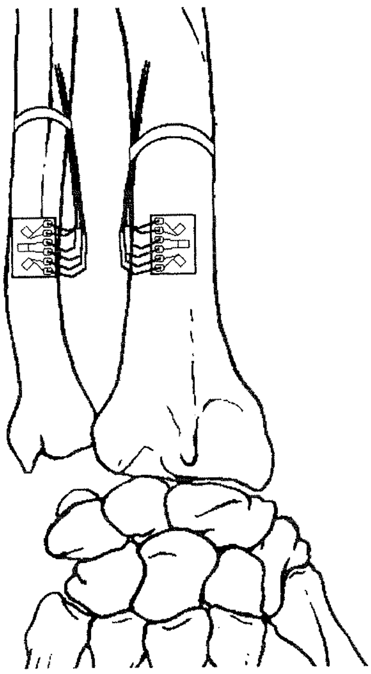

Figure 1. Strain gauge placement - gauges are on the posterior aspect of the radius and ulna.

(M-Coat-W1) was applied to the gauge and surrounding area, and allowed to set. A nylon cable tie was used to secure the wires to the bone with a loop left free for strain relief. The skin was closed with cotton mortuary sutures.

Three Endevco 7264-2000 accelerometers were positioned on a mounting block with their axes in an orthogonal arrangement as shown in Figure 2. The local coordinate system is designated as the x axis in the anterior - posterior direction with posterior positive, the y axis in the medial - lateral direction with lateral positive, and the z axis in the superior - inferior direction with inferior positive. This arrangement was positioned over the posterior wrist at the level of the ulnar styloid and another was placed at the antecubital fossa. Since it was felt that screwing the mounts directly into the bone would compromise the integrity of the bone, special mounts were designed that could be secured to the forearm with nylon cable ties. A six axis load cell in the steering wheel measured triaxial force and moment.

Subjects were positioned in a manner similar to that used in tests with anthropomorphic dummies. [10] The position simulates a driver in the process of turning the vehicle since this is an action that may bring the forearm very close to the air bag module. The subject was seated in the fixture shown in Figure 3 and centered behind the steering wheel, with the hips against the back of the seat. The forearm was positioned with the hand at the 10 o'clock position and the elbow at the 4 o'clock position for the right forearm and the 2 o'clock - 8 o'clock for the left. The steering wheel was rotated so that the seam of the air bag module was perpendicular to the forearm and the forearm

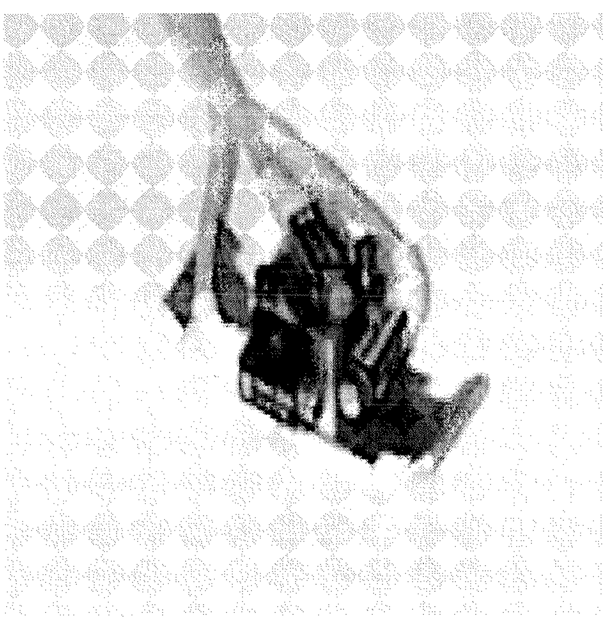

Figure 2. Forearm accelerometer mount - the accelerometers are in a triaxial arrangement.

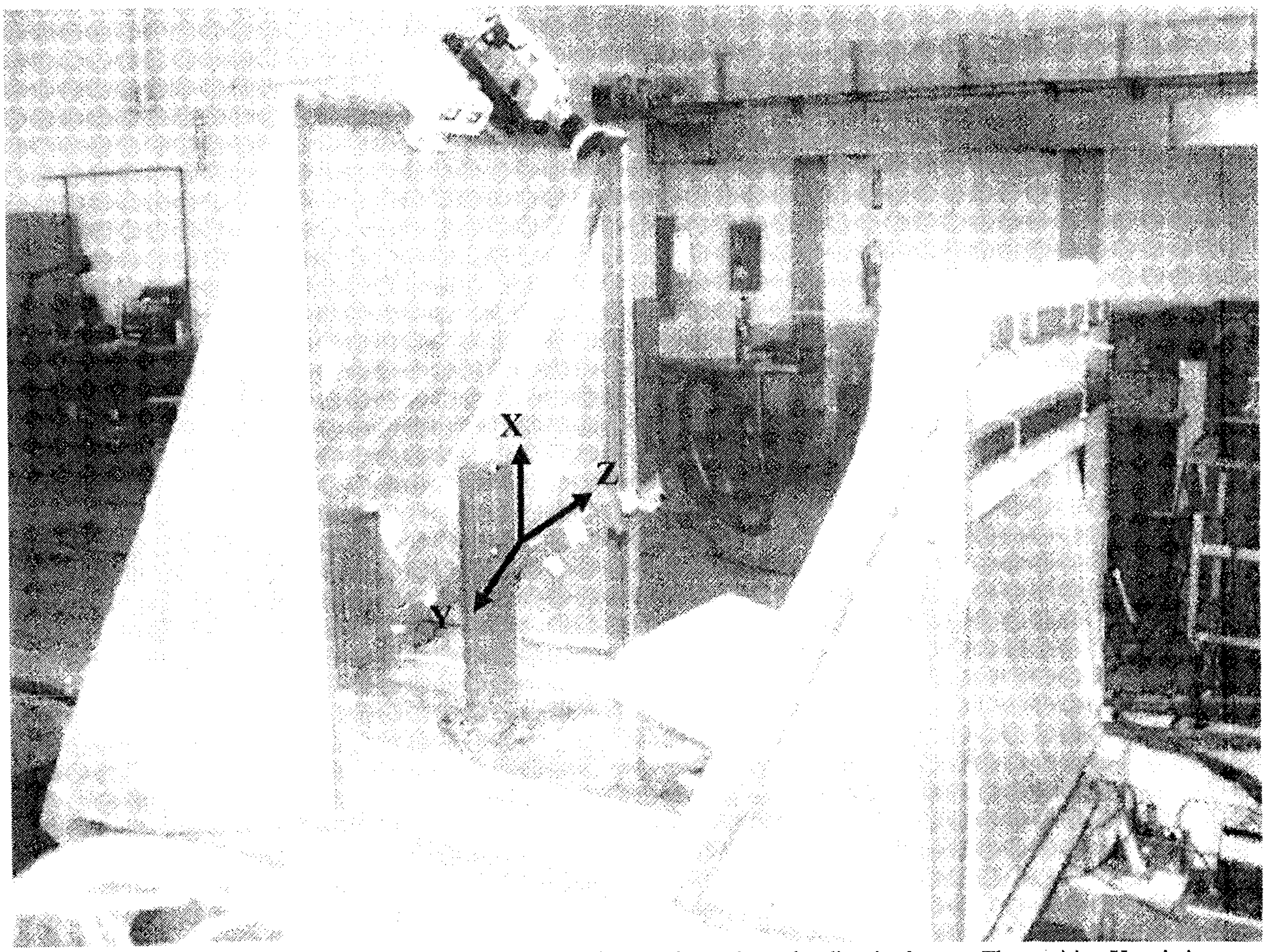

Figure 3. Test fixture. The orthogonal coordinate system for steering column loading is shown. The positive X-axis is up, the positive Y-axis is left and the positive Z-axis is toward the rear.

was placed against the air bag module. The hand was secured to the steering wheel rim with a single piece of masking tape around the fingers and steering wheel rim. The torso was positioned to allow the forearm to contact the center of the steering wheel module. This was accomplished with an additional piece of firm padding placed behind the back or shoulders of the subject.

Data was collected using a 96 channel data acquisition system. Signals from each transducer were transmitted via umbilical cable to a central data acquisition system. Analog-to-digital conversion was performed with a sampling rate of 12,500 Hz. Data was filtered to SAE Class 1000. Each test was recorded with high speed photography from overhead and from the side at 1000 frames per second.

The data from the strain gauge rosettes was reduced to give strain along the long and transverse axes, and shear strain.

Bone samples were collected at autopsy. The distal radius and ulna were disarticulated at the wrist and the distal 10 cm from each bone was removed for bone mineral and geometric property determination. The samples were stored in 10% formalin solution prior to scanning. The samples were scanned for bone mineral density and bone mineral content using a Lunar® DPX-L dual energy x-ray bone densiometer. Accuracy was assured by daily calibration against a phantom of known density. The images were analyzed for bone mineral content and bone mineral density in four 15 mm sections using custom software provided by the manufacturer.

After scanning, each sample was evaluated for cross sectional and inertial properties. Bones that had fractured were cut perpendicular to the long axis of the bone, 1 mm distal to the fracture site. The ends of each sample were smoothed and the periosteum was removed from around the cut end. Images were made of the ends and a Pascal version of the Slice program described by Nagurka and Hayes was used to calculate moment of inertia about the y axis and the cross sectional area. [16]

A logistic regression was performed to identify factors associated with bone fracture using SAS software. Bone mineral density, moment of inertia, steering column force and thickness of subcutaneous tissue and modulus of elasticity were assessed for ability to predict fracture.

RESULTS

The results of the testing is summarized in Table 2. Peak forearm acceleration and steering wheel force are listed as well as the mineral and geometric properties of the individual bone samples.

The external accelerometer mounts used for this study were designed to eliminate an invasive or destructive application. However, this presented several other problems. Although the wire ties used to secure the mounts were pulled as tightly as possible, the data was very noisy, suggesting a high signal to noise ratio or vibration in the mounts. To help compensate for this noise, the data was further filtered to SAE Class 180 for interpretation using a 2 pole Butterworth filter with a 300 Hz cut off frequency. In addition, the wire ties on the upper forearm mounts broke on every test so the upper forearm acceleration data was not considered for analysis. Other data acquisition problems resulted in no accelerometer data being collected for testing of the right forearm of the first subject and the left forearm of the second subject. Typical curves are shown in Figure 4. The H-91 bag showed consistently earlier and higher peak accelerations in the x direction than the L-92 bag. In

Table 2.
Test results

Sample	Air Bag	Fx	BMD (g/cm^2)	BMC (g)	Area (mm^2)	Iy (mm^4)	SWFZ (N)	LAXG (g)
1LR	H-91	Y	.369	.710	80.49	783.44	-1856.2	319.03
1LU	H-91	Y	.318	.554	88.02	860.92	-1856.2	319.03
1RR	L-92	Y	.387	.755	96.70	959.93	-1347.7	***
1RU	L-92	Y	.361	.647	67.80	580.72	-1347.7	***
2LR	L-92	N	.668	1.751	184.28	2987.55	***	***
2LU	L-92	N	.813	1.449	159.28	2618.48	***	***
2RR	H-91	N	.714	1.909	161.52	2195.46	-1680.0	437.72
2RU	H-91	N	.768	1.578	173.07	3038.42	-1680.0	437.72
3LR	H-91	N	.363	.781	71.48	567.45	-2073.2	402.00
3LU	H-91	N	.283	.484	58.67	394.37	-2073.2	402.00
3RR	L-92	N	.389	.884	79.77	648.85	-1340.7	376.86
3RUp	L-92	N	.265	.488	99.66	874.51	-1340.7	376.86
3RUd	L-92	Y	.187	.306	41.17	429.18	-1340.7	376.86
4LR	L-92	N	.368	.848	67.59	709.65	-1871.9	296.79
4LU	L-92	N	.482	.783	70.30	568.65	-1871.9	296.79
4RR	H-91	N	.400	1.033	89.29	1029.18	-2250.9	347.68
4RU	H-91	N	.386	.605	85.35	814.32	-2250.9	347.68

Sample = subject number- left/right- radius/ulna, Fx = fracture, BMD = Bone Mineral Density, BMC = bone mineral content, Area = Cross-sectional area, Iy = Moment of Inertia about the y axis, SWFZ = Peak steering wheel force in the z direction, LAXG = Peak forearm acceleration in the x direction, time = Time of peak value, *** = Lost data

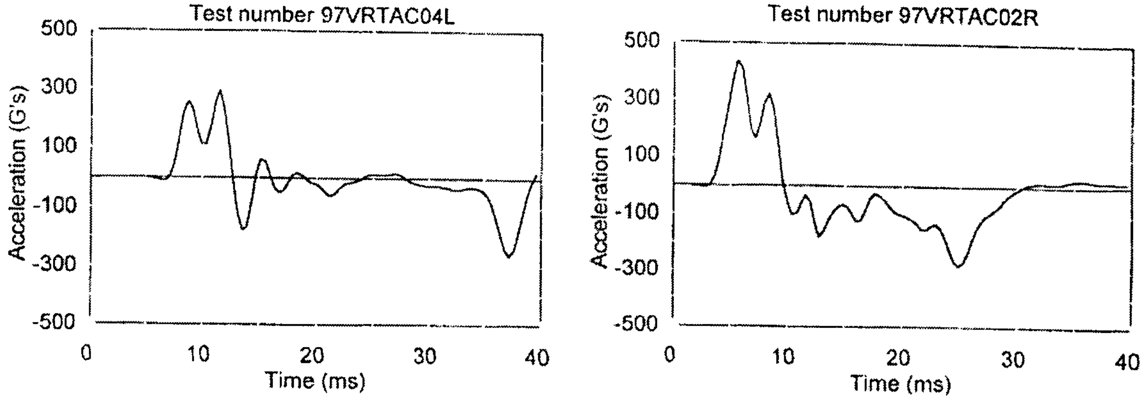

Figure 4. Typical forearm acceleration X-axis time history. Air bag L-92 is on the left with a maximum value of 297 G's. Air bag H-91 is on the right with a maximum value of 438 G's.

all cases, the peak wrist acceleration in the x direction corresponded to punchout as observed on the high-speed film recording. In tests where the high-speed film recording showed the forearm striking the face or chest, the corresponding accelerations were somewhat lower than for punchout. If the forearm struck the framework, it was characterized by a wide low amplitude spike.

Most of the data from the strain gauges was obscured by wiring failures but data that was collected was interesting. At autopsy, only 4 rosettes were found to have all wires intact, however, some useful data was collected before failure on 4 others. The data was filtered to SAE Class 180 to compensate for noise.

Two of the useful rosettes were on bones that fractured and a sudden simultaneous drop in strain of all their gauges may have occurred as a result of the fracture. Figure 5 shows strain data before the principal strains were calculated. The fracture probably occurred between 10 and 11 ms with the wiring failing at about 12 ms. The left hand graph in Figure 6 shows the same event but the strains along the long and transverse axes have been calculated. Just prior to fracture, the long axis of the bone is in tension and the transverse axis is in compression. This supports the theory that the loading pattern results in bending but demonstration of a compressive strain pattern on the long axis of the anterior side of the bone would be necessary to prove it. This pattern is not seen with tests using air bag H-91. The right hand graph in Figure 6 shows the strains from a bone in the 4th subject that did not fracture. The long axis and the transverse axis are both in tension which may be indicative of a high energy loading pattern. This could also be due to an off axis loading.

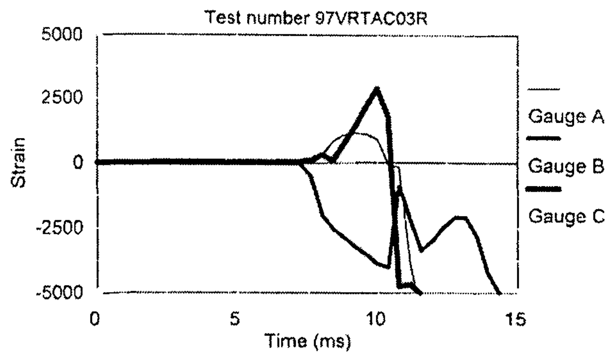

Figure 5. Raw strain gauge time history for air bag L-92. Fracture probably occurs at 10.5 ms.

The load cell measured steering wheel force in three axes and the data was very noisy. This was attributed to vibration from the high speed camera mounted on the test fixture. The data was further processed to SAE Class 180 for interpretation and is shown in Figure 7. Consistent with the forearm acceleration, the H-91 bag produced earlier and greater forces.

Bone Mineral Density (BMD) was determined at four 15 mm wide sections starting from the distal end of the bone. BMD increased from the distal to the proximal end of the bone. The fracture in right ulna #3 was about 30 mm from the distal end. This distal fracture location proved challenging to scan. The initial attempt was to scan with the broken ends pushed together. The ends could not be kept together well and results were not entirely satisfactory. Because of this, an additional scan was made with the fractured ends apart. The value shown in Table 2 for the

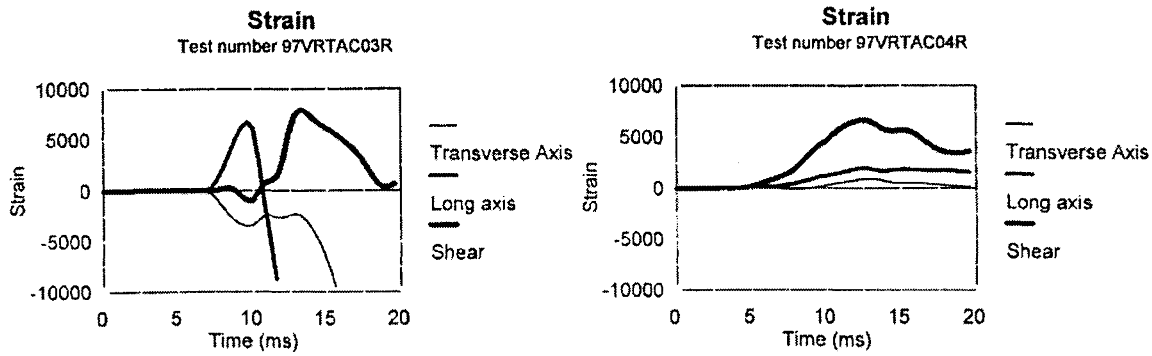

Figure 6. Typical strain time history. Air bag L-92 is on the left and shows the long axis is in tension and the transverse axis is in compression, suggesting the possibility of a bending mechanism. Air bag H-91 is on the right showing both the long and transverse axes are in tension suggesting that the loading caused an explosive injury.

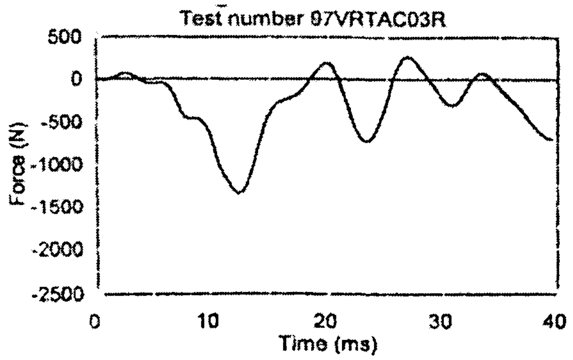

Figure 7. Typical steering wheel Z-axis force time history. Air bag L-92 is on the bottom with a maximum value of -1341 N. Air bag H-91 is on the top with a maximum value of -2073 N. The peaks fall within 1-2 ms of the peaks in forearm acceleration.

third region of right ulna #3 represents an average of the BMD values for the section with the bone ends together and the two broken ends. This procedure gave results consistent with the pattern seen for the other samples. The values reported in Table 2 are from the proximal section with the exception of 3RUd. This sample represents the distal end of the fracture site and the value for the third section is reported.

Cross sectional area and moment of inertia are reported in Table 2 on page 5. The values reported are from the diaphysis of the bone with the exception of sample 3RUd. This value represents the distal end of the fracture in that sample. Cross-sectional area was determined using both NIH Imager software and Slice software. Because the two methods gave very similar results, only the data from the Slice software is shown. Moment of inertia is calculated about the medial-lateral axis passing through the neutral axis of the bone. This is the axis of interest when considering bending in the sagittal plane.

DISCUSSION AND CONCLUSION

Whether or not a material fails is dependent on a number of factors, including the strength of the material and the magnitude of the force applied to it. Both of these factors were addressed in this study. The strength of a material is dependent on its geometric properties and its material properties. Assuming that bending is the mechanism of failure, a large moment of inertia will produce less stress for a given bending moment. Bone strength will also increase, up to a certain point, with an increase in the mineral content. A decrease in the force transmitted to the bone will also decrease the likelihood of fracture.

Logistic analysis is suitable to situations in which the dependent variable is characterized by discrete outcomes. Although some researchers [17,18] have argued that the logistic model is not a good model for assessment of injury risk unless the test conditions to cause or avoid injury are well defined and have a large number of reasonably well controlled test points, others [19] have used the logistic model where the outcome is either death or survival. In this study, since the predictor variables are continuous and the response, fracture or no fracture, is binary, a logistic model was used to assess fracture risk. Fit was assessed using a Wald Chi square test with significance defined as $p < 0.05$. Odds ratio was also calculated. It should be noted that this analysis is based upon a very limited sample size, and consequently, the results should be used cautiously.

Bone mineral density was examined first. In this study, subject 2 had larger, denser bones than the other three subjects and no fractures were produced. The other three subjects had similar BMD and moment of inertia, but there were no fractures in subject 4 and only one in subject 3. This is in contrast to the results obtained by other researchers who were able to identify a value of bone minereal content, above which no fractures were produced and below which fractures were usually produced. The results of a logistic regression shown in Table 3 suggest that there is no significant relationship between the occurrence of fracture and bone mineral density in this study. Moment of inertia is not a significant predictor either.

Table 3.
Results of statistical analysis*

Factor	P- value for Wald Chi square test	Odds Ratio
BMD	0.1665	0.000
Iy	0.2764	0.998
SQ	0.0661	0.546
SWFZ	0.1237	1.003
E	0.1446	0.000
EIy (strength)	0.2981	0.996
SWFZ / SQ (attenuated force)	0.1081	0.995
Attenuated force / strength	0.0490	8.043

*Note that analysis is based upon a very limited sample size

BMD = bone mineral density, Iy = moment of inertia, SQ = thickness of subcutaneous tissue, SWFZ = steering wheel z-axis force, E = modulus of elasticity

Modulus of elasticity was then addressed. Strain in the longitudinal direction was differentiated to give strain rate. There was noise in this data so the graphs were examined over the interval of 5 to 10 ms, the time during which punchout occurs. The H-91 air bag showed a strain rate of about 1/sec and the L-92 was about 0.3/sec.

Apparent density was calculated by dividing the BMC by the volume of the scanned region. This segment was modeled as a cylinder and the volume was calculated by multiplying the cross sectional area by the length of the scanned segment. Modulus of elasticity was calculated using the equation

$$E = 3790\, \dot{\varepsilon}^{0.06} \rho^3$$

derived experimentally by Carter et al. [19] Modulus of elasticity was not found to be significant either.

Moment of inertia and modulus of elasticity were multiplied to give an overall strength factor but this did not seem to be a significant predictor of fracture either.

Steering wheel force along the z-axis was not consistent for all subjects but it was consistently higher for the H-91 air bag than the L-92. Logistic regression demonstrates that steering wheel force is not a significant indicator of fracture. Moreover, the steering wheel force may not be an accurate indicator of force transmitted to the bone. The force is not applied in full to each bone and it is not shared equally. The magnitude of the force actually transmitted to the bones is also in question. The first two subjects had very thin subcutaneous tissue in contrast to the thicker tissue of the other two. It is possible that the thicker subcutaneous tissue attenuated the force of the deploying air bag and less energy was transmitted to the bone. This provides an additional factor that could explain the fracture pattern observed. The steering wheel force was divided by the thickness of the subcutaneous tissue and this attenuated force was assessed. However, it was not a significant predictor of fracture either. The attenuated force and the bone strength were then related by dividing attenuated force by bone strength and a force to strength ratio was obtained. This was significant by logistic regression and the odds ratio was 8.034. Fracture vs. force to strength ratio was plotted and fit with a logistic curve with the equation:

$$\pi = \frac{e^{\beta_o+\beta_1 x}}{1+e^{\beta_o+\beta_1 x}}$$

with $\beta_0 = -3.14$ and $\beta_1 = 2.08$. The probability of fracture is π and the fracture to strength ratio is x. This graph is shown in Figure 8.

This suggests a possible explanation for the observed fracture pattern. Subject 2 had very strong bones that were able to withstand the force of the deploying air bag. Subjects 3 and 4 had weak bones but their thicker subcutaneous tissue may have attenuated the force of the deploying air bag and enabled their bones to resist fracture. The first subject had weak bones and thin subcutaneous tissue and suffered fractures of all 4 forearm bones.

The fracture seen on the right ulna of the third subject due to the L-92 system would not be expected from the above explanation and deserves separate consideration. This was an oblique fracture with minimal displacement. Isolated ulna fractures are often caused by a direct blow to the ulna and are commonly called "nightstick fractures". These fractures are generally transverse or oblique. The ulna is susceptible to this type of injury because there is very little soft tissue on its medial aspect. For this test, the radial styloid was positioned about 76 mm from the center of the air bag module. The fracture was about 58 mm from

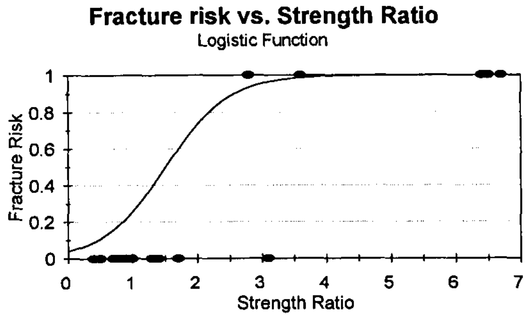

Figure 8. Graph of fracture risk vs. force to strength ratio. The logistic function is fit to data. Note that this fit is based upon a very limited sample size.

the radial styloid. Both of these measurements are subject to error. Accurate location of the radial styloid and the center of the air bag module was difficult due to instrumentation and clothing and could only be estimated. The measurement from the post-test x-ray is subject to error due to positioning for the x-ray and the displacement of the bone ends. With these considerations it is possible that the fracture site was very close to the center of the air bag module. If the forearm was not in full pronation at the time of deployment, the ulna could have taken a direct hit from the edge of the module cover as it was opening. This cannot be confirmed from the high speed film due to the unsuitable camera angle.

The strain gauges were problematic. Only 4 of the 16 gauges survived to autopsy with the wiring intact. No data was collected for two of these due to data acquisition problems. Four others generated useful data prior to failure. Only two were on bones that fractured.

Three of the surviving gauges were on tests using the less aggressive air bag. These all show a similar pattern of tension along the dorsal long axis of the bone and compression on the transverse axis. This pattern suggests a bending load. The tests using the more aggressive air bag showed a different pattern, one of biaxial compressive stress. For tests of the right forearm of the second subject and the left forearm of the third subject, there was compression in both the transverse and longitudinal axes. There was biaxial tension for the test of the right forearm of the fourth subject. This could happen for one of two reasons. If the gauge was mounted on the side of the bone instead of the posterior aspect, it could generate this pattern of stress. The post-test x-rays were examined for strain gauge placement. The radial strain gauge was positioned slightly toward the lateral aspect for the test of the right forearm of the fourth subject, but the other two were well centered over the posterior aspect of the radius. The other possible explanation is that the loading was not bending but a high energy explosive type of mechanism.

This study was limited by the small sample size and this probably accounts for the fact that there was no significance shown for any individual factor by chi-squared analysis. Statistical analysis was complicated by the fact that only 4 subjects were used and it is difficult to obtain reliable conclusions from such a small sample. Viewing each bone as a separate observation was felt to be reasonable since each bone had a unique BMD and moment of inertia, and since the alternative of testing additional subjects is not feasible at this time. The other limitation is the age of the cadavers. Only one was less than 80 years old and this is not representative of the average driver. The reduction in bone mineral density and muscle mass that occurs with aging probably increased the incidence of fracture. [21, 22, 23]

The estimation of the force attenuation was based on the assumption that the response had a linear relationship to the thickness of the subcutaneous tissue. Research by Robinovitch et al. supports this but it also assumes that the force attenuation is proportional to the force. [24] This may not be the case, instead, a given thickness of tissue may attenuate a constant amount of force despite the magnitude of the force delivered. Since Robinovitch used only one force level in his research, this relationship remains unclear.

If padding due to soft tissue is playing a significant role in force attenuation, it is possible that padding the air bag module cover could reduce the risk of injury. Experimentation with different padding materials and different thickness using dummies and the Research Arm Injury Device would be appropriate to address this question.

The strain gauge data suggests the possibility of a fracture mechanism other than bending at high energy levels. Examination of data from other laboratories for evidence of similar discrepancies and further research with isolated limbs could provide further information.

This study looked at forearm fractures as a result of the punchout phase of driver's side air bag deployment. It was determined that bone strength alone is not a good predictor of fracture risk and that the force generated by the bulging air bag module may be attenuated by the soft tissue of the forearm. The combination of bone strength and attenuated force provided a better predictor of fracture risk. Further research in the area of fracture mechanism, and force attenuation by padding is needed.

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RESULTS OF FULL-SCALE CRASH TESTS, STATIONARY TESTS AND SLED TESTS TO ANALYSE THE EFFECTS OF AIR BAGS ON PASSENGERS WITH OR WITHOUT SEAT BELTS IN THE STANDARD SITTING POSITION AND IN OUT-OF-POSITION SITUATIONS

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ABSTRACT

It can be expected that equipping new vehicles of all categories with air bags will lead to an increase of accidents in which injuries are assumed to be caused by an air bag. Answers to related questions call for comprehensive experimental findings. In this context possible injury-inducing effects of air bags in standard and non-standard sitting positions (out-of-position situations) of passengers are of particular interest.

DEKRA Automobil AG carried out several tests to analyse the effects of air bags on belted drivers in the standard sitting position and unbelted front passengers bent forward (out of position). In six full-scale crash tests the vehicle impacts a rigid barrier with 40 % frontal overlap. In four of the tests the collision speed was 55 km/h, in two tests 34 km/h the other 29 km/h. A belted dummy was placed on the driver's seat in the standard position. On the front passenger seat an identical dummy was placed unbelted and leaning forward. Two further tests were carried out with a stationary vehicle and triggered the front passenger air bag. On the front passenger's seat was an unbelted dummy bent forward. In one case its position was extreme, with the face close to the cover of the air bag. In the other case the distance between the dummy's nose and the dashboard - as in the full-scale tests - was 175 mm. Vehicle deceleration and vehicle damage measured during the tests, together with the loads on the dummies and their kinematics are described.

At the Institute of Forensic Medicine in Heidelberg seven sled tests were carried out to simulate frontal collisions at speeds around 50 km/h involving unbelted human cadavers in a standard sitting position. The restraint system used in each case was a full-size air bag in conjunction with knee pads. In addition to the dummy tests the measured accelerations of the cadavers and their injuries are described.

To summarize there follows an inter-disciplinary discussion and evaluation of all test results with regard to protective effects and possible injuries caused by air bags.

INTRODUCTION

Air bags as supplements to seat belts clearly enhance the internal safety of vehicles. To provide protection, an air bag needs to be inflated. Depending on collision parameters (angle of collision, delta-v, etc.) the time period between the begin of the collision and the end of the air bag inflation could be 40 to 80 ms. This needs a corresponding amount of energy. In this context, the possible loadings of occupants who are impacted by the air bag during its inflation are of special interest.

To study such effects, DEKRA Automobil AG carried out full-scale crash tests with a belted dummy on the driver side and an unbelted dummy bent forward on the passenger side in cars equipped with air bags. Further tests were conducted with a stationary car triggering the air bag on the front passenger side. In these tests, an unbelted dummy was sitting bent forward on the passenger seat. In addition, the Institute of Forensic Medicine in Heidelberg had carried out sled tests with unbelted human cadavers in a standard sitting position, protected by an air bag supplemented with knee bolsters. The test results, especially the mechanical loadings of the dummies and of the human cadavers and as well the injuries of the cadavers shall give more information to discuss the protective effect of the air bag and possible overcritical loadings induced by a contact with the inflating air bag..

FULL-SCALE CRASH TESTS

Test Base

Six full-scale crash tests were carried out with a 40 % frontal overlap impact of a car against a rigid barrier. In the first four tests the impact velocity was 55 km/h (**Figure 1**), in the fifth test 34 km/h and in the sixth test 29 km/h.

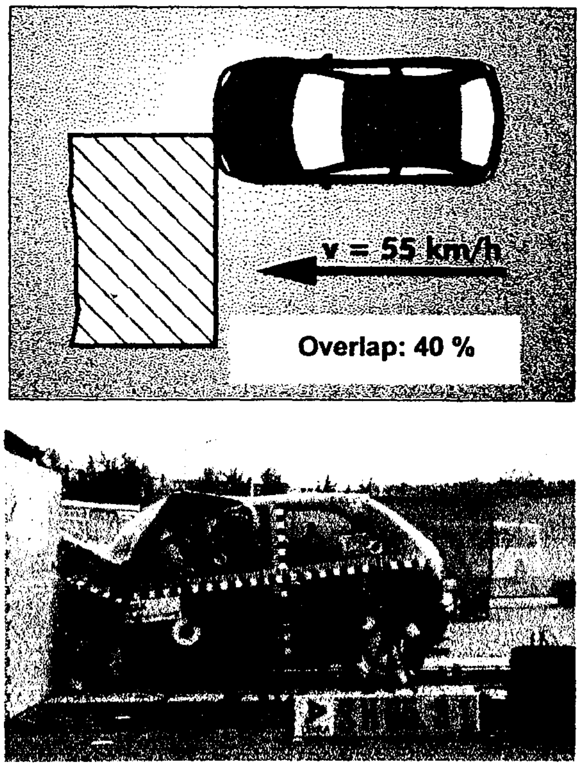


Figure 1. Example of a full-scale crash test

In each test, a belted Hybrid III dummy (50th percentile male) was located in the driver's seat in a normal seating position ("in position"). In the passenger seat an unbelted dummy of the same type was seated leaning forward ("out of position"), **Figure 2**.

The seating posture of the passenger dummy was selected to represent a position which is not normal but also not less realistic. Such a posture for example can occur when the passenger is looking for something in the glove box. Other, in some cases more extreme seating positions were proposed by the automotive industry for evaluating out-of-position vehicle occupant's interactions with inflating air bags (WEZEL, 1992).

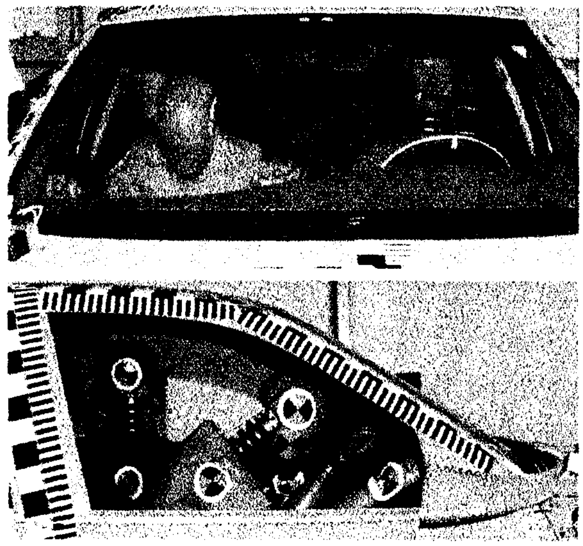


Figure 2. Seating position of the dummies in the full-scale crash tests

Test Vehicles

Table 1. gives an overview of the test speeds and the test vehicles with features of their air bags. The test weights given include both dummies and the installed data acquisition equipment (sensors, transient recorders and cables). The Ford Fiesta was equipped with smaller Eurobags and in the Opel cars were full-size bags. The gas generators in the Ford Fiesta and in the Opel Corsa employ the conventional technology with the propellant sodium azide or nitrocellulose. Hybrid gas generators are installed in the Opel Vectra. Test SH 96.01 serves to compare the loads acting on a passenger who is sitting bent forward without any restraint. The Vectra in test SH 96.02 is the same model as in test SH 96.01 but it is not the same car. In the tests SH 97.03 and SH 97.04 the same Opel Corsa was used. Between both tests, this car was repaired in a body shop with a complete interchange of all parts previously damaged in test SH 97.03.

Kinematics of and Damage to the Test Vehicles

The resulting velocities and the yaw velocities of the four vehicles with 55 km/h collision speed are shown in **Figure 3**. The curves given are results from overhead film analyses, corresponding to targets on the roof of the cars above their gravity centres. The rotational velocities rise to maximum between 2/s and 3/s within approx. 0.15 s. The reason for this is the eccentric impact force which is acting against the car front. The point of maximum rotational velocity gives an indication to the end of the bodyshell compression resulting from the (semi plastic) impact. In

Table 1. Test vehicles and their test speeds

Test No. Test Speed	Test Vehicle Test Weight	Passenger Air bag
SH 94.35 55 km/h	Ford Fiesta Fiesta 1 093 kg	Euro bags Driver: 30 litres Passenger: 60 litres Coated fabric with vent holes Conventional gas generator Propellant: Nitrocellulose
SH 95.31 55 km/h	Opel Corsa 1.2 i 1 136 kg	Full-size bag Driver: 67 litres Passenger: 100 litres Uncoated fabric with vent holes Conventional gas generator Propellant: Sodium acid
SH 96.01 55 km/h	Opel Vectra 1.6 16 V 1 434 kg	Not activated
SH 96.02 55 km/h	Opel Vectra 1.6 16 V 1 450 kg	Full-size bag (120 litres) Driver: 60 litres Passenger: 120 litres Uncoated permeable fabric Hybrid gas generator Argon (98 %), Helium (2 %)
SH 97.03 29 km/h	Opel Corsa 1.4 i 1 049 kg	Full-size bags Driver: 67 litres Passenger: 100 litres Uncoated fabric with vent holes Conventional gas generator Propellant: Sodium acid
SH 97.04 34 km/h	Opel Corsa 1.4 i 1 049 kg	Full-size bags Driver: 67 litres Passenger: 100 litres Uncoated fabric with vent holes Conventional gas generator Propellant: Sodium acid

this phase, the resulting velocities decrease from the original value 55 km/h to approx. 10 km/h. Neglecting the here minimal lateral motion, this gives an average velocity change of delta-v = (55-10) km/h = 45 km/h (12.5 m/s) and a mean deceleration of a = delta-v/delta-t = 8.5 g). Subsequently, the lateral motion of the centre of gravity superimposes its longitudinal motion increasingly. Therefore the resulting velocity does not pass through zero, but rather slightly increases at first and then dies down, until the car comes to a standstill in its final position.

An example of a curve of the longitudinal acceleration

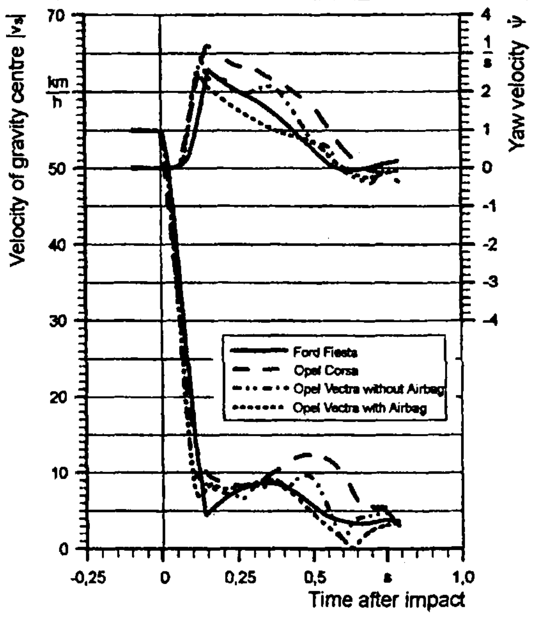


Figure 3. Resulting velocities and yaw velocities of the four cars with 55 km/h collision speed as determined by analysing the overhead films corresponding to targets on the roof of the car

(x-direction) measured at the vehicle is shown in **Figure 4.** The point of measurement is the right sill of the Opel Vectra in the region of the B-pillar base. The minimum of the CFC-60 (SAE J 211 a) filtered acceleration signal is -39,8 g. The corresponding velocity curve is determined by integrating of the CFC-1000 filtered acceleration signal.

Figure 5. gives an overview of the front damage of the four cars with the collision speed 55 km/h. The characteristics are typically for car to car offset crashes in opposing traffic with a severity clearly over the trigger threshold of the air bags. In contrast to the severely damaged driver side with deep intrusions, the passenger side is only of minor damage with less intrusions.

Figure 6. shows for the two tests with 34 km/h and 29 km/h collision speed the resulting velocites and yaw velocities of the Opel Corsa determined by film analysis as well as in Fig. 4. Here the characteristics of the velocities indicate that the crush phase ended near t = 0.12 s in both tests. During this time interval, as shown also in Fig. 6, the vector of the collision induced change of velocity once was delta-v = 29 km/h, in the other case 34 km/h. With delta-v = 29 km/h the air bags in the Opel Corsa did not trigger. Delta-v = 34 km/h triggered them.

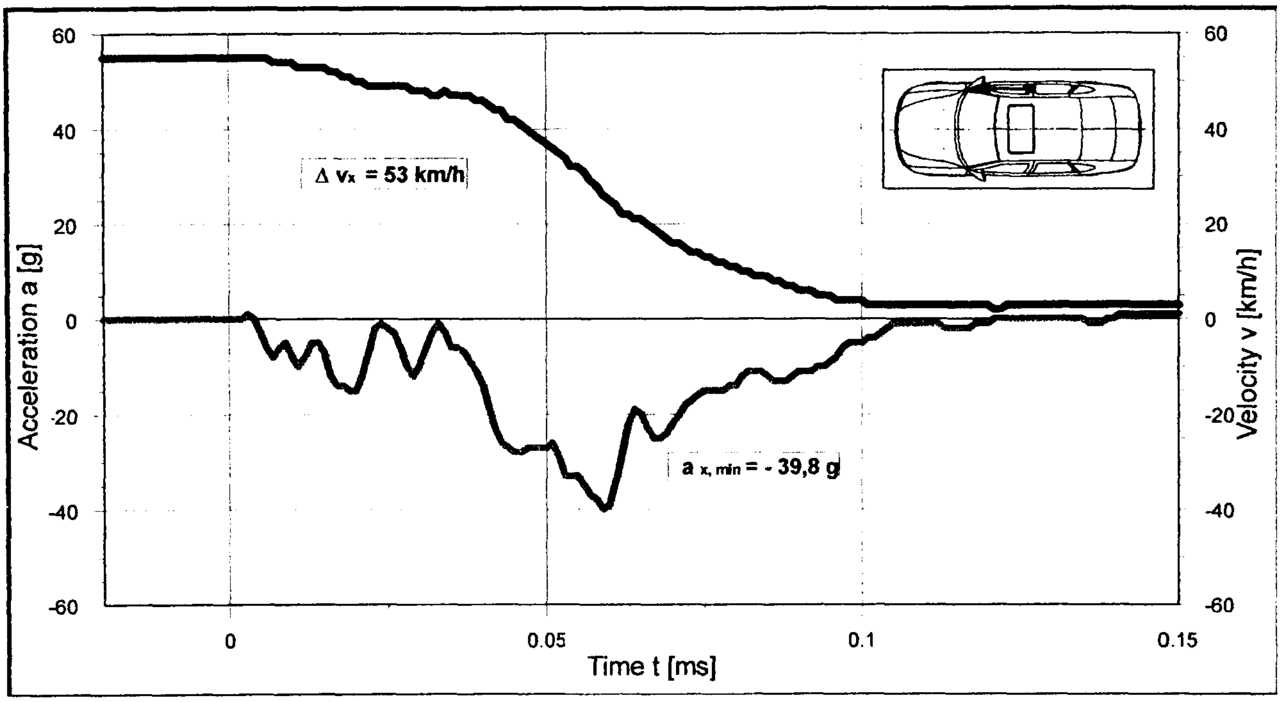


Figure 4. Acceleration measured in x-direction near the roof of the right B-pillar of the Opel Vectra and corresponding velocity (test SH 96.02)

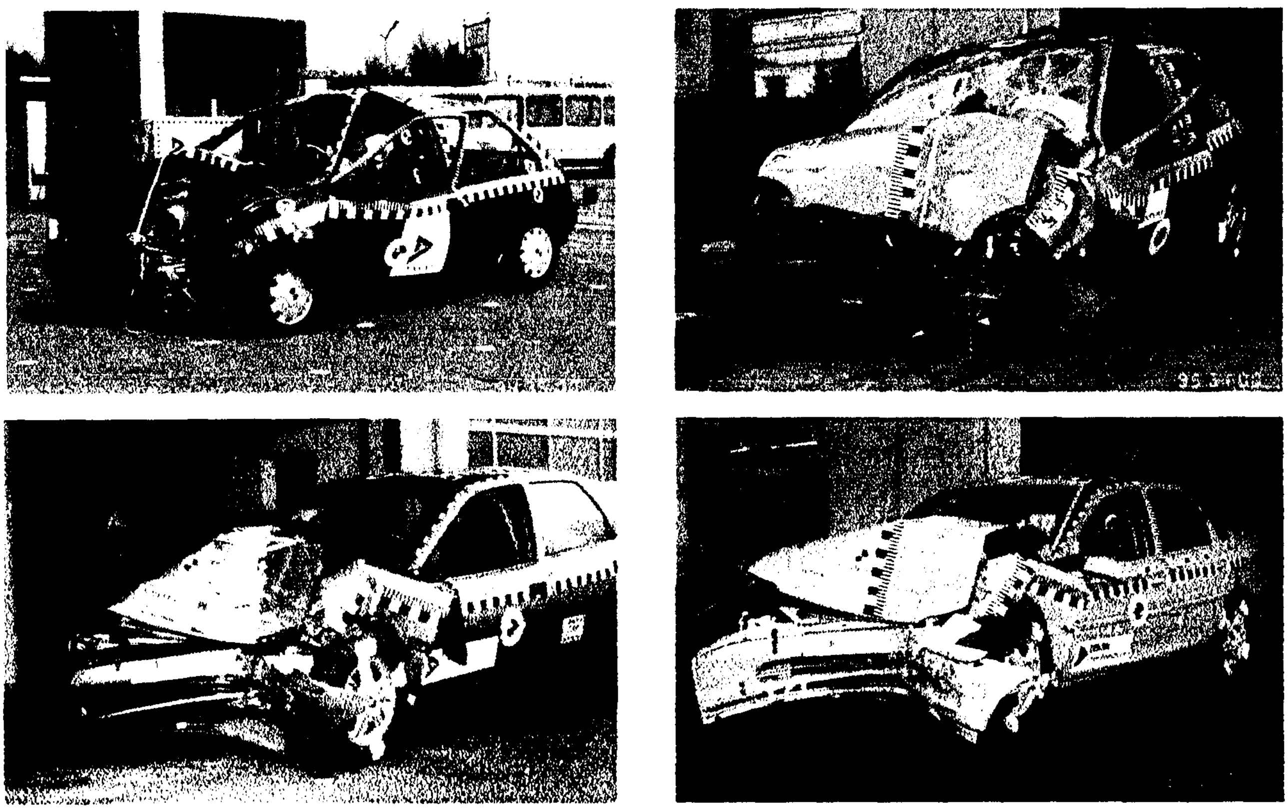


Figure 5. Damage to the frontside of the four test vehicles with 55 km/h collision speed

34 km/h. With delta-v = 29 km/h the air bags in the Opel Corsa did not trigger. Delta-v = 34 km/h triggered them.

Figure 7. shows the longitudinal decelerations (x-direction) measured on the floor of the passenger compartment of the Opel Corsa in the tests with 29 km/h and 34 km/h collision speed. Measurement point was in the centre between the B-pillars. The CFC-60 filtered deceleration signal has a maximum of 27.0 g at t = 59 ms after the start of the crash in the case without air bag activation. In the case when the air bags triggered the maximum of the deceleration signal was 39.6 g at t = 49 ms.

The corresponding velocities were determined by integrating the CFC-1000 filtered deceleration signals. They indicate a path through zero at approx. t = 80 ms. At approx. t = 100 ms the remaining velocity is close to -5 km/h. In the test without air bag ignition, the longitudinal change of velocity at the measurement point was delta-v = 33.7 km/h, in the case when the air bag triggered, it was delta-v = 38.8 km/h.

It should be mentioned that the air bag sensors of the test vehicles have not been installed in the centre of gravity or in the centre between the B-pillar roofs on the floor of the compartment. Therefore the air bag control unit in the tests carried out had not exactly the same acceleration information and velocity change as shown in Figure 3., 4., 6. and 7. But this information must be similar, so that the in Figure 6. and 7. shown kinematics give an idea of the air bag trigger threshold generated by actual designed algorithms in European cars.

An overview of the damage to the front of the car in both tests is given in **Figure 8**. The characteristic of this damage is typical in front to front collisions of two cars in opposing traffic with a medium severity close to the actual

Figure 6. Resulting velocities and yaw velocities in the two tests with 29 and 34 km/h collision speed as determined by analysing the overhead films corresponding to targets on the roof of the cars showed in conjunction with the vectors of the velocities before and after crash and the collision induced change of velocity delta-v

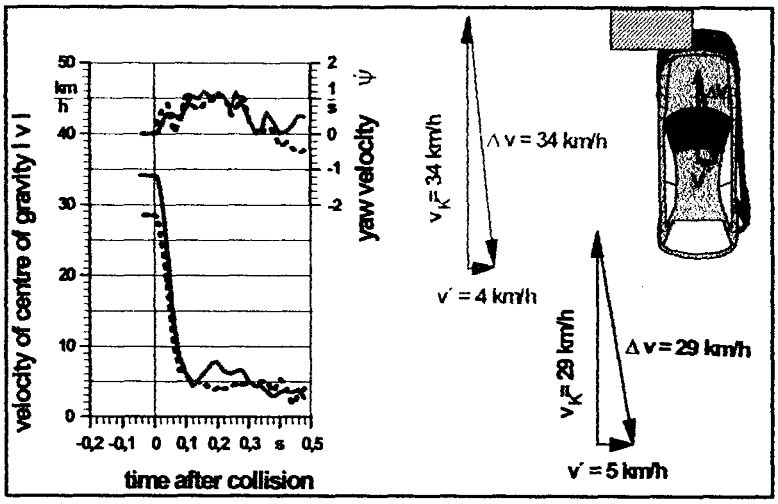
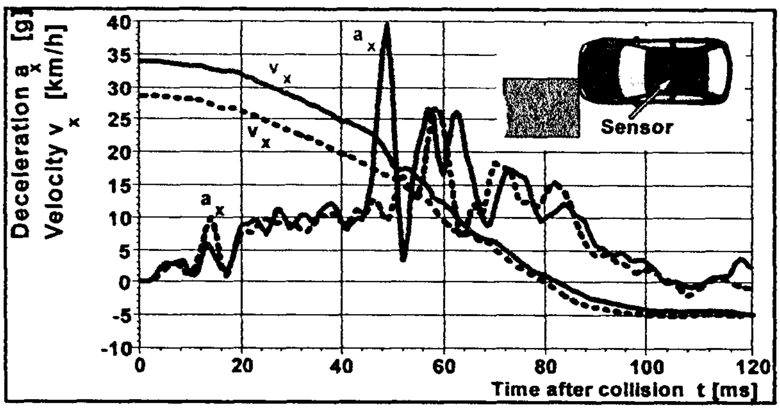
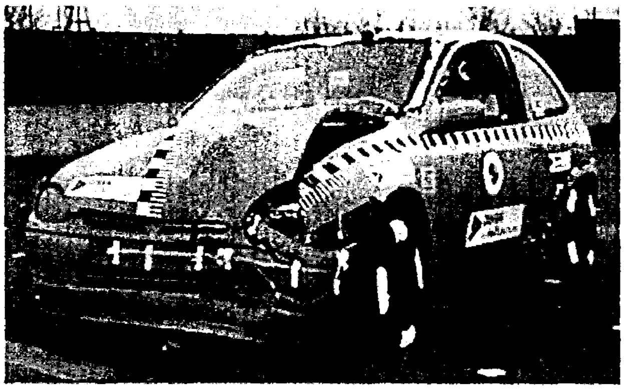


Figure 7. Longitudinal decelerations measured on the floor of the passenger compartment and corresponding velocities in the two tests with 29 and 34 km/h collision speed





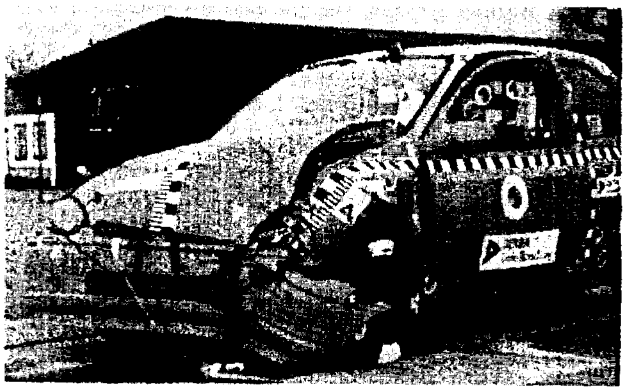


Figure 8. Damage to the front side of the test vehicle with 29 km/h (left) and 34 km/h collision speed (right)

SLED TESTS

Figure 9. shows an example of the sled tests. An overview of the test data is given in **Table 2.**

The simulated collision speeds were in the range of 47 km/h to 50 km/h. The sled retardation in these tests was in the range of 10.0 g to 17.4 g.

The occupants in the compartment on the sled were human cadavers*). The test loadings of the driver were simulated in six tests and of the loadings of the front passenger in one test. The age of the cadavers ranged between 26 and 55 years. In one case the gender was female (driver position, 37 years, weight 55 kg, height 167 cm). In the other cases the gender was male, the height between 170 and 189 cm and the weight in the range 70 to 96 kg. All cadavers were unbelted and at the start of the tests in a normal sitting position. The restraint system was a full-size air bag supplemented by knee bolsters.

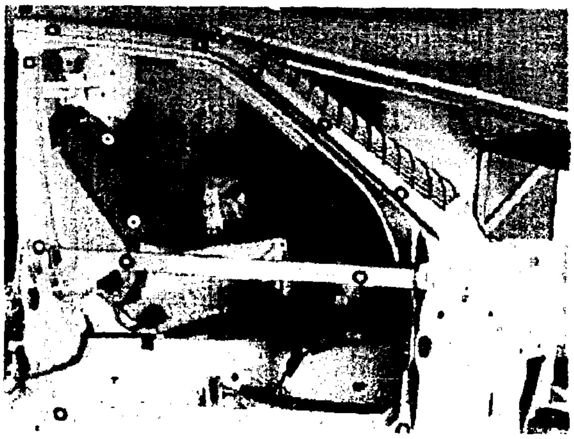


Figure 8. Example of a sled test

*) The ethic and legal precondition to use cadavers in sled tests was an agreement with their relatives who were informed about the test objectives and methods. The presumed or known attitude of the deceased was taken into consideration in the agreement. We are very grateful to all relatives whose agreement supported the improvement of injury prevention through the optimization of safety systems in the name of progress.

Table 2: Overview of the sled tests

Test	Collision Speed [km/h]	Sled Retard. [g]	Position	Height [cm]	Weight [kg]	Age [years]	Gender
L1	50	10,0	Driver	174	75	55	male
L2	50	10,8	Driver	167	55	37	female
L3	48	17,4	Driver	183	90	41	male
L4	47	16,0	Driver	170	70	31	male
L5	49	17,0	Driver	184	74	26	male
L6	47	17,0	Driver	174	79	38	male
L7	50	11,0	Pass	189	96	29	male

RESULTS

Dummy Loadings in the Four Full-scale Tests with 55 km/h Collision Speed

The loadings measured on the belted driver dummy and the unbelted out-of-position front passenger dummy in the four full-scale tests with 55 km/h collision speed are shown in **Table 3**. In addition Table 3 contains the corresponding protection criteria (according to FMVSS- and ECE-regulations).

No neck loads were measured on the driver dummy in test SH 94.35. No femur loads and no chest loads were measured on the driver dummy in test SH 96.02.

Close to its limit HIC = 1 000 is the Head Injury Criterion HIC = 1 088 of the front passenger dummy in the Ford Fiesta (SH 94.35). Above its limit M_y = -57 Nm lies the extension moment M_y = -136 Nm measured in the neck of the out-of-position front passenger dummy in the Opel Vectra without air bag activation (SH 96.01). Also above its limit a_{3ms} = 60 g lies the deceleration a_{3ms} = 75 g measured in the chest of this unrestrained dummy. All other measured dummy loadings shown in table 3. lie clearly below their respective limits.

Table 3. Dummy loadings measured in the four full-scale tests with a collision speed of 55 km/h

Part of body	Test vehicle (Test number)							Protection criteria
	Front passenger dummy (OOP)				Driver dummy			
	Ford Fiesta (SH 94.35)	Opel Corsa (SH 95.31)	Opel Vectra* (SH96.01)	Opel Vectra (SH 96.02)	Ford Fiesta (SH 94.35)	Opel Corsa (SH 95.31)	Opel Vectra (SH 96.02)	
Head								
HIC	***1 088***	465	556	206	438	245	601	1 000
a_{3ms}	71 g	62 g	64 g	38 g	60 g	50 g	64 g	80 g
Neck								
$F_{x,45ms}$	528 N	45 N	724 N	20 N	-	146 N	66 N	1 100 N
$F_{z,45 ms}$	270 N	552 N	562 N	992 N	-	417 N	323 N	1 100 N
M_y (+) Flexion	133 Nm	26 Nm	0 Nm	68 Nm	-	26 Nm	19 Nm	190 Nm
M_y (-) Extension	-48 Nm	-55 Nm	***-136 Nm***	-29 Nm	-	-36 Nm	-17 Nm	- 57 Nm
Chest								
SI	308	211	704	235	346	332	-	1 000
a_{3ms}	38 g	34 g	***75 g***	37 g	46 g	39 g	-	60 g
Deflection	13 mm	28 mm	11 mm	20 mm	34 mm	35 mm	32 mm	76 mm / 51 mm
Pelvis								
a_{3ms}	35 g	37 g	38 g	35 g	43 g	45 g	57 g	60 g
Femur								
F_{left}	6.3 kN	5.2 kN	6.0 kN	6.2 kN	3.2 kN	3.4 kN	-	10 kN
F_{right}	3.6 kN	2.5 kN	9.6 kN	4.1 kN	9.4 kN	4.3 kN	-	10 kN

* Air bags not activated - not measured OOP: Out of position

Dummy Loadings in the Two Full-scale Tests with 29 km/h and 34 km/h Collision Speed and in the Two Stationary Tests

Table 4. shows the loadings of the belted driver dummy and the unbelted out-of-position front passenger dummy measured in the two full-scale tests (SH 97.03 and SH 97.04) with the Opel Corsa colliding at 29 km/h and 34 km/h collision speed against the rigid barrier. Also included in this table are the measured loadings for the unbelted out-of-position passenger dummy in the two tests with air bag ignition in the stationary Opel Corsa (SH 97.01 and SH 97.02).

Above its respective limit of 190 Nm is the flexion momentum of the neck M_y = 243 Nm of the out-of-position passenger dummy in the dynamic test with 29 km/h collision speed (SH 97.01). Also above the limit is the head acceleration a_{3ms} = 115 g of the out-of-position passenger dummy with the nose close to the dashboard in the test SH 97.01.

All other measured dummy loadings shown in table 4. are clearly under their tolerable limits. It should be mentioned, that in the dynamic tests the head of the unrestrained passenger dummy is not loaded clearly higher than the head of the restrained driver dummy.

Table 4. Dummy loadings measured in the full-scale test with collision speed of 29 km/h and 34 km/h and in the stationary tests

Part of body	Test (Test number)						Protection criteria
	Full-Scale Crashtests				Stationary tests		
	29 km/h Driver (SH 97.03)	29 km/h Pass. (OOP)* (SH 97.03)	34 km/h Driver (SH 97.04)	34 km/h Pass. (OOP)* (SH 97.04)	0 km/h Pass. (OOP)** (SH 97.01)	0 km/h Pass. (OOP)* (SH 97.02)	
Head							
HIC	120	156	484	402	801	49	1 000
a_{3ms}	29 g	37 g	67 g	60 g	***115 g***	35 g	80 g
Neck							
$F_{x,45ms}$	636 N	169 N	180 N	161 N	200 N	192 N	1 100 N
$F_{z,45 ms}$	288 N	247 N	389 N	143 N	27 N	4 N	1 100 N
M_y (+) Flexion	56 Nm	***243 Nm***	7 Nm	17 Nm	42 Nm	12 Nm	190 Nm
M_y (-) Extension	-10 Nm	-11 Nm	-35 Nm	***-86 Nm***	-34 Nm	-42 Nm	- 57 Nm
Chest							
SI	84	128	151	172	13	*3*	1 000
a_{3ms}	24 g	34 g	31 g	40 g	12 g	7 g	60 g
Deflection	14 mm	5 mm	11 mm	9 mm	4 mm	2 mm	76 mm / 51 mm
Pelvis							
a_{3ms}	26 g	29 g	33 g	32 g	5 g	2 g	60 g
Femur							
F_{left}	1 kN	-	1 kN	6 kN	1 kN	0 kN	10 kN
F_{right}	1 kN	5 kN	-2 kN	5 kN	1 kN	1 kN	10 kN

* Distance between dummy nose and dashboard: 175 mm
** Dummy nose close to the dashboard (air bag cover) - not measured OOP: Out of position

The restraint system, consisting of belt and bag, relieved the strain on the driver dummy's neck (especially in test SH 97.03) and of its femurs. The chest of the restrained dummy is more deflected but less decelerated.

Loadings of the Cadavers

Table 5. gives an overview of the loadings of the cadaver's head, chest and pelvis measured in the sled tests. The values of chest deflection were measured at the level of the 8th rib. To tests L4, L5 and L6 two 3-ms-values of the chest deceleration are given. The first value was measured at the first thoracic vertebrae, the second value at the twelfth thoracic vertebrae. In the other test only one 3-ms-value is measured at the sixth thoracic vertebrae. Not measured are the forces and moments in the neck of the cadavers as well as their femur forces.

All the measured head loadings of the cadavers clearly lie under their protection criteria. With exception of a_{3ms} = 63 g in test L4 all the other chests were loaded under the limit a_{3ms} = 60 g. In test L6 the measured chest deflection of 72 mm is above the limit of 51 mm valid for tests without an air bag restraint but below 76 mm. This greater limit is valid if an air bag acts on the chest.

All measured pelvis decelerations clearly lie under the respective limit a_{3ms} = 60 g.

Injuries on the Cadavers

To determine the injuries in detail autopsies on the cadavers were carried out. **Table 6.** gives an overview of all the injuries coded according to the Abbreviated Injury Scale (AIS 90). Injuries of AIS 6 (maximum), AIS 5 (critical) and AIS 4 (severe) did not occur.

The maximum injury severity AIS 3 (serious) occured in test L3. Six rib fractures were observed. Furthermore in this test the cadaver was injured with AIS 2 (moderate) at the spinal column (laceration of the ligamentum flavum C6/C7) and with AIS 1 (minor) on the head (abrasion on the left forehead).

AIS 2 was also given in test L1. It was an injury to the spinal column (fracture of the sixth cervical vertebrae, degenerative predefected). In this test, with AIS 1 the thorax (rib fracture) and the headsurface (head rind laceration) were also injured.

In the three tests L2, L6 and L7 the maximum AIS was AIS 1. In two of these cases the spinal column was injured (haemorrhage) and in one case the body surface (skin abrasions at the left upper arm).

In tests L4 and L5 the cadavers remained uninjured.

Table 5. Loadings of the cadavers measured in the sled tests

Part of body	Gender and height (test number)							Protection criteria
	Driver						Passenger	
	male 174 cm (L1)	femal 167 cm (L2)	male 183 cm (L3)	male 170 cm (L4)	male 184 cm (L5)	male 174 cm (L6)	male 189 cm (L7)	
Head								
HIC	86	162	520	426	229	195	224	1 000
a_{3ms}	29 g	34 g	73 g	69 g	51 g	39 g	42 g	80 g
Chest								
a_{3ms}	26 g	33 g	*63 g*	36 g / 49 g	51 g / 46 g	46 g / 50 g	42 g	80 g (60 g)
Deflection	-	-	-	32 mm	38 mm	*72 mm*	-	76 mm / 51 mm
Pelvis								
a_{3ms}	26 g	34 g	41 g	45 g	38 g	44 g	25 g	60 g

Table 6. Severity of injuries determined in authopsies after the sled tests

Test	MAIS	HEAIS	TOAIS	ABAIS	SURAIS	SPAIS	EXAIS
L1	2	0	1	0	1	2	0
L2	1	0	0	0	0	1	0
L3	3	0	3	0	1	2	0
L4	0	0	0	0	0	0	0
L5	0	0	0	0	0	0	0
L6	1	0	0	0	1	0	0
L7	1	0	0	0	0	1	0

AIS: Classification according to the Abbreviated Injury Scale AIS 90
MAIS : Maximum AIS HEAIS: AIS Head TOAIS: AIS Thorax ABAIS: AIS Abdomen
SURAIS: AIS Surface SPAIS: AIS Spinal Column EXAIS: AIS Extremities

It is evident that in the sled tests no head injuries, abdomen injuries or injuries of the extremities occured. The maximum AIS of the body surface was AIS 1 and of the spinal column it was AIS 2. Only the thorax had an AIS 3 injury (six rib fractures) in one case.

Dummy Kinematics

The analysis of the high speed films gives an impression of the movements during the tests and the characteristics of the dummy kinematics in relation to the air bag interaction in those cases with activated bags.

Of special interest are the movements of the unbelted OOP-passenger dummies. Two examples of this are given for the 55-km/h tests SH 96.01 (Opel Vectra with unactivated air bag) in **Figure 9.** and SH 96.02 (Opel Vectra with activated air bag) in **Figure 10.**

The totally unrestrained dummy (Figure 9.) follows its inertia and impacts the front windscreen with the top of the head at t = 70 ms after the start of the collision. As a result of this impact and the superimposed forward motion of the dummy's torso, the neck becomes extended to the rear. At t = 84 ms the head penetrates the glass of the windscreen which shatters. Furthermore at t = 88 ms the dummy impacts the instrument panel with his left shoulder, followed by an impact of the right shoulder at t = 96 ms. The foremost position of the head is reached at t = 100 ms. Subsequently the dummy moves back. During the rearward motion the dummy head has chin contact with the instrument panel between t = 120 ms and t = 130 ms. Afterwards the head moves back near to his starting position.

In the test with activated air bag (figure 10.) the bag begins unfolding at t = 32 ms after the start of the collision. At t = 36 ms the OOP-dummy touches the unfolding air bag, first with the lower half of the face and shortly afterwards with the upper torso. The mean contact

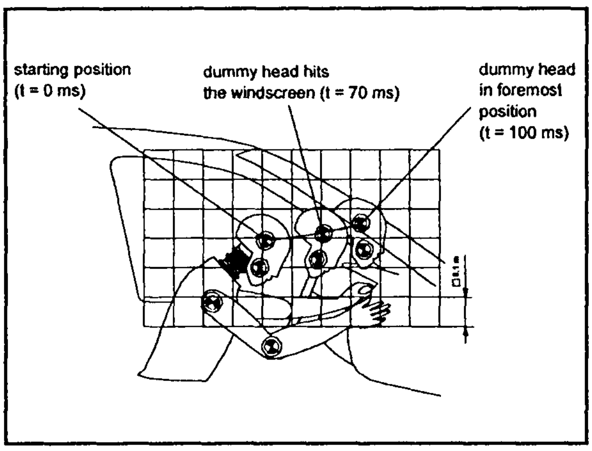


Figure 9. Movement of the unbelted front passenger dummy in test SH 96.01 (55 km/h, Opel Vectra, Air bags not activated)

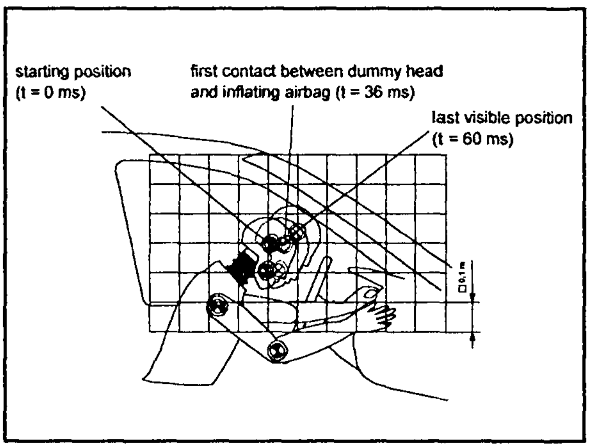


Figure 10. Movement of the unbelted front passenger dummy in test SH 96.02 (55 km/h, Opel Vectra, Air bags activated)

area between the unfolding air bag and the dummy is in the area of the dummy's upper torso. As a result of this, the air bag displaces the forward movement of the dummy in an upward direction. The air bag then forces the dummy, which is still moving forward due to its inertia, into an upward motion. The air bag is thereby compressed more on the left half than on the right. Due to this the dummy experiences a rotation to the right away from the driver. The air bag seam tears open at t = 68 ms. During the upward motion, the dummy impacts the front of the windscreen with the top of its head at t = 70 ms, then penetrates the screen. The front windscreen bows severely as a result of this impact, but remains securely anchored in its frame. Due to the penetration of the windscreen glass the dummy neck is compressed. The forward displacement of the head reaches its maximum at approx. 90 ms. At this moment the dummy has turned through approx. 17° to the right. Subsequently the rearward motion of the dummy commences.

Looking back to table 3. it can be seen that in both described tests SH 96.01 and SH 96.02 the totally unrestrained out-of-position passenger dummy has higher loading at his head than the dummy which has a remaining restrained effect of the air bag. In both cases the head impact to the windscreen is not severe so the head deceleration remains in a mid size region clearly under the tolerable limits of HIC = 1000 and a_{3ms} = 80 g. With a dummy the risk of cut injuries to the the face during the windscreen penetration cannot be measured.

The chest of the totally unrestrained dummy clearly has a higher acceleration loading than the chest of the dummy with remaining restraint effect of the acting air bag but the dummy's chest deflection in the test without air bag activation is smaller.

Not visible in the high speed films is the significant higher loading of the right femur of the totally unrestrained dummy in test SH 96.01.

In conjunction with the monitored movements it is evident that the measured extension moment of the neck M_y = -136 Nm of the totally unrestrained dummy is more than twice as high as the corresponding tolerable limit of -57 Nm. As a main result of the tests SH 96.01 and SH 96.02 should be mentioned that the neck seems to be the most endangered body part of the out-of-position passenger who has no remaining effect of an acting air bag.

The movement of the unrestrained out-of-position passenger dummy in test SH 97.03 with 29 km/h collision speed and not triggered air bag is shown in **Figure 11.** Corresponding to this in **Figure 12.** the movement of the same dummy in test SH 97.04 with triggered air bag is shown.

In test SH 97.03 the inertia of the totally unrestrained passenger dummy leaning forward out-of-position causes a pronounced forward movement relative to the vehicle beginning at t = 26 ms after the start of the collision. At t = 77 ms the dummy's head strikes the dashboard first with the nose and then with the mouth. This leads to a forward movement of the head with a forward bending (flexion) of the neck. The forehead then contacts the dashboard at t = 90 ms. This is the point at which the flexion of the neck reaches its maximum. At t = 105 ms the dummy is at its most forward position. As the movement continues the dummy's body falls back into the seat.

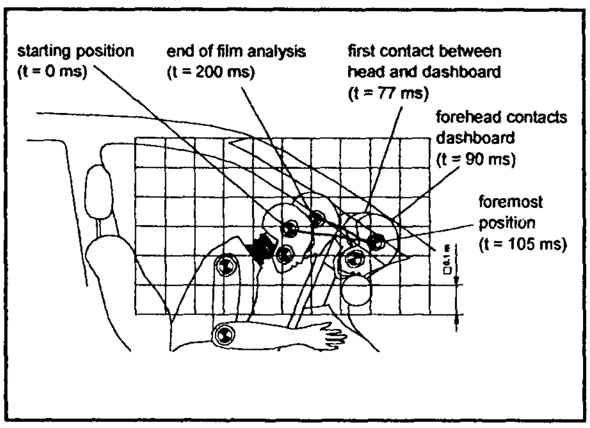


Figure 11. Movement of the unbelted front passenger dummy in test SH 97.03 (29 km/h, Opel Corsa, Air bags not triggered)

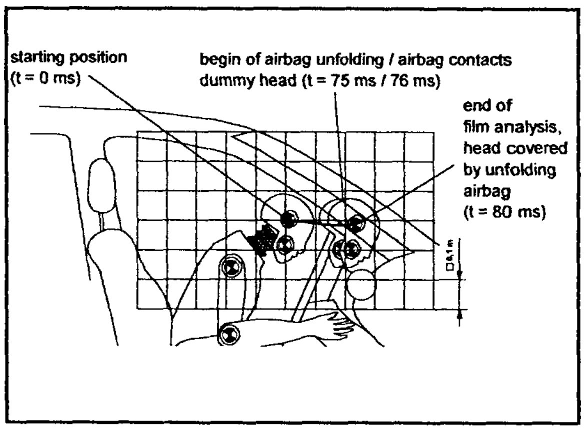


Figure 12. Movement of the unbelted front passenger dummy in test SH 97.04 (34 km/h, Opel Corsa, Air bags triggered)

In test SH 97.04 the inertia induced forward movement of the out-of-position passenger dummy begins at t = 29 ms after the start of the collision. At t = 75 ms the emergence of the air bag from the dashboard and its subsequent unfolding begins. At t = 79 ms the air bag touches the dummy's face on the right hand side. At this stage the dummy head is above the air bag, which is inflating beneath it. The further deployment of the air bag under the dummy's torso is displaced to the right. As the forward movement proceeds, the crown of the dummy's head strikes the windscreen at t = 84 ms. This results in some areas shattering and deformation of the glass. The air bag is fully deployed at t = 104 ms. The forward displacement of the dummy relative to the vehicle is completed by t = 102 ms when the head has its maximum penetration into the windscreen. A maximum deformation depth of approx. 23 mm was later determined in this region. As the sequence continues the dummy falls back into its seat.

Looking back to table 4. it can be seen that the head of the out-of-position passenger dummy in test SH 97.03 with 29 km/h collision speed (without air bag trigger) is less severely loaded than the head of this dummy in test SH 97.04 with 34 km/h collision speed (triggered air bag). In both tests the tolerable protection criteria of the head were not reached.

In the test without air bag triggering the chest of the passenger dummy is on a lower deceleration level than the chest of the dummy in the test with a 5 km/h higher collision speed (triggered air bag). The chest deflects more when acting with the air bag than in the case without air bag triggering. Chest retardations and deflections are clearly below their tolerable protection criteria.

With a flexion moment of 243 Nm clearly above the limit of 190 Nm and in conjunction with the monitored kinematics should be mentioned that the neck of the totally unrestrained out-of-position passenger dummy in test SH 97.03 is the most endangered part of his body.

To complete the description of dummy movements, **Figure 13.** contains the results drawn from the film evaluations for the driver dummy, restrained only by his safety belt in test SH 97.03 (without air bag triggering). The forward displacement of the head ends at t = 100 ms after the start of the collision before a contact with the steering wheel is possible. In conjunction with the measured loadings of this dummy as shown before in table 4 it is evident, that there is no potential for severe or life treatening injuries. Therefore it is consequent that the air bag did not trigger in this test because it was clearly not necessary.

Figure 14. shows the drawn results of film evaluation for the belted driver dummy in test SH 97.04 (with triggered air bag). In this test the air bag is completely unfolded at t = 86 ms after the start of the collision. 20 ms later the air bag has restrained the head completely and no contact of the head with the steering wheel occurs. As shown in table 4. before all measured loadings of this dummy lie clearly under their protection criteria. To summarize the seat belt and the air bag which was also triggered effectively protected the driver dummy.

Cadaver Kinematics

The sled tests also were filmed by high speed cameras from the side in order to analyse the movements of the cadavers and their interactions with the air bag. In all tests the driver has full passive protection from an air bag (volume 70 litres) supplemented by knee bolsters. The begin of the air bag unfolding was visible 8 ms after the begin of the collision.

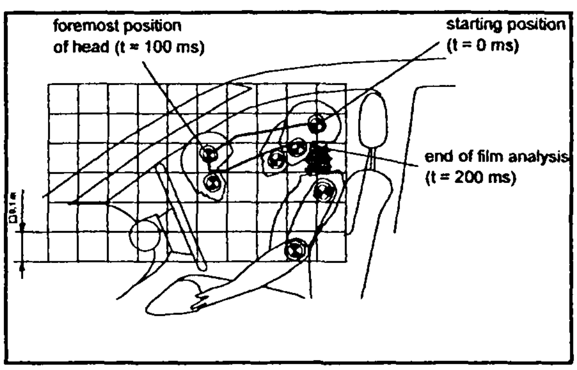


Figure 13. Movement of the belted driver dummy in test SH 97.03 (29 km/h, Opel Corsa, Air bags not triggered)

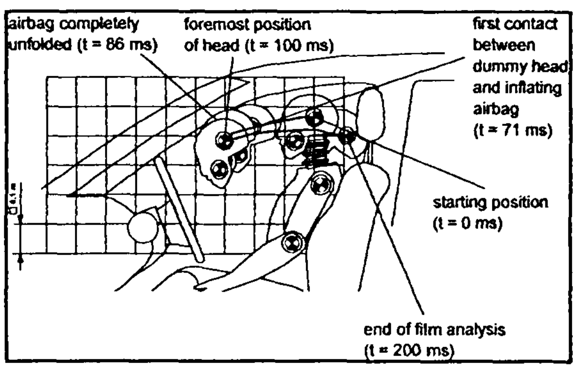


Figure 14. Movement of the belted driver dummy in test SH 97.04 (34 km/h, Opel Corsa, Air bags triggered)

The time interval to complete the unfolding of the air bag was ascertained to 30 ms.

The drivers remained in forward movement caused by inertia after the beginning of the simulated collisions. Between t = 45 ms and t = 50 ms after the start of the collision the knees make contact with the knee bolsters. At the same time the air bag touches the central region of the cadaver´s chest and chin. Between t = 70 ms and 80 ms an extensive energy absorbing and restraining interaction to the head and torso was given by the air bag.

The movement of the head occurs in forward and upward direction (x-z-plane). It was stopped at t = 80 ms to t = 90 ms after the start of the collision by a head impact to the upper region of the windscreen or to the roof area. The neck bending backwards (extension) reaches its maximum between t = 110 ms and 120 ms. In this phase the forward movement of the torso was not totally completed. This results in a bending of the neck induced by a superimposed thorax movement and a retroflexion of the head and neck caused by the impact of the head.

During the torso movement in forward direction could not be observed in all tests a symmetrically restraining effect of the air bag. In some cases this leads to a rotation of the head and torso around their vertical axis.

The volume of the air bag on the passenger side was 150 litres. In this test the kinematics of the cadaver on the passenger seat was similar to described above movements of the drivers. It should be mentioned that clear forward displacements of torso and abdomen could be observed in this test. Followed by a head impact to the windscreen a backwards bending of the neck occurs with an extension angle of more than 90°.

DISCUSSION AND CONCLUSIONS

The life saving benefit of air bags as a supplement of safety belts has been proven in real life accidents many times over.

OTTE (1994) analysed a sample of 13 cases with air bag activation in cars with a collision induced change of velocity in the range delta-v = 12 to 55 km/h. The maximum injury severity of all belted drivers was MAIS 2. It was a result of this accident analysis that the main protective effect was given by the safety belt.

An evaluation of driver injuries in 400 Mercedes-Benz cars involved in accidents with air bag activation concluded that the air bag substantially reduced the maximum injury severity in severe accidents (ZEIDLER, 1994). With an Energy Equivalent Speed up to EES = 60 km/h in 137 Mercedes cars of the newer series with triggered air bags no occupant injuries to the head and neck occurred with a severity more than AIS 3. In 292 cases involving cars of the same series but without an air bag, head and neck injuries with a severity AIS 4 to AIS 6 were given in some cases with an EES of more than 51 km/h.

Accident analysis of the BMW accident research agree with these results. In accidents with frontal collisions and severe or fatal injuries (MAIS 4 to MAIS 6) of belted drivers occurred in single cases with an EES of more than 40 km/h. In frontal collisions with a triggered air bag acting as a supplement to the safety belt up to an EES = 60 km/h the maximum of the injury severity was MAIS 3. This means that no occupants were severely injured or killed in cars equipped with air bags in this accident sample (MESSNER and HÜBNER, 1996).

Similar results are given by a study of 47 German accident hospitals to ascertain the injury patterns of car occupants saved by air bags. The analysis of 119 accidents of the year 1993 led to the result that their injuries in the region of head, neck and thorax were mostly of minor severity (SCHLICKEWEI et al., 1995). Partially air bag induced contusions and abraisons could be observed in the region of thorax and face.

The American National Highway Traffic Safety Administration NHTSA published in 1995/96, that in the USA since 1987 the air bag has saved 1 500 drivers from fatal injuries, 570 of them only in the year 1995. Furthermore NHTSA estimated that at least in 164 crashes air bags avoided fatal injuries of front passengers in cars (BIGI, 1995; VDA-Mitteilungen No. 2., February 18, 1997). Although in the USA 19 fatalities on the driver side and 32 deaths of children on the front passenger side were registered in accidents with air bag triggering in low speed crashes. The majority of these people did not use safety belts or child restraints. Some of the fatalities were children in rearward facing child restraints placed in the front passenger seat with activation of the corresponding air bag.

There is a greater probability that unbelted occupants are "out of position" in the moment of the air bag ignition. Therefore it is possible that they came into contact with the air bag during its inflation. Even an unbelted occupant who is sitting in a normal position can come into such an out-of-position situation as a result of the inertia acting in the phase of pre-crash braking.

The fast upcoming of air bag equipped cars of all categories could lead to an increase in the number of reported accidents with air bag-induced injuries of occupants. Corresponding cases are published by ZUPPICHINI et al. (1994) and LÖHLE (1996). To judge the injuries it is necessary - as in cases with acting of a safety belt only - to indicate and separate injuries which are of minor severity and therefore in severe accidents tolerable. On the other hand it is necessary to indicate and describe severe and fatal injuries which are induced by an air bag. This is the input needed for the further development of smart restraint systems which are acting in function of the accident severity.

Some test results published earlier (BERG et al., 1995, BERG et al., 1996) and repeated in this article have shown that even an unbelted forward leaning out-of-position front passenger in crashes with 55 km/h collision speed and 55 % frontal overlap against a rigid barrier could obtain a residual protection from an air bag. Therefore it is to be expected that life threatening contacts with the air bag in its unfolding phase could be a result of more extreme forward bent postures.

SCHMITZ (1997) published results from nine sled tests (collision speed 50 km/h) with two different dummies (50th percentile male, 5th percetile female) and a variety of sitting positions. Increased stresses were indeed measured both on an unbelted dummy and on a dummy sitting in a forward leaning posture, but these nevertheless lay below the appropriate protection criteria. Dummy loadings which would predict serious or fatal injuries were established in a case of extreme sitting posture, a sleeping position with the seatback reclined. However the immediate effect of the air bag was not significant in respect of the high forces but rather the unfavourable sequence of dummy movement.

The overview of the results of the dummy tests with 55 km/h collision speed and of the cadaver sled tests with 47 to 50 km/h collision speed shown in this article do not lead to an identification of body parts which are at high risk of injury. Neither the comparison of the measured loadings in the tests nor their distance to appropriate protection criteria or the AIS ranking of the injuries of the cadavers show systematically features. Most frequent were injuries to the cervical spine. However, the most severe injury occured to the thorax. It should be mentioned in this context, that there is an influence of the age and anthropometric characteristics to the response of mechanical loadings and to the injury risk of human cadavers. YOGANONDAN et al. (1993) published results from similar sled tests with cadavers (age between 70 and 75 years) suffered up to 10 rib fractures. In contrast to the autopsy results described in this article, these rib fractures often were in the lower region of the frontal thorax.

A residual protective effect of air bags for unbelted occupants in non-extreme out-of-position situations could not be established with equal clarification from the two full-scale tests with 29 km/h respectively 34 km/h described in this article. The neck of the dummy in the tests without air bag triggering (29 km/h) was stressed with a flexion moment well above the appropriate limit. In the test with air bag triggering (34 km/h) the permitted limit for the extension moment of the neck was clearly exceeded. However the neck loading was not caused so much by the air bag as by the contact with the windscreen. The deployment of the air bag, and with it the restraining effect, was hindered by the torso and head of the dummy to such a degree that a severe impact of the head against the windscreen could not be avoided.

The risk of injuries induced by the air bag increases in cases of extreme out-of-position situations. In this article two tests are described where the air bag was activated in the stationary vehicle. When the dummy sits bent forward in a non-extreme posture with a distance of 175 mm between its nose and the dashboard all the measured loadings are lying below their appropriate protection criteria. In an extreme posture with the nose close to the dashboard (air bag cover) however, the acceleration value of the resulting head movement enforced by the cover opening and air bag unfolding, are lying clearly above its limits.

Tests with cadavers also indicate an increased injury risk if there is immediate contact between parts of the body and the air bag cover at the beginning of the air bag release (SCHROEDER et al. 1997). Thus, for example, acceleration loadings of the head were measured above the appropriate protection criteria. In one case an open fracture of the nose occurred which was related to the impact of the air bag cover. Serious injuries of the neck vertebrae also were found.

Only a few cases are known from the history of real world accidents in Germany which give reason to suppose that effects of an air bag could lead to fatal injuries. Among these is the case of a belted female passenger (age 57 years, height 157 cm, weight 67 kg) in a taxi which collided head on at a speed of approx. 30 km/h with a tram at an angle between 80° and 85° (MAXEINER and HAHN, 1996). Both full-size front air bags in the taxi triggered. The driver suffered slight injuries, but the front passenger received very severe injuries to the neck vertebrae from which she died 13 days after the accident. Skin abrasions to her face provided evidence of an aggressive air bag contact. It was established that the front passenger seat was almost in the foremost position. An active forward bending movement of the torso immediately before the crash was suspected. The woman was wearing thick, bulky winter clothing and her safety belt was correspondingly loose. As the air bag released an extreme out-of-position situation caused by a further increase in the forward movement of the torso resulting from pre-crash braking and the impact deceleration can therefore be assumed.

Other published reports on air bag induced fatalities of out-of-position front passengers in cars also points to the neck vertebrae as the most endangered body part (HUELKE, 1996). In particular the loading of the neck vertebrae in its z-direction while the superimposed dynamic extension of the neck could lead to overcritical stresses in this region.

Furthermore an asymmetric contact between the unfolding air bag and the face of an out-of-position passenger could lead to a rotational loading of the neck vertebrae. This was observed on both dummies in the 55 km/h-test with the Ford Fiesta. Under such circumstances the tolerance limits of the neck loadings could be lower than under symmetrical stresses. To define adequate protection criteria, more reliable traumatomechanical studies are necessary. In particular this is relevant for the "soft tissues" like arteries, veins, nerves and muscles as for the human pain- and loading-sensors in the muscles, ligaments and condyles of the neck vertebrae.

The fact that mechanical dummy loadings did not reach their useful corresponding protection criteria (forces in x- and z-direction, bending moments in y-direction described as extension and flexion) do not guarantee that in real life accidents under similar conditions no injury to the involved occupants is possible. This is verified in particular in the results of cadaver sled tests. In this context it should be mentioned that in traumatomechanical tests with human cadavers the loading of the neck vertebrae often is underestimated (MATTERN, 1994; MATTERN et al., 1995).

Out-of-position situations of vehicle occupants are - in contrast to situations with a normal belted seating position - fundamentally undefined and numerous. The effect of an air bag acting to an occupant concerned in an abnormal position is therefore very dependent on the individual circumstances. These difficulties are being taken into account in the further technical development of smart air bags through graduated gas generators output, adjusted to the severity of the accident and to occupant parameters (BIGI et al., 1996).

To follow the philosophy predominant in Europe the air bag is not an autarchical restraint system. That means that the air bag has to supplement the safety belt. Therefore it is consequent not to design the air bag trigger threshold too low. As shown in the offset tests with 29 km/h and 34 km/h impact speed it was sufficient that the air bags did not trigger in the test with 29 km/h. In such crashes the safety belt alone delivers an adequate protection - if the occupants are using their belts.

Against this background there is a considerable need for objective public clarification of the mutual effects of air bags and safety belts, as well as of possible dangers in out-of-position situations and cases of misuse. The air bag has opened up possibilities for further reducing the number of vehicle occupants killed in accidents. A prerequisite for the realisation of these possibilities is the widespread fitting of air bags to all cars as far as possible. Tragic exceptions and the danger of injury in extreme circumstances are reasons for further development. However, the protective potential and the benefit of air bags today has been proven not only through tests, but repeatedly by the history of real world accidents.

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STUDY OF TEST PROCEDURE TO EVALUATE AIRBAG DEPLOYMENT FORCE

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ABSTRACT

Since airbags have become standard equipment on passenger cars in the U.S., a variety of organizations have reported on the effectiveness of airbags in saving occupant lives and reducing serious injuries during frontal crashes. However, there have also been numerous reports of serious injuries to occupants caused by airbag deployment. As a result, airbag deployment force is now an issue of tremendous concern. These problems primarily occur with out-of-position occupants. ISO has proposed various test methods for evaluating the effects of airbag deployment force on out-of-position occupants. This paper presents a test method for evaluating airbag deployment force at the airbag component level.

INTRODUCTION

Airbags have been installed in general mass-produced cars since the 1980's. With the enactment of FMVSS208, passenger-side airbags as well as driver-side airbags are currently standard equipment on nearly all vehicles. Airbags were considered to essentially function as restraining devices, which are supplemental to seatbelts during a frontal crash. During severe frontal crashes, they were considered to serve to prevent secondary collisions between occupants wearing seatbelts and the steering wheel or instrument panel. However, occupant usage of seatbelts through the first half of the 1990's was low. Therefore, in order to increase safety for occupants not wearing seatbelts during a crash, the U.S. government added airbags as an FMVSS208 option. In the first half of the 1990's passive seatbelts and airbags were both occupant protective devices which were compliant with FMVSS208. However, airbag installations in vehicles gradually increased, and the passive seatbelt option was eliminated for passenger cars produced on September 1, 1998 or after. This developed into the airbag installation law as a result. As the number of cars with airbags increased in the market, it gradually became clear that airbags are extremely effective at saving occupant lives. According to an NHTSA study, occupants who were saved by airbags in the U.S. number 1828 thus far. This effectiveness is especially marked in cases where airbags are used together with seatbelts. It is believed that the combination of seatbelts and airbags further reduces the number of fatalities and serious injuries.

However, in the U.S., the airbag performance requirements of FMVSS208 require capabilities to protect occupants who are not wearing seatbelts. In an increasing number of cases, satisfying this requirement necessitates relatively early deployment and strength for airbags in comparison with other countries, which have adopted performance requirements assuming seatbelt use. Since the middle of the 1990's, when an increasing number of vehicles equipped with airbags were on the market, there has been a growing concern about injuries caused by airbag deployment, as opposed to the issue of airbags' occupant protection capabilities. These conditions have led to recognition of the importance of evaluating occupant-restraining capabilities during crashes and the importance of evaluating the force of impact on occupants during airbag deployment. This paper presents the results of a study of test methods for evaluating airbag deployment injuries.

CURRENT TEST PROCEDURES

Currently a variety of test methods are being proposed as the occurrence of airbag deployment injuries gains recognition. Such deployment injuries affect out-of-position occupants. In addition, there are cases where driver seat occupants, who are fairly short, suffer injuries from airbag deployment force. This happens when an airbag deploys after such occupants, who position themselves close to the steering wheel in order to maintain their driving posture, are moved even closer to the steering wheel during a crash as a result of the deceleration force. A common type of injury involving an occupant in the front passenger seat occurs when an airbag deploys with a rear-facing child restraining system installed on the front passenger seat. Another common type of injury occurs in cases where a child sitting in the front passenger seat is not using a restraining device, and the airbag deploys after the child is displaced toward the front passenger seat airbag due to braking prior to a crash. Test methods have been studied for evaluating deployment injuries based on such out-of-position accidents.

The methods, which are most widely recognized throughout the world, are those evaluated by ISO. Common types are illustrated in Figure. 1 and 2. Currently these serve as guidelines for evaluating airbag deployment injuries.

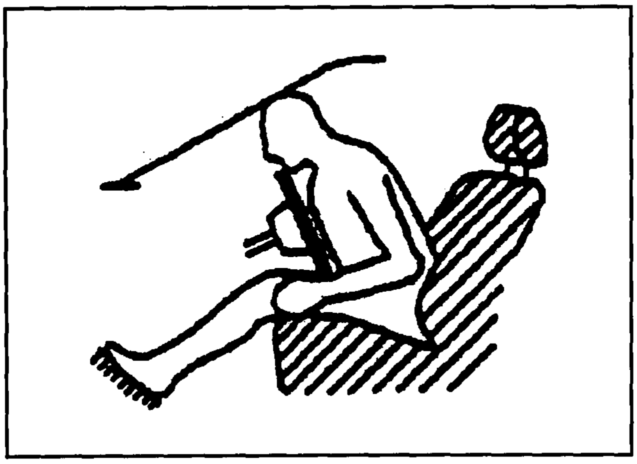


Figure 1. ISO Driver out-of-position — Chin on the rim

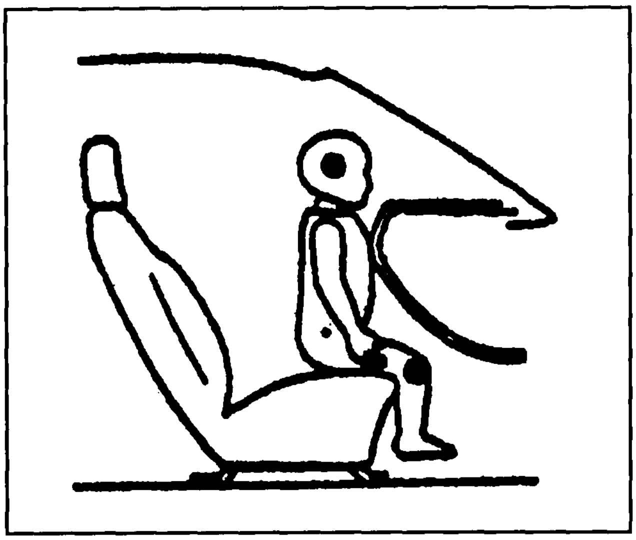


Figure 2. ISO Passenger out-of-position
3 years old dummy stands in front of instrument panel.

DRIVER SIDE AIRBAG

Evaluation of Driver-Side Airbag Deployment Injuries (Chest Injuries)

This section describes method for evaluating chest injuries in occupants who have moved close to airbags. In addition to the methods specified by ISO, there are methods, which have been proposed in SAE and ISO initial drafts (Figure. 3).

Figure. 4 illustrates a comparison of these two test methods. According to the results, injury values are nearly the same for the ISO dynamic test as well as the mode illustrated in Figure. 2, in which a dummy chest is positioned on top of an airbag module. The results for the ISO static

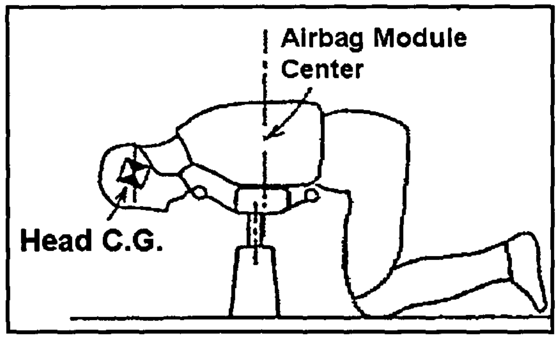


Figure 3. Driver out-of-position
Dummy's chest is placed on the driver airbag module.

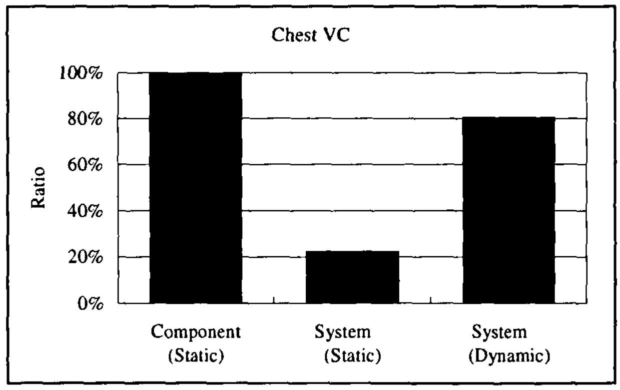


Figure 4. Comparison of chest VC results

mode were extremely low. Many actual deployment injuries occur at low or medium crash speeds. Even in such cases, it is likely that the deceleration force generated during crashes are applied to the occupant.

A comparison of the ISO static and dynamic methods naturally indicates higher injury values for the dynamic method, so verifications should be made with the dynamic method when using ISO methods. However, there are a number of inconsistent factors in dynamic tests, making it necessary to use a greater number of test runs. The method in Figure. 3 is based on static verification, and is more stringent than the static ISO method because a gravity-induced load—albeit only 1 G—is applied. For this reason we decided to verify a series of tests using the mode of "chest on module".

Even with this method, however, there is still the possibility of inconsistency in test results in relation to the use of a dummy. Possible sources of inconsistency are differences, which are unique to each dummy and inconsistency in how the dummy is set in place. However, the following discussion will focus on the location of interference between the dummy and the airbag module.

This factor is not defined in current ISO test procedures.

The parameters, which are currently used in evaluating the risk of chest injuries, are the chest (spinal column) G and the deflection of the ribs. The widely used Hybrid III dummy chest deflection scale does not measure the movement of individual ribs. Instead, it provides the rib displacement based on the angle of an arm, which is attached to a slider, attached to the sternum, which joins the six ribs together. The critical issue here is that the initial position of the arm is intermediate between the third and fourth ribs and the arm attachment point moves upward as the ribs are compressed. As a result, in chest injury measurements using a Hybrid III dummy there is a possibility that during the initial stage of deployment a true measurement may not be obtained other than for the displacement of the third and fourth ribs due to the above-mentioned structure of the dummy. One factor, which significantly affects rib bending during out-of-position tests, is the airbag deployment force against the occupant during the initial stage of airbag deployment. With the current driver out-of-position test procedures used by ISO, the chest positional reference is not determined directly, but is rather determined based on the relationship between the jaw and the steering wheel, regardless of the airbag structure. Influential factors in the acting force of the airbag during the initial stage of deployment are the pressure energy which is stored up to the time that the airbag cover tears, and the thrust of the inflator when the airbag is released through the cover opening. Of these two factors, the pressure energy, which is stored up to the time that the airbag cover tears, becomes extremely high along the tear seam of the airbag cover. For this reason the positional relationship between the deflection meter on the dummy and the tear seam on the airbag cover would be expected to be an important factor.

Results of Verification

We conducted a verification test on the relative positions of the dummy and the airbag cover tear seam during these driver out-of-position tests.

In this series of tests, verification was performed using covers in which the tear seam position was moved 35 mm or 50 mm from the standard position as shown in Figure. 5. In other respects, the driver airbag modules had completely identical characteristics and structures.

As a result, it was learned that chest deflection and chest VC value both decline as the amount tear seam position is increasingly offset from the initial position of the chest deflection scale arm. Figure. 6 illustrates a comparison of out-of-position test results with these three airbag modules. With the original module, the location of the chest deflection scale are adjusted to the cover tear seam at the same position, the amount of the chest deflection increases continuously from the point of initial bending. In contrast, when the tear seam is set at a relatively lower position, the one that is induced by the deployment force during the initial stage of airbag deployment temporarily drops. This is due to the fact that the airbag, which is released through the tear seam, concentrates its deployment force on the lower ribs in the dummy, while the displacement in the upper ribs is relatively small in comparison with the lower ribs. As a result, the chest deflection scale temporarily drops. Subsequently, the airbag presses against the entire chest, thereby increasing the amount of rib displacement. However, in cases where the tear seam has been offset from the standard position, this subsequent bending amount comes after the temporary drop in bending, so the ultimate maximum bending amount is reduced.

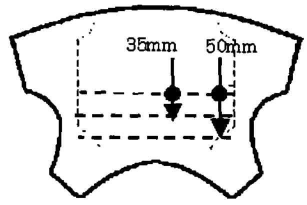


Figure 5. Tear seam location of the driver module for the varification test.

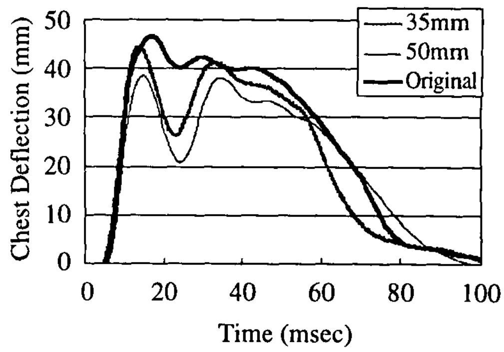


Figure 6. Comparison of driver chest deflection

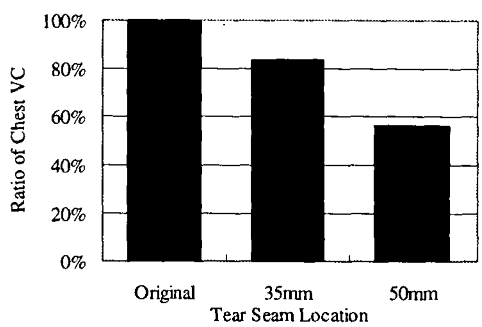


Figure 7. Comparison of chest VC among the different tear seam location

Figure. 7 illustrates a comparison of chest VC values for those cases. Offsetting the tear seam on the airbag module and the chest deflection meter reduces the chest VC value by the impact force during initial deployment. The peak value of the chest VC is also reduced as a result. During the initial stage of airbag deployment, the airbag interferes with the dummy chest along the tear seam. Therefore if the arm of the chest deflection meter and the tear seam of the airbag are at the same position, the release force of the airbag during the initial stage of airbag deployment and the subsequent deployment force will act continuously on the deflection meter (Figure. 8).

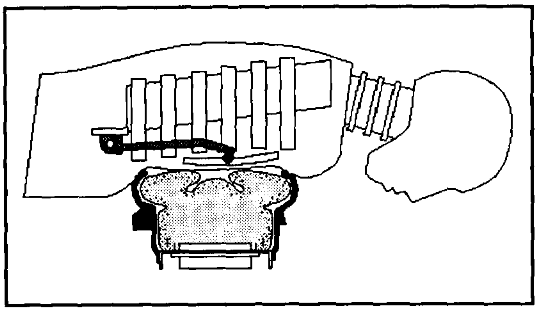


Figure 8. Chest deflection mode at 0mm distance between the arm and the tear seam

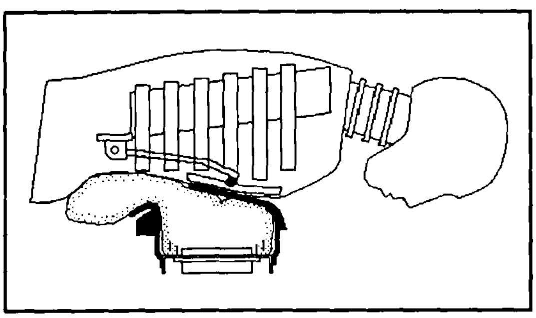


Figure 9. Chest deflection mode at 50mm distance between the arm and the tear seam

When the positional relationships are offset, the release force of the airbag deforms the shape of other ribs without pressing directly on the sternum and the deflection meter arm attachment point. This deformation indirectly displaces the deflection meter arm via the sternum (Figure. 9). In addition, during the period when the airbag is deploying, and while it is pushing the dummy aside, if the tear seam is offset downward as described above, the airbag cover will remain obstructed by the dummy's chest. As a result, the airbag to deploy downward and the sternum will rotate instead of moving parallel, and making it more difficult for the deflection meter arm to be pressed on. This explains the large difference in results among tests with identical deployment forces but different positional relationships between the dummy and the cover tear seam.

Example Evaluation of Deployment Injury for Driver-Side Airbag

Chest injury results in driver out-of-position test will be effected by the structure of the dummy's chest. A component test method without dummy was tried to evaluate the deployment force of the driver airbag. A sensing mass with a guide rod is placed in the face of the driver module.(Figure 10) The mass is moved by the deployment force of the airbag. The purpose of this test is to measure the energy of the airbag deployment as a momentum of the sensing mass instead of the deflection of dummy's chest. Figure 11 shows the relationship of the maximum velocity of the sensing mass and the maximum chest VC in the same airbag module configuration. There is good correlation in those two measures.

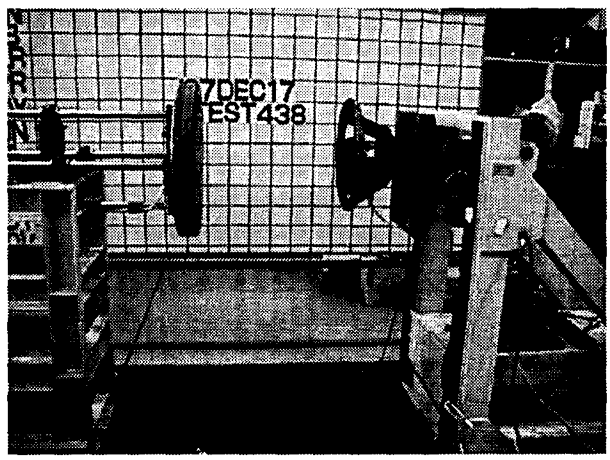


Figure 10. The whole view of the linear reactor for the driver out-of-position test

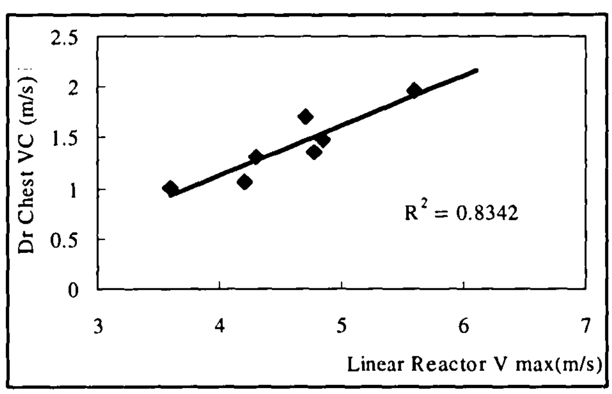


Figure 11. Linear reactor test result
Correlation between Dr. chest VC and the reactor V max.

Proposal for Dummy Placement with Respect to Driver-Side Airbag

The above results indicate that with driver-side airbag out-of-position test methods involving the use of a Hybrid III dummy based on the current ISO procedure, satisfactory dummy placement conditions are not always established. This is due to the fact that the airbag module structure includes no definition for the tear seam, which is an influential factor in deployment injuries. One way of solving this problem is to use dummies in which the deflection of the individual ribs can be measured, as in the case of ATD dummies, which continue to be evaluated at present, otherwise some suitable component test may be utilized as mentioned above. Another approach is to focus on the dummy placement position. The appropriate position should align the tear seam with the initial position of the chest deflection meter arm on a Hybrid III dummy.

PASSENGER SIDE AIRBAG

Evaluation of Passenger Side Airbag Deployment Injuries

Out-of-position evaluations of passenger-side airbags are primarily made using a child dummy, which is caused to approach the vehicle instrument panel when the airbag is deployed. The dummy is placed so that the chest position or dummy jaw is aligned with the instrument panel. Unfortunately, there is a wide range of passenger-side airbag layouts, and the line of movement of the airbag during deployment is affected by an extremely large number of parameters, including airbag folding, the angle at which the module is attached, and the distance to the windshield. Therefore, if a single dummy placement position is used with respect to the instrument panel, the injury value on the dummy could be significantly affected by non-airbag factors. This is due to the fact that different vehicles have different airbag module specifications and layouts.

Effects of Attachment Layout

We compared the layouts in two vehicles using top dash mounted airbags. Figure. 12 illustrates the differences between the two layouts. Figure. 13 is a comparison of the C3Y dummy neck moment at the ISO Z4 Position in the two vehicles. In Vehicle A, the impact force causes neck flexion during the initial stages of airbag deployment, after which the airbag continues to surround the dummy, increasing the flexion moment. In contrast, in Vehicle B there is initially an extension moment followed by a flexion moment. This is simply due to the fact that the two models have different airbag and dummy interference modes. Interference between the airbag and the occupant can be divided into two forces according to the elapsed time. One force is an impact force, or punch-out force (Figure 14), which is caused by the collision with the occupant immediately after the airbag punches out of the module cover during the initial stage of airbag deployment. The other force is a membrane force, representing the action of the

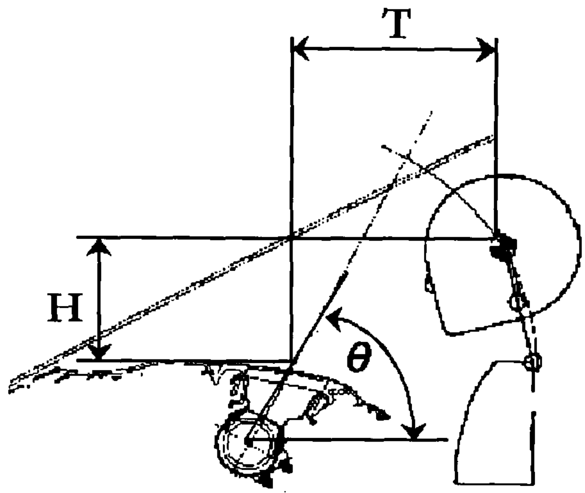


Figure 12. Dimensional parameter of passenger airbag in vehicle A and B

	Vehicle A	Vehicle B
T (mm)	240	280
H (mm)	120	110
(θ °)	62	75

Table 1 Comparison of the dimension of passenger airbag between Vehicle A and B

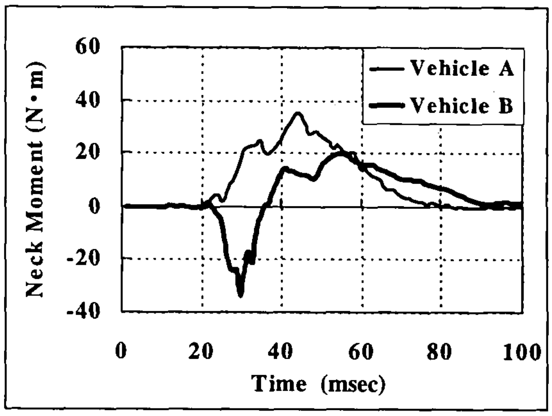


Figure 13. The comparison of neck injury results between Vehicle A and B

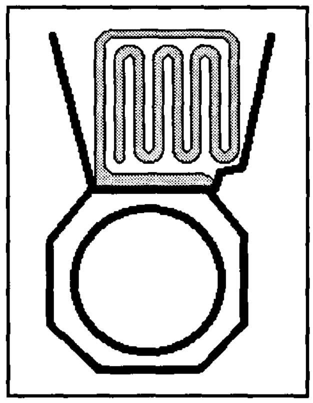
Figure 14. Punch out phase for passenger out-of-position occupant

Figure 15. Membrain phase for passenger out-of-position occupant

membrane force (Figure 15), which is generated when the airbag surrounds the occupant, taking on the shape of the occupant's body. In Vehicle A, the punch-out force acts below the head's center of gravity, generating a flexion moment, whereas in Vehicle B it acts above the head's center of gravity, generating an extension moment. Because the airbag widened to a certain extent in both Vehicle A and Vehicle B, the membrane force generated a flexion moment in both vehicles. The difference in airbag and dummy interference modes in the punch-out force seems to be strongly influenced by the positional relationship between the airbag module and the dummy.

Effects of Bag Configuration

We verified injury values under different dummy positions in vehicles with standard top dash mounted airbags using two different airbag configurations. The airbag configurations are shown in Figure 16 and 17. The inflator characteristics are the same in these configurations. However, Configuration 1 uses an orthodox bag shape with Accordion & Roll-style folding (Figure 16), whereas Configuration 2 consists of two panels (known as a two-piece bag) similar to a driver-side airbag and uses a simple accordion-style folding. (Figure. 17) The dummy position was altered with respect to the ISO Z4 Position by changing the distance 100 mm or 200 mm, parallel to the windshield. The results are compared in Figure.18. This comparison shows that Configurations 1 and 2 have different positions for the maximum neck injury value depending on the injury value parameter. In general, Configuration 1 showed maximum values at relatively close positions, while Configuration 2 showed maximum values at a somewhat greater distance (200 mm). In addition, these two configurations had different airbag deployment paths. This seems to account for the difference in interference intensity between the airbag and dummy and the difference in interference direction.



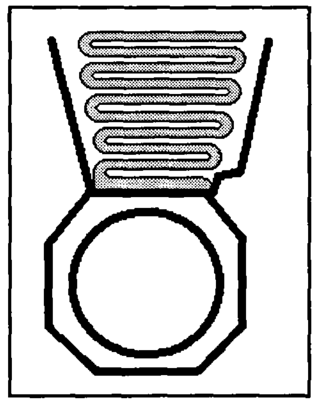


Figure 16. Accordion and roll-style folding **Figure 17. Accordion-style folding**

Example Evaluation of Deployment Injury for Passenger-Side Airbag

In some cases, high injury values occur away from the dummy position specified under the ISO position in passenger-side airbags with various test procedures and layout variations under the current instrument panel positional references. With current technology, it is extremely difficult to provide estimates for these based on the layout. In light of this situation, we conducted an impact experiment during deployment using a simple mass with Configuration. This involved suspending the head of a three-year-old dummy by itself in the passenger-side airbag deployment area. (Figure 19) The airbag was then deployed and the impact on the head was measured. The impact forces for various head positions were then compared in an attempt to identify the position where the airbag applied the strongest impact force against the occupant. Figure 20 and 21 illustrate those test results in comparison of the mass head and the maximum velocity.

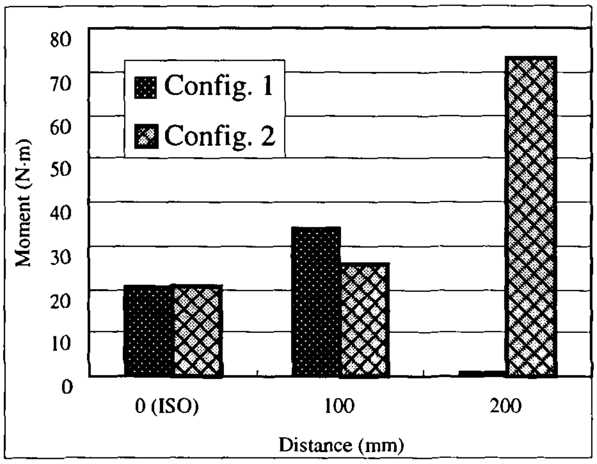


Figure 18. Comparison of the neck flexion moment in two bag configurations

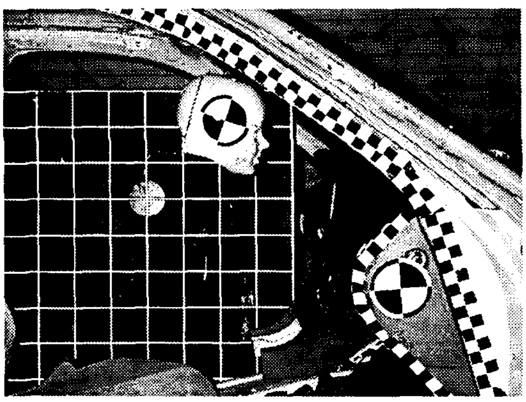


Figure 19. The whole view of the mass head test for an evaluation of the deployment force of Passenger airbag

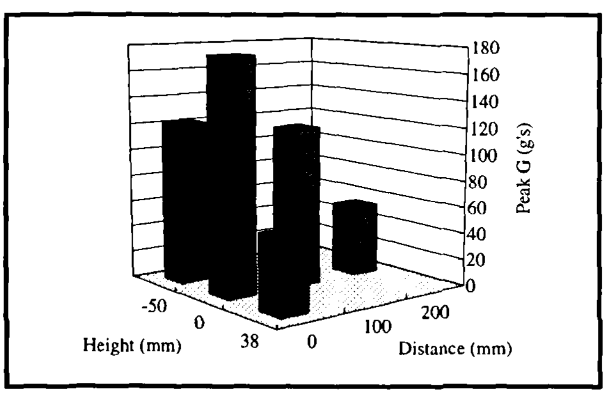


Figure 20. Maximum peak G of the mass head

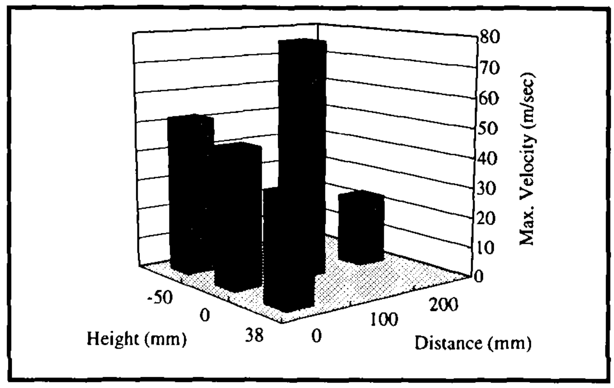


Figure 21. Maximum velocity of the mass head

Head Peak G Comparison

Figure 22 and 23 illustrate the results obtained using a mass head and C3Y dummy, with three different distances and three different heights for the head position.

The G-force occurring on the mass head and the maximum velocity which was treated as the energy moving the mass head were compared with the dummy's head peak G and the resultant of the head peak G. The HIC results were inconsistent when the head position was lowered 50 mm. On other hand the head peak G could be approximated with the peak G of the mass head test results. The inconsistency of the HIC value when the head position was lowered 50 mm seems to be due to the fact that the positional relationship between the airbag movement line and head center of gravity was different than in other cases, resulting in a different impact force vector against the head.

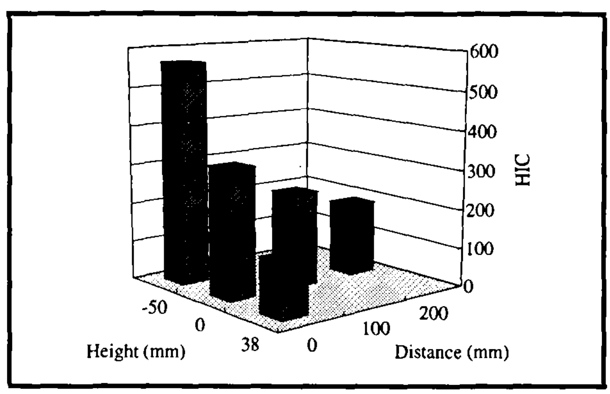


Figure 22. Comparison of HIC results of 3 years old child dummy

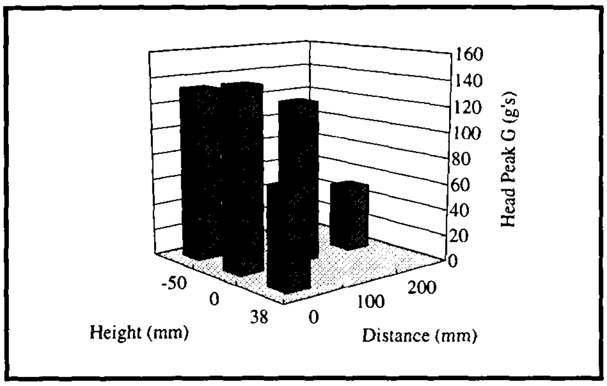


Figure 23. Comparison of the head peak G of 3 years old child dummy

Neck Injury Comparison

Figure. 24,25 and 26 illustrate a comparison of neck injuries (Flexion, Extension and Tension) under conditions, which are the same as for HIC. It was learned that the correlation with the maximum velocity of the mass head is stronger for neck injuries. This is because the neck moment and neck shear force are generated by the phase difference between the head motion and the torso when the head is moved with respect to the torso, and are thus not related to simple impact forces which are induced by the airbag. Rather, they seem to be related to the magnitude of energy moving the head. However, neck tension and compression are caused by the force in the direction in which the head is pressed against the neck and the force whereby the airbag attempts to spread on the neck. Therefore they cannot be described by the resultant G and the maximum velocity obtained with the mass head. Instead it will be necessary to study data relating to the direction of action of the deployment force, especially data relating to the correlation between the direction and position of the occupant over time.

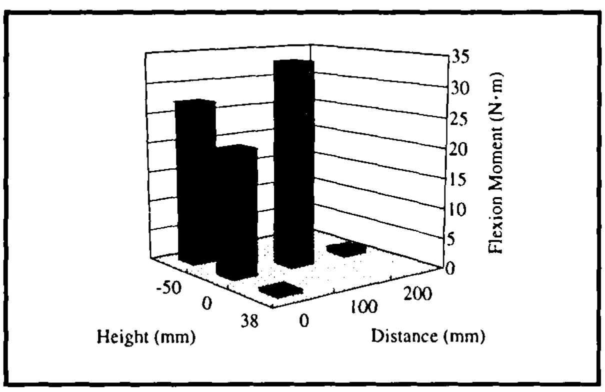


Figure 24. Comparison of the neck lexion moment

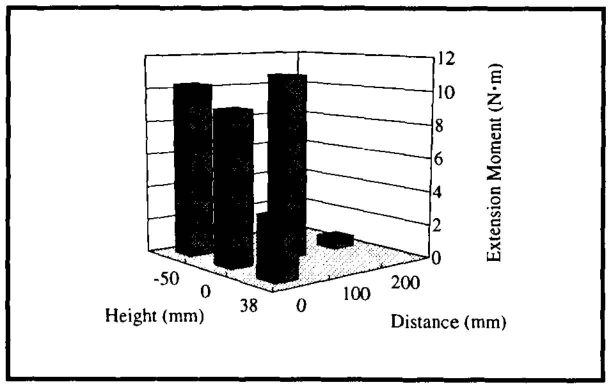


Figure 25. Comparison of the neck extension moment

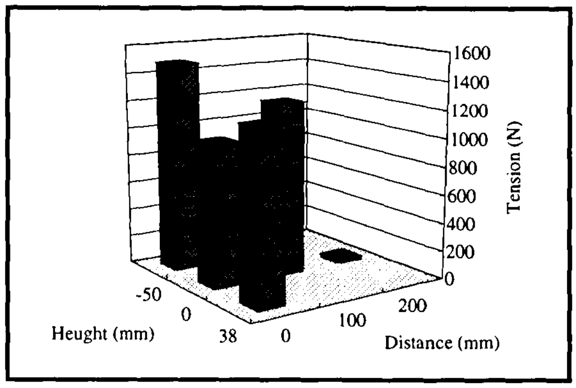


Figure 26. Comparison of the neck tension force

CONCLUSION

The results of a series of parameter studies have shown that somewhat more-detailed factors need to be established in order to enable objective evaluations through dummy set procedures in the out-of-position tests with current test procedures. The problem with these procedures is that dummy placement procedures are based on the dummy's position in relation to the internal components surrounding the airbag, instead of its position with respect to the airbag. Because occupant behavior during a crash cannot be predicted, an out-of-position evaluation at a certain position may end up being a relativistic evaluation reflecting the influence of the inflator output in a given configuration. Nevertheless, it is necessary to study the mechanisms whereby occupant deployment injuries occur, as well as the deployment characteristics and deployment modes of airbags in relation to objective injury risk evaluations for out-of-position accidents. The deployment modes of passenger-side airbags in particular are extremely complex and the front passenger seat occupant may be sitting in a variety of positions. It is therefore difficult to select a layout based on drawings. It is also unrealistic to conduct verifications of all possible modes using dummies. Therefore, methods using pretests such as the experiments described in this paper may be one means of analyzing the mechanisms whereby deployment injuries occur.

Future Issues

There is relatively little leeway for interference between an airbag and an occupant in driver chest injury evaluations. However, in verifying neck injury evaluations, which we were unable to cover in this paper, it is necessary to be very careful since there are more factors, which influence the injury value due to interference between the airbag and the dummy. In contrast, passenger-side airbags are attached in an extremely wide range of positions as mentioned above. In addition, the airbag deployment process is extremely complex in top dash mounted passenger-side airbags. Furthermore, there is a wide range of freedom in the possible position of the occupant who is affected by the airbag deployment. It would thus seem to be extremely difficult to develop a method, which would permit the dummy placement position to be established easily and objectively while taking these various parameters into account. Even in the mass head pretests with the method tried in this paper, an extremely large number of tests was required to improve the suitable dummy positioning precision. If the pretest verification position is established on a more-detailed level in order to improve positioning precision, there is a possibility that inconsistency in the airbag deployment modes would make the problem of precision in the measurements more apparent. This type of test method requires a high level of reproducibility, so it is hoped that measurement methods involving highly precise dummies, computer simulations and the like will be developed to solve this problem.

ACKNOWLEDGMENTS

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A SMART AIRBAG SYSTEM

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ABSTRACT

Pattern recognition techniques, such as neural networks, have been applied to identify objects within the passenger compartment of the vehicle, such as a rear facing child seat or an out-of-position occupant, and to suppress the airbag when an occupant is more likely to be injured by the airbag than by the accident. Neural networks have also been applied to sense automobile crashes. The use of neural networks is extended here to tailoring the airbag inflation to the severity of the crash, the size, position and relative velocity of the occupant and other factors such as seatbelt usage, seat and seat back positions, vehicle velocity, and any other relevant information.

It is well known that a neural network based crash sensor can forecast, based on the first part of the crash pulse, that the crash will be of a severity which requires that an airbag be deployed. This is extended here to enhance the capabilities of this sensor to forecast the velocity change of the crash over the entire crash period. Then a pattern recognition occupant position and velocity determination sensor is added. Finally, an occupant weight sensor is included to permit a measure of the occupant's momentum or kinetic energy. The combination of these systems in various forms will be used to optimize inflation and/or deflation of the airbag to create a "smart airbag" system.

Crash sensors can predict that a crash is of a severity which requires the deployment of an airbag for the majority of real world crashes. A more difficult problem is to predict the crash velocity versus time function and then to adjust the airbag inflation/deflation over time so that just the proper amount of gas is in the airbag at all times even without considering the influence of the occupant. To also simultaneously consider the occupant size, weight, position and velocity renders this problem unsolvable by conventional methods.

BACKGROUND

Pattern recognition techniques, such as artificial neural networks, are finding increased application in solving a variety of problems such as optical character recognition, voice recognition, and military target identification. In the automotive industry, neural networks have now been applied to engine control and to identify various objects within the passenger compartment of the vehicle, such as a rear facing child seat. They have also been proposed for use with anticipatory sensing systems to identify threatening objects, such as an approaching vehicle about to impact the side of the vehicle. Neural networks have also been applied to sense automobile crashes for the purpose of determining whether or not to deploy an airbag or other passive restraint, or to tighten the seatbelts, cutoff the fuel system, or unlock the doors after the crash. Heretofore, neural networks have not been applied to forecast the severity of automobile crashes for the purpose of controlling the flow of gas into or out of an airbag in order to tailor the airbag inflation characteristics to the crash severity. Neural networks have also not been used to tailor the airbag inflation characteristics to the size, position or relative velocity of the occupant or other factors such as seatbelt usage, seat and seat back positions, headrest position, vehicle velocity, etc.

"Pattern recognition" as used herein means any system which processes a signal that is generated by an object, or is modified by interacting with an object, in order to determine which one of a set of classes the object belongs to. In this case, the object can be a vehicle with an accelerometer which generates a signal based on the deceleration of the vehicle. Such a system might determine only that the object is or is not a member of one specified class (e.g., airbag required crashes), or it might attempt to assign the object to one of a larger set of specified classes, or find that it is not a member of any of the classes in the set. One such class might consist of vehicles undergoing a crash of a certain severity into a pole. The signals processed are generally electrical signals coming from transducers which are sensitive to either acceleration, or acoustic or electromagnetic radiation and, if electromagnetic, they can be either visible light, infrared, ultraviolet or radar. The particular pattern recognition techniques used here are neural networks.

To "identify" as used herein means to determine that the object belongs to a particular set or class. The class may be one containing all frontal impact airbag-desired crashes into a pole at 20 mph, one containing all events where the airbag is not required, or one containing all events requiring a triggering of both stages of a dual stage gas generator with a 15 millisecond delay between the triggering of the first and second stages.

SINGLE POINT CRASH SENSORS

All electronic crash sensors currently used in sensing frontal impacts include accelerometers that detect and measure the vehicle accelerations during the crash. The accelerometer produces an analog signal proportional to the acceleration experienced by the accelerometer, and hence the vehicle on which it is mounted. An analog to digital converter (ADC) transforms this analog signal into a digital time series. Crash sensor designers study this digital acceleration data and derive therefrom computer algorithms that determine whether the acceleration data from a particular crash event warrants deployment of the airbag. This is usually a trial and error process wherein the crash sensor designer observes data from crashes where the airbag is desired and when it is not needed, and other events where the airbag is not needed. Finally, the crash sensor designer settles on the "rules" for controlling deployment of the airbag which are programmed into an algorithm which appears to satisfy the requirements of the crash library. The resulting algorithm is not universal and most such crash sensor designers will answer in the negative when asked whether their algorithm will work for all vehicles. Such an algorithm also merely determines that the airbag should or should not be triggered. Heretofore, no attempt has been made to ascertain or forecast the eventual severity of the crash or, more specifically, the velocity change versus time of the passenger compartment during the crash from the acceleration data obtained from the accelerometer.

Several papers have been published pointing out some of the problems and limitations of electronic crash sensors that are mounted out of the crush zone, usually in a protected location in the passenger compartment of the vehicle (1-6). The crush zone is defined, for the purposes herein, as that portion of the vehicle that has crushed at the time that the crash sensor must trigger deployment of the restraint system. These sensors are frequently called single point crash sensors.

These papers demonstrate, among other things, that there is no known theory which allows an engineer to develop an algorithm for sensing crashes and selectively deploying the airbag except when the sensor is located in the crush zone of the vehicle. These papers show that, in general, there is insufficient information within the acceleration signal measured in the passenger compartment to sense all crashes. Another conclusion suggested by these technical papers is that if an algorithm can be found which works for one vehicle, it will also work for all vehicles since it is possible to create any crash pulse measured in one vehicle, in any other vehicle. Note in particular SAE paper 920124 (3).

In spite of the problems associated with finding the optimum crash sensor algorithm, many vehicles on the road today have electronic single point crash sensors. Some of the problems associated with single point sensors have the result that an out-of-position occupant who is sufficiently close to the airbag at the time of deployment will be injured or killed by the deployment itself. Fortunately, systems are now being developed which monitor the location of occupants within the vehicle and can suppress deployment of the airbag if the occupant is more likely to be injured by the deployment than by the accident. At Present, these systems do not provide the information necessary for the control of airbag systems that have the capability of varying the flow of gas into or out of the airbag, and thus to tailor the airbag to the position, size and weight of the occupant. More particularly, no such system exists which uses pattern recognition techniques to match the airbag deployment or gas discharge from the airbag to the severity of the crash or the size, weight, position, velocity and seatbelt use of an occupant.

Since there is insufficient information in the acceleration data, as measured in the passenger compartment, to sense all crashes and since some of the failure modes of published single point sensor algorithms can be easily demonstrated using the techniques of crash and velocity scaling described in the referenced technical papers, and, moreover, since the process by which engineers develop crash sensor algorithms is based on trial and error, pattern recognition techniques such as neural networks, should be able to create an algorithm based on training the system on a large number of crash and non-crash events which, although not perfect, will be superior to all others. Such a crash sensor has been demonstrated which is based on the ability of neural networks to forecast, based on the first part of the crash pulse, that the crash will be of a severity requiring airbag deployment.

SMART AIRBAG CATEGORIES

An improvement to this neural network based crash sensor carries this process further by using the neural network to forecast the velocity change of the crash over time so that the inflation and/or deflation of the airbag can be optimized. Then by the addition of a neural network occupant position and velocity determination system as disclosed in (10,11) the occupancy category (forward facing human, rear facing child seat, box etc.), position and velocity can be obtained. Finally, the addition of the weight of the occupant provides a measure of the occupants kinetic energy as a further input to the system. The combination of these sub-systems in various forms can be called "smart airbags" or "smart restraints". In a preferred implementation, the crash severity is not explicitly forecasted. Rather, the value of a control parameter used to control the flows of inflator gas into or out of the airbag is instead forecasted.

Smart airbags can take several forms which can be roughly categorized into four evolutionary stages, which will hereinafter be referred to as Phase 1 (2,3,4) Smart Airbags, as follows:

1) Occupant sensors use various technologies to turn off the airbag where there is a rear facing child seat present or if either the driver or passenger is out-of-position to where he/she is more likely to be injured by the airbag than from the accident.
2) Occupant sensors are used along with variable inflation or deflation rate airbags to adjust the inflation/deflation rate to match the occupant, first as to his/her position and then to his/her morphology.

The neural network occupant sensors discussed in (10,11) will also handle this with the addition of an occupant weighing system. One particular weight measuring system, for example, makes use of strain gages mounted onto the seat supporting structure. At the end of this phase, little more can be done with occupant measurement or characterization systems.

3) The next improvement is to use a neural network as the basis of a crash sensor not only to determine if the airbag should be deployed, but also to predict the crash severity from the pattern of the initial portion of the crash pulse. Additionally, the crash pulse can continue to be monitored even after the decision has been made to deploy the airbag to see if the initial assumption of the crash type, based on the pattern up to the deployment decision, was correct. If the pattern changes indicating a different crash type, the flow rate to the airbag can be altered instantaneously.
4) Finally, anticipatory sensing using neural networks can be used to identify the crash before it takes place and select the deployment characteristics of the airbag to match the anticipated crash with the occupant size, position, velocity etc..

Any of these phases can also be combined with various methods of controlling the pretensioning, retraction or energy dissipation characteristics of the seatbelt. Although the main focus here is the control of the flows of gas into and out of the airbag, the control of the seatbelt can also be accomplished and the condition of the seatbelt can be valuable input information into the neural network system.

The smart airbag problem is complex and difficult to solve by ordinary mathematical methods. Looking first at the influence of the crash pulse, the variation of crash pulses in the real world is vast and quite different from the typical crashes run by the automobile industry as reported in the referenced technical papers. It is one problem to predict that a crash is of a severity level to require the deployment of an airbag. It is quite a different problem to predict exactly what the velocity versus time function will be and then to adjust the airbag inflation/deflation control system to make sure that just the proper amount of gas is in the airbag at all times, even without considering the influence of the occupant. To also simultaneously consider the influence of occupant size, weight, position and velocity renders this problem, for all practical purposes, unsolvable by conventional methods.

On the other hand, if a neural network is used and trained on a large variety of crash acceleration segments, and a setting for the inflation/deflation control system is specified for each segment, then the problem can be solved. Furthermore, inputs from the occupant position and occupant weight sensors can also be included. The result will be a training set for the neural network involving many millions, and perhaps tens of millions, of data sets or vectors as every combination of occupancy characteristics and acceleration segment is considered. Fortunately, the occupancy data can be acquired independently and is currently being done for solving the occupant position sensing problem of Phase 1 smart airbags. The crash data is available in abundance and more can be analytically created using the crash and velocity scaling techniques described in the referenced papers. The training using combinations of the two data sets, which must also take into account occupant motion that is not adequately represented in the occupancy data, can then be done by computer.

CRASH SEVERITY FORSCASTING

When a crash commences, the vehicle starts decelerating and an accelerometer located in the passenger compartment begins sensing this deceleration and produces an electronic signal that varies over time in proportion to the magnitude of the deceleration. This signal contains information as to the type of the crash that can be used to identify the crash. A crash into a pole gives a different signal than a crash into a rigid barrier, for example, even during the early portion of the crash before the airbag triggering decision has been made. A neural network pattern recognition system can be trained to recognize and identify the crash type from this early signal, and other available information such as vehicle speed, and further to forecast ahead the velocity change versus time of the crash. Once this forecast is made, the severity and timing of the crash can be predicted. Thus, for a rigid barrier impact, for example, an estimate of the eventual velocity change of the crash can be made and the amount of gas needed in the airbag to cushion an occupant as well as the time available to inject that amount of gas into the airbag can be determined and used to control the airbag inflation.

Alternately, consider a crash into a highway energy absorbing crash cushion. In this case, the neural network based sensor determines that this is a very slow crash and causes the airbag to inflate more slowly thereby reducing the incidence of collateral injuries such as broken arms and eye lacerations.

In both of these cases, the entire decision making process takes place before the airbag deployment is initiated. In another situation where a soft crash is preceded by a hard crash, such as might happen if a pole were in front of a barrier, the neutral network system would first identify the soft pole crash and begin slowly inflating the airbag. However, once the barrier impact began, the system recognizes that the crash type has changed and recalculates the amount and timing of the introduction of gas into the airbag and sends appropriate commands to the inflation control system of the airbag to increase the introduction of gas into the airbag.

VARIABLE INFLATORS

There are many ways of controlling the inflation of the airbag and several are now under development by the inflator companies. One way is to divide the airbag into different charges and to initiate these charges independently as a function of time to control the airbag inflation. An alternative is to always generate the maximum amount of gas but to control the amount going into the airbag, dumping the rest into the atmosphere. A third way is to put all of the gas into the airbag but control the outflow of the gas from the airbag through a variable vent valve. For the purposes herein, all controllable apparatus for varying the gas flow into or out of the airbag over time will be considered as a gas control module whether the decision is made at the time of initial airbag deployment, at one or more discrete times later or continuously during the crash event.

INTEGRATION

The use of neural networks in crash sensors has another significant advantage in that it can share the same hardware and software with other systems in the vehicle. Neural networks have proven to be effective in solving other problems related to airbag passive restraints. In particular, the identification of a rear-facing child seat located on the front passenger seat, so that the deployment of the airbag can be suppressed, has been demonstrated. Also, the use of neural networks for the classification of vehicles or objects about to impact the side of the subject vehicle for use in anticipatory side impact crash sensing shows great promise. Both of these neural network systems, as well as others under development, can use the same computer system as the crash sensor and prediction system. Moreover, both of these systems will need to interact with, and should be part of, the diagnostic module used for frontal impacts. It would be desirable for cost and reliability considerations, therefore, for all such systems to use the same computer system. This is particularly desirable since computers designed specially for solving neural network problems, such as neural-computers, are now available.

THE NEURAL NETWORK SYSTEM

The neural network crash sensor described is capable of using information from three accelerometers, each measuring acceleration from an orthogonal direction. As will be described in more detail below, other information can also be considered by the neural network algorithm such as the position of the occupants, noise, data from anticipatory acoustic, radar, infrared or other electromagnetic sensors, seat position sensors, seatbelt sensors, speed sensors, or any other information present in the vehicle which is relevant. Since the algorithm is trained on data from real crashes and non-crash events, it can handle data from many different information sources and sort out what patterns correspond to airbag-required events in a way which is nearly impossible for an engineer to do. For this reason, a crash sensor based on neural networks, for example, will always perform better than one devised by engineers. The theory of neural networks including many examples can be found in several books on the subject including (7-9).

The process can be programmed to begin when an event occurs which indicates an abnormal situation such as the acceleration in the longitudinal direction, for example, exceeding the acceleration of gravity, or it can take place continuously depending on the demands on the computer system. The digital acceleration values from the ADC may be pre-processed, as for example by filtering, and then entered successively into the neural network algorithm which compares the pattern of values on nodes 1 through N with patterns for which it has been trained. Each of the input nodes is connected to each of the second layer nodes h-1,...,h-n, called the hidden layer, either electrically as in the case of a neural computer, or through mathematical functions containing multiplying coefficients called weights.

The weights are determined during the training phase while creating the neural network as described in detail in the text references. At each hidden layer node, a summation occurs of the values from each of the input layer nodes, which have been operated on by functions containing the weights, to create a node value. Similarly, the hidden layer nodes are connected to the output layer nodes, which in this example is only a single node representing the control parameter to be sent to the gas control module. If this value exceeds a certain threshold, the gas control module initiates deployment of the airbag.

During the training phase, an output node value is assigned for every setting of the gas control module corresponding to the desired gas flow for that particular crash as it has occurred at a particular point in time. As the crash progresses and more acceleration values appear on the input nodes, the value of the output node may change. In this way, as long as the crash is approximately represented in the training set, the gas flow can be varied at each one or two milliseconds depending on the system design to optimally match the quantity of gas in the airbag to the crash as it is occurring. Similarly, if an occupant sensor and a weight sensor are present, that information can additionally be fed into a set of input nodes so that the gas module can optimize the quantity of gas in the airbag taking into account both the crash deceleration and also the position, velocity, size and weight of the occupant to optimally deploy the airbag to minimize airbag induced injuries and maximize the protection to the occupant. The details of the neural network process and how it is trained are described in referenced texts and will not be presented in detail here.

A time step such as two milliseconds is selected as the period in which the ADC pre-processes the output from the accelerometers and feeds data to input node 1. Thus, using this time step, at time equal to 2 milliseconds from the start of the process, node 1 contains a value obtained from the ADC and the remaining input nodes have a random value or a value of 0. At time equal 4 milliseconds, the value which was on node 1 is transferred to node 2 and a new value from the ADC is fed into node 1. In a similar manner, data continues to be fed from the ADC to node 1 and the data on node 1 is transferred to node 2 whose previous value was transferred to node 3 etc.. Naturally, the actual transfer of data to different memory locations need not take place but only a redefinition of the location which the neural network should find the data for node 1. For one case, a total of one hundred input nodes were used representing two hundred milliseconds of acceleration data. At each step, the neural network is evaluated and if the value at the output node exceeds some value such as .5 then the airbags are deployed by the remainder of the electronic circuit. In this manner, the system does not need to know when the crash begins, that is, there is no need for a separate sensor to determine the start of the crash or of a particular algorithm operating on the acceleration data to make that determination.

In the example above, one hundred input nodes were used, twelve hidden layer nodes and one output layer node. In this example, accelerations from only the longitudinal direction were considered. If other data such as accelerations from the vertical or lateral directions were also used, then the number of input layer nodes would increase. If the neural network is to be used for sensing rear impacts, or side impacts, 2 or 3 output nodes might be used, one for each gas control module. The theory for determining the complexity of a neural network for a particular application has been the subject of many technical papers and will not be presented in detail here. Determining the requisite complexity for the example presented here can be accomplished by those skilled in the art of neural network design and is discussed briefly below. In another implementation, the integral of the acceleration data is used and it has been found that the number of input nodes can be significantly reduced in this manner.

The particular neural network described and illustrated above contains a single series of hidden layer nodes. In some network designs, more than one hidden layer is used although only rarely will more than two such layers appear. There are of course many other variations of the neural network architecture illustrated above which appear in the literature.

OCCUPANT MONITORING SYSTEM

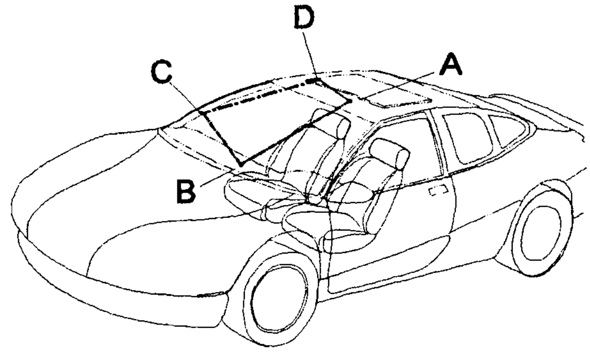

Figure 1. Occupant monitoring system

Figure 1 illustrates an occupant monitoring system that is capable of identifying the occupancy of a vehicle and measuring the location and velocity of human occupants. This system is now being developed for implementation on a production vehicle. In one implementation, four ultrasonic transducers are used to provide accurate identification and position monitoring of the passenger of the vehicle. Naturally, a similar system can be implemented on the driver side. The system is capable of determining the pre-crash location of the critical parts of the occupant, such as his/her head and chest, and then to track their motion toward the airbag with readings as fast as once every 10 milliseconds. This is sufficient to determine the position and velocity of the occupant during a crash event. The implementation described can therefore determine at what point the occupant will get sufficiently out-of-position so that deployment of the airbag should be suppressed as in solving the standard occupant sensing problem. Alternately, the information is used to determine how fast to deploy the airbag. If the weight of the occupant is also known, the amount of gas which should be injected into the airbag and perhaps the out flow resistance can be controlled to optimize the airbag system not only based on the crash pulse but also the occupant properties. This provides the design for Phase 3 Smart Airbags.

Although the system illustrated uses ultrasonic transducers, other systems use a variety of other technologies including electromagnetic (optical, passive or active infrared, radar), capacitive, seatbelt switch, seat and seatback location transducers, weight sensors and in fact any sensing system which can provide relevant information. The neural network is the ultimate "sensor fusion" technology and can use any type of sensors and will provide the system designer with a quantitative measure of the importance of any of the sensors. The optimum combination of four sensors, for example, might be one active infrared sensor, two ultrasonic sensors and a single strain gage weight sensor. The initial investigation might have included, four ultrasonic sensors, two active infrared sensors, four weight sensors, a seat position sensor, a seatback position sensor, and a seatbelt buckle sensor. A cost benefit analysis can easily be performed to determine the effect of adding any particular additional sensor to the system.

ANTICIPATORY SENSING

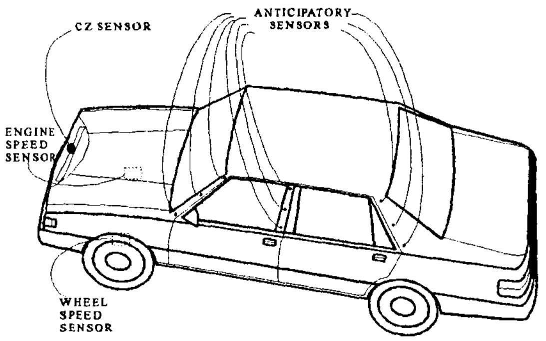

Figure 2. Side impact anticipatory sensor system.

Figure 2 illustrates a side impact anticipatory sensor system using transducers that are situated in different locations on one side of the vehicle, using the same computer system as discussed above. These sensors can provide the data to permit the identification of an object that is about to impact the vehicle at that side as well as its velocity. An estimate can then be made of the object's weight and therefore the severity of the pending accident. This provides the information for the initial inflation of the side airbag before the accident begins. If additional information is provided from the occupant sensors, the deployment of the side airbag can be tailored to the occupant and the crash in a similar manner as described above. Figure 2 also illustrates additional inputs that, in some applications, provide useful information in determining whether an airbag should be deployed. These include inputs from a front crash sensor mounted on the vehicle radiator, an engine speed sensor, and a wheel speed sensor, as used in the antilock braking system sensor.

This anticipatory sensor can act in concert with or in place of the accelerometer-based neural network crash sensor described above. In the preferred case, both sensors are used with the anticipatory sensor forecasting the crash severity before the collision occurs and the accelerometer based sensor confirming that forecast.

Collision avoidance systems currently under development use radar or laser radar to locate objects such as other vehicles that are in a potential path of the subject vehicle. In some systems, a symbol is projected onto the windshield in a heads-up display signifying that some object is within a possible collision space with the subject vehicle. No attempt at present is made to determine what that object is and to display an image of the object. Neural network pattern recognition systems have that capability and future collision avoidance systems may need this capability. Naturally, as above, the same neural network computer system which is proposed herein for sensing crashes can also the used for collision avoidance neural network as well as anticipatory sensing.

OPERATION OF THE SYSTEM

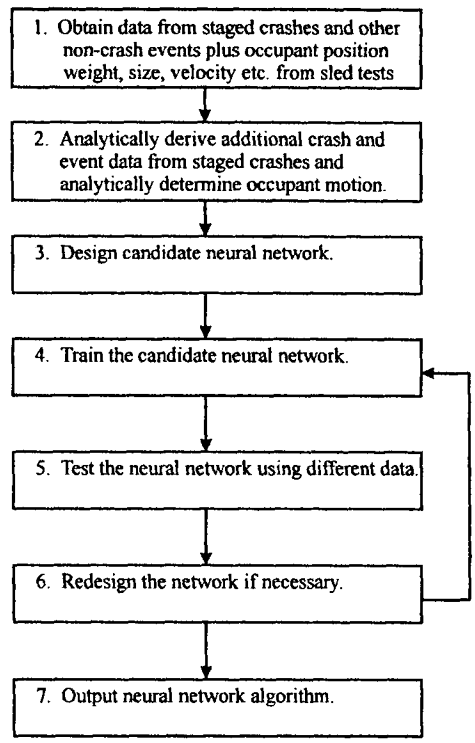

Figure 3. Smart airbag system development block diagram

The neural network algorithm which forms an integral part of the crash sensor described herein can be implemented either as an algorithm using a conventional microprocessor or through a neural computer which is now available. In the former case, the training is accomplished using a neural pattern recognition program and the result is a computer algorithm frequently written in the C computer language. In the latter case, the same neural computer can be used for the training as used on the vehicle. Neural network software for use on a conventional microcomputer is available from several commercial sources.

A block diagram of the neural network computer method of obtaining a smart airbag algorithm is illustrated in Figure 3. In the first step, one or more vehicle models are crashed under controlled conditions where the vehicle and crash dummies are fully instrumented so that the severity of the crash, and thus the need for an airbag, can be determined. An occupant sensor is also present and in use so that occupant motion data can be obtained. The acceleration during the crash is measured at all potential locations for mounting the crash sensor. Normally, any position which is rigidly attached to the main structural members of the vehicle is an adequate mounting location for the sensor.

The following crash event types, at various velocities, are representative of those which should be considered in establishing crash sensor designs and calibrations for frontal impacts:

Frontal Barrier Impact
Right Angle Barrier Impact
Left Angle Barrier Impact
Frontal Offset Barrier Impact
Frontal Far Offset (Outside of Rails) Barrier Impact
High Pole on Center Impact
High Pole off Center Impact
Low Pole (below bumper)Impact
Frontal Car-to-Car Impact
Partial Frontal Car-to-Car Impact
Angle car-to-car Impact
Front to Rear car-to-car Impact
Front to Side Car-to-Car Impact, Both Cars Moving
Bumper Underride Impact
Animal Impact - Simulated Deer
Undercarriage Impact (hangup on railroad track type of object)
Impact Into Highway Energy Absorbing Device (Yellow Barrels, etc.)
Impact Into Guardrail
Curb Impacts

The following non-crash event types are representative of those considered in establishing crash sensor designs and calibrations:

Hammer Abuse (shop abuse)
Rough Road (rough driving conditions)

Normally, a vehicle manufacturer will only be concerned with a particular vehicle model and instruct the crash sensor designer to design a sensor for that particular vehicle model. This is in general not necessary when using the techniques described herein and vehicle crash data from a variety of different vehicle models can and should be included in the training data.

Since the system is being designed for a particular vehicle model, static occupant data needs to be obtained for that particular model. Although crash data from one vehicle can be used for the training purposes for other vehicles, occupant data cannot in general be interchanged from one vehicle model to another. Dynamic position data for an occupant will be in general be analytically derived based on his/her initial position and rules as to how the body translates and rotates which will be determined from sled and crash tests. This is not as complicated as might first appear since an unbelted occupant will usually just translate forward as a free mass and thus the initial position plus the acceleration of the vehicle allows a reasonably accurate determination of his/her position over time. The problem is more complicated for the belted occupant and the rules governing occupant motion must be learned from modeling and verified by sled and crash tests. Fortunately, belted occupants are unlikely to move significantly during the critical part of the crash and thus the initial position at least for the chest is a good approximation.

The vehicle manufacturer will be loath to conduct all of the crashes listed above at several different velocities for a particular vehicle since crash tests are expensive. If, on the other hand, a particular crash type that occurs in the real world is omitted from the library, there is a chance that the system will not perform optimally when the event occurs later resulting in death or injury. One way to partially solve this dilemma is to use crash data from other vehicles as discussed above. Another method is to create data using the data obtained from the staged crash tests and operating on the data using various mathematical techniques which permits the creation of data which is representative of crashes not run. One method of accomplishing this is to use velocity and crash scaling as described in detail in the referenced papers and particularly in reference (1) page 8 and reference (2) pages 37-49 . This is the second step in the process illustrated in Figure 3. Also included in this step is the analytical determination of the occupant motion discussed above.

The third step is to assume a candidate neural network architecture. A choice which is moderately complex is suggested. If the network is too simple, there will be cases for which the system cannot be trained and, if these are important crashes, the network will have to be revised by adding more nodes. If the initial choice is too complex, this will usually show up after the training with one or more of the weights having a near zero value. In any event, the network can be tested later by removing one node at a time to see if the accuracy of the network degrades. Alternately, genetic algorithms are used to search for the optimum network architecture.

The training data must now be organized in a fashion similar to the way it will be seen on a vehicle during a crash. Although data from a previously staged crash is available for the full time period of the crash, the vehicle mounted system will only see the data one value at a time. Thus, the training data must be fed to the neural network computer, or computer program, in that manner. This can be accomplished by taking each crash data file and creating 100 cases from it, assuming that the time period chosen for a crash is 200 milliseconds and that each data point is the pre-processed acceleration over two milliseconds. This data must also be combined with the occupant data derived as discussed above. The first training case contains the first crash data point and the remaining 99 points are zero, or random small values for the crash data nodes, and the segmented occupant position data for the occupant nodes.

The second crash data case contains the first two data points with the remaining 98 points set to zero or random low values etc. For the tenth data file, data point one will contain the average acceleration at twenty milliseconds into the crash, data point two the average acceleration at eighteen milliseconds into the crash, and data point ten will contain the data from the first two milliseconds of the crash. This process is continued until the one hundred data cases are created for the crash. Each case is represented as a line of data in the training file. This same process must be done for each of the crashes and non-crash events for which there is data. A typical training set will finally contain on the order of 50,000 crash data cases and 500,000 occupant static data cases.

In the pure neural network crash sensor case, it was possible to substantially trim the data set to exclude all those cases for which there is no definite requirement to deploy the restraint, and the same is true here. For a particular 30 mph frontal barrier crash, for example, analysis of the crash has determined that the sensor must trigger the deployment of the airbag by 20 milliseconds. It is therefore not necessary to use data from that crash at less than 20 milliseconds since we are indifferent as to whether the sensor should trigger or not. Although data greater than 20 milliseconds is of little value from the point of view of a neural network crash sensor which only needs to determine whether to deploy the airbag since that would represent a late deployment, such is not the case here since, for some gas control modules, the inflation/deflation rate can be controlled after the decision to deploy. Also, the 20 millisecond triggering requirement is no longer applicable since it depends on the initial seating position of the occupant. For cases where the airbag should not trigger, on the other hand, the entire data set of 200 data files must be used. Finally, the training set must be balanced so that there are about as many no-trigger cases as trigger cases so that the output will not be biased toward one or the other decision. This then is the fourth step in the process as depicted in Figure 3.

In the fifth step, the neural network program is run with the training set. The program uses a variety of techniques, such as "back propagation", to assign weights to the connections from the input layer nodes to the hidden layer nodes and from the hidden layer nodes to the output layer nodes to try to minimize the error at the output nodes between the value calculated and the value desired. For example, for a particular crash such as a 30 mph frontal barrier impact, an analysis of the crash and the particular occupant has yielded the fact that the sensor must trigger in 20 milliseconds and the data file representing the first 20 milliseconds of the crash would have a desired output node value which would instruct the gas module to inject a particular amount of gas into the airbag. For another crash such as an 8 mph barrier crash where airbag deployment is not desired, the desired output value for all of the data lines which are used to represent this crash (100 lines) would have associated with them a desired output node value of 0 which corresponds to a command to the gas control module not to inject gas into the airbag. The network program then assigns different weights to the nodes until all of the airbag-deployment-not-desired cases have an output node value nearly equal to 0 and similarly all of the airbag-deployment-desired cases have an output value close to that which is required for the gas control module to inject the proper amount of gas into the airbag. The program finds those weights that minimize the error between the desired output values and the calculated output values.

The term weight is a general term in the art used to describe the mathematical operation which is performed on each datum at each node at one layer before it is inputted into a node at a higher layer. The data at input layer node 1, for example, will be operated on by a function that contains at least one factor which is determined by the training process. In general this factor, or weight, is different for each combination of an input node and hidden layer node. Thus, in the example above where there were 100 input nodes, 12 hidden layer nodes and 1 output node, there will in general be 1,212 weights which are determined by the neural network program during the training period. An example of a function used to operate on the data from one node before it is input to a higher level node is the sigmoid function:

In the usual back propagation trained network, let

O_{ij} be the output of node j in layer i,

then the input to node k in layer i+1 is

$$I_{i+1,k} = \sum_j W_{kj}^{(i)} O_{ij}$$

where $W_{kj}^{(i)}$ is the weight applied to the connection between node j in layer i and node k in layer i+1.

Then the output of node k in layer i+1 is found by transforming its input, for example, with the sigmoid function:

$$O_{i+1,k} = 1/(1+e^{-I_{i+1,k}})$$

and this is used in the input to the next, i+2, layer.

If the neural network is sufficiently complex, that is if it has many hidden layer nodes, and if the training set is small, the network may "memorize" the training set with the result that it can fail to respond properly on a slightly different case from those presented. This is one of the problems associated with neural networks which is now being solved by more advanced pattern recognition systems including genetic algorithms which permits the determination of the minimum complexity network to solve a particular problem. Memorizing generally occurs only when the number of vectors in the training set is not sufficiently large or varied compared to the number of weights. The goal is to have a network which generalizes from the data presented and therefore which will respond properly to a new case which is similar to but only slightly different from one of the cases presented. The network can also effectively memorize the input data if many cases are nearly the same. It is sometimes difficult to determine this by looking at the network so it is important that the network not be trained on all available data but that some significant representative sample of the data be held out of the training set to be used to test the network. It is also important to have a training set that is very large and varied (one hundred to one thousand times the number of weights or more is desirable). This is the function of step five, to test the network using data that it has not seen before, i.e., which did not constitute part of the training data.

Step six involves redesigning the network and then repeating steps three through five until the results are satisfactory. This step is automatically accomplished by some of the neural network software products available on the market.

The final step is to output the computer code for the algorithm and to program a microprocessor, or a neural computer, with this code. One important feature of this system is that the neural network system chosen is very simple and yet, because of the way that the data is fed to the network, all relevant calculations are made with a single network. There is no need, for example, to use an additional network to translate a prediction of a vehicle velocity change, and thus the crash severity, into a setting for the gas controller. In fact, to do this would be difficult since the entire time history would need to be considered. The output from the network is the setting of the gas controller in the preferred system design.

OPERATION OF THE NEURAL NETWORK CRASH SENSOR - AN EXAMPLE

In Figure 4, the results of a neural network pattern recognition algorithm for use as a single point crash sensor are presented for a matrix of crashes created according to the velocity and crash scaling techniques presented in the referenced papers. The table contains the results for different impact velocities (vertical column) and different crash durations (horizontal row). The results presented for each combination of impact velocity and crash duration consist of the displacement of an unrestrained occupant at the time that airbag deployment is initiated and 30 milliseconds later. This is presented here as an example of the results obtained from the use of a neural network crash sensor that forms the basis of the smart airbag system. In Figure 4, the success of the sensor in predicting that the velocity change of the accident will exceed a threshold value is demonstrated. Here this capability is extended to where the particular severity of the accident is indirectly determined and then used to set the flow of gas into or out of the airbag to optimize the airbag system for the occupant and the crash severity.

Airbags have traditionally been designed based on the assumption that 30 milliseconds of deployment time is available before the occupant, as represented by a dummy corresponding to the average male, has moved five inches. An occupant can be seriously injured or even killed by the deployment of the airbag if he or she is too close to the airbag when it deploys and in fact many people, particularly children and small adults, have now been so killed. It is known that this is particularly serious when the occupant is against the airbag when it deploys which corresponds to about 12 inches of motion for the average male occupant, and it is also known that he will be uninjured by the deploying airbag when he has moved less than 5 inches when the airbag is completely deployed. These dimensions are based on the dummy that represents the average male, the so-called 50% male dummy, sitting in the mid-seating position. The threshold for significant injury is thus somewhere in between these two points and thus for the purposes of this table, two benchmarks have been selected as being approximations to the threshold of significant injury. These benchmarks are, based on the motion of an unrestrained occupant, (i) if the occupant has already moved 5 inches at the time that deployment in initiated, and (ii) if the occupant has moved 12 inches by the time that the airbag is fully deployed. Both benchmarks really mean that the occupant will be significantly interacting with the airbag as it is deploying. Other benchmarks could of course be used; however, it is believed that these two benchmarks are reasonable lacking a significant number of test results to demonstrate otherwise, at least for the 50% male dummy.

The tables shown in Figures 4 and 5, therefore, provide data as to the displacement of the occupant relative to the airbag at the time that deployment is initiated and 30 milliseconds later. If the first number is greater than 5 inches or the second number greater than 12 inches, it is assumed that there is a risk of significant injury and thus the sensor has failed to trigger the airbag in time. For these cases, the cell in the table has been outlined. As can be seen in Figure 4, which represents the neural network crash sensor, none of the cells are outlined so the performance of the sensor is considered good.

The table shown in Figure 5 represents a model of a single point crash sensor used on several production vehicle models in use today. In fact, it was designed to be optimized for the crashes shown in the table. As shown in Fig. 5, the sensor fails to provide timely airbag deployment in a significant percentage of the crashes represented in the table. Since that sensor was developed, several manufacturers have developed crash sensor algorithms by trial and error which probably perform better than that of Figure 5. It is not possible to ascertain the success of these improved sensors since the algorithms are considered proprietary. Some algorithms have recently been published in the patent literature and can now be analyzed using the above methods.

SCALED VELOCITY	BARRIER SCALING FACTOR					
	1	1.2	1.4	1.6	1.8	2
8 MPH	NT	NT	NT	NT	NT	NT
10 MPH	NT	0.7/2.9	0.9/3.1	1.0/3.0	NT	NT
12 MPH	0.0/1.1	0.8/3.5	0.9/3.5	1.0/3.4	1.4/3.9	2.0/4.7
14 MPH	0.0/1.2	0.9/4.1	1.0/3.8	1.2/4.0	1.3/4.0	1.7/4.5
16 MPH	0.0/1.4	0.9/4.4	1.0/4.0	1.1/4.0	1.4/4.3	1.7/4.6
18 MPH	0.0/1.6	0.8/4.2	0.7/3.6	1.2/4.5	1.6/4.8	1.8/4.9
20 MPH	0.0/1.8	0.7/4.3	0.7/4.0	1.1/4.3	1.3/4.4	1.0/3.8
22 MPH	0.0/1.9	0.5/3.9	0.7/4.0	0.9/4.1	1.2/4.6	1.1/4.2
24 MPH	0.0/2.1	0.1/2.3	0.8/4.4	0.8/4.2	1.3/5.0	1.4/4.8
26 MPH	0.0/2.3	0.1/2.5	0.5/4.0	0.9/4.5	1.0/4.4	1.2/4.6
28 MPH	0.0/2.5	0.0/2.1	0.1/2.4	0.7/4.2	0.8/4.1	0.5/3.2
30 MPH	0.0/2.7	0.0/2.3	0.1/2.6	0.1/2.3	0.8/4.4	1.2/5.0
32 MPH	0.0/2.8	0.0/2.4	0.1/2.8	0.1/2.5	0.9/4.7	1.1/4.9
34 MPH	0.0/3.0	0.0/2.3	0.0/2.0	0.0/1.8	0.6/4.2	1.2/5.3

Figure 4. Neural network single point sensor performance.

SCALED VELOCITY	BARRIER SCALING FACTOR					
	1	1.2	1.4	1.6	1.8	2
8 MPH	NT	NT	NT	NT	NT	NT
10 MPH	4.7/10.3*	NT	NT	NT	NT	NT
12 MPH	2.2/6.7	5.8/12.1	NT	NT	NT	NT
14 MPH	2.2/7.2	2.7/7.5	3.9/8.9	NT	NT	NT
16 MPH	2.2/7.6	2.7/7.9	3.4/8.5	4.2/9.3	NT	NT
18 MPH	2.2/8.0	2.8/8.7	3.6/9.2	4.2/9.7	5.0/10.5	17.8/27.5
20 MPH	2.0/7.9	3.1/9.3	3.7/9.7	4.3/11.2	5.0/10.9	5.9/11.7
22 MPH	1.0/5.3	2.7/8.9	3.9/10.4	4.5/10.9	5.2/11.5	5.9/12.2
24 MPH	.5/4.2	1.6/6.5	3.9/10.8	4.8/11.6	5.4/12.0	6.1/12.8
26 MPH	.4/4	1.2/5.7	2.0/6.8	4.5/11.5	5.8/13	6.4/13.5
28 MPH	.4/4.1	.6/4.0	1.8/6.6	2.7/7.8	5.9/13.5	6.8/14.4
30 MPH	.4/4.2	.5/4.0	.8/4.2	2.2/6.9	6.4/14.5	7.1/15.1
32 MPH	.3/4.2	.5/4.1	.7/7.2	2.1/7.0	2.6/7.4	3.4/8.4
34 MPH	.3/4.0	.5/4.2	.7/4.3	.9/4.5	2.6/7.5	4.0/9.6

Figure 5. Optimized standard single point sensor performance.

GAS FLOW CONTROLLER

One issue that remains to be discussed is the derivation of the relationship between the gas controller setting and the desired volume or quantity of gas in the airbag. Generally, for a low velocity, long duration threshold crash, for a small light weight out-of-position occupant, the airbag should be inflated slowly with a relatively small amount of gas and the out flow of gas from the airbag controlled so a minimum value, constant pressure is maintained unitl the occupant just contacts the vehicle interior at the end of the crash. Similarly, for a high velocity crash with large heavy occupant, positioned far from the airbag before deployment is initiated, but with a significant forward relative velocity due to pre-crash braking, the airbag should be deployed rapidly with a high internal pressure and an out flow control which maintains a high pressure in the airbag as the occupant exhausts the airbag to the point where he almost contacts the interior vehicle surfaces at the end of the crash. These situations are quite different and require significantly different flow rates into and out of the airbag. As crash variability is introduced such as where a vehicle impacts a pole in front of a barrier, the gas flow decisions will be changed during the crash.

In theory the neural network crash sensor has the entire history of the crash at each point in time and therefore knows what instructions it gave to the gas controller during previous portions of the crash. It therefore knows what new instructions to give the controller to account for new information. The problem is to determine the controller function when the occupant parameters and the crash forecasted severity are known. This requires the use of an occupant crash simulation program such as Madymo™ from TNO in Delft, The Netherlands, along with a model of the gas control module. A series of simulations are run with various settings of the controllable parameters such as the gas generation rate, gas inflow and gas outflow restriction until acceptable results are obtained and the results stored for that particular crash and occupant situation. In each case, the goal may be to maintain a constant pressure within the airbag during the crash once the initial deployment has occurred. Those results for each point in time are converted to a number and that number is the desired output of the neural network used during the training. A more automated approach is to couple the simulation model with the neural network training program so that the desired results for the training are generated automatically. Thus, as a particular case is being prepared as a training vector, the Madymo™ program is run which automatically determines the settings for the particular gas control module, through a trial and error process, and these settings are converted to a number and normalized which then become the desired output value of the output node of the neural network. Naturally, the above discussion is for illustration purposes only and there are many ways that the interface between the neural network system and the gas controller can be designed.

The gas flow controller can also make use of additional inputs including in particular the pressure within the airbag. All such information inputs can be handled within the neural network or, in the case of the airbag pressure input, within the control mechanism itself. In this case the output from the neural network would be the desired airbag pressure.

The descriptions above have concentrated on the control of the gas flows into and out of an airbag. Naturally, other parts of the occupant restraint system can also be controlled in a similar manner as the gas flows. In particular, various systems are now in use and others are being developed for controlling the force applied to the occupant by the seatbelt. Such systems use retractors or pretensioners, others use methods of limiting maximum the force exert by the seatbelt, while still others apply damping or energy absorbing devices to provide a velocity sensitive force to the occupant. Also, the crash accelerometer and occupant sensors have been the main inputs to the neural network system as described above. Although not described in detail, the neural network can make optimum use of other sources on information such as seatbelt use, seat position, seat back position, vehicle velocity etc. as additional inputs into the neural network system for particular applications depending on the availability of such information.

CONCLUSION

The system described herein uses a neural network, or neural-network-derived algorithm, to analyze the digitized accelerometer data created during a crash and, in some cases, occupant size, position, seatbelt use, weight and velocity data, and, in other cases, data from an anticipatory crash sensor, to determine not only if and when a passive restraint such as an airbag should be deployed but also to control the flow of gas into or out of the airbag.

Generally, the present device provides a smart airbag system that optimizes the deployment of an occupant protection apparatus in a motor vehicle, such as an airbag, to protect an occupant of the vehicle in a crash. The system includes an accelerometer mounted to the vehicle for sensing accelerations of the vehicle and producing an analog signal representative thereof; an electronic converter for receiving the analog signal from the sensor and for converting the analog signal into a digital signal, and a processor which receives the digital signal. The processor includes a neural network and produces a deployment signal when the pattern recognition system determines that the digital signal contains a pattern characteristic of a vehicle crash requiring occupant protection and further produces a signal which controls the flow of inflator gas into or out of the airbag. In some cases, the system also includes an occupant position and velocity sensor which outputs a signal that is also used by the processor in producing the signal which controls the flow of gas into or out of the airbag.

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THE COMBINATION OF A NEW AIR BAG TECHNOLOGY WITH A BELT LOAD LIMITER

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ABSTRACT

This study deals with the development of a restraint system in order to improve occupant protection in frontal impact. In frontal collisions where vehicle intrusion is minor, the main lesions caused to occupants are thoracic, mainly rib fractures resulting from the seat-belt. In collisions where intrusion is substantial, the lower members are particularly vulnerable. In the coming years, we will see developments which include more solidly-built cars, as offset crash test procedures are widely used to evaluate the passive safety of production vehicles. If this trend will continue, restraint forces from the belt will increase and as a consequence more thoracic injuries will occur in frontal collisions.

In order to address this risk, it has become necessary to work on an optimized limitation of the restraining forces, while taking account of the broadest possible population, especially elderly people. A first step in this reduction was taken in 1995 with the introduction of the first-generation Programmed Restraint System (PRS), with a seat-belt force threshold of 6 kN combined with a belt pretensioner. Thirty seven frontal accident cases involving this type of restraint were investigated.

Analysis of these data combined with findings from the University of Heidelberg / NHTSA study, shows that it is necessary to go a step further by reducing the shoulder belt force to 4 kN. As this objective cannot be achieved with a standard restraint system, it was necessary to redesign the airbag and its operating mode that is, a new seat-belt + airbag combination called PRS II.

This paper summarizes the data obtained with the 6 kN load limiter restraint in real-world collisions. A description of the new system is given and its performance in offset crash configurations with respect to a European standard belt + air bag system is discussed.

INTRODUCTION

IMPORTANCE OF FRONTAL COLLISIONS. Detailed analyses of all fatal accident reports in France in 1990 and of the accidentology file of the PSA/Renault Laboratory enabled to determine the distribution of fatalities and seriously injured occupants with respect to collision configurations. The percentages related to frontal impact are respectively 50°/0 and 70%, as shown in Figure 1 ; illustrating the predominant role of this crash configuration on occupant injuries. In order to assess the distribution of lesions in frontal collisions as regards the main body segments, an analysis was conducted on 100 belted front seat occupants taking into consideration serious injuries. Figure 2 presents the distribution of AIS 3+ injuries for the head, the thorax, the abdomen and the lower members. It can be observed that the thoracic risk is highest for the passenger, and secondly, for the driver. For the latter, injuries to the lower member's constitute the most frequent risk. Since 1992, improvements have been noted in Europe in cars as regards the resistance of the passenger compartment, especially the reduction in intrusion. In addition the majority of cars are today equipped with belt pretensioners. The combination of these improvements would suggest a certain benefit in reducing the severity of injuries to the occupant. To assess this hypothesis two accident files, including belted drivers involved in frontal collisions, were selected. The first file (A) comprises 2000 vehicles manufactured before 1991 and with no belt pretensioners in the restraint system. The second file (B)

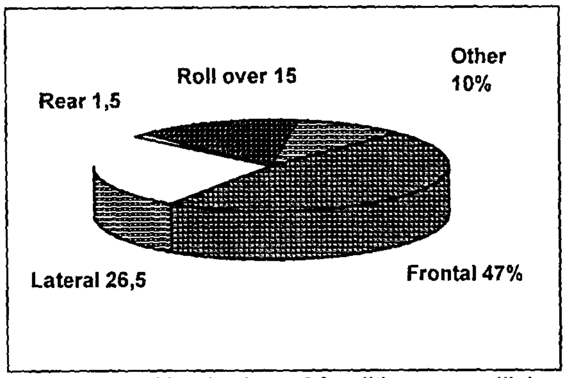


Figure 1a : Distribution of fatalities per collision type. LAB PSA/Renault accident database.

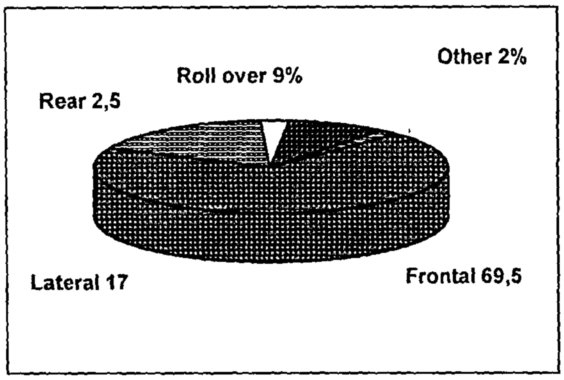


Figure 1b : Distribution of severely injured occupants per collision type. LAB PSA/Renault accident database.

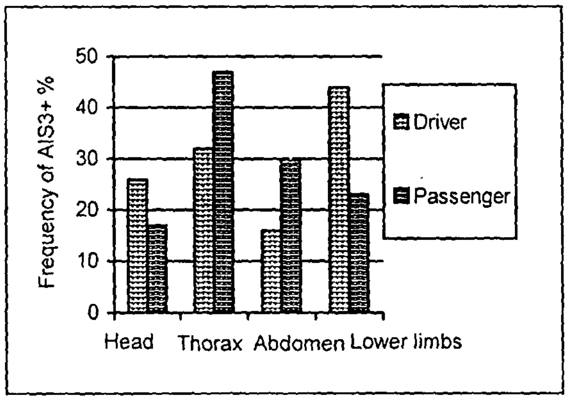


Figure 2 : Distribution of severe injuries per body regions for 100 seriously injured occupants (MAIS 3+) in frontal collisions. Driver and front seat passengers (belted).

includes 160 vehicles, manufactured since 1992, all equipped with belt pretensioners and structural reinforcements. The two files were compared taking into account the frequency of moderate to serious injuries, AIS 2+ , corresponding to the main body segments, as shown in Figure 3.

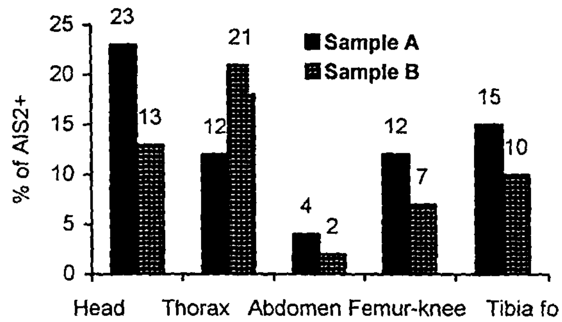


Figure 3 : Risk of AIS 2+ injuries in frontal collisions involving belted drivers. Comparison of 2 accident samples with cars manufactured before 1991 (A) and cars manufactured since 1992 (B).

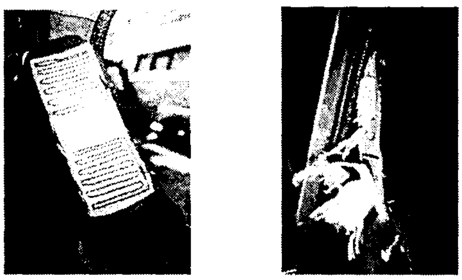
When comparing files A and B, a tendency in the reduction of injury frequency is observed for the head, the abdomen, the lower limbs. For the thoracic segment an opposite trend appears with an increase of risk. As this tendency to reduce intrusion will continue and, as airbags will become more widespread in Europe, one may expect gains as regards the risk of injuries to the head and lower members, and abdominal risks will be maintained. For the thorax, there will be increased risk since rigidifying the structure will result in a direct increase in restraining forces on the occupant. A study presented by Bendjellal, 1997 (1), showed accident cases in frontal collisions with cars manufactured after 1992, where front seat occupants, restrained with a combination of a belt pretensioner and an air bag, sustained severe thoracic lesions.

The study presented in this paper was initiated in order to address this rising risk of chest injuries.

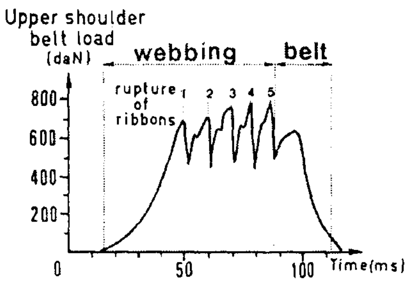
THORACIC RISK LINKED TO SEAT-BELT

BELT INDUCED INJURIES AND OCCUPANT AGE - The 3-point seat-belt was designed to protect the occupant as regards contact with the passenger compartment and to avoid ejection from the vehicle. In order to provide this protection, the seat-belt exerts substantial and localized forces on the thoracic cavity. These forces, which may reach 10 kN, generate broken ribs which may or may not be combined with internal lesions of the thorax. The first relationship between seat-belt tension and the associated thoracic risk level was established by J.Y. Forêt Bruno in 1978 (2) based on an analysis of 90 accident cases. The vehicles in question, sold in France in the

1970's, were equipped with 3-point static seat-belts in the front seats with a load limiter located in the belt webbing between the occupant's shoulder and the upper anchorage point. The load limitation was obtained by tearing of the stitching which was used to sew loops in the webbing. In case of impact the stitching tore, thus allowing more webbing from the loop: as a consequence the torso can move relative to the vehicle at a controlled load level. A view of such a load limiter before and after impact is shown in Figure 4a and its force-time response in dynamic test is illustrated in Figure 4b.



a) Load limiter before and after impact



FORCE LIMITER type B

b) Response of load limiter in dynamic test

Figure 4 : A load limiter installed in cars sold in France between 1970 and 1977

In 1989, other cases were added to this investigation, bringing the total of this database up to 290 accidents (3). The key point of this unique database is the possibility of showing a relationship between the seat-belt tension exerted on the occupant, his age and the type of resulting lesions: this relationship, reproduced from Forêt Bruno study (3), is given in Figure 5. This data clearly shows that thoracic risk among occupants restrained by seat-belts increases with age and that a shoulder belt force of 8 to 9 kN may induce a high risk for the chest.

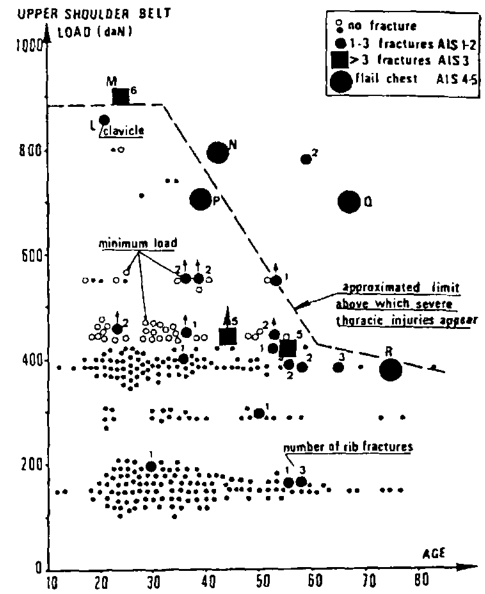


Figure 5: Relationship between shoulder belt tension, age of occupant and injury severity to the chest. Reproduced from (3).

LIMITATION OF THORACIC RISK LINKED TO SEAT-BELT

The data discussed in the previous sections and these accident cases show the necessity of reducing seat-belt tension forces in frontal crashes. An initial stage, consisting of limiting this force to 6 kN, was carried out in 1995 on Renault vehicles with the introduction of the PRS system (Programmed Restraint System). This system is comprised of a pretensioner pyrotechnic buckle, a retractor webbing clamp and a steel part, fastened between the retractor and the seat- belt anchoring point as shown in Figure 6. This part, designed to deform at a given level of force, acts like a force limiter. The system's operating method includes 3 phases: at the beginning of the impact (15 milliseconds),the buckle pretensioner triggers in order to take up the seat-belt/occupant slack. The occupant's coupling is increased in this phase with the action of the strap blocking mechanism in the retractor (17 ms). This combination enables one to substantially reduce the occupant's initial displacement. In Phase 2, restraining forces are gradually applied. When the belt tension level reaches 6 kN (70 milliseconds) the force limiter comes into play, authorizing controlled displacement of the retractor in the B-pillar, upwards. Movement of the retractor will enable a displacement of the torso under controlled load, thus allowing the rib cage to be relieved of seat-belt stresses. Complete operation of this device is shown in Figure 7.

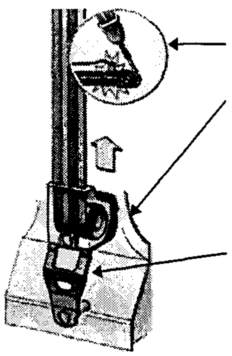


Figure 6: The Programmed Restraint System installed in Renault cars since 1995 (6 kN shoulder belt load limiter)

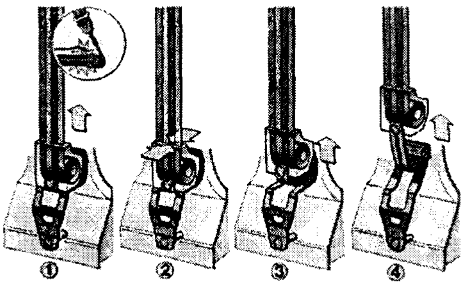
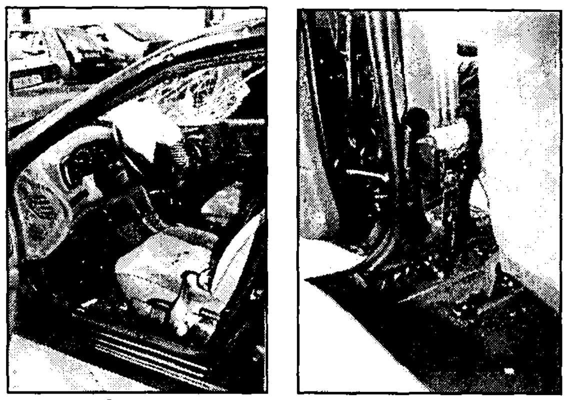


Figure 7. The PRS operating mode - Phase 1 Initial part of the crash and belt pretension activation, Phase 2 Action of the webbing clamp, Phase 3 Load limiter activation, Phase 4 End of impact

Behaviour of the Programmed Restraint System in Real - World Accidents - To date, 80 accident cases related to frontal collisions with cars equipped with this device have been investigated since 1995. Thirty seven cases are discussed in this paper. The main parameters of this sample are summarized in Figure A1 in the appendix. Age distribution of occupants ranges from 17 years to 72 years , with 11 cases (30%) with age < 25 years, 7 cases (19%) with age ranging from 26 to 35 years, 3 cases (8%) between 36 and 45 years, 8 cases (21.5%) between 46 and 55 years, and 8 cases (21.5%) with age > 56 years. The severity of the collisions, expressed in terms of EES, ranges from 35 km/h to 75 km/h. Nearly half of this sample (48.6%) corresponds to a severity which is superior to EES of 55 km/h.
Regarding the injury severity for the thorax, only 2 cases(5.4%) are related to an AIS level of 3. In the first case the driver a 72 old male sustained 3 right rib fractures and lung contusion. The car was involved in an offset collision to the left, with an overlap of 85% and with an EES of 50- 55 km/h. Except fractures to the left metatarsi, no other injuries were found. In the second case two front seat occupant were involved; a 58 years old male in the driver position and a 60 years old female in the passenger position. The driver sustained a fracture to the sternum (AIS 2) and. the passenger had 4 left rib fractures (AIS 3). In both .accident the shoulder belt load. estimated from the PRS deployment, was 6 kN. The other thoracic AIS levels observed for the rest of the sample are AIS 2 with 7 cases (19%) , AIS 1 with 13 cases (35%) and AIS 0 with 15 cases (40%).
Regarding the overlap distribution among these accident cases , half of the sample corresponds to offset configuration with an overlap below 74%° and the other half is close to a full barrier test. An illustration of one accident, case No . 12041, is given in Figure 8 with photographs of the car deformation and the PRS deployment.



8a **8b**

Figure 8 : Illustration of car deformation in a frontal collision Case No 12041 (9a) and the PRS actual deployment (9b).

Belt limitation threshold - The accident cases presented in the previous section, are encouraging, but they show that a threshold of 6 kN for belt load limitation is not sufficient to prevent a risk of serious injury to the thorax as 2 cases with occupants having sustained an AIS 3 level were found. This observation is consistent with the data from Forêt Bruno (3) published in 1989. It is therefore necessary to go a step further in the reduction of shoulder belt load. As this reduction will result in an increase in excursions of the head and thorax it is therefore essential that with this kind of seat belt it is necessary to combine the pretensioner and quite obviously the airbag. The combination of an airbag and a 3 point belt restraint is discussed in various publications among them are the paper from Kompass in 1994 (4), the study of Kallieris et al in 1995 (5) and Mertz et al investigation in 1995 (6). According to the data discussed in Kallieris paper (5) and the mathematical simulation investigated by NHTSA (5) for a variety of crash conditions (frontal and rollover) crash severities and occupant sizes (5, 50 and 95 percentiles) a threshold of 4 kN for the shoulder belt load limitation appears to be suitable for reducing the risk for thoracic injury without negative consequences on other injury measurements. Therefore a 4 kN load limitation threshold is chosen for the belt system. Whilst working in the same stopping distance for the thorax, i.e. a distance from thorax to steering wheel of 300 to 350 mm, it is necessary for the airbag to play an important role by taking part of the thoracic restraint. The question is : which type of air bag has to be chosen for this occupant protection approach ?

Air bag accident data in the USA and in France - When the FMVSS 208 was introduced in the USA in the beginning of the 1980's, according to investigations carried out by NHTSA, most people did not use seat belts. The percentage of people wearing seat belts at that time was on the order of 15%; this suggested the necessity of protecting the majority of unbelted occupants, by means of a restraint system independent of the seat belt The physics of a vehicle, impacting a rigid barrier at 50 km/h and with 50th percentile dummies not restrained by a seat belt, imposed de facto paddings or knee plates for the protection of the femurs and knees and the airbag for protection of the upper part of the body. The performance of such a restraint system combined with the seat belt is quite positive with more than 1500 lives saved (7) during the 1990 1996 period. However cases of fatal accidents have been noted involving either adults not restrained by seat belts or else children in rearfacing seats or even children without any restraint system whatsoever. This problem stems mainly from the energy parameters of the airbag dimensioned in order to absorb energy on the order of 3000 J. In comparison, a Eurobag or « facebag ». designed to protect the head of a 50° percentile restrained by seat belts has an energy potential of 200 J. If one wants to design a seat belt airbag restraint system which takes account of OOP situations, it is therefore necessary to explore other possibilities.

Current situation in France - Out of the total number of automobiles in France - some 25 million - only 2 to 3% of vehicles are equipped with driver airbags. We lack data on airbag efficiency in Europe since the target survey files remain statistically low in comparison with the USA, only 100 cases have been studied in France by the Laboratoire d Accidenlologie et de Biomécanique Peugeot Renault; 75 cases involved frontal collisions with belted drivers.

In Figure 9 a risk comparison for the head, with and without airbags, is given. For the 25 to 45 km/h speed range, one notes moderate lesions (11%) for cases with no air bag as opposed to 0% for cases with air bag. For the 46 to 65 km/h speed range, the frequency of AIS > 2 is 40% without air bag and only 14°/o with air bag. No facial fractures were observed with air bag, whereas half of the sample without air bag represents facial fractures. The tendency of air bag to improve head protection is confirmed.

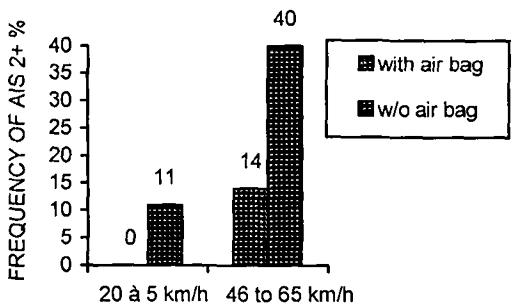


Figure 9: Accident survey with frontal collisions involving occupants with 3 points belt + Air bag restraint system. Frequency of AIS 2+ injuries to the head. All cases with Eurobag type of air bag.

SPECIFICATIONS FOR AN OPTIMIZED SEAT-BELT + AIR BAG RESTRAINT SYSTEM - The basic principle is that occupant restraint energy must be managed, whilst complying with human tolerance limits. In this context, the thoracic cavity is more tolerant to distributed pressure (air bag) than to a very localized pressure (belt). With the same stopping distance for the occupant in the vehicle, it is possible for the airbag to take a part of the seat-belt forces.

Once the basic elements of the seat-belt, that is, pyrotechnic pretensioner and force-limitation, have been determined, it is now necessary to define the airbag characteristics. The corresponding specification is based on 2 separate parts: to contribute actively to restraining the occupant, and to control the aggressiveness of the deployment of the airbag. This results in the 3 following main functions:

1. The airbag must inflate very early on in the impact and "wait for" the occupant's contact; this is the anticipation function, analogous to the effect of a pretensioner on the PRS seat-belt.
2. Having a law of force which is as constant as possible. This is equivalent to controlling

the pressure in the airbag and the force exerted on the occupant. This is similar to the action of the force-limiter in the PRS seat-belt.

3. These two functions result in an increase in the generator power in relation to the Eurobag. In order to control the bag aggressiveness in OOP situations, it is necessary to compensate this through a more elaborate airbag-folding strategy, in order to reduce the punch out transmitted to the occupant. This objective results in a deployment mode distributed in 3 directions: first downwards and sideways and then toward the occupant.

Based on these elements, a new airbag has been developed in the frame of the new system called the PRS II.

DEVELOPMENT OF THE PRS-II DESCRIPTION AND VALIDATION

The system comprises 3 main components. These are the pretensioner, the belt load limiter and the air bag.

The pretensioner - This is a device which enables the seat-belt strap to be drawn taut very quickly at the initial moment of impact. For the PRS-II system, and given the experience acquired on Renault vehicles since 1992, a pyrotechnic buckle pretensioner has again been selected, especially for its efficiency with respect to submarining. In 4 milliseconds, it enables to take up the seat-belt slack and secure the occupant to the seat.

The seat-belt force-limiter - The force limitation function is located at the core of the retractor with a torsion bar whose plastic deformation comes into play as soon as the seat-belt force at the shoulder reaches 4 kN. For this function an another option is to use the deformable steel plate, as in the PRS-1 generation, providing a sufficient space in the B-pillar packaging.

The airbag - The airbag is a 60 liters bag with a pressure limitation function and a folding which allows a deployment from top to bottom and to the sides. As opposite to Eurobag, this bag is defined to protect the head and the thorax. There are different ways to control the pressure of the air bag; the system described here refers to a set of vents in a row, contained in a meltable seam. After an impact, the air bag deploys to its full volume, while the vent is still closed. Ones At a given pressure of the gas inside the bag, the seam tears and the vents open successively. The restraint force acting on the occupant from the air bag is thus controlled.

Development of the PRS II - After a computer simulation phase, the opening pressure of the airbag vents has been validated during tests using a free fall pendulum system. At the same time, the seat-belt force limiter was developed. Then, sled tests were conducted in order to fine-tune the system's characteristics. The validation program also included static tests in OOP , according to ISO recommendations (8), and crash tests with vehicles.

Figure 10 provides a description of PRS-II components. The operating phases of the system, as obtained in a 50% offset rigid barrier test, are illustrated in the same figure where the 4 upper sequences indicate the air bag work and the 4 lower sequences relate to the belt actions. Sequence 1 in Figure 10 represents the firing of the belt pretensioner at 12 ms followed by the start of air bag deployment at 15 ms. Note that once the air bag deployment is achieved (sequence 2) , the vents are still closed; the air bag is waiting for the occupant. When the thorax contacts the air bag, in sequence 3, the seam covering the vents starts to tear, thus liberating the first vent. The bag pressure is now under control; in sequence 4 the belt load limiter function starts to work in conjunction with the opening of the remaining vents in the air bag: with this last sequence the thoracic restraint loads are controlled thorough the impact duration.

COMPARISON OF PRS II WITH A CONVENTIONAL RESTRAINT SYSTEM - Various mathematical simulations and sled tests were conducted in order to assess the PRS-I I performances in frontal collisions. In addition two crash tests with the same vehicle model (mass of the vehicle 1200 kg) were performed; the test configuration corresponds

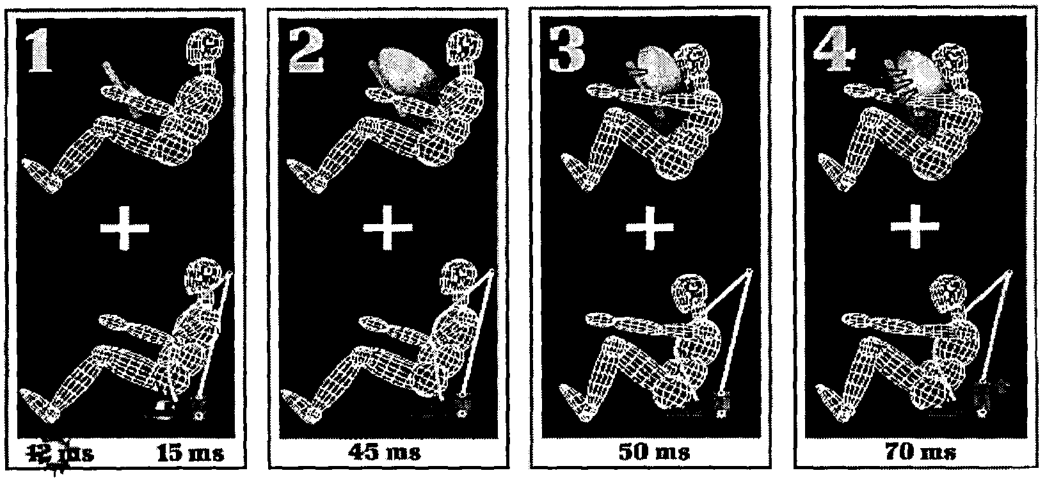


Figure 10: PRS II principle - 1- Pretensioner action and air bag deployment ; 2- air bag full deployment ; 3- Opening of the first vent of the bag ; 4- Combination of belt load limiter action and air bag pressure control (opening of the other air bag vents).

to a 50 % offset rigid barrier test at 56 km/h. One of the vehicle was equipped with a conventional belt + air bag system; the belt included a pyrotechnic buckle pretensioner and the air bag was of Eurobag type(volume of 45 liters). The other vehicle had the PRS-II system. In the front seats of both vehicles instrumented Hybrid III 50° dummies were installed. The results from both tests are illustrated in Table 1 and time-histories for the head acceleration, the chest acceleration and the shoulder belt load are provided in Figure A2 in the appendix. With the PRS-II the head HIC and 3ms acceleration are reduced, respectively 75% and 55% : the neck shearing force is also reduced respectively 60% for -Fx and 57% for +Fx. The neck extension moment is increased with the PRS II with a maximum of 35 Nm as opposed to 11 Nm with the conventional system. The shoulder belt load reduction with the PRS-II is significant -55%, as a direct result of the combined work of the belt and the airbag. The thoracic acceleration is also reduced but the amount of reduction (24%) is smaller than those observed with the other criteria. This last result shows that 1) the occupant stopping distance is the same for the 2 systems we are comparing and 2) the energy distribution on the thorax is spread differently with the PRS-II. Chest injury parameters, such as the chest deflection and the VC, cannot be compared as the data corresponding to the conventional system (with the same vehicle) are not available. The maximum chest deflection and VC with the PRS II are 25 mm and 0.09 m/s. Compared to the conventional system the PRS II allowed an increased x-displacement of the chest (+60 mm).

Results of PRS-II validation in vehicles tests - Vehicles from the same model whose front seats were equipped with PRS 11 were tested according to 3 impact configurations . 1. Rigid obstacle, 15° barrier, 50°70 offset and a speed of 56 km/h according to AMS procedure (9), 2. Deformable barrier at 0°, 40°70 offset and a speed of 56 km/h. This configuration reproduces the future European regulatory test, ECE 94 (10), 3. Full rigid barrier, wall at 0°, and a speed of 56 km/h. This test is the representation of the New Car Assessment Program (NCAP) as used by NHTSA in the USA. The interest of such a test matrix is to combine demanding conditions for the restraint system - the case of the US NCAP test - and for the structure of the vehicle with the other two offset crashes. The first offset test condition allows to assess both the structure of the vehicle and the restraint system. The test according to the procedure defined by the EEVC (ECE 94) is a special case, since this configuration enables to simulate a car to car collision and also to judge the quality of the triggering system for the belt restraint and the airbag restraint, in particular as the first part of the crash is soft compared to the two other test configurations.

The results of these tests are documented in Table 2, which includes the resulting accelerations of the head and thorax, the Head Injury Criterion (HIC 36 ms) the upper neck shear force, the upper neck extension moment, and the shoulder belt tension, the chest acceleration, the chest deflection and VC. All the maximum values refer to measurements obtained from Hybrid III 50° percentile dummy, for both the driver and passenger.

Table 1: 50% offset rigid barrier test at 56 km/h. Comparison of PRS II responses with those of a conventional belt + air bag system - Same vehicle used in both tests, driver data.

	Measurements & injury criteria with a Hybrid III 50° percentile dummy	50% Offset rigid barrier test, 56 km/h with a conventional restraint system	50% Offset rigid barrier test, 56 km/h with the PRS II
Restraint system	Buckle pretensioner activation time (ms)	18	16
	Belt pretension (mm)	49	49
	Initiation of belt load limitation (ms)	None	70
	Duration of belt load limitation (ms)	None	40
	Air bag type	Eurobag 45 liters	PRS II 60 liters
	Time of actiation of air bag pressure limitation (ms)	None	72
Body segments	HIC 36 ms	763	186
Head	3 ms acceleration (G)	74	33
Neck	Shear Force -Fx (kN)	0.5	0.2
	Shear Force +Fx (kN)	0.7	0.3
	Extension moment (Nm)	11	35
Thorax	Shoulder Belt Load (kN)	9.7	4.3
	3 ms acceleration (G)	53	40
	Chest deflection (mm)	na	25
	VC (m/s)	na	0.09
	Thoracic X-displacement measured at shoulder level (mm)	290	350

Table 2 : Summary of crash test results with a production vehicle (mass 1200 kg) equipped with PRS II in offset and full barrier tests. Driver and passenger injury criteria and measurements.

Body segments	Measurements & injury criteria with a Hybrid III 50° percentile dummy	50% Offset rigid barrier test, 56 km/h		100% rigid barrier test,56 kmh US NCAP		40% Offset deformable barrier test, 56 km/h EEVC procedure	
		Driver	Passenger	Driver	Passenger	Driver	Passenger
Head	HIC 36 ms	186	257	347	519	74	111
Neck	3 ms acceleration (G)	33	37	45	53	24	28
	Shear Force -Fx (kN)	0.2	0.03	0.5	1.2	0.009	0.02
	Shear Force +Fx (kN)	0.3	0.6	0.4	0.2	0.5	0.3
	Extension moment (Nm)	35	28	29	na	11	12
Thorax	Shoulder Belt Load (kN)	4.3	4.5	4.6	4.8	3.9	4.1
	3 ms acceleration (G)	40	36	42	45	23	24
	Chest deflection (mm)	25	27	40	40	23	15
	VC (m/s)	0.09	0.22	0.64	0.64	0.01	0.03

The PRS-II system behaved well in all 3 configurations, both belt load limiter and air bag pressure limiter worked. The shoulder belt tension was between 3.9 kN and 4.8 kN. The lowest value was recorded for this parameter was obtained in the EEVC test (for the driver) and the highest value in the US NCAP test (for the passenger). This difference is due to the friction in the D-ring. As this friction is directly related to the dummy forward displacement, its effect on the shoulder peak load is more pronounced for the passenger. Chest accelerations were all below 46 G; this result indicates no chest to steering wheel contact. Neither head to steering wheel contact was observed as illustrated by the low values recorded with the HIC (between 74 and 519) and with the head 3ms acceleration - between 24 G and 53 G. Chest deflections ranges from 15 mm to 40 mm; the lowest value was obtained in the EEVC test for the passenger and the highest in the NCAP test for both the driver and the passenger.

VC values were between 0.03 m/s and 0.64 m/s. Both head and chest accelerations and also chest deflections and VC's ensure that the use of belt load limitation, in the test conditions described here, combined with air bag pressure control has no negative effects on injury measures.

Consideration of neck secondary risk in OOP - An evaluation of the new airbag was performed in static deployment tests using the Hybrid III 50° dummy, in order to measure the risk for the neck region. The results indicate that none of the IARV (11) levels was exceeded. Detailed results of these tests, as well as a biomechanical evaluation of this airbag can be found in Trosseille paper (12).

SUMMARY AND CONCLUSION

This study was initiated to address the rising risk of belt induced chest injuries in frontal impact. The starting point was the analysis of 290 frontal accident cases with vehicles that were equipped in France in the 1970's with a belt load limiter in front seats. The load limiter was based on a tear-webbing principle and was located near the upper belt anchorage point. This database shows that older people (≥ 50 years) may sustain severe chest injuries. Based on this experience a program was initiated at Renault with a view to reduce the shoulder belt load. In 1995, a belt restraint system called PRS was introduced; it comprises a combination of a pyrotechnic pretensioner located at the buckle, a clamp retractor and a steel part attached to the retractor and to the belt anchorage point. This steel part designed to deform at a given load, acts as a load limiter. This allowed to control the shoulder belt load at 6 kN level. Accident cases involving this type of restraint were collected and analyzed; in particular the behavior of the belt load limiter was investigated in relation with occupant injuries. The data from 37 cases with belted front seat occupants, are reported in this paper. Crash severities ranged from 35 km/h to 75 km/h. A significant part of this sample, 27% of occupants with age > 50 years, sustained minor to moderate chest injuries. The combination of belt pretension and a 6 kN belt load limitation appears to have benefits in reducing thoracic loads from the belt for this population; the 6 kN level is however not sufficient to cover the whole population. Thus, a further step in reducing the shoulder belt load is necessary. As this reduction will involve increased excursions of the head and the thorax, the belt load limitation has to be combined with an air bag.

The combination of an air bag and a 3-point belt restraint was discussed in various publications among them are the paper from Kompass in 1994 (4), the study of Kallieris et al. in 1995 (5) and Mertz et al. investigation in 1995 (6). According to the data discussed in Kallieris paper (5) and the mathematical simulation investigated by NHTSA (5) for a variety of crash conditions (frontal and rollover), crash severities and occupant sizes (5° , 50° and 95° percentiles) a threshold of 4 kN for the shoulder belt load limitation appears to be suitable for reducing the risk for thoracic injury, without negative consequences on other injury measurements.

From the experience acquired with the PRS a new approach in the occupant restraint system was developed. The PRS-11 combines a pyrotechnic buckle pretensioner with a 4 kN belt load limiter and an air bag specially designed with respect to 2 key factors: a deployment to the sides and from top to bottom in order to reduce the risk in OOP situations and a pressure control which operates when a certain load is applied by the thorax. One the major concern with the belt load limitation was the possibility to increase the injury risk for the head and for the thorax. A comparison of PRS II with a conventional restraint system was performed, for the driver , on the basis of offset frontal collisions involving the same car model. The data with PRS II show substantial reductions for the head and chest acceleration, HIC values and neck shear forces. Neck extension moment is increased with the PRS II but the value , 35 Nm, remains below the 57

Nm suggested IARV (11). Maximum chest deflection and VC obtained with PRS II were 25 mm and 0.09 m/s. These data were not compared to those of conventional system, as the corresponding data were not available for the same car model.

The PRS II was also evaluated in 3 frontal collisions: offset rigid barrier test at 56 km/h, offset deformable barrier test at 56 km/h (EEVC frontal impact test procedure), and in full rigid barrier test at 56 km/h (NHTSA frontal NCAP test). In the test conditions described here, the combination of a 4 kN belt load limitation with the pretensioner and air bag pressure control has no negative effects on injury measures.

ACKNOWLEDGMENTS

The PRS 1I principle was initiated by the Renault Safety Eng. Dept. Many people were involved in its development in particular vehicle platforms teams and advanced research groups. The authors would like to thank Michel Kozireff and his team from Autoliv France for their important contribution. This study was made possible thanks to the sled and crash tests performed at the Renault Lardy Test Center. Views and opinions expressed here are those of the authors and not necessarily those of Renault.

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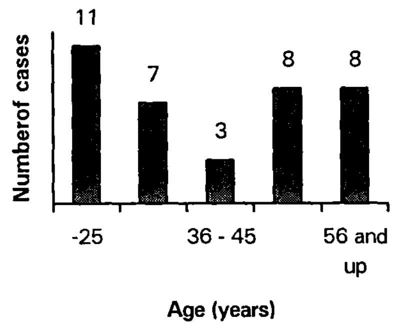
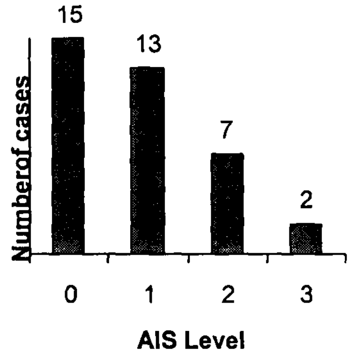
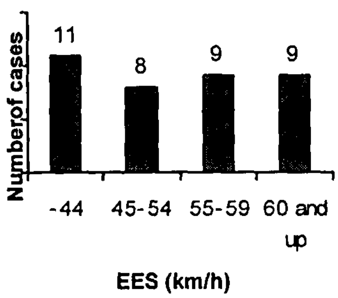


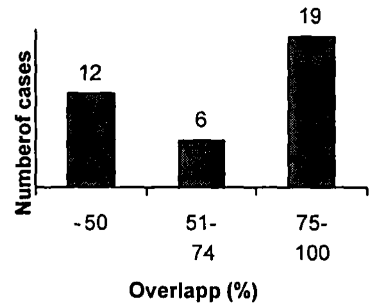
a) : Age distribution



c): Maximum thoracic AIS



b). Collisions' severity



d): Range of overlap

Figure A1 : Summary of data from accident investigations with frontal collisions involving the PRS.

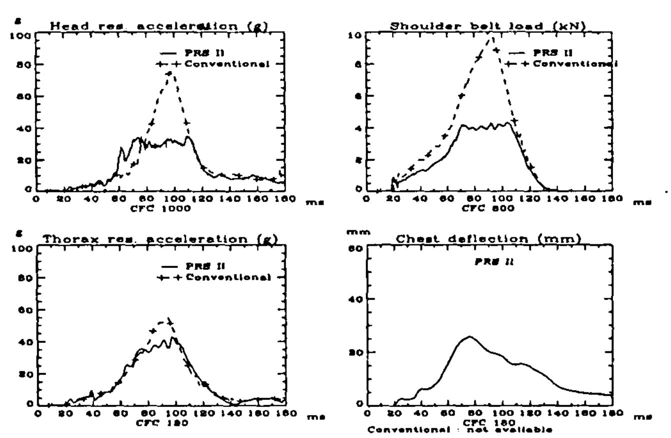


Figure A2 : Comparison of PRS II responses with those of a conventional belt + air bag system. Driver data from a 56 km/h offset rigid barrier test.

A COMPARISON STUDY OF ACTIVE HEAD RESTRAINTS FOR NECK PROTECTION IN REAR-END COLLISIONS

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Paper Number 98-S5-O-15

ABSTRACT

Neck injuries caused by rear-end collisions have become a major problem in traffic safety over the last two decades, however, surprisingly little effort has been made so far to improve car seat and head rest design. Several studies have shown, that whiplash injuries can be reduced by minimizing the gap between head and head restraint during the first phase of a rear-end impact. On the other hand, the requests for comfort from the car passengers limit the reduction of this distance. Various publications show that generally neither drivers nor passengers are aware of the necessity to adjust current head rests to the their head position. The conclusion is, the head rest should either be large enough to protect all occupants or should be automatically adjusted to protect all occupant sizes.

This study shows a comparison of different active head restraint concepts, which guarantee a reduction of the distance between head and head rest during a rear-end collision. In addition the size of the head rest is enlarged. Different concepts were validated by sled tests using Hybrid-III Dummies equipped with the newly developed TRID-neck. Also volunteer tests were performed to prove the effectiveness of the new concepts.

From these concepts, the inflatable head rest has proven to be the most efficient system. It is big enough to protect occupants up to the size of the 95th-percentile male, independently from the preadjusted position. If the head rest is positioned too low the upward increase in volume will be sufficient for occupant protection, whereas if the head rest is positioned too high the downward increase in volume will fill the gap between seat back and head rest. Thus the inflatable head rest concepts will be appropriate for almost all occupant sizes, independent from the preadjusted position.

The results have shown that relative motions between head and neck, as well as neck loads, were reduced significantly at all impact velocities and in all occupant positions. The inflation noise was reduced to a level that was hardly audible for the volunteers, at least when compared to the crash noise. Further sound pressure measurements in the cabine alpha showed a 99.99 % probability, that no hearing damage will occur.

This report shows that the inflatable head rest is a promising new concept that can reduce Whiplash Associated Disorders (WAD) following rear-end impacts especially in low speed collisions. It allows a comfortable head rest position and is suitable for almost all occupant sizes without the need for adjustment.

INTRODUCTION

So far the injury mechanism of soft tissue neck injuries, following rear end impacts has not been clarified even though a lot of research has been performed. Swedish research (Svensson 1993, Örtengren 1996, Boström 1996) claims that pressure effects in the spinal canal causes damage to spinal ganglia and is therefore responsible for Whiplash Associated Disorders (WAD). The injury is induced in a certain phase of the head neck movement, the so called S-shape. Several studies relate the injury to hyper-extension of the neck. Some studies indicate that the rebound phase could be responsible and explain the fact by increased seat belt usage, that may in turn increase neck loads in the rebound (vKoch, 1995). To summarize, it can be stated that any extensive relative motion between head and torso leads to loads exerted to the neck that are potentially dangerous. Therefore a neck protective system has to minimize the relative movement between head and torso during the whole impact and reduce neck loads to a minimum.

Safety concepts

An intensive study of different safety concepts was carried out. From these concepts the inflatable head rest was selected taking into account the following criteria:

- Feasibility
- Effectiveness of the system in regard to occupant protection
- Effort
- Maintenance and replacement

Mechanical Active Head Rests (Prototype 1 and 2)

An alternative to the inflatable active head rest are head rests containing a mechanism that is activated in the case of a rear end collision.

App. 30 different concepts were investigated and evaluated, taken into account the following parameters: function, effectiveness, cost, design, and safety. The two most promising concepts were built and tested.

<u>Prototype 1</u> consists of a sophisticated mechanism for enlarging the head rest. The elements of the head rest are sliced and interlock in the non-activated position. The head rest is thus compact and its dimensions are similar to the standard head rest.

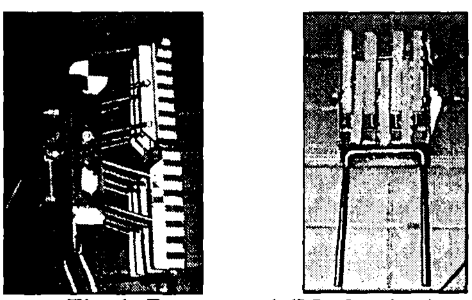

Fig. 1. Prototype 1 (Mechanism)

<u>Prototype 2</u> - The mechanism is arranged in a V-shape. Two telescopic rods, with a tension band between the extremities, are extended during deployment to enlarge the headrest. The tension band is simultaneously tightened. The mechanism is driven by pretensioned springs that are released after app. 30ms.

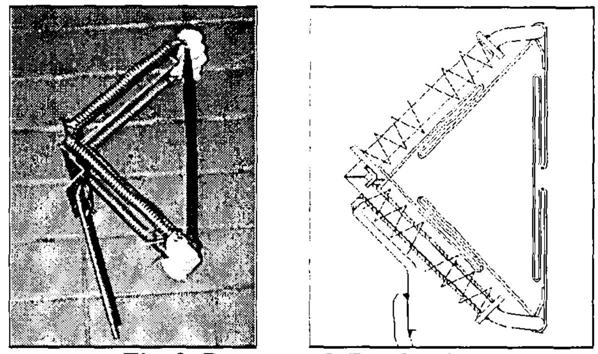

Fig. 2. Prototype 2 (Mechanism)

Both prototypes were tested in sled tests and compared to a standard head rest design.

Inflatable Head Restraint

After analysing the results of many math models a prototype of an inflatable head rest was designed. An airbag is integrated in a way that the whole head rest is enlarged (Fig. 3 and Fig. 4). The bag is covered by foam blocks so that the usual occupant comfort is guaranteed whilst keeping inflation noise to a non-injurious level. Fig. 4 shows the prototype of the inflatable head rest in the normal and in the expansed position.

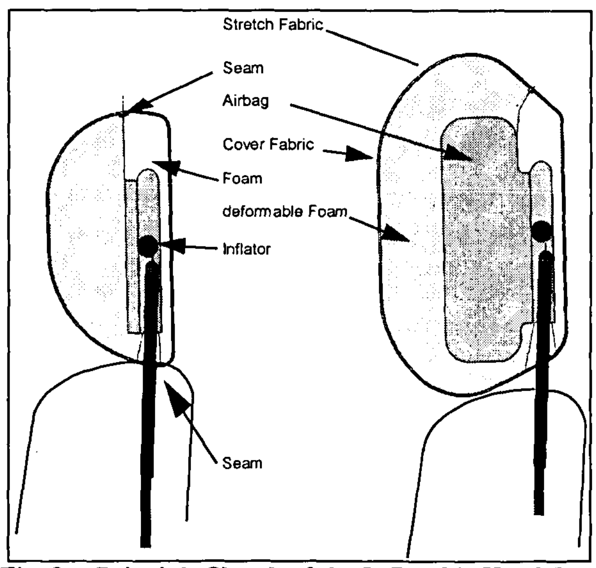

Fig. 3. Principle Sketch of the Inflatable Head Rest

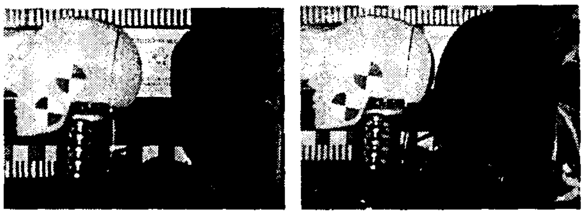

Fig. 4. Inflatable Head Rest in Non - Activated and Activated Position

METHODOLOGY

Computer mathematical simulations (MADYMO™) were performed to analyze the effectiveness of the system and detecting design parameters. From these simulations several prototypes were designed and tested in sled tests. The test setup and impact conditions were chosen comparable to common rear-end impact. Each test with an active head restraint system was repeated by a test using standard head rests. Conclusions were drawn by comparing the test results from the standard car seat with standard head rest to the new active head restraints.

NUMERICAL SIMULATIONS

A generic seat was modeled using the multibody crash simulation software MADYMO. Characteristics of the seat were gained by simple seat loading tests. As test subject, the validated MADYMO database for the HYBRID-III Dummy equipped with the TRID neck was used. As a first step the standard seat was simulated and used for validation of the model. Sled tests were performed to correlate the accuracy of the model.

The head rest of the validated model was then replaced by different concepts for active head rests (Fig. 5 shows the numerical simulation of the inflatable head rest). Initial results have shown that neck loads can be reduced simply by closing down the initial gap between head and head rest in the early stage of a rear impact.

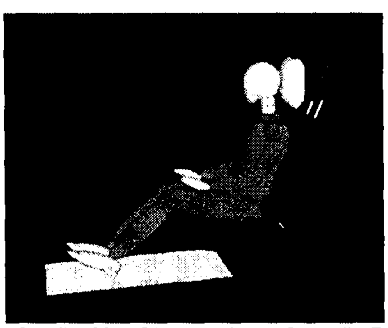

Fig. 5. MADYMO™ Simulation of the Inflatable Head Rest

The model parameters were optimized in order to gain design parameters for the active concepts, examples of which are the flow characteristics of the inflator, bag shape and size.

Several numeric simulations were also performed for the two mechanical concepts described before (Fig. 6). The activation process was optimized so that the neck loads were reduced to a minimum, without endangering the occupant by a high energy activation.

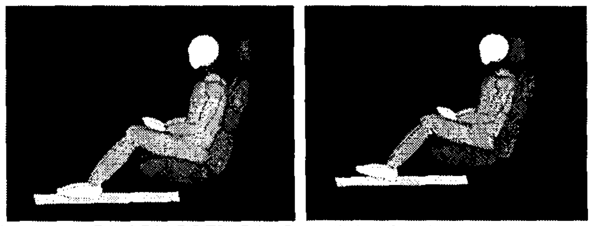

Fig. 6. MADYMO™ Model of Active Head rest

The numerical simulation showed in a very early stage of the research the most efficient way to reduce neck loads is to close down the horizontal gap between head and head rest and to adapt the height of the head rest to the occupant size. A further important result is that by the bending of the seat back (due to the loading of the torso) the head rest is moved away from the head, even if the initial horizontal gap is already rather low.

SLED TESTS

The sled tests have been performed at the University of Graz in Austria. The sled buck is driven by a bungy and the crash pulse is simulated with a friction brake system.

For the first series with the inflatable head rest, the inflator was not integrated in the head restraint but was designed as a gas container with an adjustable filling pressure (Fig. 7). It was necessary to adjust the gas volume in order to allow for a fast inflation as well as to modify the pressure in the airbag after inflation.

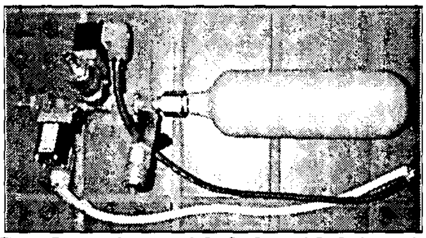

Fig. 7. **Gas Container with Solenoid driven Valves**

The airbag was activated by an adjustable trigger system that allows for variation of the ignition time. Usually an ignition time of 30ms was set.

DUMMY TESTS - Active head rests were tested in several sled tests under different impact conditions. Test object was a 50%ile Hybrid-III dummy equipped with the so-called TRID neck. This neck - developed by TNO - has proven to be more biofidelic than the standard Hybrid-III neck (Geigl 1995, Svensson 1993, Thunissen 1996).

The main parameters of the tests were:

- initial position of head rest
- sled impact velocity

Fig. 8 shows the comparison of the max. (3ms) head acceleration of the tests with the first inflatable head rest prototype.

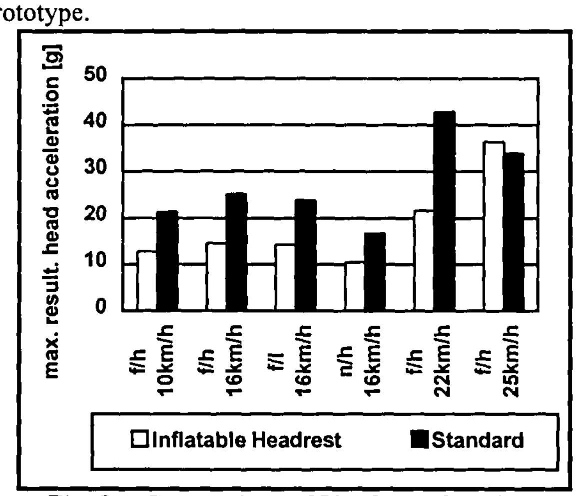

Fig. 8. Comparison of Head Accelerations

Tests were performed at different sled impact speeds (10, 16, 22, 25 km/h) and different initial head rest positions (f...far[1], n...near[2], h...high[3], l...low[4]).

[1] horizontal distance head to head rest: 80mm

[2] horizontal distance head to head rest: 0mm

[3] vertical distance top of head to top of head rest: 30mm

[4] vertical distance top of head to top of head rest: 80mm

Head accelerations were reduced significantly by 30% to 50%. Only at higher speeds is the benefit reduced due to the seat back yielding.

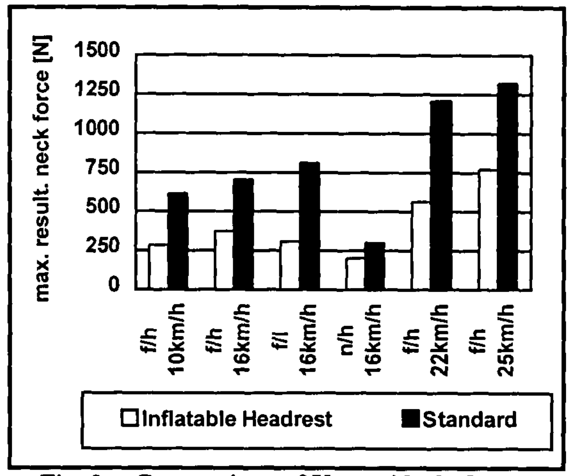

Fig. 9. Comparison of Upper Neck Forces

Maximum resulting neck forces and moments were also reduced significantly (Fig. 9 and Fig. 10).

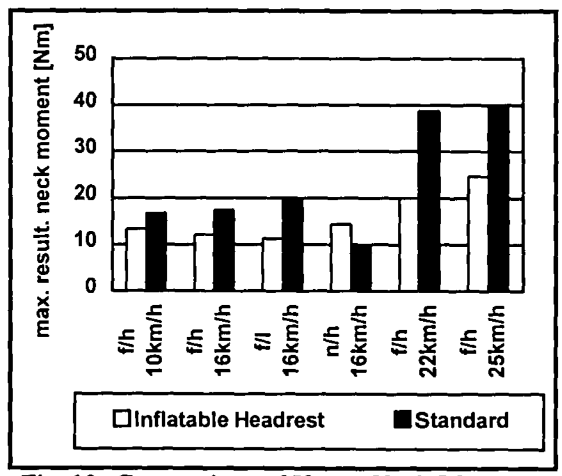

Fig. 10. Comparison of Upper Neck Moments

Recently, Swedish research has proposed a new criterion for Whiplash Associated Disorders (WAD) following rear-end collisions. This criterion is not validated on human beings - so no critical limit of the Neck Injury Criterion (NIC) exists. This criterion was calculated for all tests according to the formula:

$$NIC = 0.2 \cdot a_{rel} + v_{rel}^2$$

a_{rel} ...relative acceleration between torso (T1) and head (C1)

v_{rel}...relative velocity between torso (T1) and head (C1)

The NIC was defined as the maximum value at the so called maximum retraction phase (immediately before the head rotation starts). Fig. 11 shows results of the NIC calculation. The NIC is reduced significantly at all impact conditions, especially at medium speeds. Even in tests with initial head to head rest contact, the inflatable head rest is beneficial because of the head rest displacement due to the bending of the seat back. This effect is compensated by the inflatable head rest.

As mentioned before, at higher speeds the benefit of the inflatable head rest is lower, because of seat back collapsing. It is still possible to compensate the "displacement" effect of the head rest.

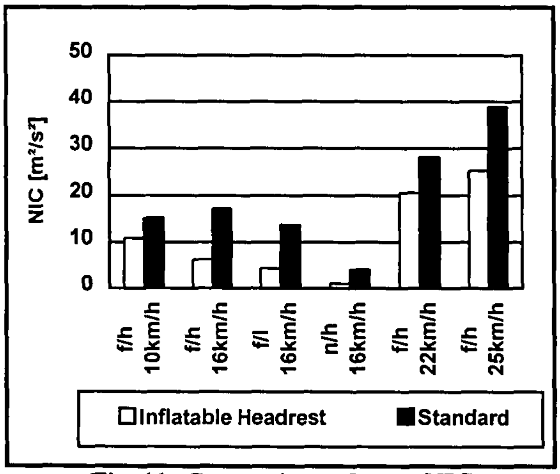

Fig. 11. Comparison of max. NIC

Fig 12 and Fig 13 show the results and the kinematics of a dynamic test with a ΔV of 16 km/h. The initial head rest to head distance was in this case 80 mm. The reduction of relative head motion can be observed in Fig. 12. The relative head rotation is reduced significantly in tests where the head rest is unfavorable positioned for the occupant.

Fig. 13 shows the comparison between the inflatable head rest and the standard head rest. The inflatable head rest is activated just in time (approximately 50 ms after first contact), so that an extensive relative head motion can be prevented.

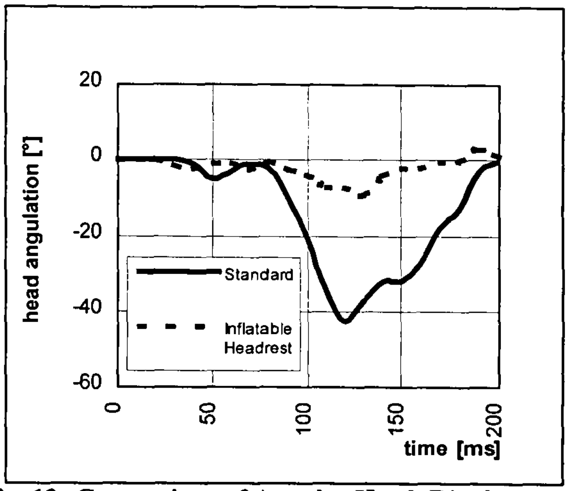

Fig. 12. Comparison of Angular Head Displacement

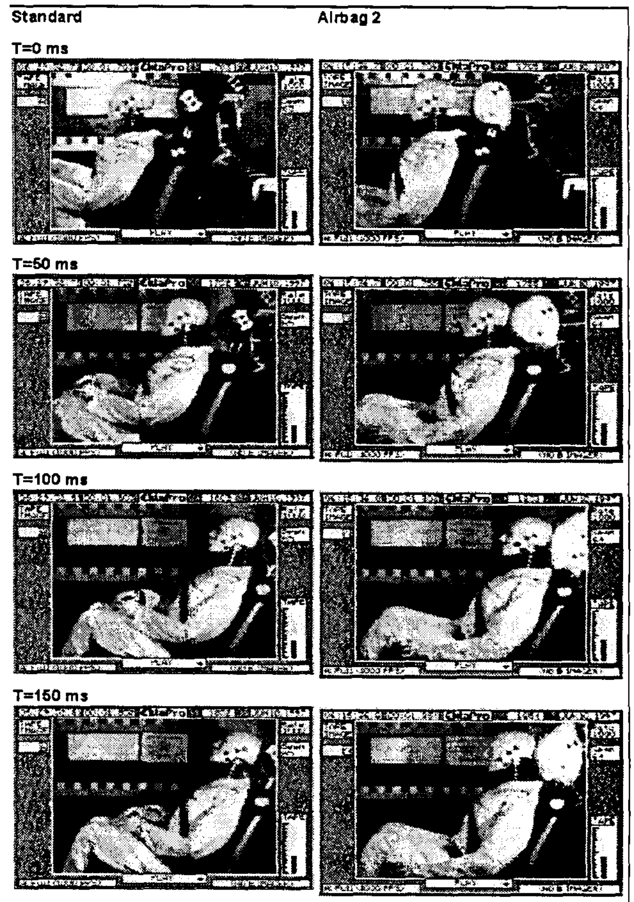

Fig. 13. Comparison of Standard and Active Head Rest

VOLUNTEER TESTS - In order to prove the harmlessness of the system several volunteer tests were performed. The volunteers were not instrumented but asked to tell about their subjective feeling to the activation of the inflatable head rest. An impact speed of app. 10 km/h was chosen. No volunteer complaints of any injuries were noted immediately after the test nor some days later. The inflatable head rest was felt subjectively comfortable, no inflation noise could be observed by the subjects, because the crash noise seemed to be louder than the inflation noise. Even in a test where the head was in direct contact to the head rest no negative effect could be observed. In Fig. 14 some sequences from volunteer tests are illustrated.

Fig. 14. Volunteer Tests at Different Head Rest Positions

Sled tests with a stored gas inflator - as a next step, the inflator was integrated into the head rest. The inflator consist of a bottle filled with compressed air (special mixture of inert gas) and an opening mechanism. The results of sled tests, which have been done in the same configuration like before (ΔV 16 km/h, 80 mm distance head to head rest) can be observed in Fig. 15. NIC, neck moment and forces of the internal inflator prototype were reduced to a level that is comparable to the external inflator. An optimization of the inflation process itself could further reduce the loads exerted to the neck.

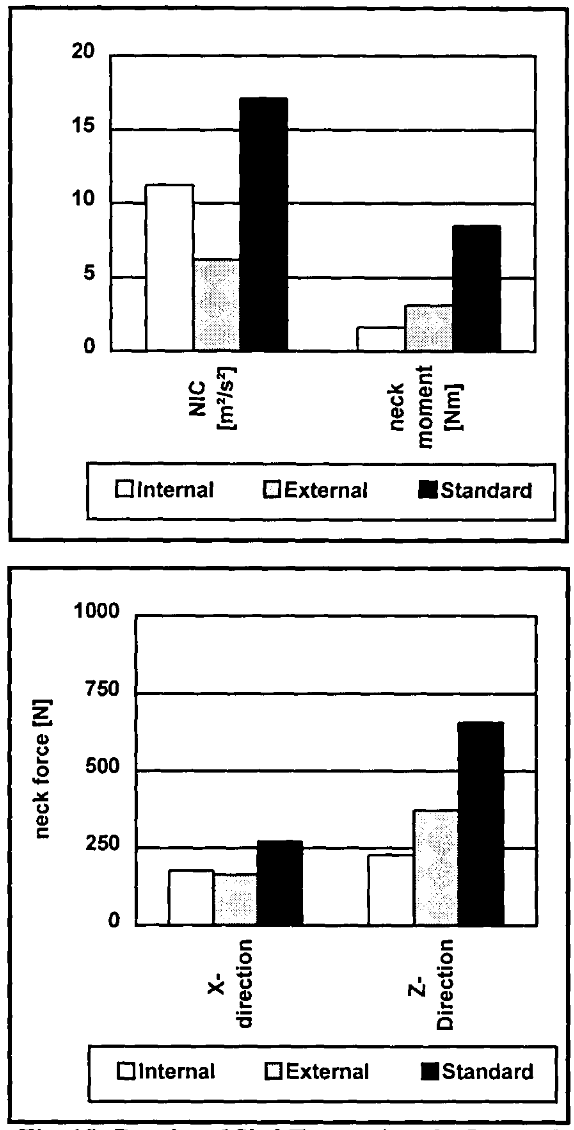

Fig. 15. Results of Sled Tests using the Internal Inflator

Head Rest Design with a Pyrotechnical Inflator

A pyrotechnical inflator (Fig. 16) has also been tested in a prototype head rest.

The inflator and the airbag are attached to the plastic element of the head rest. The bag will be covered by a foam element to allow comfort and good feeling for the occupant, as well as damping the deployment noise and the contact forces. The volume increase of the "class A" cover material is realized with 2 different approaches, either a tear seam with elongation fabric or a stretchable cover material over the entire head rest. Dynamic tests also show with this inflators benefits in occupant loads and improved dummy kinematics.

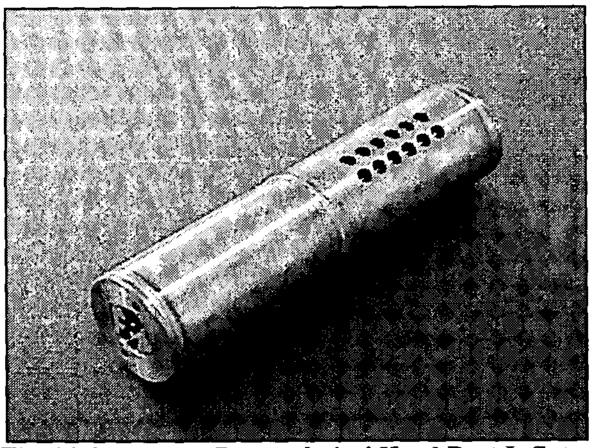

Fig. 16. Prototype Pyrotechnical Head Rest Inflator

DEPLOYMENT NOISE

Sound pressure measurements have been performed with the latest design status, as described earlier. That means the head rest was equipped with a pyrotechnical inflator. The measurement was made in a cabine alpha and showed acceptable results (Table 1). By looking to all the static and dynamic tests with this design, the deployment noise was absolutely not felt dangerous or showed any evidence of hearing damage.

Table 1.

Sound Pressure Measurements from the Cabine Alpha

	EAR	DURATION TIME [ms]	MAX. LEVEL [dB]
A - Duration	Left	3,5	147,4
	Right	2,8	149,8
B - Duration	Left	14,2	147,7
	Right	13,9	149,9

CONCLUSION

The inflatable head rest has proven to be a promising alternative for active head restraint systems. Effectiveness in regard to occupant loads and kinematics is excellent and also the deployment noise has been reduced to a non dangerous level. In sled tests it has proven to work safe and efficient. No negative effects to the occupant could be observed. Also there are no restrictions for comfort, styling and safety due to the fact, that the airbag and the inflator is below the styling cover and the foam bolster of the head rest.

Active head rests on a mechanical basis are more complicated in design and function. The mechanism has to be highly sophisticated in order to avoid larger head rests. This means that a lot of additional parts are required compared to the inflatable head rest. For the described mechanical solutions the optimization of the operating parts is quite difficult. Also a too aggressive mechanical system results in additional neck loads, especially in situations where the head is close to the head rest, compared to the inflatable design, where serious loads to the occupant were never reached in a various number of tests in different head to head rest positions were found.

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ESTIMATION OF OOP FROM CONDITIONAL PROBABILITIES OF AIRBAG FIRE-TIMES AND VEHICLE RESPONSE

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ABSTRACT

The airbag can fire at any given time during a crash. To qualitatively and quantitatively address the probabilistic nature of the airbag fire-time as a result of a crash, a statistical data based model was used. Two models were constructed: one was based on rigid barrier impacts and the other used offset deformable barrier impacts. These models were developed previously and some of the preliminary results were presented at the 1998 SAE conference in Detroit. Since that time the models have been refined by inclusion of additional data, and the results of the refined models were compared to the results from the previously constructed models. The models were used to address the effects of raising the "threshold velocity" and the risks of an occupant contacting the airbag module as a result of late firing. Although the individual numerical values have changed, the indicated general trends remain the same. Raising the "threshold velocity" may or may not decrease the number of occupants on the module, depending on the accuracy of NASS/CDS and fire/no-fire as a function of velocity (c-censor*), but it appears to reduce the effectiveness of the airbag when it does fire. The model indicates that decreasing the width of the c-censor, i.e., delta V from no fire to all fire, may be useful in reducing the number of occupants on the module without decreasing the effectiveness of the airbags.

* the term c-censor refers to censoring of the data in terms of airbag firing. To distinguish sensor from censor when speaking the term c-censor is used.

INTRODUCTION

A statistical model was developed to estimate the occupant position at the time the airbag fires in Ref. 1. Inputs to the model were: 1) the airbag fire-time probability surface representing the frequency of the probability of airbag fire-time as a function of time and impact velocity; 2) the occupant displacement distribution surface representing the displacement histories at any given velocity; 3) the accident distribution representing the accident percentage at any given velocity; and 4) the c-censor representing the airbag firing percentage at any given velocity. The outputs were the number of occupants at any given position at the time the airbag fires. This is a data based model and the surfaces and distribution curves mentioned above were constructed from data which were obtained from multiple sources, such as Insurance Institute for Highway Safety (IIHS), Transport Canada (TC), National Highway Transportation Safety Administration (NHTSA), and National Automotive Sampling System/ Crashworthiness Data System (NASS/CDS).

When the airbag fire-time probability surface, the occupant's displacement probability surface and the initial position distribution are developed, the model can then estimate the number of occupants at a given distance from the airbag module at any given impact velocity. This estimate is computed by using the accident distribution and a c-censor assumption. In the previous study, the accident distribution and the c-censor played important roles in determining the estimates of the number of occupants at any given distance from the module. As mentioned above, the accident distribution is objective, since it is obtained from collecting the accidents in the field. The c-censor characteristics are, however, variable. Its performance can be controlled through the airbag sensor algorithm. The effect of the c-censor performance on the number of occupants on the module when airbag fires is also investigated in this study. It is believed that this study provides some theoretical basis that may be useful in estimating a preliminary aspects of airbag sensor performance in the field.

The following conclusions were drawn from the previous paper [1]. 1) A later airbag firing will result in more occupants on the module when the airbag fires. 2) The model developed from the rigid barrier impacts indicates that it is unlikely that the occupants will contact the airbag module when the airbag fires. 3) The effects of changing the "threshold velocity" is indeterminate, because threshold is poorly defined. 4) The effect of changing c-censor velocity distribution for the airbag depends on the number of crashes at a given velocity and the probability of firing for all velocities. 5) The effect of tightening the band of the c-censor velocity distribution may be useful in decreasing the number of occupants on the module without decreasing the effectiveness of the airbag.

We anticipated that the results predicted in [1] would change once a significant amount of new airbag fire-time data became available. This was thought probable because new data would affect the construction of the airbag fire-time distribution surface. With the new data, although some changes were noted, the overall conclusions were similar. The later the airbag fires, the more occupants will be on the module at the instance of airbag firing. The trends of the number of occupants on the module as a function of increasing the c-censor velocity or shifting the accident distribution curve are the same as those in the previous paper [1]. In addition, this paper provides an estimate of the number of occupants on the module for different initial seating positions, i.e. the distance from the airbag module. These results are applicable to the occupants on both driver and passenger sides.

METHOD

The method used in this paper is the same as the one used in [1]. In order to get the estimated number of occupants at a given distance from the module, the airbag fire-time probability surface, the occupant's displacement surface, occupant's initial position distribution, the accident distribution curve, as well as the c-censor are necessary. The airbag fire-time probability surface is constructed by curve fitting techniques. For each velocity, the parameters for the best fit of a chosen function are obtained. The parameters of the fitting function family are then used to generate a surface. The occupant displacement surface is constructed by using a simple analytical model and the vehicle displacements. The simple analytical model treats the occupant as a free moving point mass while the vehicle decelerates. The occupant's initial position distribution and its standard deviation were obtained from TRW, IIHS and the University of Michigan Transportation Research Institute. The accident data were collected from the NASS/CDS. The data were then used to define a distribution function through a curve fitting technique. The c-censors, which are defined as the percentage of airbags that fire at a given velocity, illustrate the probabilistic nature of whether the airbag fires at that given velocity. The c-censors can be constructed using frontal barrier impact test data or offset test data. However, this may not represent the real world conditions. The reason is that even for the same type of impact tests conducted in the laboratory, different c-censors can be obtained for different cars. Crashes in the field are much more complicated. They consist of uncountablely different types of crashes with a wide variety of vehicles.

The model uses the airbag fire-time surface, occupant displacement surface, their standard deviations and the occupant's initial seating position to produce the probability that the occupant is at a given position or less from the airbag module. This probability includes the possibility of occupants' contacting the module when the airbag does not fire. The process of censoring the data will remove the effect of the airbag not firing. The estimation of the number of occupants on the module can then be finally determined by including the accident distribution.

Since the publication of the last paper, additional airbag fire-time data have been obtained. The data are for 25 mph, 35 mph, and 40 mph offset impacts. New fire-time data for 40 mph offset tests exhibit a distribution similar to the data used in the previous paper. However, fire-time distribution characteristics for the 35 mph and 25 mph show some differences. Efforts have been made to find another fitting function family. However, the lognormal function is still found to be the best fit. Figures 1a, 1b, 2a and 2b show those differences. Due to an insufficient amount of data used in 25 mph offset tests in the

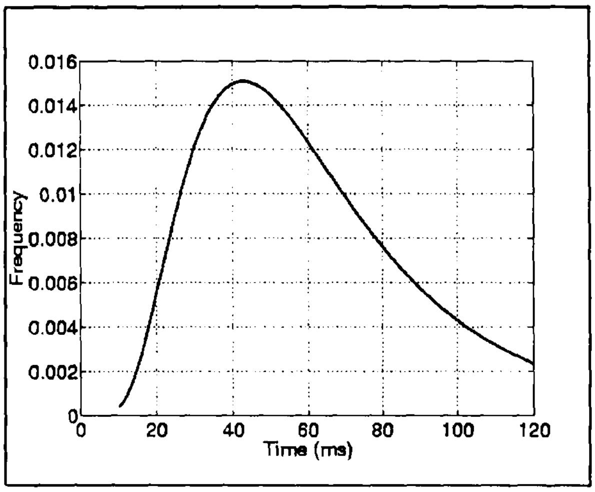

Figure 1a: Airbag fire-time for 25 mph offset impacts using previous data

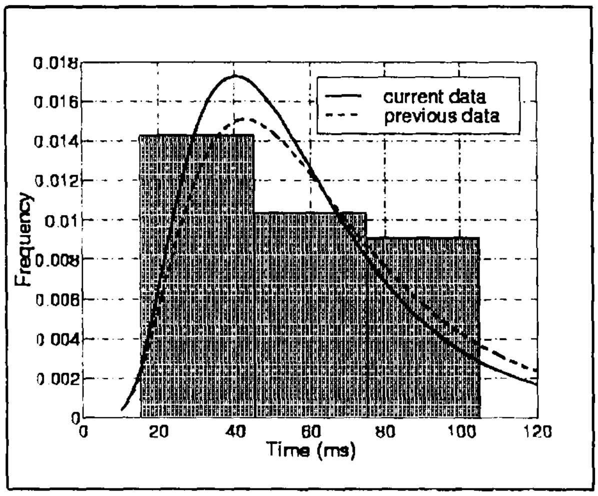

Figure 1b: Airbag fire-time for 25 mph offset impacts

previous paper, the histogram could not be constructed properly. Figures 2a and 2b indicate that the 35 mph fire-time distribution is similar to the previous results, however, there are some differences in the shape and peak. The figures also indicate that the most probable fire-time for 35 mph offset tests is around 27 or 28 ms. The times when peaks occur for the 25 mph offset impacts show the differences for both sets of data. The old set of data indicates that the most frequent fire-time is 43 ms, while it is 39 ms for the new set of data, which indicates that there are less late firings.

In order to estimate the number of occupants at a given position, the accident distribution curve and the c-censors are required by the model. The accident distribution and c-censors which have been used in [1] will be used in this paper. As shown in [2], it is possible that NASS/CDS underestimates the velocity in the accident distribution to some degree. To

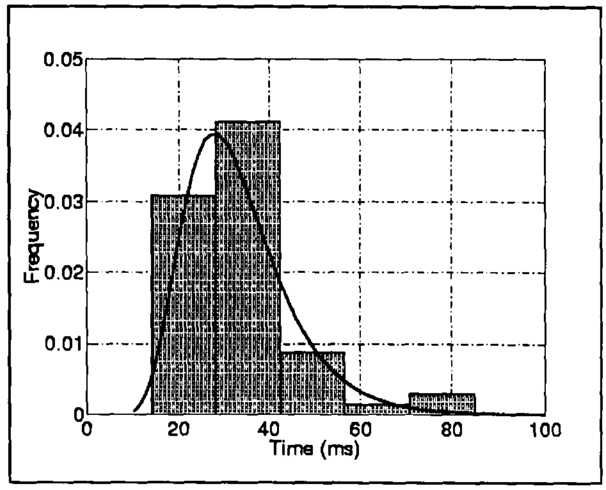

Figure 2a: Airbag fire-time for 35 mph offset impacts using previous data

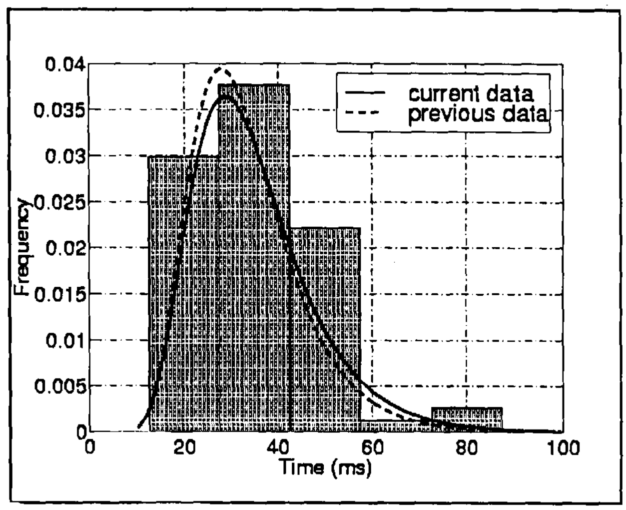

Figure 2b: Airbag fire-time for 35 mph offset impacts

evaluate this effect, the accident distribution is parallel transported, i.e., shifted, by +3 mph.

Figure 3 shows the accident distribution curve and its shifted curve. A sum of Hyperbolic functions were used to fit the accident distribution. The shifted accident curve will be used to illustrate the influence of underestimation on the number of occupants on the module. Four c-censors are shown in Figure 4 which were designed in an attempt to capture the variation of real world fire/no-fire probability. It can be seen that those c-censors have different cut off times for no airbag firing and all airbag firing times. Field estimated c-censor #1 is an attempt to capture fire/no-fire distribution in the field. It has a wider range in velocities from no fire (7 mph) to all fire (20 mph) than that from the barrier impacts. Field estimated c-censor #2 is based on field estimated c-censor #1, but it has a higher all fire velocity of 25 mph. Barrier estimated c-censor is based on the data

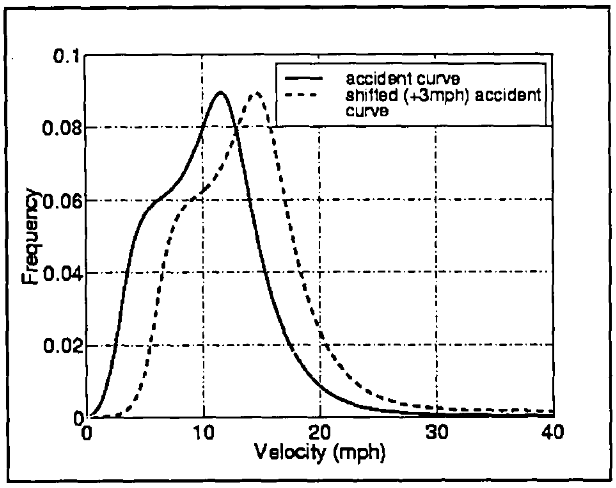

Figure 3: Accident density as a function of impact velocity

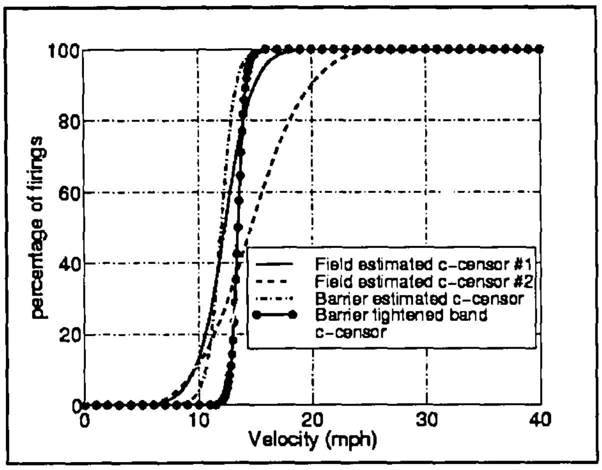

Figure 4: Four c-censors used in the study

from frontal rigid barrier impact tests. It has a narrower band of velocities from no fire to all fire compared to the Field estimated c-censors. The Barrier tightened band c-censor was constructed to see the effect of raising no fire velocity while keeping all fire velocity the same.

RESULTS

The influences of the accident distributions, the fire/no-fire c-censors, as well as occupant's initial seating positions have been investigated in this study. In the previous paper, it was found from the model developed for the rigid barrier impacts that it is unlikely that any occupant will contact the airbag module when the airbag fires and the same results were found with the additional data. Therefore, the following results are only for the offset type crashes with unbelted occupants. It should be mentioned that the term raising "threshold velocity" by +2 mph, as used in this paper, means parallel transporting of the c-censor velocity by +2 mph.

Figure 5 shows the percentage of occupants on the module as a function of impact velocity. It should be noted that the mean fire-times in data sets [1] are

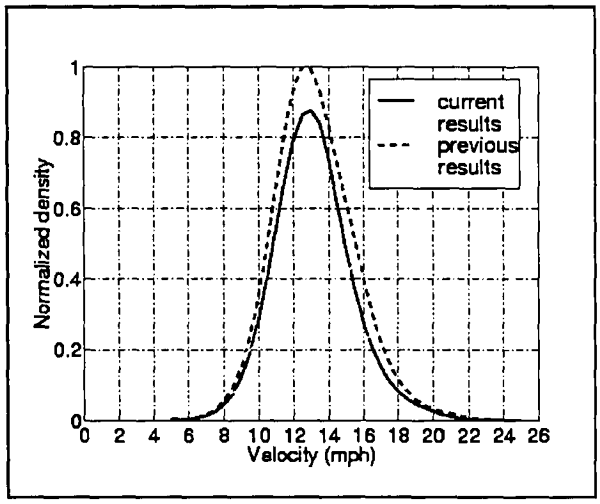

Figure 5: Normalized density of the occupants on the module

later than those shown in the new data sets. The results based on the previous data sets indicate that there will be more occupants on the module when the accident distribution and the c-censor assumptions remain the same. The figure also shows that the velocity at which the peak occurs is higher with the current data sets than that with the previous data.

To determine the effect of changing the c-censor on the occupant assessment values for the 50th percentile "in position" male occupants, over 200 crash simulations were run using MADYMO V5.2. More simmulations were conducted in this study than that in the previous study. These simulations include 30 mph, 14 mph rigid barrier impacts and 40 mph, 35 mph, and 25 mph offset impacts. At each impact velocity, three different vehicle configurations were simulated, representing small, medium, and large vehicles. Some vehicle simulations were run with two different airbag configurations and some were run with three different airbag configurations. The results of these simulations are summarized in Table 1, which shows that the range of the assessment values increases compared to the previous study. Although the results presented are different from the previous results [1], the trends are the same.

As mentioned in the previous section, the c-censor and the accident distribution are important for estimating the number of occupants at a given distance from the airbag module. A complete tabulation of results for the effects of the c-censor and the accident distribution on the number of occupants on the module is presented in Tables 2 to 4.

Table 1. Increase of assessment values as a result of parallel transporting c-censor by +2 mph

HIC		Chest		
15ms	30ms	Acc. (G's)	Compression (in)	travel (in)
50~300	50~500	0~21	0.1~0.6	0.1 ~2

Column 1 of Table 2 shows the number of occupants on the module at the initiation of airbag deployment for each of the 4 c-censors. The results are non-dimensionalized by the results obtained for the "field estimated c-censor #1", which the model estimates to be in the range of 200 to 600 occupants. The second data column of Table 2 shows similar results for the case where the c-censor velocity distribution values for each of the c-censors was parallel transported by +2 mph. The data here was normalized by the corresponding numerical results from the first column. The table shows that the number of occupants on the module for all the c-censors are reduced when the c-censor velocity is raised. The "barrier tightened band c-censor" shows the greatest reduction. It should be noted that the total HARM may not necessarily be reduced if the results shown in Table 1 are also considered.

Table 2. Percent of of occupants on the module due to effect of parallel transporting c-censor by +2 mph

	percent with respect to field c-censor#1	resulting percent by parallel transporting c-censor by +2 mph
field estimated #1	100%	71%
field estimated #2	57%	80%
barrier estimated	99%	73%
barrier tightened band	49%	47%

As was noted in the previous section, the accident rate was expressed as a function of velocity based on the NASS/CDS data. The model then was used to determine the sensitivity of the results to the variation in the NASS/CDS impact velocity estimates. Table 3 shows the number of occupants on the module using the accident density curve obtained by shifting the curve, as shown in Figure 3, by +3 mph, i.e. adjusting the data as if the NASS/CDS velocities were consistently underestimated by +3 mph. For reference, the data in the first column of Table 2 is taken and the second column is again normalized by the corresponding numerical results from the first column. The results show that the number of occupants on the module are significantly increased when the accident density curve is shifted to the right, i.e. if the NASS/CDS impact velocities were considered to be underestimated.

Table 3. Percent of occupants on the module due to the effect of shifting the accident density by +3 mph

	percent with respect to field c-censor #1	resulting percent by shifting accident density by +3 mph
field estimated #1	100%	133%
field estimated #2	57%	134%
barrier estimated	99%	134%
barrier tightened band	49%	183%

Table 4 shows similar results for the case where the accident density curve is shifted by +3 mph (as in Table 3) and the c-censor velocity distribution is parallel transported by +2 mph (as in Table 2). The reference data in the first column is from Table 3, and the data in the second column is again normalized by the corresponding numerical results from the first column. The results in the second column show that although again the numbers are

Table 4. Percent of occupants on the module due to the effects of both shifting accidents density by +3 mph and changing c-censor by parallel transporting +2 mph

	resultin g by shifting acciden t curve by +3 mph	resulting percent by both shifting accident density by +3 mph and parallel transporting c-censor V by +2 mph
field estimated #1	133%	94%
field estimated #2	134%	98%
barrier estimated	134%	96%
barrier tightened band	183%	70%

reduced by changing the c-censor velocity, the reduction in this case is much less than that shown in Table 2. Therefore, it is possible that the number may actually increase if the accident density is underestimated by some value more than +3 mph.

To facilitate comparison of the results from the previous and the current model, Table 5 presents again the data shown in Tables 2, 3, and 4, respectively, together with the additional corresponding data from the previous study. A review of the Table 5 shows that the trends indicated by both the old and current model are the same, even though individual values have changed.

The effect of the occupant's initial positions on the number of occupants on the module is shown in Figure 6a and Figure 6b. It is assumed that each initial position is not exact. Instead, there is a Gaussian distribution with the initial positionn representing the mean value. Two types of initial position distribution are considered: one has its standard deviation of 1 mm which means that the population sits very close to the position of a given x-value. The other is with a standard deviation 50 mm which means all the population sits on the average at the position of a given x-value, but some will sit behind and some will sit in front of that average position. The figures show that the number of occupants on the module are continuously decreasing as the mean initial distance from the module increases. If an occupant initially sits 700 mm or more away from the airbag module, it is, as a results of late firing, almost impossible for the occupant to be on the module when the airbag fires.

The results in Figure 6a are obtained by using Field estimated c-censor #1 and those in Figure 6b by Field estimated c-censor #2. For a given mean initial position, a higher value of standard deviation will give a greater number of occupants on the module.

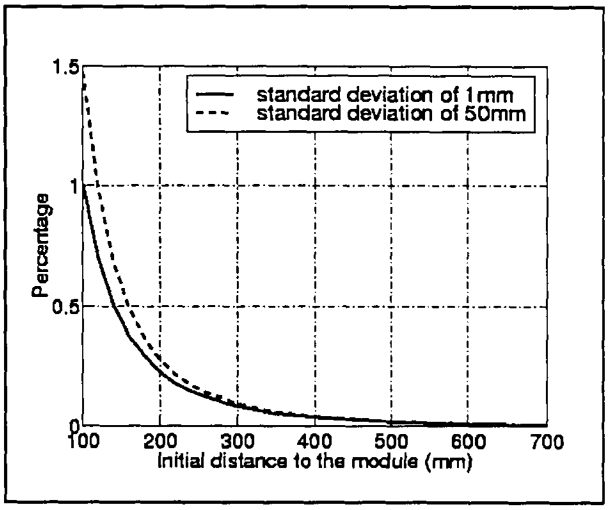

Figure 6a: Percentage of the occupants on the module using Field estimated c-censor #1

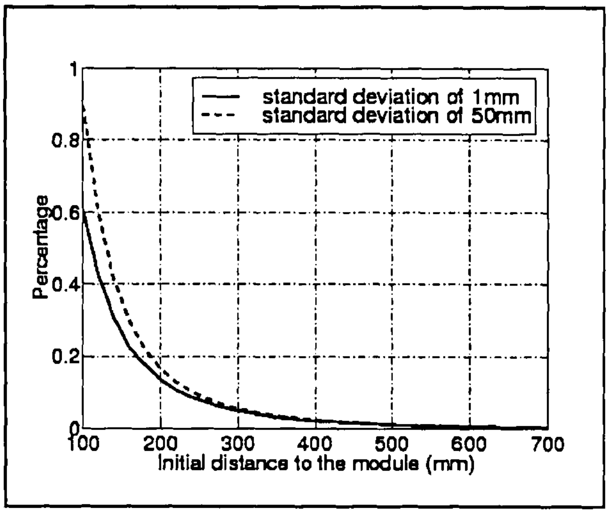

Figure 6b: Percentage of the occupants on the module using Field estimated c-censor #2

Table 5. Comparison of the percent of occupants on the module between current and previous results

	percent with respect to field c-censor #1 (current,previous)	resulting percent by parallel transporting c-censor by +2 mph (current,previous)	resulting percent by shifting accident density by +3 mph (current,previous)	resulting percent by both shifting accident density by +3 mph and parallel transporting c-censor V by +2 mph (current, previous)
field estimated #1	100% ,100%	71% , 70%	133%, 120%	94%, 92%
field estimated #2	57% , 56%	80% , 75%	134%, 129%	98%, 87%
barrier estimated	99% , 99%	73% , 80%	134%, 120%	96%, 97%
barrier tightened band	49%, 56%	47% , 52%	183%, 150%	70%, 77%

Field estimated c-censor #2 gives a significantly lower number of the occupants on the module compared to Field estimated c-censor #1. For example, if the average initial seating position for the small females is 270 mm from the module, the percentages of such occupants on the module are 0.12 (with standard deviation of 50 mm) and 0.1 (with standard deviation of 1 mm) for the c-censor #1. If the c-censor #2 is used, those percentages will be 0.074 (with standard deviation of 50 mm) and 0.064 (with standard deviation of 1 mm), respectively.

These figures can also be used to estimate results for occupant groups of various sizes. If the mean position and standard deviation are known, the percentage of the number of occupants on the module can be computed. For example, if the small occupants sit at a mean initial position of 270 mm, then the percentage of the number of the small occupants on the module can be considerably greater than that for the 50th percentile males who sit at a distance of 400 mm. In addition, similar estimation can be made for the occupants on the passenger side.

Figures 7a, 7b and 7c show that raising the c-censor "threshold velocity" decreases the number of occupants on the module. In Figure 7a, the probabilities are obtained from the airbag fire-time surface, occupant displacement surface and occupant's initial positions. However, the results are obtained without considering the accident distribution and the c-censor. The probabilities in Figure 7b, labeled "the probability with accident curve", are the

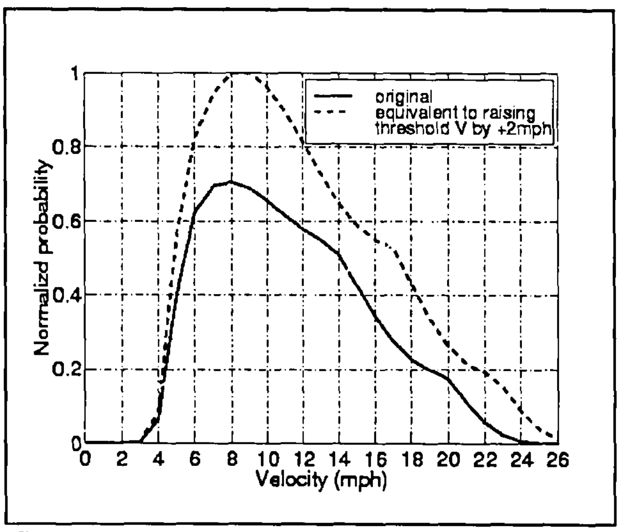

Figure 7a: Probability of the occupants on the module

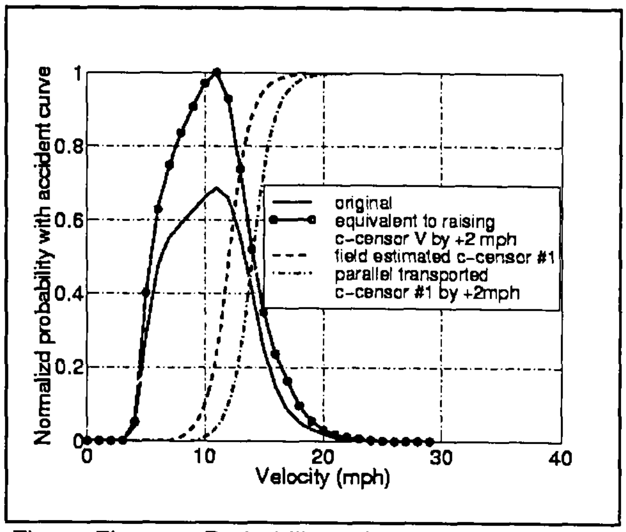

Figure 7b: Probability (with accident curve) of the occupants on the module and Field estimated c-censor #1

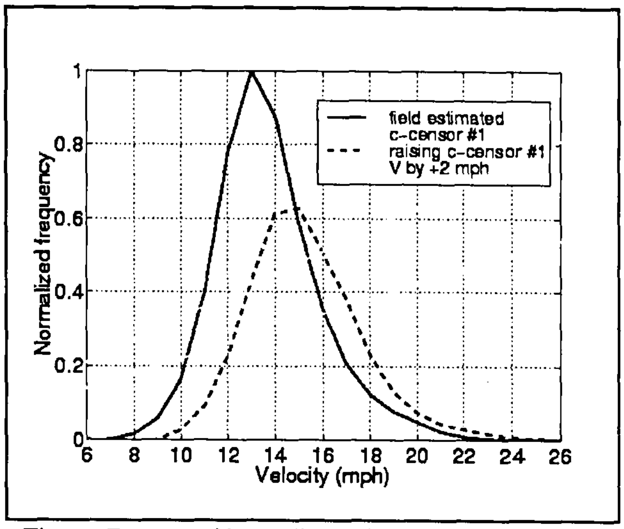

Figure 7c: Normalized density of occupants on the module using Field estimated c-censor #1

probabilities in Figure 7a multiplied by the accident distribution curve at each corresponding velocity. As the "threshold velocity" is increased, two factors will affect the number of occupants on the module. One is the fire-time distribution as a function of velocity. This factor tends to increase the probability of the number of occupants on the module because its effect is equivalent to later firing. Therefore, this probability increases as shown in the Figure 7a.However, the other factor, parallel transporting the c-censor in the direction of increasing the velocity, tends to decrease the number of occupants on the module. By parallel transporting the c-censor velocity by +2 mph, as shown in Figure 7b, the number of no fires increases, and hence, the number of the occupants on the module are significantly reduced when the airbag fires. The multiplication of the two curves, i.e., the probability with the accident curve and the c-censor curve, is shown in Figure 7c. It indicates that the numbers from raising the "threshold velocity" are less than that from without raising the "threshold velocity".

Figures 8a and 8b show the effect of accident distribution on the number of occupants on the module. The curve with the solid line represents the probability multiplied by the original accident distribution, while the curve with the dashed line represents the probability multiplied by the shifted (by +3 mph) accident distribution. It can be seen that the probability with shifted accident distribution shows greater area under the normalized probability-velocity curve. This results in a greater total number of occupants on the module after multiplying the c-censor values at corresponding velocities (Figure 8b).

It should be noted that raising c-censor velocity by +2 mph will not always reduce the number of occupants on the module. Figures 9a and 9b illustrate a case where raising the c-censor velocity by +2 mph will increase the number of occupants on the module. In this case, the accident distribution is

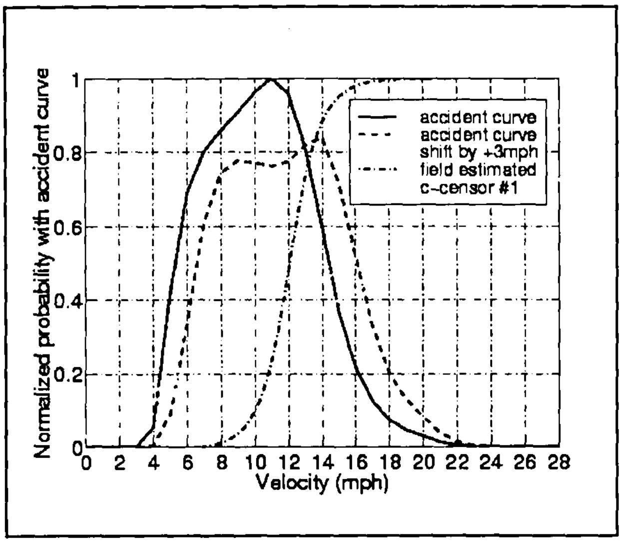

Figure 8a: Probability with accident curve of the occupants on the module and Field estimated c-censor #1

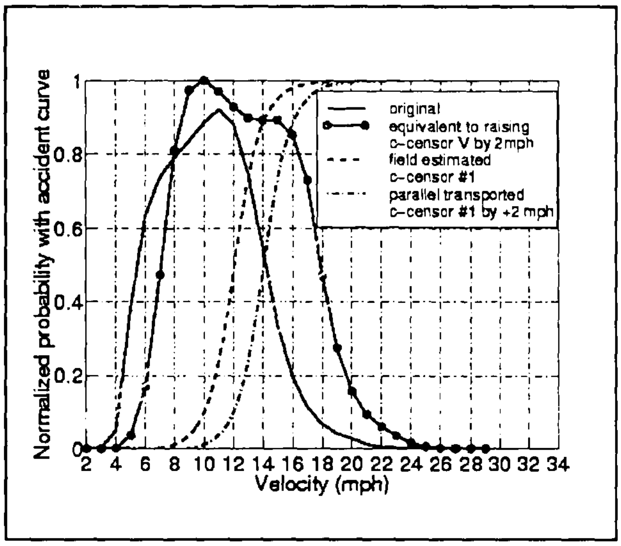

Figure 9a: Probability with accident curve of the occupant on the module and Field estimated c-censor #1

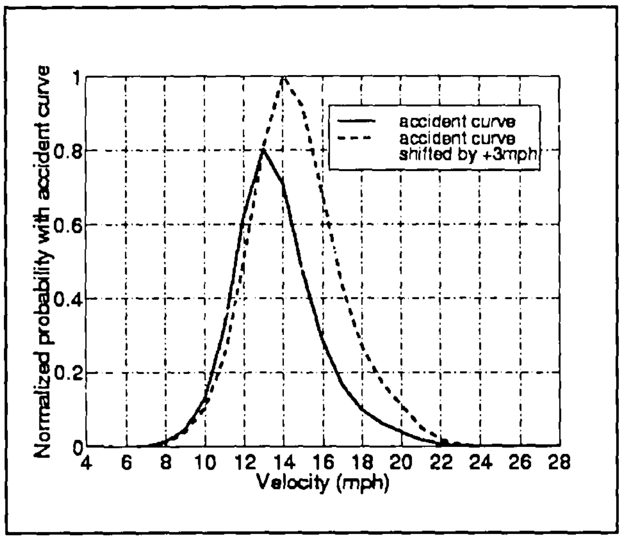

Figure 8b: Normalized density of the occupants on the module using Field estimated c-censor#1

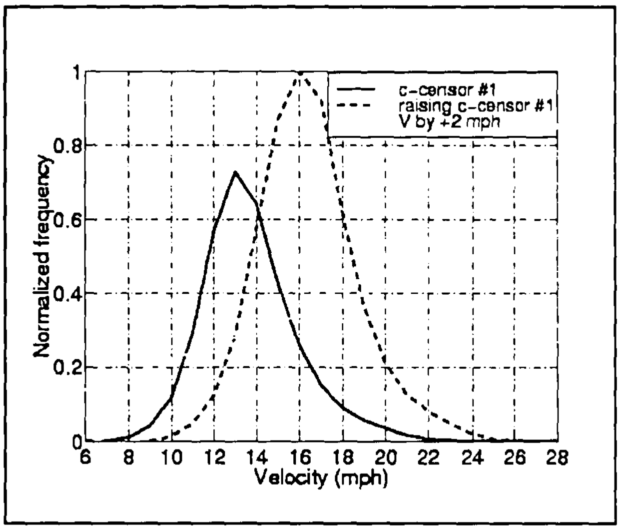

Figure 9b: Normalized density of the occupants on the module using Field estimated c-censor #1

shifted, i.e., parallel transported by +4 mph. Figure 9a shows that after the multiplication of the accident distribution, the probability with shifted accident distribution results in higher peak values, a longer duration of peak values, i.e. from 10 mph to 16 mph, and the average velocity is higher. Because of this, raising c-censor "threshold velocity" by +2 mph may increases the number of occupants on the module, as shown in Figure 9b.

DISCUSSION

The general solution process is to construct a model from functions of: the airbag fire-time probability and occupant displacement probability surfaces, accident distribution and c-censors. The model can then be exercised to estimate the number of occupants at a given distance from the module when the airbag fires. In addition, the effects of potential inaccuracy in the accident-velocity distribution, and different c-censors on that estimate can be analyzed. For example, if it is assumed that the airbag fire-time probability surface for the offset barrier impacts is an accurate estimate of the real-world crashes, then estimates of the number of people making contact with the module can be made. However, the results depend on the data used to construct both the fire-time probability and occupant displacement surfaces as well as the accident distribution and the c-censor. Additional or different data could significantly change the results. For example, if a significant amount of impacts are added with late fire-times, then the model will predict more occupants on the module.

The effects of the accident distribution and the c-censor on the number of occupants on the module were demonstrated previously [1]. Raising the "threshold velocity"(parallel transporting of the c-censor) by +2 mph can decrease or increase the number of occupants on the module depending on the accident distribution. Figure 10 represents the probabilities after processing with c-censors, which means those probability curves multiplied by the accident curves will produce the number of occupants on the module. It indicates that if the velocity for peak frequency occurring in the accident distribution is less than or equal to 15 mph, raising the "threshold velocity" could reduce the number of occupants on the module. However, if that velocity is greater than or equal to 16 mph, raising the "threshold velocity" by +2 mph may increase the number of occupants on the module. Once the airbag fire-time surface and the c-censor are determined, the accident distribution is the dominant factor in deciding the effect of raising the "threshold velocity" by +2 mph.

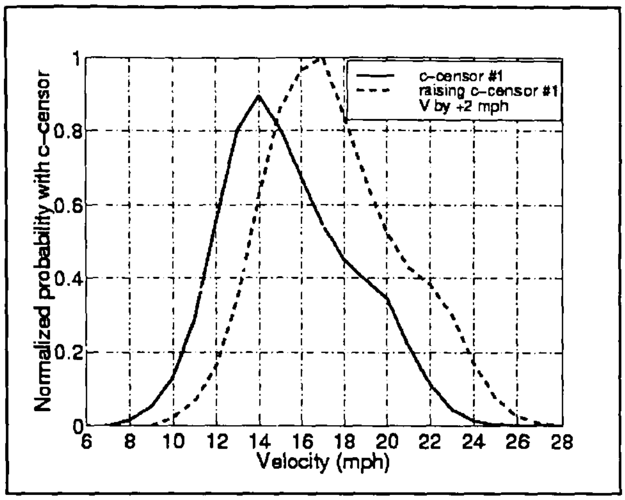

Figure 10: Probability with field estimated c-censor #1 of the occupants on the module

The conditions controlling the determination of when and if the airbag will fire were developed using rigid barrier frontal impacts at different velocities. The velocity dependent censoring of the airbag firing used in our model is defined by the barrier estimated c-censor. Observation from our results indicates that the barrier c-censor, when tightened always results in a fewer number of occupants on the module regardless of whether the accident distribution is underestimated or not . Figure 11 illustrates this result. This is because the values from the barrier estimated c-censor are always greater than the values from the barrier tightened c-censor. As a result, if the c-censor is tightened, it reduces delta v from no fire to all fire. By raising the no fire level, the number of occupants on the module could be significantly reduced without the potential for losing the effectiveness of the airbag.

Since the airbag fire-times were collected form either the frontal rigid barrier impacts or frontal offset impacts, the estimates from our model for the number of people on the module at the time airbag fires may not represent the numbers in the field, which include a significant number of car to car crashes. It is possible that the real numbers could be between the results for rigid barrier impacts and the results for offset impacts. This is because the impact of a car to rigid barrier is a rare event and does not represent the real world and the impact of a car to offset deformable barrier could be softer than most car crashes. From the model, the estimated number of occupants on the module is zero for the rigid barrier impacts, therefore the real number may be lower than the one estimated from the offset impacts.

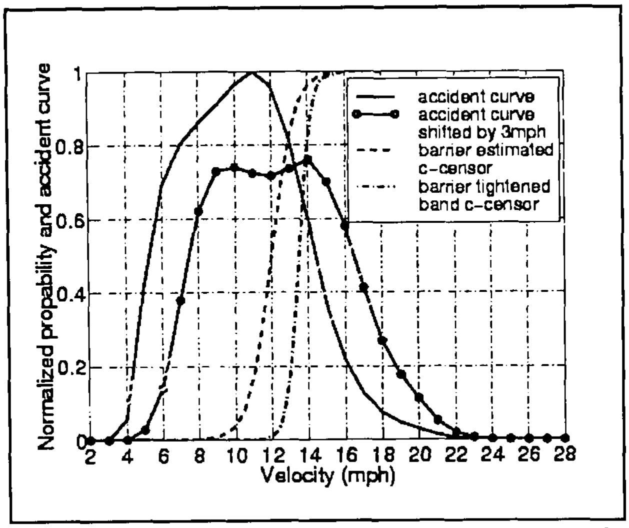

Figure 11: Probability with accident curve of the occupants on the module and two c-censors

The method of determining the distribution of the occupant's position at the time the airbag fires is straight forward. However, some processes used were not statistically rigorous. For example, the censoring of the data was not included in the statistical modeling. Instead, it was extracted out for the sake of constructing a calculus and ease of changing the censoring process.

The results and conclusions presented in this paper are obtained from a data based model constructed using both full frontal rigid barrier impacts and offset deformable barrier impacts, with the primary analysis done on the later. Although this process can lead to constructive insights, there are limitations to this approach and some of the assumptions may not be fully justifiable. For example, the lognormal function was chosen because among the functions evaluated it gave the best fit and it passed the Kolmogorov-Smirnov statistical test. In addition, the increased number of data points used to construct the model in this paper gave an even better fit for the 40 mph and 35 mph fire-times, but a worse fit for the 25 mph fire-times. However, we have been unable to identify the physical mechanisms that would imply a lognormal distribution. The choice of lognormal could disguise the relevant physics. Associated with the airbag firing initiation, the distribution could be more complex, such as bimodal.

Figure 12 shows a deployment rate of airbag fire-times for the 25 mph, 35 mph and 40 mph offset impacts. The deployment rate at time t_0 is defined as the probability that an airbag will deploy in the next millisecond after t_0 if it has not deployed before t_0. The deployment rate is estimated by counting how many airbags deployed between t_0 and t_1 and then dividing by how many were undeployed at t_0, giving us a percentage, and then dividing by t_1-t_0. Another way to visualize deployment rate is to imagine a large number of vehicles simultaneously suffering an offset collision at the same speed. The deployment rate at t_0 is the percentage of airbag deploying per millisecond at time t_0. The deployment rate is introduced here because an increasing deployment rate, such as observed for the 40 mph data indicates a lognormal distribution. For a lognormal distribution, it is expected that the deployment rate increases with time. However, no increase is observed in 25 mph and 35 mph data. Their deployment rate actually falls to zero for several milliseconds. It is to be hoped that when a large amount of new data become available, a more accurate deployment rate can be reached, and a better understanding of the statistical process can be developed. It should be noted that, there is no deviation for the airbag fire-time surface for the rigid frontal impacts by using a lognormal as a fitting function.

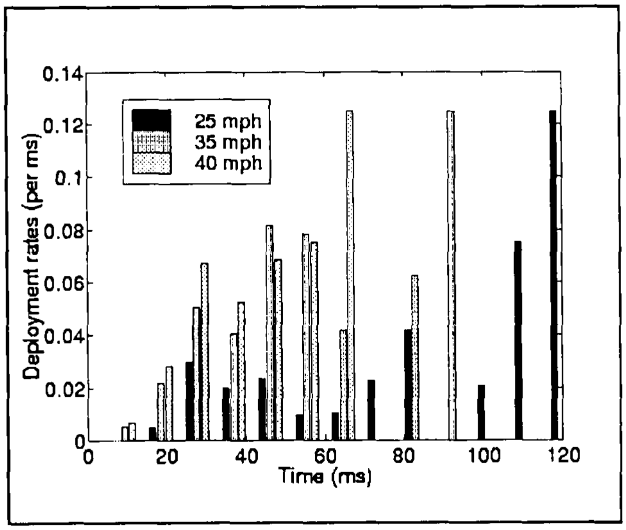

Figure 12: Deployment rates for 25 mph, 35 mph and 40 mph offset impacts

Another limitation is that the stability and the accuracy of the predictions from this data based model still depend on the fire-time data, the accuracy of NASS/CDS data and c-censor estimates. The extrapolating process may also affect the results. Therefore, this is still an on-going process. Improvements in the numerical procedure are still under development. In the future, if the results from the model no longer vary with the new data, the model can then be considered complete.

The c-censor as well as the airbag fire-time probability surface are not stationary in time or space. This is, in part, a result of the changing structure of the vehicles on the road as well as the changing nature of the highway structures. Even if a vehicle and it's sensor, once designed, stay the same there could still be significant changes in the c-censor and airbag fire-time probabilities for that vehicle. For example, although the c-censor is designed against a well defined set of tests, such as barrier impacts, crashes in the field are not predictable and they will change with the mix of cars, trucks and highway structures. A vehicle designed in one year may have a c-censor and airbag fire-time probability with certain characteristics in the field, but those characteristics will change over time as new vehicles of different designs become available. They will also change over the space if the vehicle is driven in different areas with an altered mix of vehicles and different highway structures.

CONCLUSION

This has been a limited preliminary study to determine the effect of probabilistic airbag fire-time on occupant position. A method for constructing probabilistic models, which calculates the probability of an occupant at a given position, has been developed. The models are a function of the initial seating position, crash severity, and airbag sensor nature, as well as occupant motion. The accuracy of the results is significantly dependent on the data used to construct the models and the numerical method to some degree. The two sets of data used in this study to construct the two different models were, rigid barrier and offset deformable barrier. Although these two models gave significantly different results in terms of absolute numbers, the trends observed were the same: airbag fire-time is probabilistic with inherent uncertainty. Although new data was used in the analysis, the conclusions are similar to the previous work [1]. The following conclusions are the result of analysis using the two models:

1. The model developed from the rigid barrier impacts indicates that it is unlikely for an occupant to contact the airbag module when the airbag fires.

2. The model developed from the offset deformable barrier indicates that it is possible for the occupant to contact the module as a result of late airbag firing.

3. Increasing the number of low velocity offset impacts (25 mph) did not significantly change the results.

4. The effect of changing "threshold velocity" is indeterminate because threshold is poorly defined. Airbag fire/no-fire probability distribution (c-censor) as a function of velocity is significantly more complicated than can be described by a single value.

5. The effect of increasing the c-censor velocity distribution for the airbag sensor is dependent on the number of crashes at a given velocity and the probability of firing for all velocities (characteristic of the c-censor).

   A. If the NASS/CDS velocity is accurate, then increasing c-censor velocity distribution will reduce the number of occupants in contact with the module when the airbag fires.

   B. If the NASS/CDS velocity is an underestimation, then increasing the c-censor velocity distribution may increase or decrease the number of occupants on the module. The amount of underestimation will affect the magnitude and direction of the change.

   C. The probability of fire/no-fire characteristics of a sensor is a significant factor in determining the effect of late fire on the number of occupants that may contact the module at the time of airbag initiation.

   D. The probability of fire/no-fire characteristics of a sensor is a significant factor in determining the effect of increasing the c-censor velocity distribution.

   E. Increasing the c-censor velocity distribution decreases the effectiveness of the airbag by increasing the number of late fires in those crashes in which the airbag fires.

6. The effect of tightening the band from c-censor velocity distribution may be useful in decreasing the number of occupants on the module without decreasing the effectiveness of the airbag.

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PRELIMINARY EXPERIENCE OF PASSENGER AIRBAG DEPLOYMENTS IN AUSTRALIA

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98-S5-W-17

ABSTRACT

19 cases of passenger airbag deployments in a frontal crash in which a passenger was present have been investigated. These investigations were conducted as part of an on-going study of vehicle crash performance and occupant injury currently on-going at the Monash University Accident Research Centre (MUARC). Preliminary results suggest that the US experience of fatalities caused by interaction of the passenger with the deploying airbag is not shared in Australia. This is probably because the seat-belt use in the study was high (18/19 or 95%). These preliminary results support the view that such airbags should be used as supplementary restraint systems. Further studies are planned to monitor the performance of passenger-airbags and to provide more in-depth analyses when more data are available.

INTRODUCTION

A picture is just beginning to emerge about the relative merits of driver-airbag effectiveness in frontal crashes. In countries where restraint use is high, driver airbags have been found to be relatively effective in preventing serious injury to the driver (Fildes et al, 1996; Langwieder et al, 1996; Morris et al, 1996).

However, as Huelke and Reed (1996) have observed, passenger side airbag effectiveness is relatively unknown for infrequently is there a passenger in the front seat when the airbag deploys.

As a necessary precursor to a more in-depth study, this is preliminary study of Australian experience with deploying passenger airbags. Initial experience of injury outcomes to restrained and unrestrained passengers in frontal crashes is recorded.

METHODOLOGY

The Monash University Accident Research Centre conducts in-depth research into car-crash performance and occupant injuries in Australian passenger cars involved in real world crashes. All vehicles in this study were involved in crashes of sufficient severity to warrant a tow-away from the scene of the crash.

In addition to the tow-away criteria, for inclusion in this study of passenger airbag deployments, the vehicles had to meet additional criteria; firstly, that the vehicle was involved in a frontal impact in which the principal direction of force (PDoF) applied to the front of the vehicle was between 2 o'clock and 10 o'clock; secondly, that there was a passenger in the front seat at the time of the crash; thirdly that the passenger airbag deployed during the crash

Front seat passengers were included in the study whether they wore the seat belt or not although 95% were in fact wearing their belts at the time of the crash. Seat belt use was determined retrospectively at the time of the vehicle inspection and was based on evidence of seat belt loading, such as markings on the seat belt webbing, buckle and tongue or distortion to the B-pillar cladding (the inspection procedure is described in some detail below).

Vehicle Inspections and Occupant Injury

All crashed vehicles were inspected by an engineer a few days after the crash at recovery yards and panel shops. Inspections were undertaken according to the National Accident Sampling System (NASS) procedure using an inspection proforma, modified where necessary to suit Australian conditions. Data were collected on seat belt use, airbag deployment, impact direction, vehicle damage (deformations and intrusions), occupant contacts and impact speed. The collision severity measures Delta-V and Equivalent Barrier Speed (EBS) were calculated in this study; Delta-V, was defined as the change in velocity from the moment of impact until the study vehicle separated from its impacting source (MUARC, 1992) while EBS was also used as a measure of collision severity. EBS is defined as the speed in the case vehicle at which equal energy would be absorbed in a frontal energy impact into a test barrier ie. an estimation of the velocity change at impact that would be required of a crash test if it were to re-create the same amount of crush that occurred in the real crash with a vehicle of equal mass and stiffness.

Both EBS and Delta-V were calculated by computer software (CRASH3), made available from the National Highway Traffic Safety Administration (NHTSA) in the U.S. The assessment and classification of injures was undertaken by State Registered Nurses, trained in the collection of injury information using the NASS system. Injuries were coded according to the Abbreviated Injury Scale system (AAAM, 1990).

RESULTS

In total, MUARC has gathered data from some 19 frontal crashes involving deployment of the passenger airbag where a passenger was present. Of these 19 occupants, all but one occupant wore the seat belt. The mean collision Delta-V was calculated to be 38.9km/h and the mean collision EBS was 39.1km/h. The object struck by the vehicles in the study is shown in table 1.

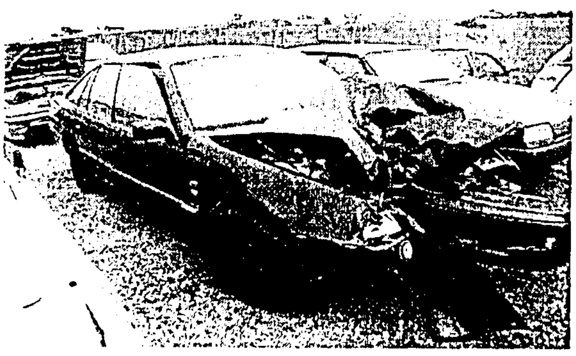
Collision Partner	N
Car	10
Tree	4
Pole	2
Truck	2
Van	1
Total	**19**

Table 1; Object Struck by 19 Vehicles in which Passenger airbag Deployed

With such a small number of examples of airbag deployments available, a definitive analysis was not possible. Therefore this paper offers only preliminary evidence of occupant experience with deploying passenger airbags as deduced from field studies in Australia. The following six cases are examples in which the passenger sustained a MAIS 2+ injury;

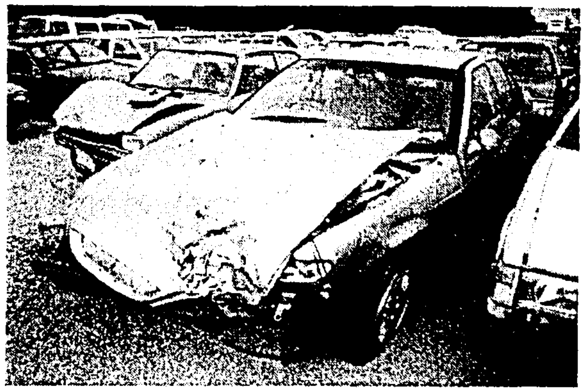
Case No. 1

This vehicle was involved in a frontal impact with a pole (CDC=12FYEW3) and the Delta-V and EBS were calculated to be 27km/h. The restrained front seat passenger, a 46 year-old male (height 165cm, weight 59kg) sustained 7 fractured ribs on the right-side of the chest (AIS = 3) together with a myocardium contusion (AIS = 3). In the absence of intrusion, both injuries were attributed to seat-belt interaction. The driver of the vehicle, a restrained female, sustained a fractured wrist (AIS = 2) and a sprained left ankle (AIS = 1).



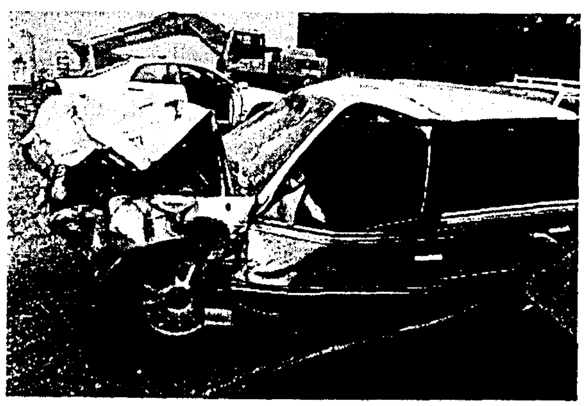
Case No. 2

This vehicle was involved in a frontal crash with a tree in which the Delta-V and EBS were both calculated to be 30km/h. The CDC was adjudged to be 11FZEW2. The front seat passenger, a 45 year-old female (height 160cm, weight 53kg) sustained contusions to the jaw and shoulder (AIS = 1; from the side window-frame) together with a contusion to the left hip (AIS = 1; seat-belt) and to both knees ((AIS = 1); which she claims she 'knocked' together). She was also knocked unconscious (AIS = 2) for a brief period (<15mins) from the head contact on the window-frame. The driver sustained a minor injury to the right knee (AIS = 1).



Case No. 3

This vehicle was involved in a head-on crash with a second vehicle on a two-lane highway (CDC = 12FYEW4). The Delta-V was calculated to be 59km/h and the EBS 62km/h. There was approximately 22cm of intrusion on the passenger side at facia level. The restrained front seat passenger, a 55 year-old female (height 173cm, weight 65kg) sustained bi-lateral fractured wrists (AIS = 2; from upper facia or airbag) together with subluxation of C3 and C4 (AIS = 2; non-contact injury), and a lacerated left thumb. The driver sustained numerous minor injuries (MAIS = 1).



Case No. 4

This vehicle was involved in a partial over-lap crash with a tree (CDC = 12FREE6) and the Delta-V and EBS were calculated to be 58km/h. There was approximately 12cm of intrusion at the front seat passenger's facia level whilst the intrusion on the driver's side was substantially greater (35cm). The front seat passenger, a 6 year-old restrained male (height and weight unknown) sustained a fractured sternum (AIS = 2) from interaction with seat belt. The driver, a 40-year old male sustained numerous serious lower limb injuries (MAIS = 3) together with other cuts and bruises.

Case no. 5

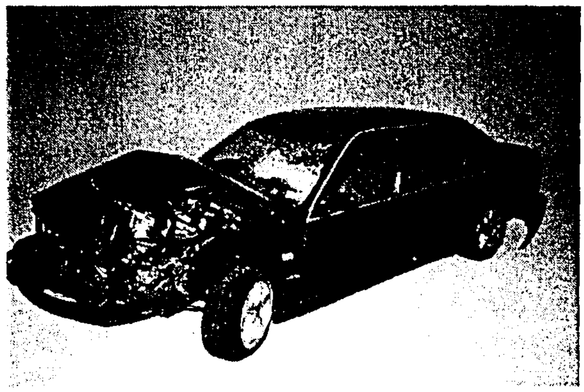
This vehicle was involved in a collision with a second vehicle at an intersection. The CDC was 10FLEW2 and the Delta-V was calculated to be 16km/h. The 74 year-old restrained female passenger (height 173cm, weight 68kg) sustained a fractured wrist (AIS = 2; possibly from 'fling' from the airbag onto a harsh interior surface) together with bruising to the right lower limb (AIS = 1). The driver sustained minor bruising only (MAIS = 1).

In addition to these cases, MUARC has investigated three crashes in which injuries have been sustained through direct interaction with the airbag. All of these cases have resulted in minor bruising or abrasions only to the occupants.

The study has investigated only one crash involving an unrestrained front passenger. This is of particular interest since in the case of non-restraint use, the airbag becomes the primary restraint system;

Case No. 6

The vehicle struck a pole head-on (12FLEN4) and the Delta-V and EBS were calculated to be 49km/h. The occupant, a 17 year-old male (165cm, 70kg) sustained bruising to the back of the head (AIS = 1; possible interaction with rear seat passenger) only.



Of the remaining ten cases we have investigated, no anomalies were observed in terms of occupant interaction with the airbags. In all these cases, the driver MAIS was observed to be equal to or greater than the MAIS of the passenger. Collision Delta-V's for these cases ranged between 20-41 km/h. All the occupants in these remaining cases wore the seat belt.

DISCUSSION

Preliminary experience of passenger airbag deployments in Australia has shown that such systems do not present problems in terms of injury outcomes to restrained occupants. Out of the 19 passengers seated in front of the deploying airbag, this study found two isolated example of where an AIS 2 or above injury could be possibly attributable to the deploying bag (Case No's. 3 & 5 listed above). However, the evidence in each case is not conclusive since there are confounding factors. In other exemplar cases, minor surface injuries to the face and forearms have been observed but these may be trade-off injuries against more severe injuries that may have been experienced without the airbag deployment. This preliminary study supports the view that the seat-belt should always be worn when a passenger airbag is present. This is primarily because in our predominantly restrained sample of passengers, we have not witnessed the same problems as those experienced in the US (Huelke and Reed, 1996) when unrestrained passenger interact with the deploying airbag.

In some cases, it is debateable whether the deploying airbag provided any additional protection over what may be expected of the seat-belt system. This is so particularly where there was an absence of compartmental intrusion at the facia-level and where the collision severity was relatively minimal. Approximately one-third of the cases we have investigated may fall into this category.

It is stressed that this study is only a preliminary review of experience to date in Australia. When more data are available, it will be possible to undertake a case-control approach whereby an enhanced investigation of the effects of passengers airbags on occupant injury outcomes can be undertaken. With a more in-depth study, the issue of inappropriate deployments can be investigated more thoroughly.

ACKNOWLEDGEMENTS

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IN-DEPTH INVESTIGATION AND RECONSTRUCTION OF AN AIR BAG INDUCED CHILD FATALITY

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ABSTRACT

A minor rear-end collision resulted in the death of a four-year old child, occupying the right-front seat of the striking vehicle. The child was restrained by means of a lap belt, the shoulder portion of the belt system having been placed behind the child's back. The child was leaning forward, when the vehicle's brakes were suddenly applied, just prior to the crash. The passenger air bag deployed and the child sustained fatal neck injuries.

The case incident was subject to an in-depth collision investigation. Physical evidence associated with the crash, combined with witness statements, and medical data, enabled the vehicle dynamics, occupant kinematics, and occupant contact points to be accurately determined. The collision was subsequently reconstructed using an instrumented child dummy and static deployment of exemplar air bags. A car to rigid barrier dynamic test was also conducted.

High-speed film and video recordings of the tests revealed that even minor changes in the position of the dummy had considerable effect on the post-deployment kinematics. Combining the experience gained from a number of such trials, the real-world event was successfully reconstructed in the laboratory.

INTRODUCTION

Following multiple reports of similar tragic incidents in the United States, this first Canadian case of a child fatality resulting from air bag deployment garnered considerable public attention. The results of an in-depth collision investigation of the incident, coupled with the findings from other Canadian field accident data on air bag deployment crashes (Dalmotas, 1996), led to recommendations from Transport Canada for specific measures to protect children being transported in motor vehicles from air bag-induced injuries.

For the subject case, detailed observations made by the collision investigation team relating to the vehicle dynamics, crash severity, and the resulting occupant kinematics correlated well with the injuries determined at autopsy, and the recollections of the driver with regard to the pre-crash situation. It was evident that the child was lap-belt restrained, and was leaning forward and to his left, at the time of impact. The resulting fatal injuries were attributed to adverse interaction between the deploying air bag and the out-of-position child.

The level of detail available in this crash presented an opportunity for a reconstruction of the collision in the laboratory, using a child anthropomorphic test dummy (ATD) in a simulated vehicle interior. The ATD was fully instrumented and the series of static air bag deployments were recorded on high-speed film and videotape. Following the series of static tests, a full-scale crash test of a car into a rigid barrier was also conducted.

This paper gives the background to the real-world collision, provides the detailed findings of the collision investigation, in the context of the medical data, describes the test series of static and dynamic air bag deployments, and gives the highlights of the analysis of the resulting data.

COLLISION INVESTIGATION

Pre-Collision Events

On a morning in May, 1996, the father of a family of four awoke early at 5:00 am. Since he had a day off work, and wanted to use the family car, a 1995 Hyundai Accent four-door sedan, he placed both his children safely in the back seat, and drove his spouse to her place of work at approximately 6:30 am. On his way home, he purchased two trees to plant in his backyard, bought some candy for his children, and stopped at a video store. He dropped off his 6-year-old son at school, and then went back home to unload the trees, and have breakfast with his 4-year-old son.

At 10:30 am, he was back in the car with his youngest son, intending to pick up the elder child from school. As a special treat, and at the child's request, he let his son sit next to him in the right front passenger seat.

A few months earlier, this child had outgrown his forward facing child restraint. Ever since, when the right front passenger seat was available, the two children would fight over this seating position but the parents would generally end up putting them both in the rear seat. On this occasion, the father made a rare exception, as he sometimes did when alone with his 6-year-old.

He didn't think twice about any safety issues. He had purchased this family car new, just two months earlier, and it came with all the safety features which he had heard about on television: ABS brakes, three-point seat belts with adjustable D-rings, as well as both driver and passenger air bags. There was no reason for him to believe that his son would be exposed to any danger sitting in the right front passenger seat. Although, he had seen the warning label on the sun visor, he didn't pay much attention to it. He had never actually read it, nor had he studied the owner's manual.

Collision Events

The Accent was travelling southbound in the left lane of a four-lane, undivided, urban arterial, in an area with a posted speed limit of 50 km/h.

A 1992 Honda Civic four-door sedan was travelling in front of the Accent. The Civic stopped as a vehicle ahead was trying to turn left but was prevented from doing so by heavy northbound traffic.

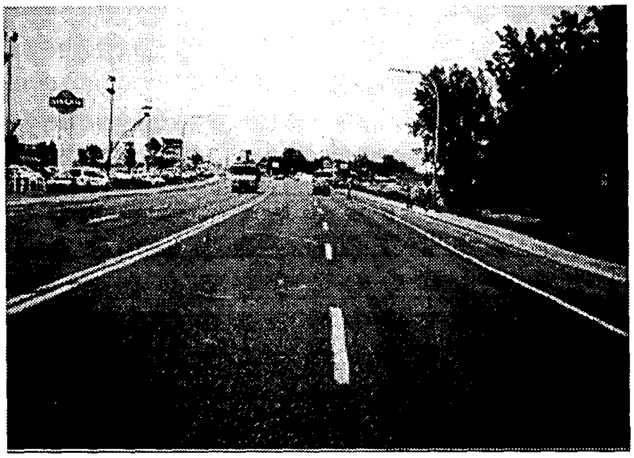

Figure 1. Collision scene looking southbound.

At this instant, the driver of the Accent was inattentive because his child was leaning forward, either to play with the radio controls, or to reach for some candy placed in a foam cup in the cup holder. The driver's eyes left the road for a few seconds as he reached with his right hand to reposition his child in the seat. Re-focusing his attention to the road, he noticed the cars ahead were stopped. He braked hard; however, the front of the Accent struck the rear of the Civic.

Post-Collision Events

The driver of the Accent was aware that the vehicle's air bags had deployed, and that there was something wrong with his son, as the latter was lying on his side, unconscious. He pulled the child out of the car through the driver's door, and quickly carried him over to a nearby medical clinic. Resuscitation attempts were commenced immediately. The child was transported to a local hospital, and was subsequently transferred to a paediatric trauma centre. Cervical spine X-rays revealed an atlanto-occipital dislocation which suggested spinal cord transection at C1. Further aggressive treatment was withheld and the child was officially pronounced dead several hours after the crash (Giguère, 1997).

Vehicle Damage

Minor damage resulted to the front bumper and hood of the Accent (CDC: 12FDEW1). Maximum residual crush, measured at the level of the front bumper, was 5 cm. The radiator support was lightly twisted on both ends and the radiator was leaking. Both headlights were partially detached but were unbroken.

The corresponding direct damage to the rear of the Civic was limited to the rear bumper assembly, with induced damage to the trunk lid and the spare wheel well (CDC: 06BDLW1).

Figure 2. Left-front three-quarter view of the Accent.

Figure 3. Right-rear three quarter view of the Civic.

Imprints of the Accent's front license plate, hood ornament, and headlights were observed on the Civic's bumper. These were used to position both vehicles and hence to determine the exact collision configuration. This confirmed that the Accent was under braking at impact.

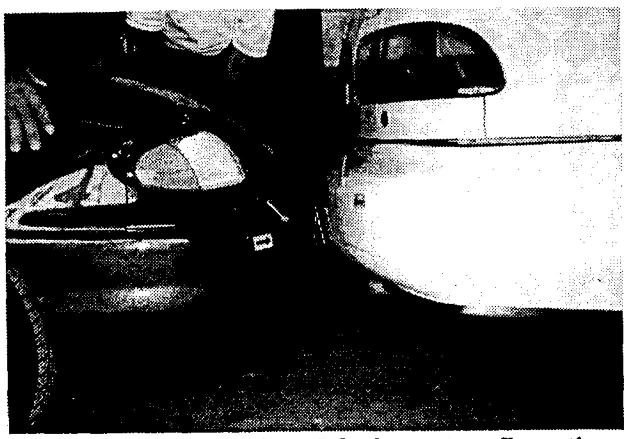

Figure 4. Reconstruction of the impact configuration.

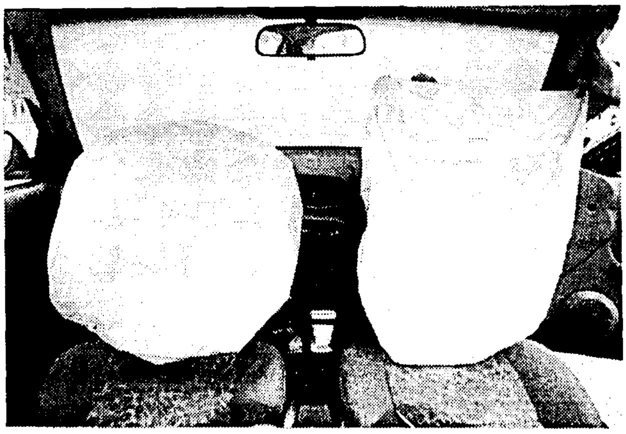

Figure 5. Dual air bags in the Accent.

The Accent was equipped with three-point seat belts with adjustable D-rings, and dual front air bags. Both air bags deployed as a result of the crash.

Occupant Injuries

Driver - The 35 year old, male driver of the Accent was 178 cm (5'10") tall and weighed 113 kg (250 lb). He was seated in a bucket seat that was adjusted fully rearward. He was using the seat belt correctly, as confirmed by observed loading evidence on the system. There were striations on both the D-ring and the sliding tongue, along with a diagonal abrasion on the webbing, corresponding to the location of the D-ring, which was adjusted fully upward.

The driver suffered only a minor contusion to the outside surface of his left hand, probably resulting from his hand being thrown against the side interior surface by the deploying air bag.

Right-Front Passenger - The 4-year-old, male, right-front passenger, was 107 cm (3'6") tall, with a mass of 18 kg (40 lb). The right-front seat was adjusted to the mid-position of its range of travel. The driver believes that he had buckled the child's seat belt prior to departure for the trip; however he does not recall unfastening the belt when he removed the child from the vehicle immediately following the crash. It was the driver's habit to place the shoulder belt behind his son's back because of the child's small stature. Faint loading marks on the seat belt tongue were identified. Consequently, it is believed that the seat belt was indeed in use, and that the child was only using the lap portion of the system at the time of impact.

As the air bag deployed it made forceful contact with the child. Transfer marks from the occupant's green, nylon jacket were found on the fabric on the left side of the air bag, adjacent to the exhaust vent.

Due to contact with the air bag, the child received a large abrasion to the right side of the neck and face. A thermal burn to the right cheek was consistent with the vent location. There was complete dislocation of the cervical spine, between C1 and the base of the cranium, accompanied by a complete transection of the spinal cord, and a large haematoma in the region of C1-C7.

The child's upper torso was propelled rearwards and down by the air bag. His head impacted and broke the floor-mounted automatic transmission shift lever resulting in a contusion (7 cm x 4 cm) to the occipital region. Other injuries noted were contusions to the right atrium of the heart, and avulsion of portions of skin from the little finger and wrist of the right hand.

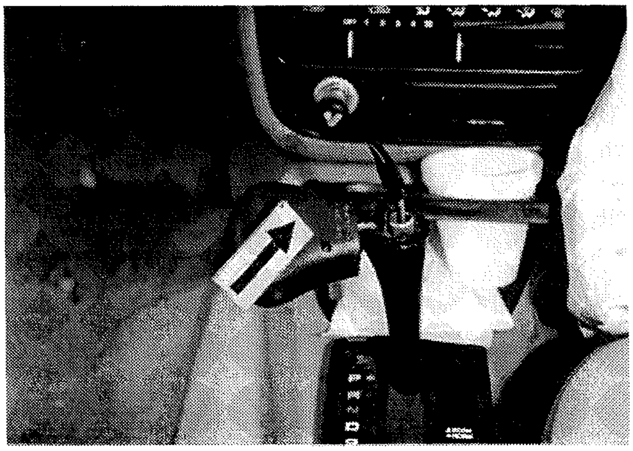

Figure 6. Broken transmission shift lever.

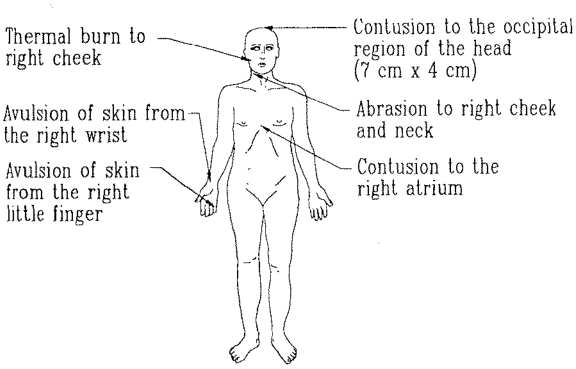

Figure 7. Soft Tissue Injuries.

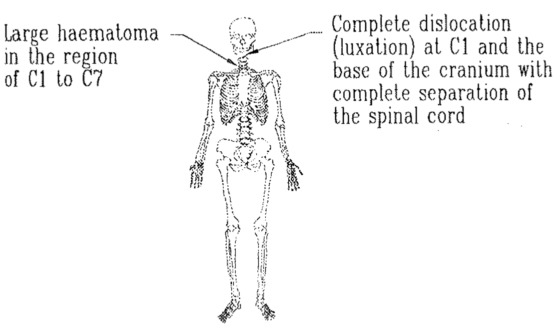

Figure 8. Skeletal Injuries.

RECONSTRUCTION METHODOLOGY

The interaction between the passenger air bag and the child was reconstructed using a series of static air bag deployments in a custom test fixture. The tests were performed with an instrumented, 6-year-old ATD.

The test fixture incorporated a dashboard, an automatic transmission shift lever, and a seat from an exemplar vehicle. The generic windshield, forming part of the test fixture, and all the above components, were adjusted to correspond with dimensions taken from an exemplar vehicle.

In the tests, a seat belt was not used because in the actual collision the child was only wearing the lap belt and, since the child was determined to be on the forward edge of the seat cushion, with the belt extended, it was felt that the lap belt had minimal effect on the occupant kinematics.

The known injuries to the child, the observed damage to the vehicle interior, and the description of the pre-crash events from the driver were all used to approximate the position of the child prior to air bag deployment.

As noted above, green transfers from the child's jacket were observed, primarily on the left side and the top portion of the air bag. These witness marks, the abrasions to the right side of the child's neck, and the thermal burn to his right cheek, were indicative of the child's head being in close proximity to the air bag's vent. The large contusion to the occipital region of his head corresponded to contact with the transmission shift lever.

It was felt that the avulsion of skin from the wrist and little finger on his right hand were consistent with contact by the air bag cover. The driver reported that the child was leaning forward, towards the centre console, either to play with the radio controls, or obtain some candy from a cup in the cup-holder. A child of similar age was placed in this scenario. It was observed that when the child moved forward in the described manner, it was natural for him to support himself with his left hand on the seat cushion, and to use his right hand to obtain the object. Pre-impact braking in the real-world collision may well have caused the actual right-front passenger to support himself with his right hand against the upper dashboard and air bag module.

Test Series

The broken gear shift lever was the critical occupant contact point, demonstrating that the child's head had been propelled both rearwards, and down towards the centre console. Consequently, achieving head contact with the transmission shift lever was a major goal of the reconstruction. Static testing revealed that minor changes in the position of the dummy had considerable effect on its kinematics. Four passenger air bags were deployed before successful contact between the dummy's head and the lever was achieved. These tests were done to establish the position of the dummy prior to performing a final dynamic test. A description of each of the four static tests, and the results of each test are as follows:

Test 1 - The dummy was positioned on the front part of the seat cushion, leaning forward, with the head adjacent to, but not touching the right side of the centre console. The right arm was extended, with the hand lightly taped to the leading edge of the air bag cover, just to the right of the cover's centreline. The left arm was beside the thorax, and the forearm was on the seat cushion.

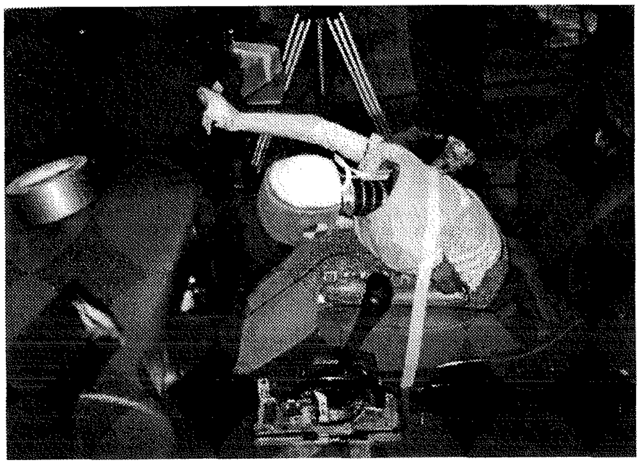

Figure 9. Dummy position in Test 1.

The air bag deployed around the extended arm, propelling the arm rearwards. In the process, the hand detached from the arm. The air bag engaged the dummy's head and thorax and drove the dummy rearwards into the seatback. The head passed well over the top of the gearshift lever.

Test 2 - The dummy was positioned on the front part of the seat cushion, leaning forward with the head contacting the right side of the centre console.

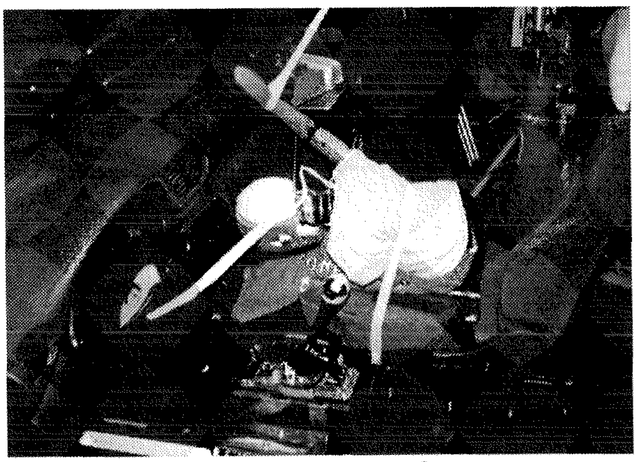

Figure 10. Dummy position in Test 2.

The head was placed slightly lower than in Test 1. The right arm was extended, and the right hand was suspended a few inches away from the centre of the air bag cover. The left arm was beside the thorax with the forearm on the seat cushion.

The air bag deployed over the dummy's right shoulder, around the extended arm and, as it reached maximum inflation, it propelled the arm rearward. The air bag engaged the upper thorax and sent the dummy rearward. Although there was contact to the dummy's head, it still travelled well above the gearshift lever.

Test 3 - The first two tests revealed that the interaction between the air bag and the dummy was missing a downward component.

For the next test the dummy was positioned on the front part of the seat cushion, leaning forward, with the thorax rotated towards the right. The head was placed lower, between the lever and the centre console, but not touching the centre console. The right hand and forearm were on the dummy's lap, and the left arm was beside the thorax with the forearm on the seat cushion.

The air bag now deployed essentially over the top of the dummy, with little contact to the dummy.

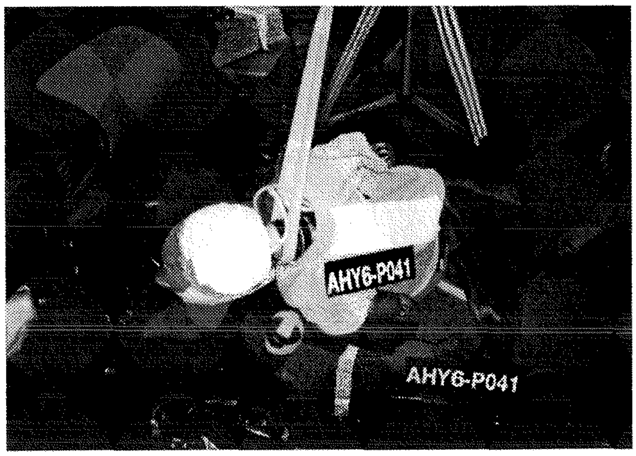

Figure 11. Dummy position in Test 3.

From this test it was concluded that the right arm was a critical component in the deployment characteristics of the air bag. The arm provided an obstruction which altered the inflation of the fabric envelope, and consequently substantially influenced the kinematics of the dummy.

Test 4 - The dummy was placed in a forward leaning position, similar to Test 2 with the head touching the right side of the centre console. The right arm was now extended, with the hand on the leading edge of the air bag cover. The hand was placed on the right side of the cover. The left hand was placed on the seat cushion, with the elbow bent at 90 degrees.

The air bag initially deployed between the right arm and the neck of the dummy. The head was in the area of the lower left corner of the air bag and, as the air bag reached maximum inflation, it drove the head down and rearwards. In this test, the occipital region of the dummy's head struck the end of the gearshift lever, fracturing this component.

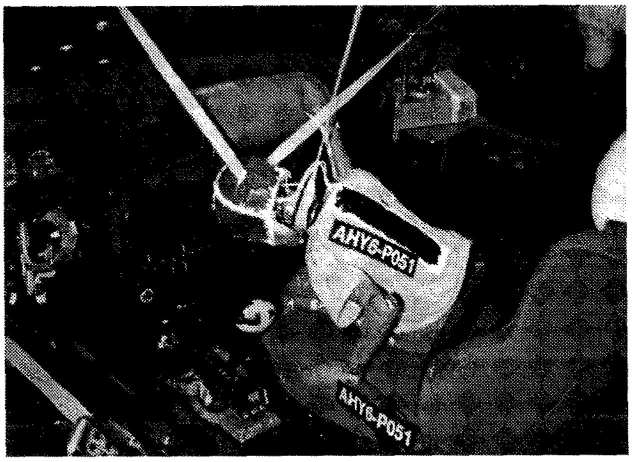

Figure 12. Dummy position in Test 4.

Dynamic Test

A dynamic reconstruction of the interaction between the airbag and the child was also performed. The dummy was placed in the same position as Test 4. In the dynamic test the lap belt was positioned around the dummy's hips, with the torso belt behind the back, to simulate the actual collision situation. The vehicle was run into a fixed barrier at a speed of 26 km/h.

At impact, the dummy moved forward, loading the lap belt. The airbag deployed and the dummy's right arm was propelled rearward. The airbag started to fill out above the head and right shoulder of the dummy; however, some of the air bag fabric inflated lower down. Consequently, the head of the dummy was located more towards the middle of the left side of the air bag, rather than at the lower left corner of the bag as was observed in Test 4. Rather than the head being driven rearwards and down, it was projected rearwards and more laterally. Although the dummy's head travelled close to the gearshift lever, it did not make contact. In fact, the dummy's kinematics were comparable to Test 2.

The dynamic test confirmed that the positioning of the dummy was critical. The static testing reconstructed the position of the child at deployment, the occupant kinematics, and injury mechanism. Positioning the dummy in a dynamic environment, and trying to account for vehicle deceleration, in order to produce the desired occupant kinematics, is extremely difficult when the initial tolerances on positioning are small.

DATA ANALYSIS

ATD Kinematics

Motion analysis was conducted on high-speed film and video recordings made of the above-noted full-scale test. Detailed examination of these records, illustrates an exceedingly complex head-neck-torso motion sequence. In broad terms, the child ATD motion is as follows:

- At t=29 ms, the instant that the air bag first begins to deploy, the ATD neck is flexed forward and slightly to the left.
- At t=37 ms, the bag completely fills the space between the right side of the head and the top of the right shoulder. It is beginning to engage the top of the chest.
- At t=42 ms, the bag completely envelopes the right side of the head and, presumably, the neck. The neck has begun to flex to the left.
- At t=52 ms, the head is flexed to the left to the maximum. At this time, the head/neck, which is also twisting counterclockwise, begins to go into extension as the bag continues to unfurl under the chin.
- At t=59 ms, the neck is extended to its maximum and the head begins to rotate clockwise. The torso also begins to rotate clockwise (but at a lower speed) due to the bag interacting with the right upper chest and shoulder of the ATD. At this point, the bag appears to fully engage the chin of the ATD and causes the head and neck to continue twisting. As the torso is accelerated, the head and neck begin to return to a seemingly neutral alignment with the torso.
- At t=90 ms, the ATD has rotated clockwise fully 90 degrees from its original position and the left side of the air bag appears to interact with the front of the ATD in much the same way that a non-out-of-position occupant would with a frontal air bag deployment. The neck is no longer extended and is about to go into flexion. The ATD then disengages from the deflating air bag and is propelled toward the left passenger compartment.

Instrumentation

Load cells at the top and bottom of the neck provided axial, lateral and fore-aft shear forces, as well as bending moments in all three planes, at both the head/neck and neck/thorax junctions. Though the primary injuries of interest are at the top of the cervical spine, consideration of the forces and moments at the bottom of the neck may also be helpful in understanding the loading mechanisms.

It will be noted at the outset that this series of measurements predicts a fatal neck injury by virtually every conceivable mechanism. Commonly accepted tolerance data are so far exceeded for every mode of injury, except compression, that the present data will not be able to refine further the numerical values of neck injury assessment criteria.

A recent study, designed to develop child injury protection reference values (Klinich et al, 1996), proposed the following function to take into account axial loading and bending of the neck.

$$N_{T;F,E} = \frac{(F_x^2 + F_z^2)^{1/2}}{F_c} + \frac{M_y}{M_{c;F,E}}$$

where:

- N_{TF} is the neck tension-flexion index,
- N_{TE} is the neck tension-extension index,
- $F_{x,z}$ are the forces in the x and z directions,
- M_y is the bending moment in the y direction,
- F_c is the critical force value, 3000 N for the 6-year old dummy,
- M_{cF} is the critical flexion moment value, 70 Nm for the 6-year old dummy,
- M_{cE} is the critical extension moment value, -35 Nm for the 6-year old dummy.

In order to comply with these protection criteria, the value of the weighted neck injury assessment functions should not exceed 1.0.

The neck tension-extension index (N_{TE}) for this test case is equal to 1.56 at the upper load cell and 2.72 at the lower load cell.

The neck tension-flexion index (N_{TF}) is 1.78 at the upper load cell and 1.20 at the lower load cell.

It is important to note that these neck protection reference functions do not include lateral bending moments, which, in the present case, are the most significant of all the bending moments.

In terms of the expected mechanism of injury, one should also not disregard the axial twisting moments. Though numerically smaller than any of the other directions, these values are consistent with estimates of the torsional loading associated with serious neck injury. Certainly if combined with the other bending moments in the fashion proposed for extension or flexion loading, the effects would be dramatic.

Observations and Discussion

To more fully understand the loading mechanisms to the child ATD neck, the loads at both the upper and lower load cell locations, and the timing or phasing of the various loads and moments were considered. Examination of the data traces reveals some interesting features of this air bag induced loading:

1. There is a direct correlation, both in terms of magnitude and curve shape, between head a_z and F_z. The correlation at the upper load cell reflects the rigid connection between the head and load cell. The correlation to the lower load cell is due to the relatively rigid coupling between the head and chest through the neck by way of a metal cable.
2. Maximum neck load is in the z direction and occurs after the head has extended rearward about as far as it's going to go. At this point, the steel cable is producing high resisting loads and, because of its strength, retains the structural integrity of the neck.
3. Maximum head acceleration is in the y direction and exceeds the limit for low risk of brain injury. The pulse maximum is over 110g and the duration is about 10 ms. This is very much a "slap". Disengagement with the side of the head occurs fairly quickly. The head accelerates in the positive z direction (i.e. downward) as the head is rotated and the bag continues to engage the ATD chin.
4. No obvious correlation exists between head acceleration and the two shear components, F_x and F_y, at either the upper or lower neck load cell positions. However, shear forces at the upper location persist long after the head has ceased to be accelerated by the air bag. The reaction loads may not correlate because there may be some direct loading on the neck assembly by the air bag. More likely, these loads are associated with the head, now moving laterally relative to the neck axis, (having been accelerated by, but no longer in contact with, the air bag), deforming the neck of the ATD.
5. F_y is significantly higher at the lower load cell than at the upper. This could reflect that the resisting forces are associated with the additional mass of the neck, or that there may be some direct loading by the bag. Algorithms to ascertain the extent of each could be developed.
6. F_x is significantly higher at the upper load cell than at the lower. This probably reflects that the reaction load here tracks a_x while the lower load cell "sees" relatively little fore-aft loading until the head actually starts to move.
7. For the first 10 ms of neck loading, M_x is negative at the upper load cell while being positive at the lower. At 45 ms, the moments at both locations become positive and remain so till 75 ms. The initial reversal suggests the neck is bending in an "S" shape. This suggests that the head is initially translating to the left, on top of the neck, as a result of the loading to the head. This appears consistent with the line of force being below the centre of gravity of the head.
8. The maximum value of M_x at the lower load cell is twice as high as at the upper. There is no obvious explanation for this observation. However, it appears

that the head may be partially supported by the upper shoulder of the dummy at maximum extension. This would have the effect of transferring some of the resisting moment to an external reaction load. The lower neck is perhaps not benefiting from any external support.

9. The maximum values of M_y at the upper and lower locations are virtually the same but the directions are opposite and out of phase. The upper bending moment, a flexion moment, is maximum at about 48 ms. At this time the lower moment is virtually zero. At 60 ms, the lower neck exhibits maximum extension moment while the moment at the upper location is near zero. As in the case of M_x, the neck is adopting a curious shape. Initially, the neck is straight and the head flexed at the head/neck region. Later, the upper part of the neck returns to an essentially neutral orientation, but the lower neck is bent rearwards.
10. The bending moments reach their maximum value well after the head has stopped accelerating. For example, at the upper neck location, M_x is at a maximum (left lateral flexion), some 20 ms after a_y (to the left) has subsided. As with the shear forces, these moments persist because, though the head is not accelerating (substantially), it is moving, and the neck must retain the head to the torso, which is being accelerated by the neck.

CONCLUSIONS

Based on the static and dynamic reconstruction testing, and the injuries indicated in the autopsy, the following conclusions are drawn:

1. This fatal neck injury was due to the structural failure of the atlanto-occipital junction because the ligament structure, responsible for retaining the base of the head to the top of the neck, failed. The head, no longer retained, exposed the spinal cord and brain stem, as well as the surrounding muscle and soft tissue, to direct tensile loading. Being unable to sustain significant tensile stress, the stem/cord tore apart.
2. The precise mechanism is somewhat unclear because not all the injuries are described in the autopsy report with adequate detail. Also, it is obviously not possible to determine the sequence of the injuries from the autopsy report, only the actually injuries at the end of the process. The ability of the ATD to respond in a biofidelic manner is not clear. Notwithstanding these shortcomings, an injury mechanism is postulated:
3. The victim's head was rapidly pulled from the top of his neck as a result of the expanding air bag partially enveloping and accelerating his head.
4. The neck structure was subjected to axial loading, bending, and twisting by the air bag.
5. Tensile loading destroyed the ligament structure responsible for retaining the head on the top of the neck. It was both avulsed from the base of the skull and was ruptured around the top two vertebra. The head of the victim thereafter was retained only by the surrounding muscle and soft tissue, which was also partially ruptured in the process. The spinal cord was extruded and stretched to the point of complete rupture in the process.
6. The rapidity of the event is consistent with the absence of ligament failure around the lower cervical spine.
7. It is likely that the victim's head was separated from the torso by many centimetres. This motion cannot be replicated by the ATD because of the strong, stiff central cable running through the ATD neck.
8. The biofidelity of the ATD neck is dubious for all kinds of direct loading to the head (and/or torso) but especially so in the z direction. Certainly the measured high axial loads are attributable to the high stiffness in this direction. Because of this, head acceleration in the z direction will also be artificially high. While one would hope to be able to use the artificially high neck loads as part of an ATD neck protection criterion function, this study suggests that positive values of a_z should not be included in the calculation of resultant head acceleration.
9. It is expected that the axial neck loads experienced by a child would be of vastly lower magnitude and of longer duration. The skull-cervical spine load would persist only until the upper cervical structure failed. The ATD load, on the other hand, (whose neck does not fail), would continue increasing even further. Without stating the obvious, since one cannot know at what load or time the actual neck would have failed, one cannot expect to correlate the actual injury with the maximum ATD neck axial load measured during such a test as this.
10. The mechanical replication at the top and bottom of the cervical spine is poor. The ATD cannot articulate the way a human spine does, thus possible correlation with measured shear loading and bending moments, is dubious. Though it is acknowledged that the actual forces and moments may be different due to what are basically stiffness effects, the real issue is that the head and neck may not be able to orient themselves in a way that the induced loading even begins to approximate the expected reality of an air bag. The significance of this point depends, obviously, on when during the event the actual ligament injury occurs. If it happens very early, the absence of good motion replication may be less important. In cases of excessive overloading, such as the present, perhaps

this factor is less important. In cases where one is attempting to reproduce threshold injury situations, it will be more so.

11. Maximum loading of the neck occurs after the head has been accelerated by the air bag. The ATD head, moving away from the torso, but connected to it by the neck, places the neck under loading as it "tries" to further accelerate the torso.
12. Measured neck twisting moments are numerically smaller than those for flexion and extension. However, the injury threshold moment for twisting is lower than for flexion or extension and thus should not be disregarded in assessing the neck injury potential associated with a particular ATD test.

ACKNOWLEDGMENTS AND DISCLAIMER

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The conclusions reached, and opinions expressed, in this paper are solely the responsibility of the authors. Unless otherwise stated, they do not necessarily represent the official policy of Transport Canada.

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5TH % FEMALE DUMMY UPPER EXTREMITY INTERACTION WITH A DEPLOYING SIDE AIR BAG

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ABSTRACT

This paper presents the results from experiments designed to characterize the upper extremity response of the small female during side air bag loading. A seat mounted thoracic side air bag was deployed statically using three different inflators. The aggressivity of the inflators varied in peak pressure and pressure onset rate. The 5th% female HIII dummy was utilized in three positions which were chosen to maximize loading of the humerus and elbow joint. Two had the dummy positioned outboard with the forearm on the armrest, and the third had the dummy inboard such that the humerus was positioned horizontally in front of the air bag module with the forearm supported above the armrest. Instrumentation for the 5th% female dummy included the fully instrumented SAE upper extremity with six axis load cells in the humerus and forearm as well as accelerometers and angular rate sensors attached to each segment. All inflators produced resultant humerus moments below published injury tolerance values for the small female with the more aggressive air bags producing higher responses. The upper extremity response was correlated to inflator peak pressure and pressure onset rate.

INTRODUCTION

Although driver side air bags have reduced the risk of fatal injuries in automobile collisions, they have increased the incidence of nonfatal injuries including upper extremity injuries. It is suggested that there may be a 40% increase in risk of serious (AIS 3) upper extremity injury to belted occupants with air bags versus those without air bags [NHTSA, 1996]. Kuppa (1997) showed that 1.1% of drivers who were restrained by only a seat belt experienced an upper extremity injury, versus 4.4% of drivers in the presence of a deploying air bag who experienced an upper extremity injury. Although air bag depowering is expected to have a beneficial effect on the rate of upper extremity injuries from driver side air bags, it is unclear whether or not the implementation of side air bags will provide a new upper extremity injury mechanism. Since side air bags have been installed in only a few cars, it currently is not possible to evaluate the upper extremity injury potential through the typical real world crash investigation techniques. Thus, experiments with instrumented dummies and cadavers are performed to better understand this interaction. The goal of this paper is to evaluate the interaction of the small female upper extremity with a deploying side air bag.

The interaction between a side air bag and the average male upper extremity was evaluated by Kallieris (1997) using both the HIII 50th male dummy and five male cadavers. A seat mounted combination thorax-head bag was used with the upper extremity positioned in contact with the seat seam. Only one humerus fracture was recorded for all five tests. Thus, it was suggested that there is a low risk of upper extremity injury during side air bag deployment. In addition, the kinematic differences between the dummy and cadaver were significantly different given the poor biofidelity of the dummy shoulder joint.

HUMERUS INJURY REFERENCE VALUES

Before evaluating the dummy tests, it is useful to establish reference injury assessment reference values (IARV) for the humerus. Several studies have addressed the humerus bending strength and the results are presented in Table 1. The studies by Weber (1859) and Messerer (1880) are dated and involve populations that are likely different than the modern population. The 5th% female injury criteria is best established by tests with female humeri. The research by Duma (1998) is the only study to use an appreciable number of female humeri (n = 12), moreover this is the only study to test the humeri dynamically with strain rates between 1 and 3 strain/second. Thus, the injury tolerance for the 5th% female will be selected as the scaled value of 128 Nm. Since all but one of the humeri tested (n = 19) by Kirkish (1996) were male, the injury tolerance for the 50th% male could be taken as the scaled value of 230 Nm.

Table 1: Published Humerus Tolerance Data

Author	Year	Male Bending Failure (Nm)	Female Bending Failure (Nm)
Weber	1859	115	73
Messerer	1880	151	85
Kirkish	1996	157 ± 41	84
	scaled	230 ± 65 (50^{th}%)	134 ± 38 (5^{th}%)
Kallieris	1997	137 ± 7	
Duma	1998		154 ± 24
	scaled	217 ± 32 (50^{th}%)	128 ± 19 (5^{th}%)

METHODOLOGY

Three types of seat mounted, thoracic side air bags were used that varied only in their level of inflator output. Table 2 outlines the relative differences in peak pressure and pressure onset rate between the three inflators as measured in a 1 ft^3 tank test. The inflators utilize hybrid technology and the bags have two vents on the outboard side.

Table 2: Side Air Bag Inflator Characteristics

Inflator Type	Increase in Peak Pressure Relative to Type 1B	Increase in Pressure Onset Rate Relative to Type 1B
1B	0%	0%
2A	23%	63%
3C	54%	160%

Dummy instrumentation included triaxial head and chest c.g. accelerometers. MHD angular rate sensors were attached to the head and upper spine to track body rotation throughout the event. Upper and lower chestbands were used to measure any possible chest deformation. All tests were captured with high speed color video (1000 fps) and high speed color film (3000 fps).

The 5^{th}% female dummy was also equipped with the SAE 5^{th}% female instrumented upper extremity. This device has been shown to be effective at characterizing the upper extremity response due under air bag loading [Bass 1998]. Although the arm was used to develop the injury criteria for the forearm under loading from a driver side air bag, this is the first published study to use it for the analysis of side air bags [Bass 1997]. The arm with the appropriate polarity is shown in Figure 1. The forearm is a single shaft incorporating a six-axis load cell located approximately mid-shaft. The elbow is a single degree of freedom joint which allows flexion/extension but not the pronation/supination rotation as in the human upper extremity. This loss of motion is not significant given the application and symmetry of the shaft. On the proximal side of the elbow joint, two strain gauges measure bending moments along the X and Y axis. The humerus is similar to the forearm with a single shaft design which includes a six-axis load cell. The shoulder joint allows for the three principle rotations of the shoulder, but the lack of clavicle/scapula movement accounts for the poor biofidelity of the dummy shoulder joint. Additional accelerometers and MHD angular rate sensors were added to the forearm and humerus.

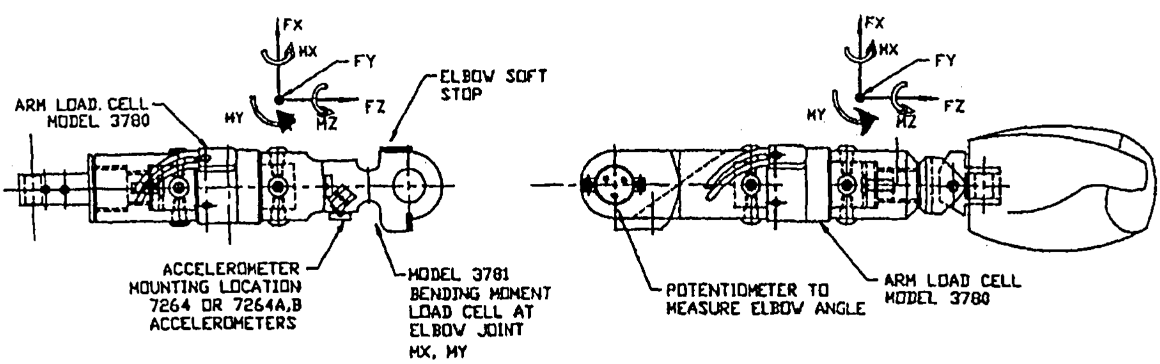

Figure 1: SAE 5^{th}% Female Instrument Upper Extremity

Initial Positioning

A new computer model for studying side air bag and occupant interaction was developed using the CVS/ATB multi-body dynamics program [Sieveka 1998]. The model employed standard ellipsoids to represent the type 2A side air bag. Using this model, several initial positions were developed that maximized loading to the humerus, elbow joint, and thorax, with emphasis on the humerus response. The instrumented 5^{th}% female HIII with the SAE instrumented arm were then used to evaluate the positions recommended by the simulation study. Figure 2 shows the peak resultant humerus moment for this first round of dummy tests. Since the primary goal was to maximize loading of the humerus, positions 11B, 5, and 8B were selected as the final three positions to be tested with each of the three side air bags.

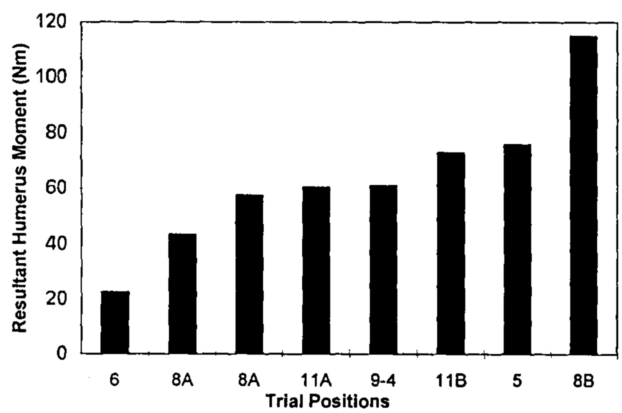

Figure 2: Peak Humerus Resultant (MX + MY) Moment for Dummy Trial Positions

The frontal and lateral views of the three worst case positions are displayed in Figure 3. The humerus, shoulder, and elbow are loaded in position 8B which has the humerus in contact with the seat back and the forearm resting on the armrest. In position 11B the humerus is placed across the path of the side air bag and the forearm is raised from the armrest. The dummy is moved slightly inboard to allow for proper upper extremity placement. This position is designed to maximize the load on the humerus and the elbow joint. Finally, in position 5 the dummy is placed completely outboard with the forearm on the armrest such that the air bag loads the humerus and posterior thorax.

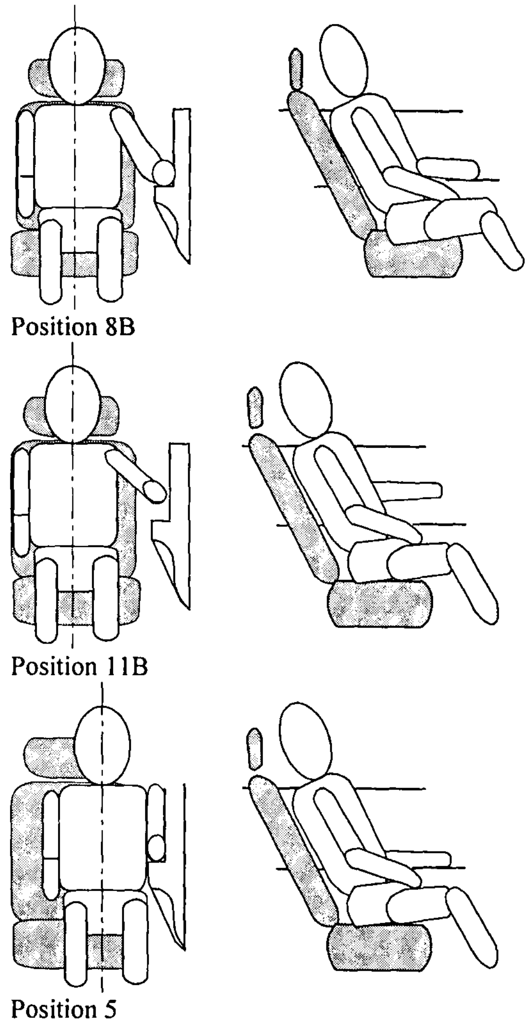

Figure 3: Three 'Worst Case' Positions

Preliminary tests suggested that an positioning accuracy of ± 2 mm along any axis was the tolerance needed to repeat the tests. Given the long and thin side air bag, any error in positioning would result in the air bag deploying along the path of least resistance. Thus, if the humerus is out of position by more than 2 mm in any direction, the air bag may not completely load the humerus. For this reason a FARO® arm was used for final positioning to remain within the allowed tolerances.

RESULTS AND DISCUSSION

The upper extremity response can be characterized using the kinematic and kinetic sensor data. Neck and torso rotations were insignificant for all tests given the stiffness of the dummy and the lack of direct loading to these body regions and therefore are not presented.

Kinematics

Although the SAE 5th% female arm contains a potentiometer at the elbow joint to measure forearm flexion/extension, there are no other angular motion sensors. For this reason an array of MHD angular rate sensors was installed on the dummy that allowed for the measurement of all upper extremity rotations. To compare the accuracy of the MHD sensors, the elbow flexion angle is plotted using both the potentiometer data and the MHD data as shown in Figure 4. Since both traces are nearly identical and the potentiometer wires failed in two of the nine tests, the MHD data will be used to discuss all rotations.

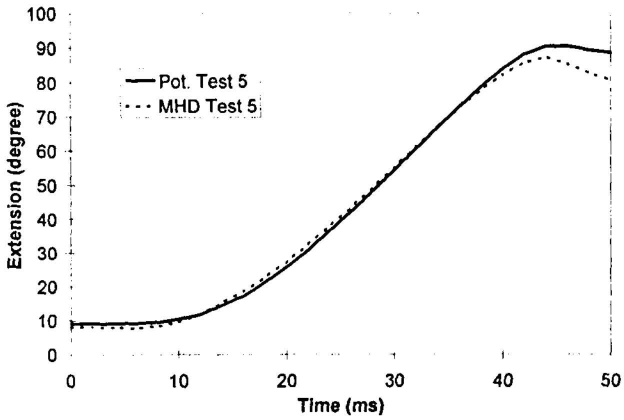

Figure 4: Potentiometer and MHD Data for the Elbow Flexion Angle in Test 5

The dummy shoulder joint consists of three rotations that are defined for this discussion as follows. Movement of the humerus in the sagital plane is defined as flexion when the humerus is moved forward and extension when the humerus is moved rearward. Rotation of the humerus in the frontal plane is defined as adduction toward the body and abduction away from the body. The neutral position for both flexion and adduction is with the humerus vertical and the distal end pointing down. The third rotation is called medial/lateral rotation. The neutral position has the humerus vertical and the elbow bent 90 degrees and pointing forward. Rotating the hand towards the body defines medial rotation, while rotating the hand away from the body is defined as lateral rotation.

A difference between the three positions can be seen by the amount of adduction at the shoulder joint. Figure 5 details this for all three positions with air bag 2A. The negative adduction angle is the same as a positive abduction angle. So, for positions 8B and 11B the humerus is initially abducted 37 and 64 degrees respectively. Despite the initial positioning difference, both position 8B and 11B rotate in a similar manner as the humerus rotates towards the body as shown by the increasing adduction angle. This motion corresponds to the air bag loading the posterior and lateral side of the humerus. However, in position 5 the air bag deploys between the thorax and humerus and forces the humerus against the door which results in the slight decrease in adduction angle.

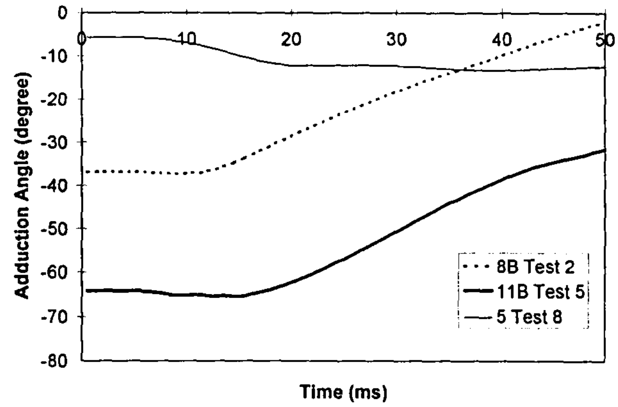

Figure 5: Shoulder Adduction for Three Positions with Air Bag 2A

A second kinematic difference between the positions is seen in the medial/lateral shoulder rotation. In Figure 6 the lack of shoulder rotation for position 5 is again seen as the medial rotation remains below 10 degrees for the duration of the test. The medial rotation for position 8B is nearly opposite that for position 11B. In position 8B the elbow is forced down which results in the negative medial rotation, whereas in position 11B the air bag forces the elbow slightly upward and therefore induces a positive medial rotation. Despite the separate direction, the magnitudes of the rotation for both positions 8B and 11B are similar at 29 and 35 degrees respectively.

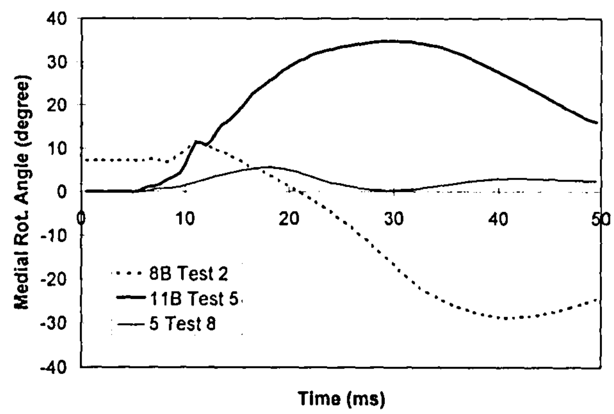

Figure 6: Shoulder Medial/Lateral Rotation for Three Positions with Air Bag 2A

While the air bag type had little influence on the shoulder rotation, it did affect the elbow flexion response. In position 11B the magnitude and rate of elbow flexion

Figure 7. The most notable difference is in bag 1B which produces approximately one half the elbow flexion response versus bags 2A and 3C.

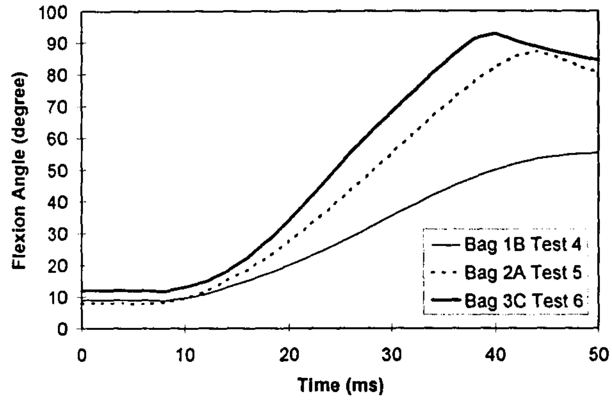

Figure 7: Elbow Flexion for All Air Bags in Position 11B

As seen with the shoulder rotations, elbow flexion is quite different among positions as Figure 8 details for all positions with air bag 2A. Again, position 5 reveals negligible upper extremity motion, while positions 8B and 11B follow similar rotations. When the initial flexion angle is considered for positions 8B and 11B, it can be seen that the air bag forces full elbow extension in position 11B versus a slightly flexed elbow for position 8B.

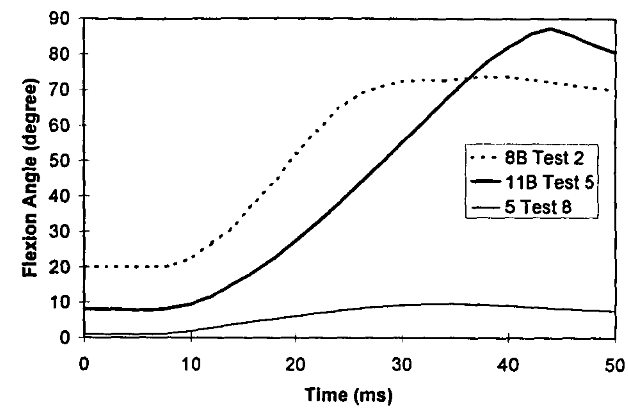

Figure 8: Elbow Flexion for Three Positions with Air Bag 2A

Kinetics

A summary of the upper extremity response for each test is presented in Table 3. A linear regression analysis was performed to identify any correlation between the peak sensor readings and inflator peak pressure and pressure onset rate.

Table 3: Peak Resultant Accelerations, Forces, and Moments for the Upper Extremity

Test	Position	Bag Type	Forearm Accel. (g)	Time (ms)	Humerus Accel. (g)	Time (ms)	Humerus Resultant FX + FY (N)	Time (ms)	Humerus Resultant MX + MY (Nm)	Time (ms)
1	8B	1B	170	9.2	207	8.7	720	8.4	59	9.0
2	8B	2A	207	7.5	220	10.0	1249	10.4	103	11.2
3	8B	3C	233	11.4	392	10.2	815	7.0	96	7.6
4	11B	1B	186	8.5	202	12.9	645	12.9	36	8.2
5	11B	2A	187	6.4	388	11.7	662	16.9	62	9.5
6	11B	3C	378	7.4	410	11.0	617	6.7	89	7.2
7	5	1B	102	9.4	187	14.1	550	14.7	73	17.2
8	5	2A	265	23.5	151	7.4	615	6.8	76	15.3
9	5	3C	343	22.2	213	7.8	1029	11.5	106	14.0

The peak forearm accelerations ranged from a low of 102 g to a maximum of 378 g for all air bags and all positions, and increased with increasing inflator aggressivity. The forearm accelerations for position 8B showed the best correlation to inflator properties with R^2 values of 0.96 for the peak pressure and 0.95 for pressure onset rate. No correlation was seen with the forearm accelerations in positions 11B or 5. In tests 8 and 9 the peak accelerations occur much later than the peaks for the other tests as a result of the different loading pattern. In position 5 the peak is affected by the upper extremity interaction with the door.

The forearm sheer forces FX and FY were insignificant given the type of air bag loading; however, the axial compression load FZ of the forearm demonstrates the early timing of the peak loads and air bag dependence as shown in Figure 9.

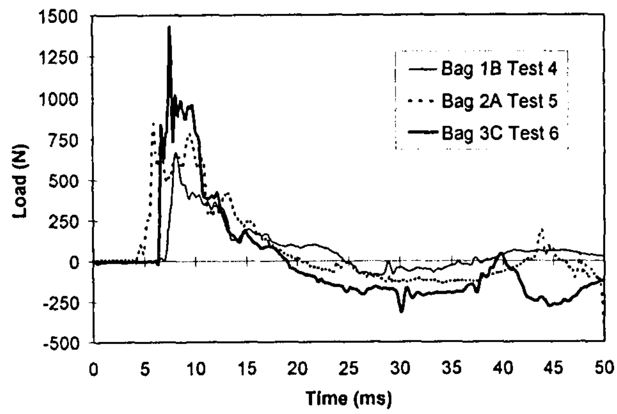

Figure 9: Axial Forearm Load (FZ) for All Air Bags in Position 11B

The humerus accelerations increased with increasing inflator aggressivity. In position 5 the humerus acceleration correlated reasonably well with the peak pressure and pressure onset rate with R^2 values of 0.92 and 0.90 respectively. The correlation was less with position 8B which gave R^2 values of 0.86 and 0.89 for peak pressure and pressure onset rate, while no correlation was seen with position 11B. The forearm and humerus accelerations are similar to those recorded by Kallieris (1997). Although Kallieris used a much larger side air bag, he also used average male cadavers so that the larger mass counteracted the larger bag to produce upper and lower humerus accelerations ranging from 193 g to 334 g.

The peak resultant FX and FY humerus forces ranged between 550 N and 1249 N with all peaks occurring before 14.7 ms as the air bag initially loaded the posterior humerus. The tests in position 8B resulted in a higher load of 1249 N with air bag 2A versus the higher aggressivity bag type 3C which gave a 815 N peak response. This trend was seen in position 11B where the resultant humerus sheer force was lower for bag 3C than for the 1B or 2A. Only position 5 gave humerus loads that correlated reasonably well with peak pressure and pressure onset rate with R^2 values of 0.90 and 0.92 respectively.

Dummy joint stops often dramatically increase the response due to high inertial accelerations when a particular joint reaches its limit. This is the case for the elbow joint in the SAE 5^{th}% female arm. Position 11B best illustrates this behavior as it is the position that induces the most extension in the elbow joint as seen previously in Figure 8. Using the strain gauge located at the distal humerus shaft, the bending moment MY for each air bag in position 11B is shown in Figure 10. Between 5 ms and 15 ms the response is due to the air bag contact, but the large peaks at 40 ms for bag 3C and 45 ms for bag 2A are a result of the elbow joint completely extending and reaching the joint stop. Due to the lack of known human elbow joint properties it is impossible currently to determine if this response is appropriate or not. Also, it is interesting to note that bag 1B does not impart enough energy to the upper extremity to cause the humerus and forearm velocities needed to see the peak at the joint stop.

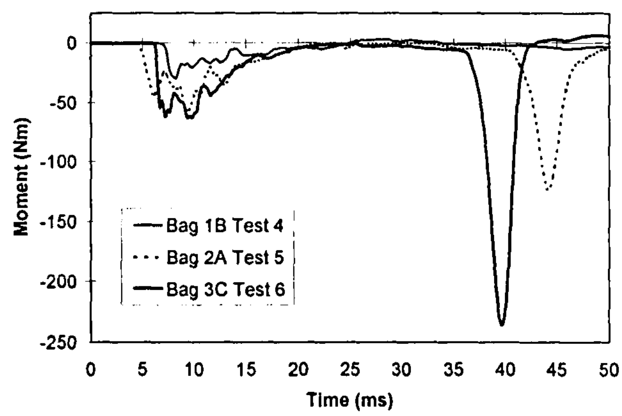

Figure 10: Elbow Moment MY for All Air Bags in Position 11B

The resultant humerus moments (MX, MY) presented in Table 3 were taken only during the first 30 ms given the uncertainty of the high values occurring after 30 ms as a result of the joint stop. As shown in Figure 11, the resultant humerus moment for position 11B demonstrates the same trend as seen with the elbow strain gauge, as bags 2A and 3C have peaks that correspond to the joint stop while the lesser bag 1B does not. Although the humerus moments in position 8B do not correlate with inflator properties, the humerus moments for positions 11B and 5 correlate very well. In position 11B, the resultant humerus moment correlates to peak pressure with a R^2 of 0.99 and to the pressure onset rate with an R^2

of 0.99. The correlation is less with position 5 with R^2 values of 0.87 and 0.90 for peak pressure and pressure onset rate.

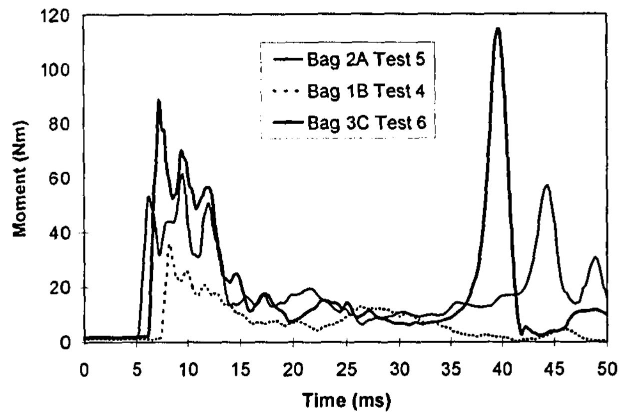

Figure 11: Resultant Humerus Moment (MX, MY) for All Air Bags in Position 11B

Using Duma's (1998) IARV of 128 Nm for the 5^{th}% female humerus, Figure 12 was created to summarize the humerus response for the most severe tests. Since all values are well below 100% of the IARV, no humerus fractures are expected under loading by any of the three side air bags.

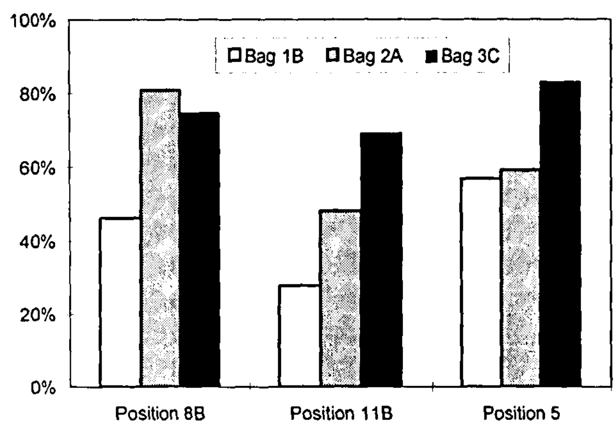

Figure 12: Percent of IARV for Resultant Humerus Moment (MX, MY) for All Air Bags in Three Positions

As expected the chest deflections for positions 8B and 11B were negligible. Only position 5 recorded any deflection of the upper or lower chestband as summarized in Table 4. Given that the injury reference value for peak sternal deflection by a distributed load is 53 mm, no thoracic injuries are expected for this test configuration [Mertz 1993].

Table 4: Peak Chest Deflection for All Air Bags in Position 5

Airbag Type	Upper Chestband (mm)	Lower Chestband (mm)
1B	4.1	2.1
2A	2.5	2.5
3C	12.1	3.1

CONCLUSIONS

The SAE instrumented upper extremity proved effective at evaluating the response under side air bag loading. Using the IARV of 128 Nm for the 5^{th}% female, no humerus fractures are expected as a result of side air bag loading the upper extremity. Further tests are needed to compare the dummy response to that of a small female cadaver in order to examine the biofidelity of the SAE arm.

The MHD angular rate sensors proved useful in determining the rotations of both the shoulder and elbow joints. The large moments that were recorded in the humerus when the elbow reached the joint stop must be evaluated relative to human data to determine their relevance.

The upper extremity response correlated well with the inflator properties for certain positions and sensors. The peak pressure and the pressure onset rate correlated in the same manner for each comparison. Position 5 showed the best correlation with an increase in resultant humerus acceleration, force and moment corresponding to increase inflator aggressivity.

Slight changes in positioning have a significant effect on the occupant response. The long and narrow design of the side air bag allows it to travel the path of least resistance easier than the much larger driver side air bags. For this reason the positioning tolerance was established as ± 2mm for each axis. In addition, the more aggressive the air bag, the higher the tendency for the air bag to deploy to either side of the upper extremity rather than load it fully.

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EVALUATION OF SECONDARY RISK WITH A NEW PROGRAMED RESTRAINING SYSTEM (PRS2)

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ABSTRACT

The new safety standards or car assessment programs for passive safety lead to the stiffening of car bodies. Consequently, the loading of occupants increases, generating a higher injury risk to the thorax. To avoid this increase in undeformed cars, more efficient restraining systems have to be developped. But the improvement of performances should not increase out-of-position (OOP) risks, in particular to the neck and thorax of adults and to children.
This paper deals with the development of a new restraining system combining a belt with 4 kN force limiter and an airbag with pressure limitation. In order to have a biomechanical evaluation of real protection on human beeing, the OOP injury risk is studied by Post Mortem Human Subject (PMHS) experiments.

THE PROGRAMED RESTRAINING SYSTEM

This system was presented by Bendjellal, 1997 [1]. It consists on 3 main components for the optimisation of thorax restraint : the pretensioner, the belt load limiter and the air-bag. The pretensioner and the belt load limiter are designed to restraint the thorax as soon as possible but with a load which complies with human tolerance (4 kN). Then, the airbag is designed to contribute actively to the thorax restraining while avoiding agressiveness of the deployment. This leads to an increase in the generator power, associated to an elaborated airbag-folding which reduces the punch out and to a pressure limitation in the airbag.

OUT-OF-POSITION INJURY RISKS

In order to evaluate the real OOP injury risk and to generate biomechanical data, a test protocole on PMHS was elaborated with and realized by CEESAR. Four static tests have been conducted up to now with PMHS and can be compared with Hybrid III tests conducted in the same conditions.

Test method - The subject is seated on a Renault Megane seat, leaning over the steering wheel equiped with PRS2 Airbag. Two positions of the occupant were used. In the first position (Figure 1), the forehead rests on the steering wheel rim and the chin is on the top of the airbag module. In the second position (Figure 2), the nose was located on the module.

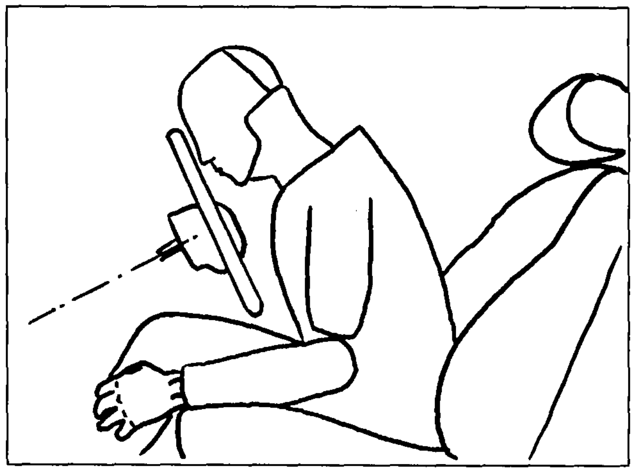

Figure 1 : Occupant relative position to steering whell in static air bag deployment OOP tests. Position forehead on rim.

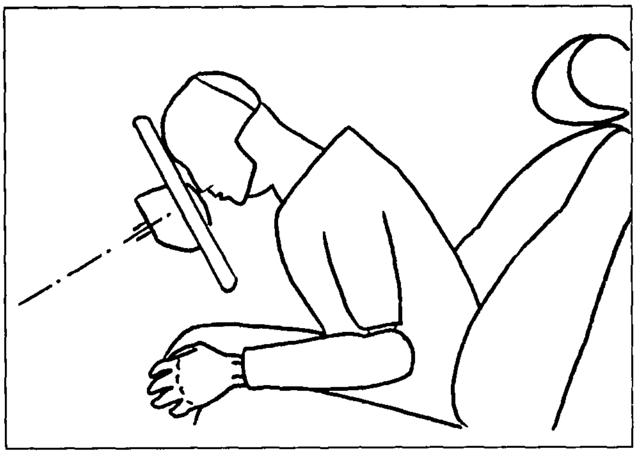

Figure 2 : Occupant relative position to steering whell in static air bag deployment OOP tests. Position nose on module.

Preparation of subjects - The subjects are fresh cadavers from the Anatomical Donor's service of the Anatomical Laboratory of the Saints-Pères Faculty, Paris V. The vascular system is re-pressurized through a bi-carotid injection of a solution of formaldehide, water and china ink. The pulmonary volume is re-established.
For the Hybrid III, tests were performed with and without neck shield (FTSS n° 103 9006).

Instrumentation - The subjects are equiped with a 12-acceleration array fastened to the occiput of the head in order to measure 3 linear and 3 angular head accelerations. 3-axes accelerations are measured at T4, T12 and sacrum level. Thoracic deflection is measured with a chest band at level T5. Vascular and pulmonary pressures are also measured.
For Hybrid III, measurements include 3-axes head, thorax and pelvis accelerations, neck loads, head and thorax angular velocity and chest deflection (potentiometer).
The airbag pressure is measured as well as steering wheel forces

Test results - Table 1 gives the subject characteristics, Table 2 the test results with HIII and PMHS in the position with the nose on the module and Table 3 test results with HIII and PMHS in the position with the forehead on the rim.

DISCUSSION

OOP injury risk with PRS II - For the PMHS tests, three subjects were tested in the first configuration (forehead on rim) and one subject in the second one (nose on module).
In the forehead/rim position, two subjects sustained AIS2 thoracic injuries, while the third one just sustained a slight burn on the forearm (AIS1). It is to be noted that these two subjects where repectively 76 and 81 year old men, the first one having metastases on the ribs. No injuries were observed to the neck, nor to the head.
In the nose/module position, the subject sustained no injuries.
The results of these 4 tests are satisfying and suggest that the airbag folding as well as the pressure limitation worked well.

Neck injury analysis- For the nose/module position, the kinematic is similar for the PMHS and the HIII : the head has a movement of extension from the begining of the deployment, while the thorax goes backward. However, the head acceleration is the double with PMHS compared to HIII.

For the forehead/rim position, the head kinematic is different on PMHS and HIII. Indeed, for PMHS the head is pushed upward at the begining of deployment, without extension. The thorax goes backward, pulling the head which goes in extension when the thorax comes in contact with the seat-back. On the contrary, for HIII, the head goes in extension from the begining of deployment to the end of test. As a consequence, it is difficult to associate neck injury on PMHS to neck measurements on HIII for these tests.

Thoracic injury criteria - For the two test conditions, the kinematic of the thorax is similar for PMHS and HIII. More, the air bag pressure is comparable and the thorax accelerations are on the same range. On the contrary, the thorax deflections are in the range of 13 to 18,5 mm for HIII, against 63 to 73 mm for PMHS, or 50 to 60 mm if we reduce chest compression by 13 mm to take account for the effect of compression of the flesh covering the thorax. The Viscous Criterion (VC) are in a ratio of 10 between HIII and PMHS. It can be conclued that HIII is more stiff than PMHS in these test conditions.
These data, for the test conditions discussed here, lead to a 50% risk of AIS2 and 0% of AIS3 in the range of 50 to 60 mm of internal deflection, for males in the range of 54 to 81 years. If we refer to Mertz analysis [2] of Neathery data (distributed chest impacts), the same range of deflections is associated to a risk between 10% and 40% of AIS3+. It is to be noted that these figures refer to cadaver data.

CONCLUSIONS

A preliminary investigation to evaluate the risk of neck injury with the PRS II air bag was performed, using the Hybrid III 50° percentile dummies and 4 subjects (PMHS). Two occupant/steering wheel positions, i.e. forehead on rim and nose on module, were used. The air bag pressure control worked in all tests. For the PMHS, only two AIS2 thoracic injuries and a slight burn on the forearm for one subject (AIS 1) were found during the autopsies. In addition, no neck injuries were found. These data appears to be satisfying at this stage of analysis; further investigations with the Hybrid 5° percentile and a more in-depth analysis of the PMHS test data remain to be performed to increase the knowledge in the field of human behaviour and tolerance in OOP conditions.

AKNOWLEDGMENTS

Many thanks to the Faculté des Saints Pères and to the CEESAR for the biomechanical evaluation.

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TABLE 1 : Subject characteristics and injuries

	PMHS 500	PMHS 501	PMHS 503	PMHS 505
WEIGHT (kg)	68	96	78	70
HEIGHT (m)	1,72	1,76	1,75	1,68
Buste (m)	0,945	0,91	0,90	0,875
CHEST WIDTH (seating position) (m)	0,200	0,235	0,200	0,210
AGE (years)	54	73	76	81
SEXE	Male	Male	Male	Male
Cause of death				
HEAD	No injury	No injury	No injury	No injury
NECK	No injury	No injury	No injury	No injury
THORAX	No injury	No injury	R3-5 Fx on left side R3-5 Fx on right side AIS = 2	R3-4-5 Fx on left side R3-4-5-10 Fx on right side AIS = 2
Comments			metastase on ribs	

TABLE 2 : Test results with HIII and PMHS (nose on the module)

	Limits		Nose on the module		
			HIII 997	HIII 998 with neck shield	PMHS 501
HEAD	1000	HIC 15 ms (t1-t2)	113 (23-38)	98 (24-39)	436 (3-9)
	80	Acc 3 ms (g)	44	38	81
		max Rotation (deg) (ATA)	84	81	8
	60	Ext neck/thorax (deg) (film)	61	56	
NECK	3.1/ -3.1	Fx Upper neck (kN) (tmax)	0.84 (34) / -0.19 (53)	1.1 (35) / -0.1 (155)	
	4.0/ -3.3	Fz Upper neck (kN)(tmax)	1.55 (33) / -0.3 (10)	1.27 (29) / -0.12 (11)	
	190/ -57	My Upper neck condyles (Flex/Ext) (Nm) (tmax)	49 (11) / -33 (59)	77 (36) / -26 (61)	
		Fx Lower neck (kN) (tmax)	6.94 (11) / -1.38 (21)	5.08 (48) / -1.52 (6)	
		Fz Lower neck (kN) (tmax)	1.36 (33) / -0.15 (16)	1.1 (8) / -0.23 (11)	
		My Lower neck (Nm) (tmax)	19 (343) / -97 (37)	17 (343) / -100 (9)	
THORAX	60	Acc 3 ms (g)	15	17	T4 = 24 T12 = 9
	76	Déflection (mm)	15 (9%)	13 (8%)	63 (19%)
	1	VC (m/s)	0.058	0.045	0.47
PELVIS	60	Acc 3 ms (g)	3	3	5

TABLE 3 : Test results with HIII and PMHS (Forehead on rim)

	Limits		Forehead on rim				
			HIII 995	HIII 996 with neck shield	SPHM 500	SPHM 503	SPHM 505
HEAD	1000	HIC 15 ms (t1-t2)	44 (25-40)	52 (26-39)	295 (8-12)	71 (7-15)	34 (31-46)
	80	Acc 3 ms (g)	29	35	46	38	27
		max Rotation (deg) (ATA)	69	64	26	8	15
	60	Ext neck/thorax (deg) (film)	48	40			
NECK	3.1/ -3.1	Fx Upper neck (kN) (tmax)	0.2 (6) / -1.11 (31)	0.14 (5) / -0.73 (27)			
	4.0/ -3.3	Fz Upper neck (kN)(tmax)	2.09 (9) / -0.02 (330)	1.78 (35) / -0.01 (-93)			
	190/ -57	My Upper neck condyles (Flex/Ext) (Nm) (tmax)	8 (326) / -62 (32)	3 (332) / -39 (28)			
		Fx Lower neck (kN) (tmax)	3.11 (45) / -0.47 (33)	2.51 (36) / -2.50 (37)			
		Fz Lower neck (kN) (tmax)	1.77 (9) / -0.43 (11)	2.02 (35) / -0.03 (212)			
		My Lower neck (Nm) (tmax)	50 (11) / -128 (9)	21 (10) / -100 (7)			
THORAX	60	Acc 3 ms (g)	15	15	T4 = 24 T12 = 14	T4 = 28 T12 = 17	T4 = 20 T12 = 11
	76	Déflection (mm)	17 (10%)	18.5 (11%)	72 (28%)	73 (26.2%)	63 (24.9%)
	1	VC (m/s)	0.08	0.106	0.66	1.06	0.92
PELVIS	60	Acc 3 ms (g)	5	4	6	4	5

DEVELOPMENT OF A NEW CRASH CUSHION FOR THE PROTECTION OF PEOPLE IN WHEELCHAIRS IN A ROAD ACCIDENT

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ABSTRACT

All vehicles produced today are, as a matter of course, equipped with systems designed to protect the occupants should the vehicle be involved in an accident. Three point seat belts and airbags are fitted as standard in all modern vehicles.

Developments in the field of transport for disabled persons have not yet reached the same level. The demands placed on a wheelchair restraint system are considerably less than those which are standard for a restraint system in a passenger car. In Commercial Vehicle Development at Volkswagen AG in Wolfsburg a crash cushion has been developed improving safety in the transport of disabled persons to meet the higher, passenger car standards of safety and also take into account the special requirements of people in wheelchairs and staff accompanying them.

The first measure to improve levels of safety in the transport of disabled persons - a new development - is a cushion which is secured with a lap belt and which rests on the thighs of the person seated in the wheelchair. The cushion improves the kinematics of the occupant in an accident to such an extent that good biomechanical load results are achieved under stringent testing requirements.

INTRODUCTION

According to the VdK in Bavaria (Association for disabled ex-servicemen, surviving dependants and social insurance pensioners) there are approximately 800,000 people in wheelchairs in Germany. The necessity to be mobile is important for this group, as it is for those who are not disabled, in order to play an active role in daily life. The journey to work, to an event, to the doctor etc. is made by most people in wheelchairs in a disabled transport vehicle, with the exception of the group who are in a position to drive themselves. That means that over 5000 such trips are made every day in a city the size of Cologne (approx. 1 million inhabitants). In most cases the person in the wheelchair is not transported in seats fitted in the vehicle, but rather in their own wheelchair. The tasks of the accompanying staff are thus reduced as well as the time needed to get in and out of the vehicle. The person and the wheelchair are secured using a special wheelchair restraint system in the vehicle. This system is designed not only to prevent the wheelchair from moving or even from falling over in the vehicle, but also to offer safety in the most common accident situations.

DESCRIPTION OF THE TEST REQUIREMENTS

Elaborate passive safety systems have been introduced in the passenger car sector over the course of the past few years. The securing systems for the transport of people in wheelchairs have also been improved. These systems are tested according to DIN 75 078. In addition to a static test, a dynamic test must be carried out using an accelerating sledge with 12 g load over 20 ms to test the safety of the restraint system in a front-end collision.

According to the results of the crash tests against a solid wall carried out at Volkswagen AG with passenger cars and minibuses, however, the average vehicle deceleration during a full frontal collision is considerably higher than the values stipulated in the DIN.

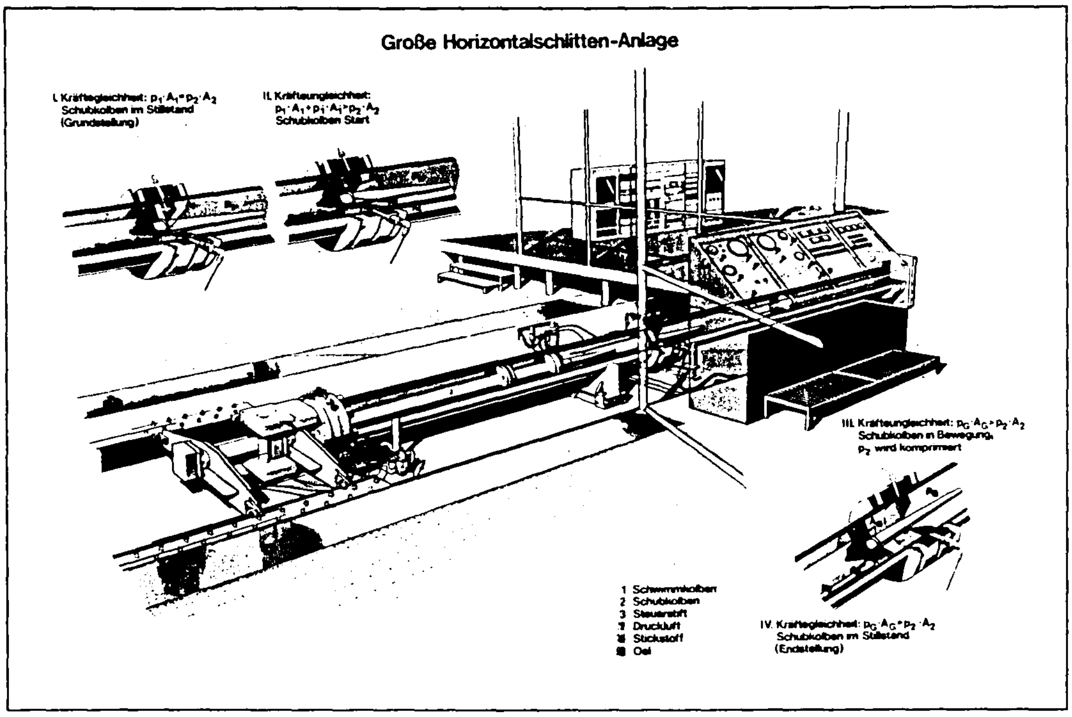

Figure 1. The large acceleration sled of the VW-AG.

In an accident with a passenger car, minibuses, such as are normally used for the transport of disabled persons, have a lower vehicle deceleration than the passenger car due to their heavier weight and greater stiffness. But even in this case, deceleration rates of the minibus exceeding 12 g are measured.

On the basis of the above test results, more stringent test requirements than in DIN 75 078 are used for the development of the restraint systems for people in wheelchairs as described below. For this reason, a test is used based on ECE-R17, which applies to passenger car seats and restraint systems. This requires an acceleration test at 20 g over 30 ms. The aim is to give people in wheelchairs a similarly high degree of safety at this increased load as is standard in today's passenger cars.

TEST SET-UP AND PROCEDURE

The tests presented here were carried out on the large horizontal sledge at Volkswagen AG in Wolfsburg (fig. 1). The sledge is propelled by a compressed gas thrust piston and is designed as a deceleration sledge, i.e. it is accelerated in the vehicle's reverse direction. The sledge body acceleration curve is set by a control pin and by adjustment of the load pressure. For the requirements of ECE Directive 17 [2] (20g over 30 ms) a half-sine sledge pulse of 70 ms duration is used. The maximum acceleration of the sledge is around 26 g (fig. 2).

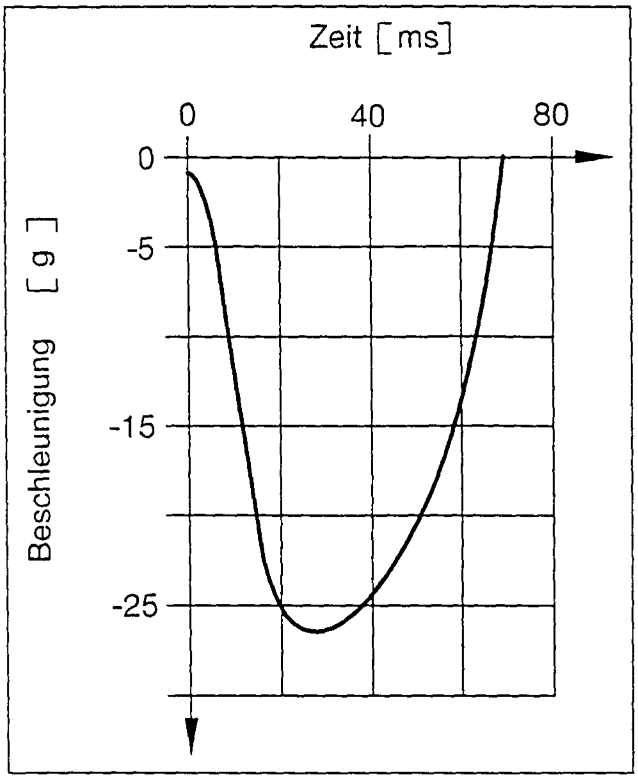

Figure 2. Used half-sine impulse for the tests.

INITIAL TEST AND DERIVED REQUIREMENTS

A comparison test was carried out with the most commonly used restraint system for transport of people in wheelchairs (fig. 3) at 12 g and 20 g acceleration pulse over 30 ms.

With this restraint system the wheelchair is stayed by four belts which are looped around the wheelchair frame with retractors on rails on the vehicle floor. The occupant is secured by an adjustable-length lap belt which is attached to the rails on the vehicle floor.

The test at 12 g acceleration resulted in a low to medium risk of injury for the occupant. The wheelchair sustained almost no deformation or damage at all. In the second test at a load of 20 g the sequence of movement of the dummy was similar to that in the first test. This sequence of movement is illustrated in figure 4 and described in table 1.

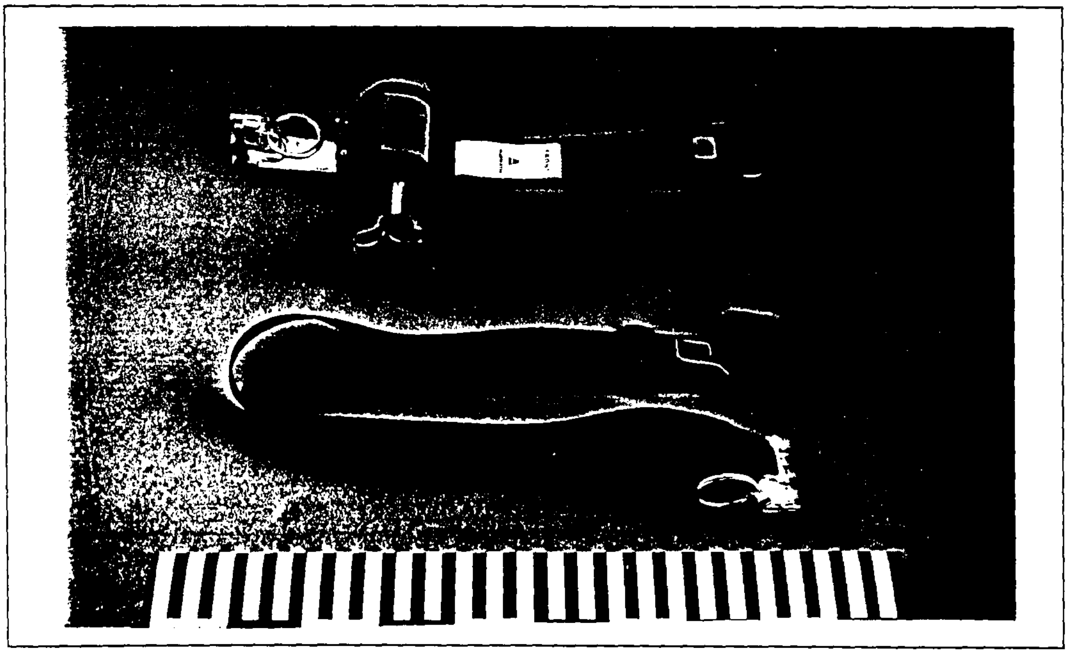

Figure 3. Pelvis- and wheel-chair belt with fittings.

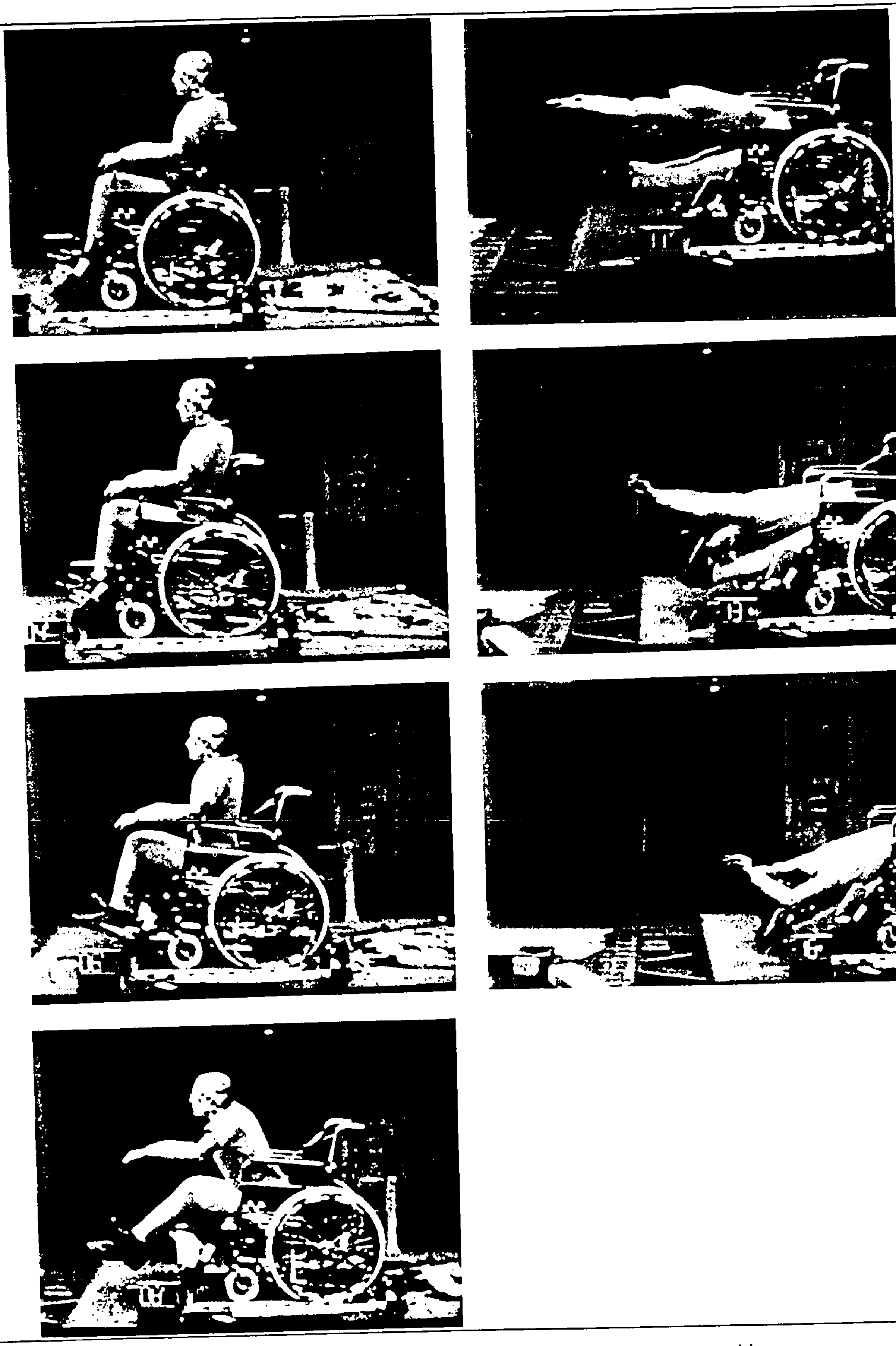

Figure 4. Movement of the dummy in the wheel-chair test with 20 g without impact cushion

Table 1. Sequence of movements at a load of 20 g

Phase	Time	Sequence
one	0 ms	Test start
	40 ms	Translatory forwards motion of the dummy on the seat base begins
	60 ms	The belt slack has been taken up, the max. belt forces at the pelvis and the max. pelvis acceleration are reached; the translational movement of the dummy is completed
two	80 ms	The jack-knifing effect causes the upper body and the legs to rotate around the H point and lap belt
	110 ms	The upper body and legs are horizontal; in this position the head acceleration peaks at a marked maximum of up to 90 g The head and upper body begin to overswing; the chest makes contact with the thighs and is supported by them; due to the belt sliding out of position a sequence of load peaks in the acceleration of the chest and pelvis occur
	135 ms	As a result of the severe overswinging of the upper body, the head impacts with the right foot and lower leg at a peak acceleration of 185 g The chest and pelvis acceleration drop down to insignificant levels
three	162 ms	The head strikes the right footrest of the wheelchair, two further head acceleration peaks occur
	200 ms	The process has ended; no upper body rebound occurs; the wheel chair has not tipped over, the dummy has not slipped off the seat base

The consequences in this test would be severe to fatal head injuries with possible fracture of the pelvis. Injuries to the cervical vertebrae caused by the impact of the head on the thighs cannot be ruled out. The wheelchair withstood the stresses of the test without breaking. The seat base was slightly torn and the wheels were severely buckled. In a real accident it would still be possible to rescue the disabled people from the vehicle.

Table 2. Test results of the wheel chair test.

	Wheelchair test without cushion	Limits
HIC value	1250	1000
Maximum head acceleration/3 ms figure [g]	185 / 88	/ 80
Maximum chest acceleration [g]	37	60
Maximum pelvis acceleration [g]	61	60
Maximum lap belt force [kN]	9.6	
Maximum wheel chair belt force [kN]	4.8	

Taking the existing system of a lap belt and belts fastening the wheelchair as a starting basis, the findings of the first test at 20 g load were used to develop the following catalogue of requirements.

The main objective of this process is to improve the safety of people in wheelchairs in a front-end collision, as this is statistically the most common type of collision. At the same time, consideration is also to be given to the loads placed on the wheelchair and the user-friendliness of the system.

Safety requirements:

- low risk of injury at an acceleration pulse of 20 g
- protection for persons with different types of disability, e.g. with hemiplegia which causes a slanting body position
- optimum belt position, prevention of submarining effect and risk of injury from the belt slipping out of position.
- reduction of the jack-knifing effect
- prevention of risk of injury from the belt buckle
- protection in other types of collision

Comfort requirements:

- quick and easy to use
- must function effectively with various types of wheelchair
- variability which allows use in different disabled persons transport vehicles
- must not severely restrict user's movement
- low weight
- cushion must be easy to fit between the armrests
- pleasant cloth covering
- high user acceptance

Requirements regarding load on wheelchair:

- no breakage of supporting structures of the wheelchair frame and wheels
- deformation of the wheelchair frame and wheels must not affect the occupant's sequence of movement
- forces acting on the seat base of the wheelchair must be low. The seat base material must be sufficiently prevented from tearing at its points of attachment or coming away from them, so as not to represent any additional risk of injury for the occupant.
- the wheelchair must remain stable throughout the course of the accident
- the wheelchair must not be locked in place by its wheels

CUSHION

In order to fulfil the safety requirements set out in the foregoing chapter, the primary need is to reduce the critical effect on the wheelchair occupant's head, i.e. the jack-knifing effect and the rotation of the occupant's upper body around the H-point must be restricted.

The basic idea is a wedge similar to those used in familiar child restraint systems. When positioned between the upper body and the thighs it prevents the critical upper body overswing of the. The intention is for the upper body to fold over the wedge in a controlled sequence of movement. The restriction of the movement prevents contact between the head and the lower leg or the wheelchair. At the same time, deformation of wedge should convert some of the occupant's kinetic energy into deformation work. This reduces the forces acting on the occupant.

The wedge should rest on the occupant's thighs and shall be referred to below as a cushion.

Other safety requirements may be fulfilled by having a belt which passes through the cushion. The belt buckle is relocated away from the abdominal region. This means that there is no longer any risk of injury from the belt buckle. The position of the belt inside the cushion is secure, preventing any risk of injury due to the belt slipping out of position. The cushion is still effective for an occupant with a bent or slanting upper body position.

The deformation of the cushion between the belt and the occupant's pelvis lowers the acting belt forces. As the cushion has a larger surface, the force acts over a greater area of the abdomen, leading to a more even distribution of the forces.

Another difference to the standard system as described in the foregoing chapter, is that the belt fastening points are relocated to the wheelchair frame (similar to the configuration in DIN 75 078, Part 2), in order to optimise the forwards movement of the occupant caused by slack and stretching of the belt, and to reduce the belt forces by improving the floor attachment angle and attachment height.

It is to be expected that the cushion also provides a protective effect in other forms of collision.

The cushion simultaneously fulfils a number of major demands set out in the foregoing chapter concerning comfort and ease of use. It is easy to fasten making almost no extra work for helpers. The cushion presents no problems for use in various types of vehicle and with the most common wheelchair types. It causes no major restriction of movement for the user. The weight of the cushion may be restricted to a reasonable level by selection of suitable materials. The cushion may by all means be used while travelling as a resting surface for objects or as a base to write on.

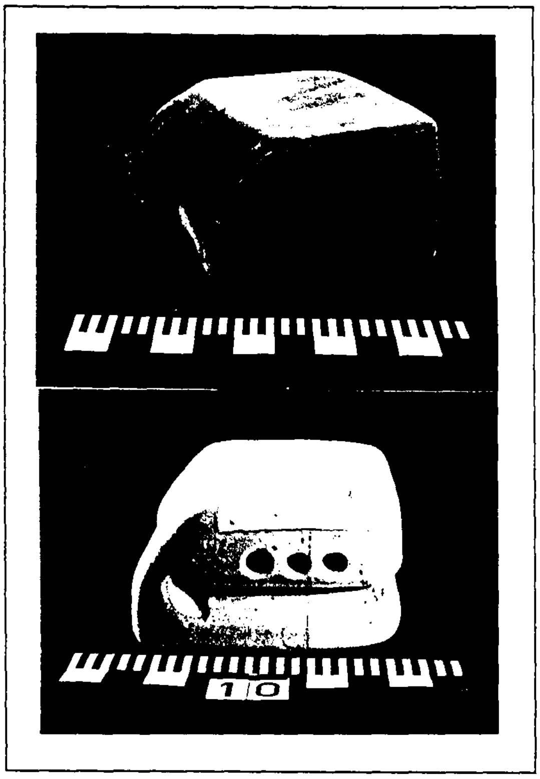

Figure 5. Crash cushion.

The cushion fulfils the demands concerning loads acting on the wheelchair. A greater load on the seat base is, however, to be expected as the forces of the upper body folding over the cushion are transferred via the thighs to the seat base. However, no breakage or dangerous deformation of the wheelchair was observed in the tests described below.

Description of the crash cushion

In the cushion (fig. 5) the belt is located in a belt rail between the flanks of the cushion. The cushion has a flat shape. Its dimensions are L=33cm, W=36cm, H=22cm. Holes were drilled in the blank to save weight. The top side of the blank is made of a very soft, comfortable foam in order to protect the head should it strike the cushion.

The tests show that with this cushion the occupant of a wheelchair is well protected in an accident. The detailed test results for this cushion are presented in the next chapter.

Material selection

The main materials that may be used for the cushion are polypropylene (PP) and polyurethane (PUR) foams. They effectively fulfil the demands of sufficient durability and moisture resistance with low weight, low production costs and sufficient suitability for recycling. Polystyrene was not selected due to its unsuitable damping characteristics.

Volkswagen AG has extensive findings on the energy absorption and deformation behaviour of PP and PUR foam with regard to their use as a damping element for passive safety [10].

In a series of tests a body block representing the chest and pelvis area of a dummy with a mass of 33.45 kg was accelerated to impact with a material sample of size 200 x 300 mm. Acceleration pickups in the model were used to determine the energy absorption and the maximum deceleration forces of the material at a speed of approx. 30 km/h. The tests were carried out on PP and PUR foam samples of varying density and height.

The model test shows that when a material of lower density is used the maximum deceleration force decreases (fig. 6). When the height of the material sample is reduced below a certain level the entire available deformation distance is used up by the impact. The remaining energy is passed on to the base plate via the material, which has reached full compression. This is accompanied by a serious increase in the maximum deceleration force.

Use of a greater material density results in a rise in the maximum deceleration forces with lower depth of deformation (fig. 6). Due to the lower depth of indentation, the surface area of material taking load from the body model is reduced. This is a geometrical effect which leads to a lower efficiency of the energy absorption system h.

The implications for the design of the cushion are that at a given cushion height xp the material density must not be below a certain level in order to prevent the cushion reaching full compression when the body impacts against it. At the same time, the material density should be sufficiently low as to achieve an optimum depth of indentation and, thus, transmit the load to as large an area of cushion as possible. This has the aim of maximising the efficiency of the energy absorption system. The maximum deformation force acting on the occupant at impact F_{max} must not exceed a certain level in order to prevent critical biomechanical load levels.

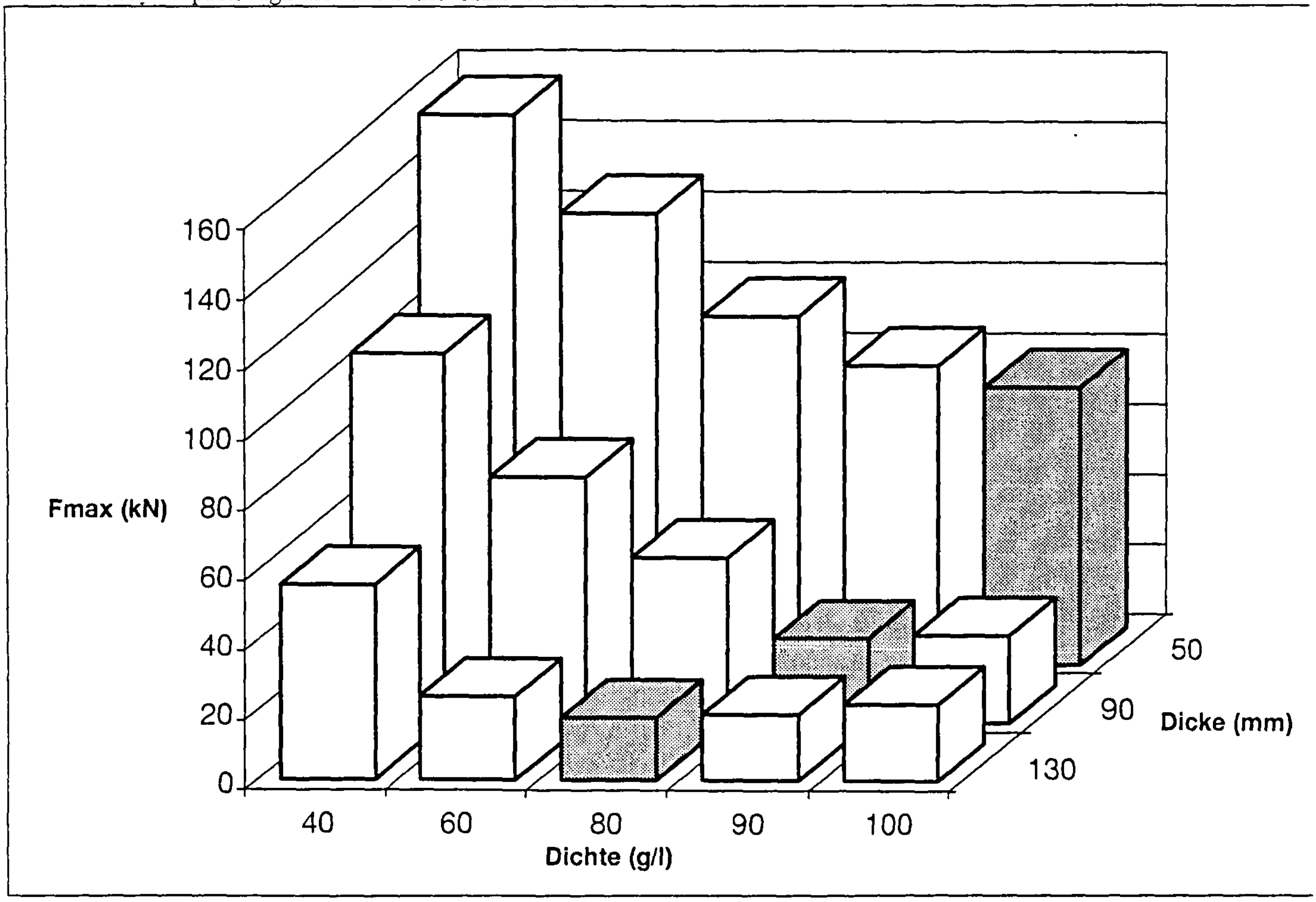

Figure 6. Maximal deformation force Fmax depending on material density and thickness for PUR.

The boundary conditions determine the material density at which the best efficiency of the absorption system h is achieved.

$$h = \int F\, ds \,/\, (F_{max}\, xp) < 1 \qquad (1.)$$

Using a cushion height of approx. 200 mm the best efficiency for PP foam is achieved at a density of approx. 30 g/l. With the same design PUR foam requires the twice this density, i.e. approx. 60 g/l. This weight disadvantage is compensated for by its efficiency at high indentation depths, which is approx. 10% greater than that of PP foam.

At these material densities PUR and PP foam have almost the same energy take-up capability. They differ greatly, however, in their reverse deformation (fig. 7). The PP foam releases again in reverse deformation a large proportion of the energy transferred to it. In the case of a body impact on the cushion this can lead to a severe rebound effect. The risk of injury is seriously increased by the high change in the velocity of the chest and unfavourable kinematics of the rebound with strong forces affecting the cervical vertebrae. PUR, on the other hand, absorbs the greater proportion of the energy, thus largely preventing any hazardous rebound.

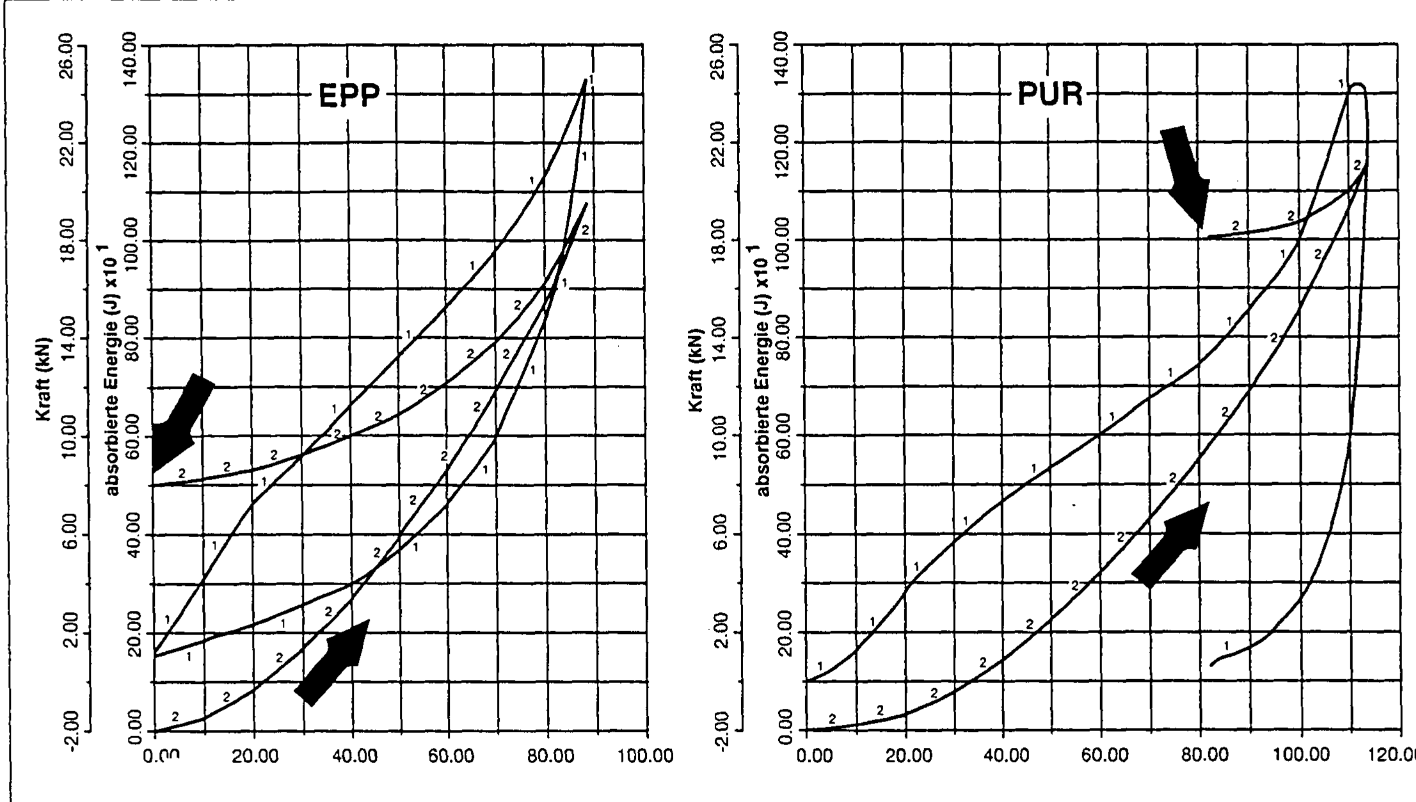

Figure 7. Energyabsorption and deformation force of PUR and EPP derived from drop tests with a thorax-pelvis-model

Table 3. Test results with PUR and EPP cushions

	PUR Cushion	EPP Cushion	Limits
HIC value	443	245	1000
Maximum head acceleration/3 ms figure [g]	60 / 48	50 / 41	/ 80
Maximum chest acceleration [g]	24	34	60
Maximum pelvis acceleration [g]	50	66	60
Maximum belt force [kN]	13	12	

Acceleration tests (20g over 30ms) were conducted with the test frame using cushions made of PP foam with a density of 30 g/l and PUR foam with a density of 60 g/l. The results are shown in Table 3.

The load on the chest from the PUR 60g/l cushion is 30% below that exerted with the PP 30g/l cushion. The reason for this is the better energy conversion as the upper body folds around the cushion. This is confirmed by the more severe deformation or breakage of the PUR cushion

The load on the pelvis from the PUR 60 g/l cushion is approx. 25% lower than that of the PP cushion. In the case of the PP cushion the measurements show a critical acceleration of the pelvis of 65g.

Due to contact between the head and the cushion occurring with the PUR cushion, the load affecting the head is around 55% higher with this cushion than with the PP cushion with which this head contact did not occur. However, the head injury risk - the HIC value of the PUR cushion is well below the limit of 1000 at 443. The higher deformation of the PUR cushion in the pelvis area is the reason for the greater forwards motion of the head leading to contact.

The maximum belt force is virtually the same with both cushions.

The PUR foam will be used for the further development of the cushion due to its better energy absorption behaviour and better load figures.

COMPARISON OF THE TEST RESULTS FOR A WHEELCHAIR OCCUPANT WITH AND WITHOUT CUSHION

The section describing the INITIAL TEST AND DERIVED REQUIREMENTS shows a wheelchair test at 20 g without a cushion. In this chapter, this test is compared with a wheelchair test with cushion. In figure 8 the sequence of motion of the dummy for the test with the cushion is shown at 1, 43, 61, 81, 112, 136 and 164 ms. Figures 9, 10 and 11 show the sequences of head, chest and pelvis acceleration. In each case the blue curve (1) represents the rates of acceleration in the test without a cushion and the red curve (4) represents the acceleration in the test with the cushion.

The sequence of motion may be divided into three phases.

In the **first phase** of the sequence the dummy moves forward in an upright posture. The upper body does not rotate! This horizontal forwards motion of the dummy is made possible by the stretching of the belt, compression of the cushion and compression of the dummy in the pelvis area. At 60 ms the belt guide area of the cushion absorbs energy and is considerably deformed.

The first phase ends for the dummy with the crash cushion at 78 ms. At this point in time all three acceleration values reach their maximum levels. At this moment the acceleration rates for the chest (26 g) and pelvis (43 g) reach their highest values for the whole sequence of movement in the test with the cushion. The figures for the head and pelvis acceleration show that in the test without a cushion the maximum acceleration is reached roughly 10 ms earlier than in the test with the cushion. This is caused by the longer path of movement of the dummy in the test with the cushion. During these 10 ms the cushion is deformed in the pelvis area.

At this point the feet have already slid off the footrests.

In the **second phase** of the sequence of motion the upper body begins to fold forwards. At 80 ms the head begins to rotate.

In figure 8 it may be seen that the flanks of the cushion have been forced apart at 90 ms.

From 100 ms the cushion seriously impedes the rotation of the upper body. This also considerably restricts the rotation of the head. The upper body of the dummy is considerably further away from its legs in the test with the cushion than in the test with no cushion. It may also be clearly observed that in the test without the cushion the chest acceleration reaches its maximum value (45 g) between 110 and 130 ms: the upper body strikes the legs (jack-knifing effect). In contrast to this, no increase in chest acceleration is observed in the test with a cushion.

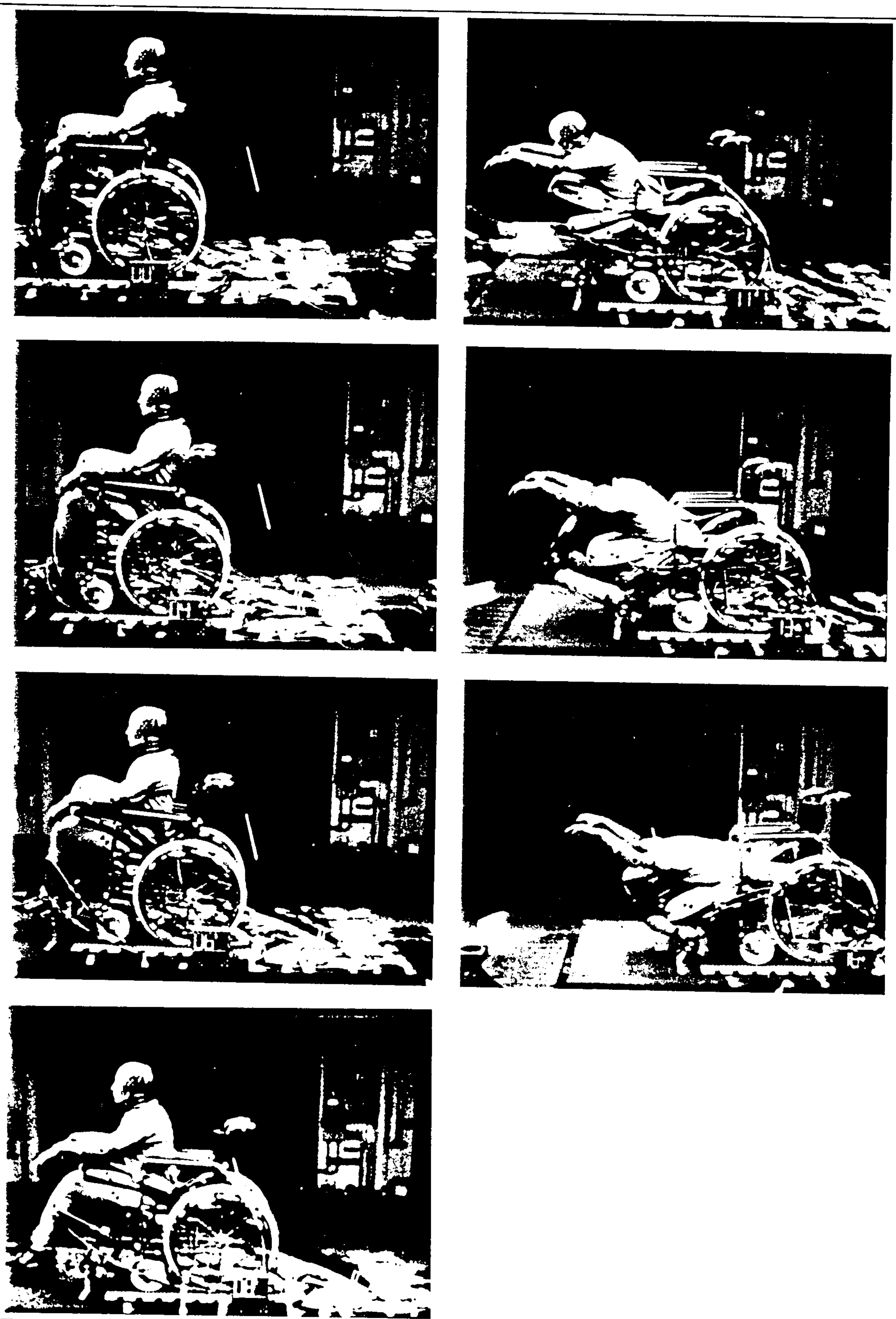

Figure 8. Movement of the dummy in the wheel-chair test with 20 g with impact cushion

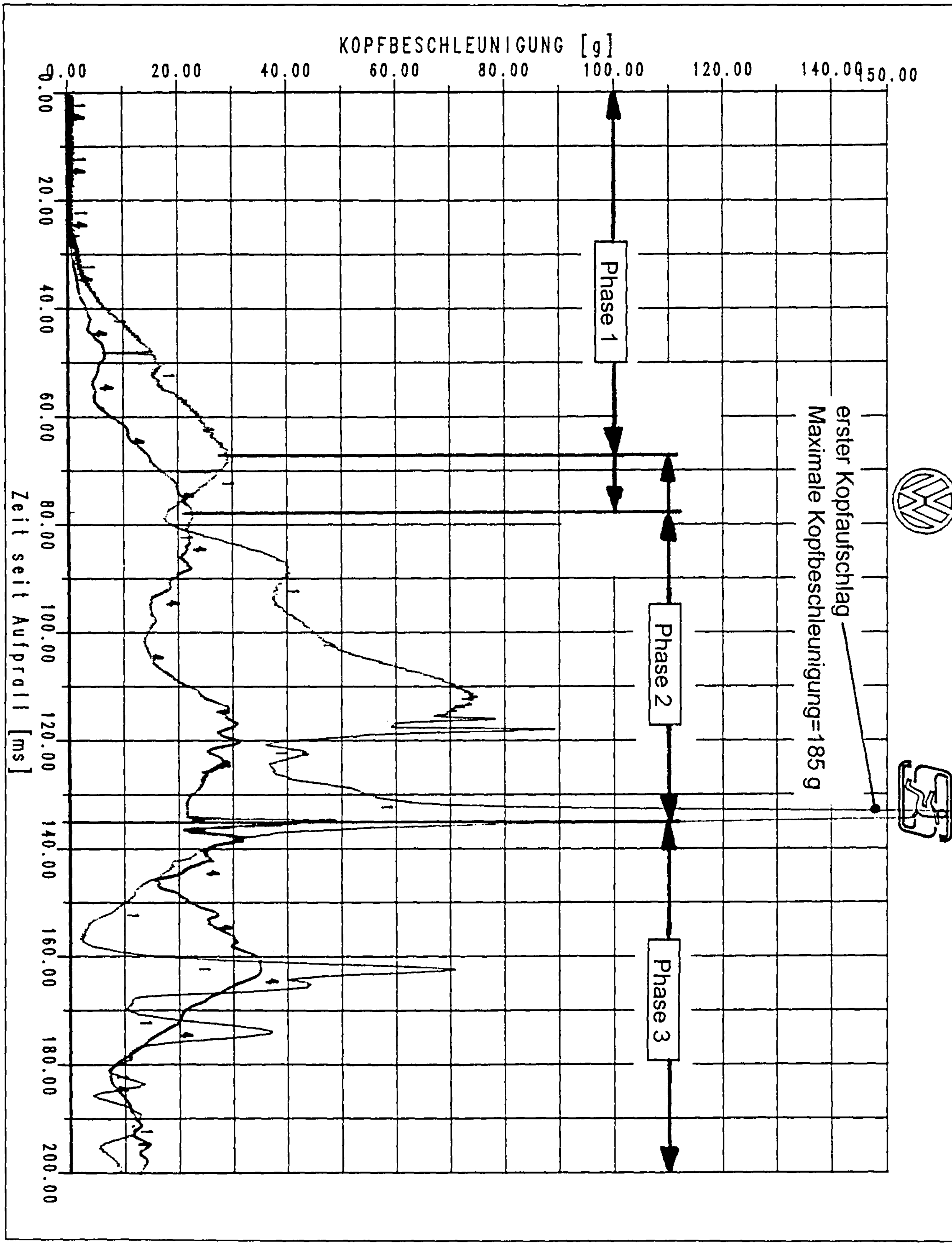

Figure 9. Head acceleration curve for the wheel-chair test with 20 g (curve1=without cushion, curve4=with cushion)

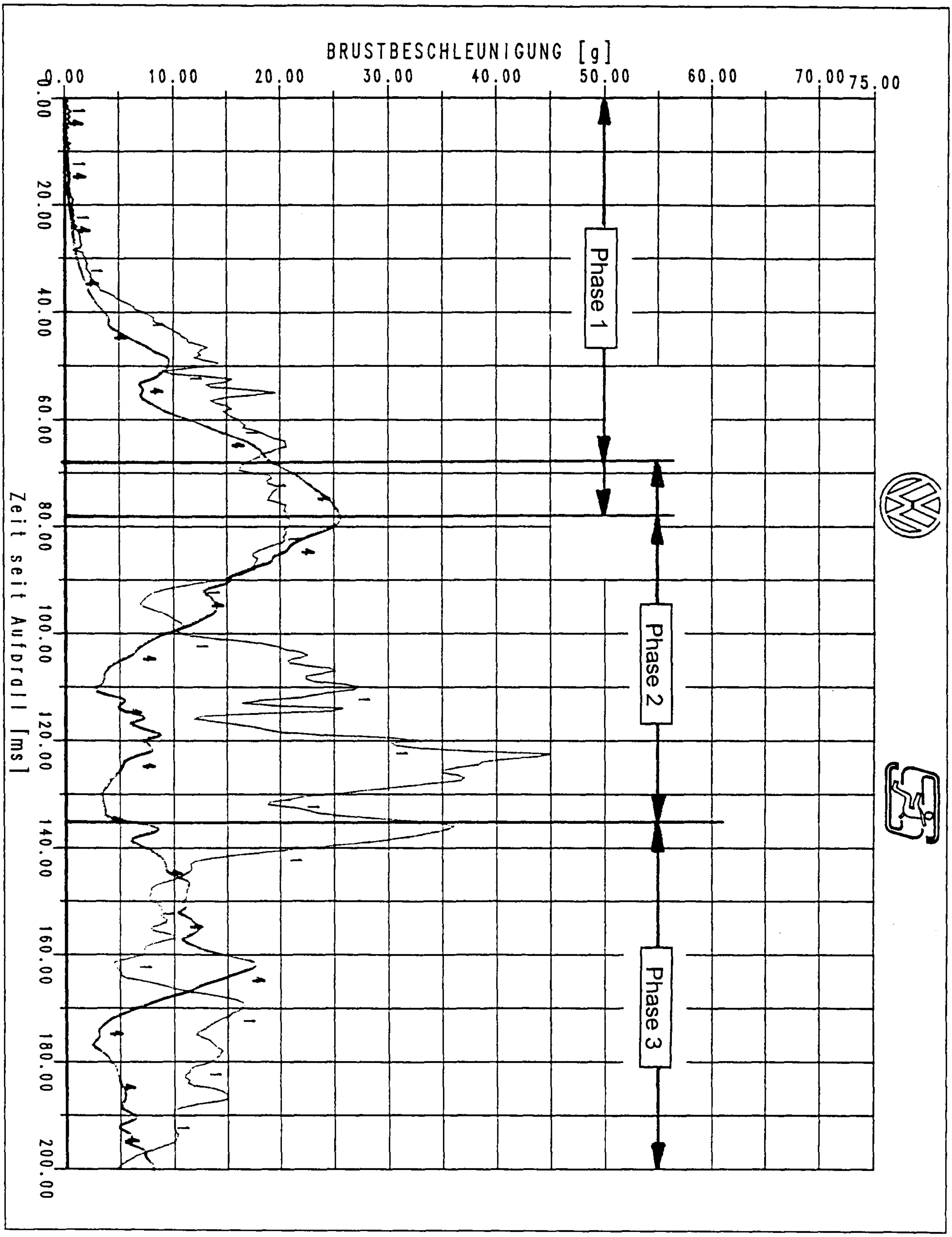

Figure 10. Thorax acceleration curve for the wheel-chair test with 20 g (curve1=without cushion; curve4=with cushion)

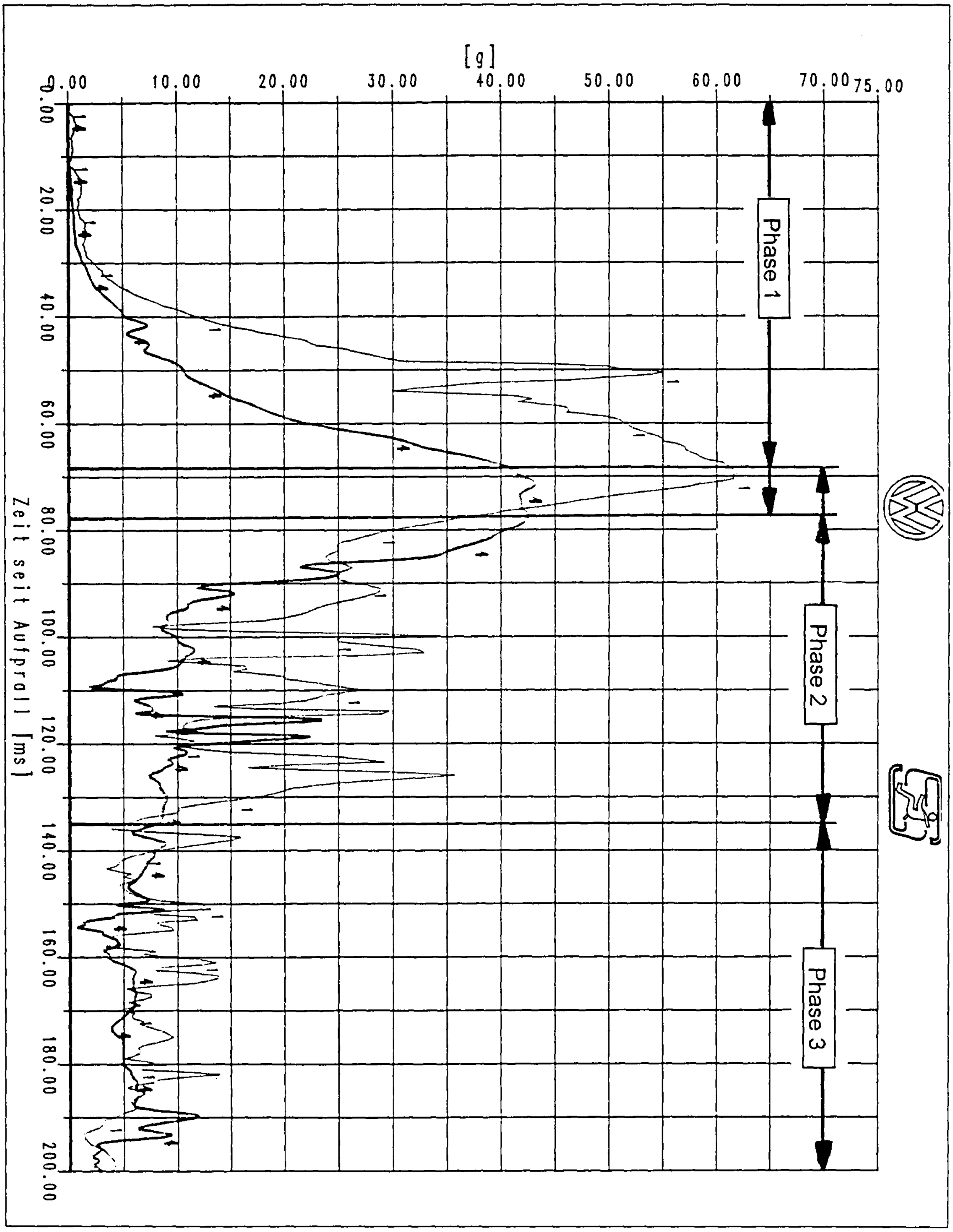

Figure 11. Pelvis acceleration curve for the wheel-chair test with 20 g (curve1=without cushion; curve 4=with cushion)

The second phase ends at 135 ms. At this point the head makes its first contact. In the test without a cushion the head strikes the lower leg hard. The resulting head acceleration is 185 g, which is well above the limit (see table 4). The cushion prevents any contact between the head and the lower legs. The head merely brushes against one of the feet. The head acceleration is 49 g. The contact of the head with the shoe is the result of the knee joint of the dummy bending upwards. In figure 8 the very unnatural position of the dummy's lower leg in the test with the cushion may be clearly seen. It is the authors' view that the lower leg of a human being cannot move into such a position as the entire knee joint is held and supported by the ligaments. The situation on a dummy is quite different. Here the knee joint is only prevented from snapping upwards by a thin pin. This model-type fastening system does not work as required in the test.

The **third phase** from 135 ms describes the end of the motion as the dummy comes to rest in its final position. A second head impact occurs during this stage at 162 ms. In the test with the cushion this is caused by the extreme overbending of the lower leg. The head acceleration of 35 g is only half as high as in the test without a cushion.

Table 4 . Test results on a wheel chair with and without cushion.

	Wheelchair test without cushion	Wheelchair test with cushion	Limits
HIC value	1250	274	1000
Maximum head acceleration/3 ms figure [g]	185 / 88	49 / 35	/ 80
Maximum chest acceleration [g]	45	26	60
Maximum pelvis acceleration [g]	62	43	60
Maximum belt force [kN]	7.3	10.4	

Table 4 compares the maximum acceleration rates with statutory limits. The table clearly shows that without the cushion the head acceleration considerable exceeds the limit and the pelvis acceleration is slightly over the limit. Under these circumstances a disabled person in a wheelchair would suffer considerable injuries in the accident.These extreme loads are prevented by the use of the cushion. The reductions in load achieved by use of the cushion amounted to 73% for the head 42% for the chest and 30% for the pelvis. The cushion prevents the serious exceeding of the statutory limits. This effectively eliminates the danger of severe injuries from the accident.

CONCLUSION AND FUTURE PROSPECTS

Disabled persons who are transported sitting in wheelchairs in minibuses are not yet protected by the same safety measures which are available to a passenger in a vehicle seat. Three point seat belts are fitted in minibuses, but cannot be used for ergonomic reasons. Solutions involving equipment which can be retrofitted have been developed, but have up to now failed to achieve success on the market, due to their relatively high costs and cumbersome handling.

The crash cushion developed by VW AG, however, may be used immediately in any model of vehicle without the need for modifications and may contribute considerably to improving the safety of persons in wheelchairs in a collision. It can only be hoped that this type of cushion is accepted by the operators of vehicles for the transport of disabled persons and by the people in wheelchairs themselves.

The potential for the further development of these crash cushions lies in the use of new materials and combinations of composite materials which distribute and absorb energy within the cushion even better.

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NHTSA'S ADVANCED AIR BAG TECHNOLOGY RESEARCH PROGRAM

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Paper 98-S5-W-29

ABSTRACT

This paper reports on the National Highway Traffic Safety Administration's (NHTSA's) research program on Advanced Air Bag Technology. This program was initiated to establish the technical basis for new vehicle performance requirements for improved occupant crash protection. The primary tasks include: real-world crash investigations, development and certification of test dummies and associated injury criteria, evaluation of advanced air bag technology, and development of test procedures. NHTSA also has initiated cooperative research programs with NASA/Jet Propulsion Laboratory and Transport Canada, and is gathering information and data through the Motor Vehicle Safety Research Advisory Committee (MVSRAC). Research work will be used to support rulemaking activities on advanced air bag systems. This paper presents an overview of this effort.

BACKGROUND

In recent years, a number of crashes have been reported where injuries and fatalities have been the result of aggressive air bag deployment; that is, the severity and crash environment did not warrant the severity of injury/fatality sustained by the occupant. Those most susceptible to injuries/fatalities from aggressive air bag deployments include out-of-position child passengers, out-of-position adult drivers (usually unbelted), and infants in rear-facing child safety seats. As of May 1, 1998, 99 fatalities have been attributed to the air bag deployment. These include 57 fatalities of children (13 infants in rear facing child safety seats) and 42 fatalities of adults (38 drivers, 4 passengers).

On March 19, 1997, NHTSA published a final rule that temporarily amends the agency's occupant crash protection standard to ensure that vehicle manufacturers can quickly depower air bags so that they inflate less aggressively. More specifically, the agency adopted an unbelted sled test protocol as a temporary alternative to the standard's full scale unbelted barrier crash test requirement. The agency took this action to provide an immediate, interim solution to the problem of the fatalities and injuries that current air bag systems are causing in relatively low speed crashes to a small, but growing number of children and occasionally to adults. This final rule was one that allowed modification of the air bag performance to address the identified safety problem. A number of other actions also were undertaken by the agency. These actions included the following:

- On October 27, 1995, NHTSA issued a strong warning in a press release, "SAFETY AGENCY ISSUES WARNING ON AIR BAG DANGER TO CHILDREN." The release warned that children who are not protected by a safety belt could be seriously injured or killed by an air bag, and in the strongest possible terms urged parents to insist that their children ride belted in the back seat whenever possible. Three "rules" were advocated:
  - Make sure all infants and children are properly restrained in child safety seats or lap and shoulder belts for every trip,
  - The back seat is the safest place for children of any age, and
  - Infants riding in rear-facing child safety seats should never be placed in the front seat of a vehicle with a passenger-side air bag.
- On November 9, 1995, NHTSA published a request for comments to inform the public about the agency's efforts to reduce the adverse effects of air bags and to invite the public to share information and views with the agency.
- On May 21, 1996, Secretary Peña announced the formation of an air bag coalition. Coalition members pledged almost $10 million to pursue a three-point program:
  - An extensive national effort to educate drivers, parents, and care-givers about safety belt and child safety seat use in motor vehicles, with special emphasis on those equipped with air bags.
  - A campaign to assist states to pass "primary" safety belt use laws.
  - Activities at the state and local level to increase enforcement of all safety belt and child seat use laws, such as increase public information and use of belt checkpoints.

• On August 1, 1996, NHTSA published a notice of proposed rulemaking, proposing amendments to FMVSS Nos. 208 and 213 to reduce the adverse effects of air bags, especially those on children. NHTSA proposed the following for passenger cars and light trucks whose passenger-side air bags lacks smart* capability:

- To require new, enhanced warning labels, and
- To permit manual cutoff switches for the passenger-side air bags (to accommodate parents who need to place rear-facing child seats in the front seat).

• On November 27, 1996, NHTSA issued the final rule on new air bag warning labels. The rule stated that:

- Vehicles with air bags are required to have three new warning labels, two of which replaced the then existing labels.
- Rear facing child safety seats are required to have a new label to replace the then existing label.

• On January 6, 1997, the agency issued three notices. The first was a final rule extending the time period for the installation of manual cutoff switches for specified passenger vehicles until September 1, 2000. The second was a notice of proposed rulemaking for allowing the vehicle manufacturers to depower air bags so that they inflate less aggressively. The third was a notice of proposed rulemaking to allow automobile dealers and repair shops to deactivate air bags at a customer's request.

• The latest regulatory action was announced on November 18, 1997. In this, the agency issued its final rule regarding air bag on-off switches. The switches would be permitted for specific circumstances. These include:

- For front seat occupants experiencing a medical condition that poses a special risk that outweighs the risk of hitting their head, neck, or chest in a crash if the air bag is turned off,
- For drivers who are not able to adjust their customary driving position to allow a minimum of 10 inches between their breastbone (sternum) and the center of the steering wheel,
- For people who must transport infants in rear-facing infant seats in the front passenger seat,
- For people who must transport children ages 1 to 12 in the front passenger seat, and
- For people who are unable to avoid situations, such as a car pool, that require a child 12 years or younger to ride in the front seat.

As can be seen, the agency has undertaken a substantial regulatory effort to reduce the safety problem resulting from aggressive air bag deployment. However, the agency has determined that these steps fall short of solving the problem. In the final regulatory evaluation [1] published in conjunction with the issuance of the March 19, 1997, final rule, the agency estimated that if manufacturers depowered their air bag systems on average by 20 to 35 percent, 47 children's lives could be saved from the estimated 140 children who otherwise would be killed over the lifetime of one model year's fleet. Furthermore, projections were made regarding the disbenefits to adult occupants that would occur in high severity crashes as a result of depowering the air bag systems. The estimated disbenefit was that 45 to 409 driver and passenger adult fatalities would result from depowering the air bag systems by 20 to 35 percent.

In addition to the regulatory actions, NHTSA held a "Smart Air Bag Public Meeting," on February 11-12, 1997. This meeting was attended by a broad array of parties interested in air bag issues. Based on the discussions that took place at that meeting, the agency established objectives for an advanced air bag technology research program, and determined that the agency would need detailed information regarding advanced air bag technology and the ability to evaluate such technology in order to meet its objectives. The documents describing these objectives and information needs have been placed into Public Docket NHTSA-1997-2814. The agency determined that meeting its objectives would require industry cooperation, since the industry would be the source of advanced technologies and could provide detailed information regarding these technologies. The agency concluded that a cooperative research effort under the sponsorship of the Motor Vehicle Safety Research Advisory Committee (MVSRAC) would be the best means for achieving these objectives. As a result, the Advanced Air Bag Technology Working Group was established under the MVSRAC Crashworthiness Subcommittee. The purpose of this working group is to perform research and to compile information regarding advanced air bag technology. In particular, the working group is performing research activities to define safety problems that are likely to continue despite the introduction of depowered air bags, to develop advanced systems that would address the identified safety problems, and to

* In this proposal, the agency considered smart air bags to include any system that automatically prevents an air bag from injuring the two groups of children that experience has shown to be at special risk from air bags: infants in rear-facing child seats, and children who are out-of-position (because they are unbelted or improperly belted) when the air bag deploys.

develop procedures that could be used to evaluate the safety performance of advanced air bag systems. Members represent those in the best position to assist in the performance of the research and in the gathering of information regarding advanced air bag technology, and include representatives of government, domestic and foreign automobile manufacturers, restraint system suppliers, the insurance industry, academia, and the medical community.

In addition to the agency actions, the National Transportation Safety Board (NTSB) convened a Public Forum on Air Bags and Child Passenger Safety on March 17-20, 1997, in Washington, DC. As a result of reviewing the testimony from this meeting, NTSB issued 9 safety recommendations, H-97-10 through H-97-18, to the agency regarding improved adult and child occupant protection standards and evaluation procedures. These recommendations are:

- H-97-10: Develop and implement a set of crash test standards that utilize the currently available 5th percentile crash test dummy.
- H-97-11: Develop and implement a set of vehicle crash test standards using biologically representative child dummies and appropriate injury criteria.
- H-97-12: Develop and implement, in conjunction with the automobile industry, a comprehensive crash investigation program to evaluate the effectiveness of air bags. This program should provide for long-term and short-term evaluation of variations in air bag designs, advanced air bag technologies, and various methods to deactivate air bags.
- H-97-13: Develop, in conjunction with the Centers for Disease Control and Prevention, data collection procedures and establish a database for recording all air bag-induced injuries identified by the medical community.
- H-97-14: Revise the Fatality Analysis Reporting System and the National Automotive Sampling System to record specific information regarding the air bag equipment installed in the vehicle and its performance in the crash, such as the following: Did the air bag deploy, was it a depowered air bag, was there a cutoff switch, and was it on or off.
- H-97-15: Develop, in conjunction with the States, uniform measurement procedures and tools for the States to use when conducting surveys on seatbelt and child restraint use and revise the 1992 guidelines to ensure that a probability-based design is used to select a representative sample of the population. Provide this information to the States.
- H-97-16: Develop guidelines for the collection of standardized data elements, including data fields for air bags, which will provide for better comparisons and evaluation of traffic crashes. Revise and update the guidelines as necessary. Provide these guidelines to the states.
- H-97-17: Evaluate, through public comment, the New Car Assessment Program (NCAP) test procedures to determine (a) if the crash test procedures are counterproductive to development of air bag technology that is safe for all occupants, and (b) if the NCAP program provides consumers with the safety information they need to purchase a vehicle. If necessary, develop new methods for providing meaningful information to consumers on vehicle safety in high speed and other types of crashes.
- H-97-18: Develop and implement, in conjunction with the domestic and international automobile manufacturers, a plan to gather better information on crash pulses and other crash parameters in actual crashes, utilizing current or augmented crash sensing and recording devices.

While the agency already had efforts underway addressing these recommendations, the recommendations resulted in added impetus to achieve and expedite the research activities.

With the above as background, the agency has initiated an extensive research program on Advanced Air Bag Technology. This program is to establish the technical basis for new vehicle performance requirements that lead to improved occupant crash protection. The objective of this research activity is to eliminate the fatalities and reduce the severity of the injuries resulting from aggressive air bag deployment, while simultaneously providing benefits to normally seated restrained occupants and restoring full protection for unbelted large adults in high severity crashes. The requirements will be established using the state-of-the-art developments of advanced air bag technology. The program includes tasks to investigate real-world crash performance, to develop and certify test dummies and associated injury criteria, to develop test procedures, and to evaluate advanced air bag technology. In undertaking this program, the agency has joined in cooperative efforts with Transport Canada, the Australian Federal Office of Road Safety, and with the National Aeronautics and Space Administration/Jet Propulsion Laboratory. This paper presents an overview of the program.

REAL WORLD CRASH INVESTIGATIONS

Various analyses of real world crash data are being conducted in order to evaluate effectiveness of occupant protection systems. To date (and as directed by Congress in the enactment of the Intermodal Surface Transportation Efficiency Act of 1991), the agency has published a total of three reports on the effectiveness of occupant protection systems and safety belt use, the third having been published December 1996 [2]. As part of the effort undertaken for developing the report, the National Automotive Sampling System is utilized to analyze air bag-related issues such as effectiveness as a function of driver height and gender interaction, specific body region effectiveness estimates for various sub-populations, etc. Other analyses involve investigations of injuries and fatalities with air bags, analysis of fatalities to children under 15 with air bags, and analysis of injuries/fatalities to adult drivers, specifically to identify cases of air bag aggressiveness contributing to the injuries/fatalities. Specifically, NHTSA's Special Crash Investigation (SCI) program was established to collect detailed in-depth data on specific crashes of interest to the NHTSA. SCI cases are an anecdotal data set used to examine, document, and qualify the state-of-the-art safety systems. In the SCI program, professional crash investigators perform an extensive examination of the vehicles and scene from which they secure and analyze the evidence necessary to reconstruct the events before, during, and after the crash.

As noted earlier in the background section, NHTSA has identified 99 fatalities (57 children, 42 adults) that have been attributed to the air bag deployment, as of May 1, 1998. In the SCI investigations, it was found that pre-impact braking was involved in many of the crashes. Also, it was determined that many of the fatally injured children were unrestrained or improperly restrained. Table 1 provides a breakdown regarding the 57 child fatalities and Table 2 provides a breakdown of the 42 adult fatalities.

Table 1.
Confirmed Fatal Children from Air Bag Deployment

Children fatally injured by the passenger air bag (US=56; Puerto Rico=1)	57
- Rear Facing child safety seats	13
- Forward Facing child safety seats	2
- Unrestrained or improperly restrained children	
With pre-impact braking	35
Without pre-impact braking (US=3; Puerto Rico=1)	4
- Wearing lap and shoulder belt	
With pre-impact braking	3

Table 2.
Confirmed Fatal Adults from Air Bag Deployment

Drivers fatally injured by the Air Bag	38
- Drivers belted	11
- Drivers misused belt	3
- Drivers not belted	21
- Unknown if driver belted	3
Passengers fatally injured by the Air Bag	4
- Passengers belted	1
- Passengers misused belt	0
- Passengers not belted	3
- Unknown if passenger belted	0

With the introduction of vehicles equipped with air bags systems certified by the generic crash pulse specified as an option in the March 19, 1997 rulemaking, the SCI program also is investigating the field performance of production vehicles certified in this manner. The agency has implemented several early notification mechanisms to identify these crashes, including using notifications provided by State Farm Insurance Company as of April 1, 1998. (The State Farm notification was made possible through their and the Insurance Institute for Highway Safety's participation in the Advanced Air Bag Technology Working Group of the Motor Vehicle Safety Research Advisory Committee.) As of April 1, 1998, the SCI has initiated 56 cases involving such vehicles. The reader is referred to a companion ESV paper that has been written regarding the SCI investigations for further details regarding the program [3].

DEVELOPMENT AND CERTIFICATION OF TEST DUMMIES

In the advanced air bag technology research program, NHTSA has been conducting experimental testing and developing test procedures for a range of adult and child anthropomorphic test devices (ATD's) to cover a broader range of occupant sizes in the real world. Adult ATD's included the 5th percentile female, 50th percentile male, and the 95th percentile male Hybrid III dummies. Child ATD's included the 6-year-old and 3-year-old Hybrid III child dummies, and the 12-month-old CRABI dummy. Currently only the 50th percentile male Hybrid III dummy is included in the CFR Part 572, and utilized in current FMVSS No. 208 testing. However, research and testing is being conducted to finalize the certification procedures necessary for incorporating the alternative test dummy sizes into the Federal motor vehicle safety standards.

Calibration and Testing

NHTSA's Vehicle Research and Test Center (VRTC) has conducted numerous types of tests with the 5th percentile female Hybrid III adult dummy, the 6-year-old and 3-year-old Hybrid III child dummies, and the 12-month-old CRABI dummy. For each of the dummies, initial calibration tests are conducted to document baseline performance and to ensure that the test dummies meet the required biofidelity corridors, as delivered by the manufacturer. Periodic calibration tests are also conducted throughout component and sled tests to document deviations from the baseline performance, and post-test calibration tests are conducted following the completion of the sled tests to establish final dummy response. VRTC also has conducted static out-of-position tests with the 5th percentile female Hybrid III adult dummy on the driver's side, and the 6-year-old and 3-year-old Hybrid III child dummies on the passenger side to establish repeatability, and durability performance in the component level environment. Tests with the 12-month-old CRABI dummy in a rear facing child safety seat also have been conducted in static deployment tests of the passenger side air bag. Finally, VRTC is evaluating the performance of each of the test dummies in the sled environment with various restraint conditions. Again, determination of repeatability and durability of the test dummies are the primary objectives of this program.

The agency has been working in conjunction with the dummy manufacturers and the SAE committees to develop and assemble the required documentation for each of the test dummies. Tasks have included finalizing a set of drawings for each dummy, reviewing, updating, and revising user manuals, and collecting applicable literature and test data documenting the development and performance of the dummies relative to biofidelity characteristics and injury assessment reference values. The agency, in cooperation with vehicle manufacturers, has been working closely to rapidly evaluate new modifications to the dummies as they become available, as well as respond to concerns raised by the various dummy users. NHTSA plans to complete testing and publish rulemaking proposals for most of the alternative test dummy sizes tested in the summer of 1998. Research on the 95th percentile male dummy may require additional time.

Advanced Dummy Modifications

Longer term research programs will focus on improving the biofidelity of current test dummies so that advanced air bag systems utilizing technologies, such as infrared or capacitive sensing, will be able to detect their presence. A project has been established (under the NHTSA-GM C-K settlement agreement) at the Johns Hopkins University Applied Physics Laboratory to develop technology that will enhance the biofidelity of the test dummies. Comparisons will be made of the characteristic output signals generated by both human subjects and test dummies. Specialized dummy treatments then will be investigated, as they may be required to enable the test dummy to be properly sensed by the full range of future advanced sensor systems. However, some sensor technologies, such as ultrasonic and active infrared, may only require a relatively straightforward surface treatment or clothing selection.

In the interim, NHTSA has observed that many manufacturers currently use human volunteers to conduct static tests of occupant presence detection systems that utilize infrared or capacitive sensing. Others have made use of fluid-filled dummies to emulate the capacitance level of the human body. Alternatively, suppression systems which dynamically track the motion of the occupant entering a designated "keep-out zone" may only require a component test fixture to be heated or fluid filled for performance evaluation, rather than a full dummy modification.

INJURY CRITERIA DEVELOPMENT

For each test dummy size utilized in the advanced air bag technology research program, NHTSA is undertaking research to establish appropriate injury criteria that correlate dummy measurements to human injury tolerance. Two body regions of particular importance in the advanced air bag research program are the head/neck complex and the thoracic region. In the majority of reported child injury/fatality cases, the right front passenger air bag has deployed into the area of the upper chest, neck, and face of the child. The rapid translation and rotation of the skull caused a number of cervical spine and closed head injuries. Thoracic injuries such as lung contusions and atrial hemorrhages also have been reported in the child cases. The air bag related injuries/fatalities in adults (mostly drivers) have been associated with three primary injury patterns. The first pattern involves multiple rib fractures, usually bilateral, with additional associated lacerations of the underlying thoracic and abdominal organs (i.e., injuries where AIS $\geq$ 4). The second pattern results from air bag contact with the face or chin causing basilar skull fracture with associated brainstem lacerations and/or subdural and subarachnoid hemorrhages. The thira pattern is not as common as the first two, but involves cardiac and pulmonary contusions and hemorrhages without any accompanying rib fractures [4].

For the neck region, developing injury criteria for children is particularly challenging due to the limited amount of biomechanical information and test data [5]. Therefore, NHTSA is conducting research to provide experimental data on the scaling between adult and child injury tolerances and to investigate the age-dependent properties of the cervical spine, with focus on the head-neck junction. Data from these tests and other published research will result in establishing a consistent set of injury criteria for adults and children. NHTSA also is investigating upper cervical spine trauma resulting from air bag loading. Dynamic tests of head/neck specimens are being conducted to determine the injury tolerance of the adult cervical spine.

For the thoracic region, NHTSA is conducting research to analyze the human thoracic response resulting from rapid impulsive loading of the anterior chest wall (as for occupants who are out-of-position), and to develop an improved thoracic injury criterion for use in air bag testing. Existing cadaver tests, dummy tests, and published data have been re-analyzed; and correlations between newly-proposed thoracic injury criteria and real world incidences of thoracic trauma are being evaluated and compared to correlations from previously published criterion. NHTSA also has conducted out-of-position testing with the 5^{th} percentile female Hybrid III dummy and small stature female cadaveric subjects to better assess the relationship between air bag aggressivity and occupant injury response.

NHTSA is preparing to publish a document on injury criteria (for the various test dummy sizes) in conjunction with upcoming rulemaking on advanced air bags.

EVALUATION OF ADVANCED TECHNOLOGIES

Advanced Air Bag Technology Assessment

A number of advancements in air bag technology have been under development in the industry over the past few years to address the adverse effects air bags have found to have on out-of-position occupants. To evaluate the current state-of-the-art in advanced air bag technology and its future potential to improving occupant crash protection, NHTSA signed a memorandum of understanding (MOU) with the National Aeronautics and Space Administration (NASA) in December of 1996. The MOU stated that NASA was to "evaluate air bag performance, establish the technological potential for improved (smart) air bag systems, and identify key expertise and technology within the agency (NASA) that can potentially contribute significantly to the improved effectiveness of air bags"[6]. NASA selected the Jet Propulsion Laboratory (JPL) to conduct this assessment. During the course of the program, JPL visited and surveyed automobile manufacturers and restraint system and component suppliers to gather data and conduct their analysis.

In their final report, JPL made projections on the types of technologies that are being developed and may be available for model years 2001 and 2003 to provide improved information and improved response to occupant protection systems.

Model Year 2001 - For model year 2001, JPL identified five technologies that could provide improved information to an advanced safety restraint system. First, crash sensors/control systems with improved algorithms could make a number of improvements. They could better discriminate crashes when air bag deployment is beneficial for occupant crash protection, they could regulate better control of the deployment threshold, and they could make determinations on the appropriate inflation level for dual-stage inflators. Second, belt use status sensors can provide information on whether an occupant is belted or not. This could enable the air bag system to be designed to deploy at a higher threshold speed for belted occupants. This deployment strategy is currently in use in some production vehicles. Third, seat position sensors can be used to approximate an occupant's initial seating distance from the air bag module, and also can be used in combination with the seat belt status sensor. A restraint system could be designed to deploy with a less aggressive inflation level for a belted occupant in the full forward seating position, and to deploy with the full inflation level for an unbelted occupant sitting in the full rearward seating position. Fourth, JPL reported that seat belt spool-out sensors could also provide additional information about an occupant's size and proximity to the air bag module. A large amount of spool-out could indicate the presence of a larger occupant, likewise a small amount of spool-out could indicate the presence of a smaller occupant. However, an extremely small amount of belt spool-out could potentially flag other scenarios, such as the occupant has placed the torso portion of the safety belt behind his/her back (as small children often do). However, JPL noted in their final report that belt spool-out sensors were not a part of any industry strategy at the time of their survey. Lastly, JPL noted that static proximity sensors could provide occupant position information by identifying occupants in a designated "keep-out zone." By identifying an occupant in a designated "keep-out zone," the restraint system could be designed to deploy only a benign level of inflation or to suppress air bag deployment entirely. While JPL reported that ultrasonic/IR sensing systems held the greatest promise at the time of their survey, they noted that they will only be available if an aggressive development plan was undertaken. JPL further noted that these systems would not reduce injuries to all out-of-position occupants, and they could be fooled some of the time (i.e. register "deploy" in a "no deploy" scenario, and vice versa).

JPL also identified four ways that the response of an advanced safety restraint system can be improved for model year 2001. First, given the information that an occupant is located in the "keep-out zone", an automatic suppression feature can prevent the air bag from inflating. This could potentially prevent inflation induced injuries to out-of-position occupants. Second, JPL noted that dual stage inflators can provide relatively soft inflation levels for crashes of lower threshold velocity and higher inflation levels for crashes of higher severity. Third, JPL reported that advancements in air bag materials, and construction, such as compartmented air bags, radial deployments, and air bags with lighter weight fabrics, could improve the response of an advanced air bag system. These air bag improvements would not rely upon sensing schemes for additional information, rather they would deploy the same for all crash scenarios, and occupant sizes/positions. JPL reported that air bags with multiple compartments are beneficial to reducing the forces on out-of-position occupants since the chambers can be pressurized sequentially. Tear strips or perforated ports allow the gas to fill secondary chambers at a specific pressure level. Similarly air bags that deploy radially are also designed to reduce the amount of force on an out-of-position occupant by controlling the deployment direction away from the occupant. JPL reported that the lower mass attributes of lighter weight fabrics used in conjunction with lower-output inflators may have the potential for reducing the magnitude of punch-out forces on out-of-position occupants. JPL finally noted that advanced safety belt systems can greatly improve the response of an advanced restraint system. Pretensioners can initiate the coupling of the occupant to the seat earlier in the crash, and force limiters can limit the maximum belt loads exerted on the occupant. Both of these safety belt enhancements are installed in some current production vehicles.

Model Year 2003 - For model year 2003, JPL reported that there could be evolutionary changes in advanced restraint systems including the potential introduction of occupant and proximity sensors. JPL identified four technologies that could provide improved information to an advanced safety restraint system for model year 2003. First, vehicle crash sensors and control algorithms will continue to be enhanced and improved. Second, seat belt status sensors will be in wide use by model year 2003. Third, integrated occupant and proximity sensors could be available that would identify occupants in a defined "keep-out zone." Finally, precrash sensors may be available for use, but it is anticipated that their application may require further research and investigation.

JPL also identified four ways that the response of an advanced safety restraint system can be improved for model year 2003. First, automatic suppression technology to prevent air bag inflation will be available for use with occupant proximity sensors. Second, multistage inflators which may provide tailored responses for different occupant sizes and crash severities could be available. Third, advancements in air bag design will continue to evolve. Fourth, advanced safety belt features, such as pretensioners and load limiters, will be placed in an increasing number of vehicles, and inflatable safety belts will be available for use to improve safety belt effectiveness.

JPL cautioned in their final report that the expected improvements in safety and protectiveness of air bags, as described above, must be tempered by the understanding that there are key technology advances to be made.

(1) Air bag deployment time variability must be reduced by improvements in the vehicle crush/crash sensor system.
(2) Inflator variability must be reduced so that dual-stage inflators can be applied effectively.
(3) System and component reliability must receive diligent attention to achieve the high levels required under field conditions.
(4) Occupant sensors must be developed that can distinguish between small, medium, and large adults, children and infant seats with high accuracy.
(5) Position sensors to measure occupant proximity to the air bag module with the required response time and accuracy must be demonstrated.

JPL finally noted that all of the above are the subject of current development; but development, test, and integration of the advanced technologies needs to be accelerated to enable its incorporation into production vehicles [6].

NHTSA notes that in the advanced air bag research program, testing was conducted of both driver and passenger dual stage air bag inflators with multi-stage inflation capabilities [7]. The air bag inflators were able to generate a third, mid-level of inflation by staging the firing of the primary and secondary stages by a small period of time (approximately 20 msec). This mid-level of inflation was designed to be approximately equivalent to a "depowered" level of inflation (i.e., having a lower pressure onset rate and peak pressure). Assuming sufficient technological advances are made, as listed by JPL above, this could allow a belted occupant of small stature (sensed by a belt spool-out sensor), or a belted occupant sitting in the full forward seating position (sensed by a seat position sensor), or any belted occupant, regardless of size and position, the opportunity for a "depowered" inflation level to minimize the risk of inflation induced injuries. (The full power inflation could then be utilized for an unbelted occupant.) The mid-level of inflation could also be used in moderate severity crashes based on input from the crash sensor signal.

MVSRAC Participation

At the third meeting of the Advanced Air Bag Technology Working Group, NHTSA presented a formal plan and test matrix for evaluating advanced air bag inflators and crash sensors at NHTSA's Vehicle Research and Test Center (VRTC). The objective of the program was to assess the potential for advanced air bag systems to reduce injury to out-of-position occupants and maintain protection for adults in higher speed collisions. NHTSA sought to test three vehicle platforms: a small car, a minivan, and a sport utility vehicle. It was agreed upon among the working group members that two platforms would be provided by members of the AAMA, and one platform would be provided by the members of the Association of International Automobile Manufacturers (AIAM).

The first platform (referred to as Platform 1) was provided to NHTSA by the AAMA, and included advanced driver and passenger multi-stage air bag inflators and an advanced single-point crash sensor. VRTC conducted three phases of testing on this platform: static out-of-position tests, moderate and high speed sled tests, and a full scale crash test.

The static out-of-position tests were conducted with a 5th percentile female Hybrid III dummy on the driver's side in two test positions. On the right front passenger side, tests were conducted with both the 6-year-old and 3-year-old Hybrid III children in two positions. Using the first position as a baseline, two additional tests were conducted with the 3-year-old Hybrid III dummy by translating the dummy 100 mm and 200 mm back from the instrument panel. Two additional tests were conducted in the second position to test repeatability with both the 6-year-old and 3-year-old Hybrid III dummies. In all the static out-of-position tests only the primary stage of the multistage inflator was used.

Results from the out-of-position tests suggested that the 5th percentile female could potentially meet the injury assessment reference values in the out-of-position tests with small improvements in the advanced air bag. However, the 6-year-old and 3-year-old Hybrid III children could not meet the injury assessment reference values on the passenger side. The proximity tests using the 3-year-old Hybrid III suggested injury measures decreased as the dummy was moved further away from the air bag and larger distances were required for the 3-year-old dummy. The repeat tests suggested that the test procedure was repeatable for HIC, chest G's and neck measurements [7].

The second phase of testing on Platform 1 consisted of conducting sled tests with the normally seated adult 5th female and 50th male Hybrid III dummies, belted and unbelted. The sled tests simulated two conditions: a 48 kmph rigid barrier crash and a 32 kmph center-pole crash. Three different inflation levels were used: primary only, primary + 20 msec delay (mid-level), and primary + 5 msec delay (full-power). Results from the sled test indicate that the advanced multi-stage inflator successfully restrained the 5th percentile female and 50th percentile male dummies in a 48 kmph sled test using variable outputs of the inflator [7].

The final phase of testing on Platform 1 consisted of a full scale 40 kmph offset pole test to the left of the vehicle centerline. The advanced single point sensor was used to detect the crash severity and deploy the appropriate level of inflation. An unbelted 5th percentile female Hybrid III dummy was positioned in the driver's seat, and a unbelted 6-year-old Hybrid III was positioned in the passenger's seat. The advanced sensing system was able to detect the crash and fire only the primary stage of deployment; however the sensor fired late in the crash event resulting in the 6-year-old being severely out-of-position [7]. Therefore, the advanced system tested for Platform 1 was not able to meet the out-of-position testing requirements on the passenger side for the child dummies; however, the system was able to meet the high speed requirements for the 5th percentile female and 50th percentile male adult dummies. Further development is needed to improve sensor timing and aggressivity to out-of-position occupants. (The reader is referred to a companion ESV paper for detailed information about the testing [7].)

Cooperative Research Programs

NHTSA conducted a test series with the VS Holden Commodore Vehicle in conjunction with the Australian Federal Office of Road Safety (FORS). The Holden Commodore vehicle contains air bags designed for the Australian environment which has a very high safety belt usage rate. Frontal barrier crash tests with unbelted adult occupants and out-of-position tests were conducted to assess the performance and aggressivity of the air bag system. The driver air bag system marginally passed the high speed requirements, and resembled a next generation air bag system in the out-of-position tests. However, the passenger air bag system did not perform well in the out-of-position tests, but passed all the high speed test requirements. The reader is referred to a companion ESV paper for further details regarding this testing [7].

NHTSA has also evaluated advanced driver air bag modifications through a cooperative research program with Automotive Systems Laboratory, Inc. (ASL)/Takata Corporation. The objective of the program was to identify critical parameters that could reduce the risk of injury to out of position drivers yet still satisfy the crash test requirements of FMVSS No. 208 in a 48 kmph barrier crash using unbelted dummies. Prototype driver air bag inflators and modified air bag folds and cover designs were considered both in isolation and in combination. The results demonstrated that modifications to the inflator module (through air bag folding and cover design) produced substantial reductions in the risk of air bag-induced injury to the out of position driver while still matching the FMVSS No. 208 performance of the production system. Recently a new cooperative research program was initiated between NHTSA and ASL/Takata to evaluate dual stage passenger side air bags in terms of both restraint performance and aggressivity for different size occupants. The project will examine the influence that variations in inflator rise rate, peak pressure and deployment timing can have on both restraint performance and aggressivity.

NHTSA also has a cooperative research agreement with Automotive Technologies International (ATI) to adapt their ultrasonic pattern recognition system for sensing occupant position to the passenger compartment of a prototype vehicle. The passenger acoustic detection device was installed and trained to identify the presence of a rear facing child safety seat, and further trained to recognize that a person is out-of-position. The system utilizes a set of ultrasonic transducers and a neural network decision algorithm which is programmed or trained to recognized conditions for air bag suppression and non-suppression.

DEVELOPMENT OF TEST PROCEDURES

In the advanced air bag technology research program, NHTSA has been developing and evaluating test procedures for advanced air bag systems. To evaluate air bag aggressiveness to out-of-position occupants, NHTSA has developed driver and passenger static air bag deployment test procedures. On the driver's side, the 5th percentile female Hybrid III dummy is used in two positions. The first positions the dummy head/neck in close proximity to the air bag module (Figure 1) and the second elevates the dummy such that the chest is against the module (Figure 2). These positions were based on ISO DTR 10982 test procedures for testing out-of-position occupants.

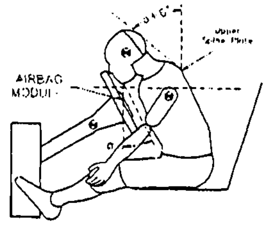

Figure 1. 5th Female, Position 1.

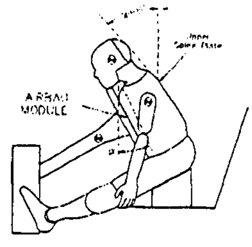

Figure 2. 5th Female, Position 2.

For the right front passenger, NHTSA has developed test procedures for the 6-year-old and 3-year-old Hybrid III child dummies. Again, two positions are used: one positions the dummy's chest in close proximity to the air bag module with its spine vertical, while the other positions the dummy on the seat edge and rotates the upper torso toward the air bag module. The two dummy positions were developed based on the ISO 10982 [8] procedures for out-of-position testing. Figures 3 and 4 illustrate the positioning of the 6-year-old Hybrid III dummy and Figures 5 and 6 illustrate the positioning of the 3-year-old Hybrid III dummy.

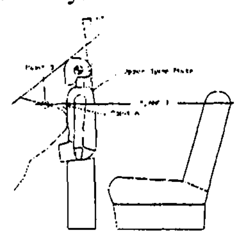

Figure 3. 6YO, Position 1.

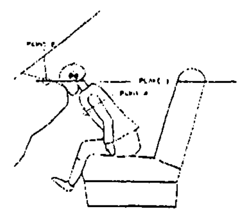

Figure 4. 6YO, Position 2.

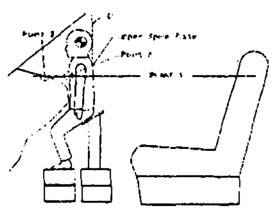

Figure 5. 3YO, Position 1.

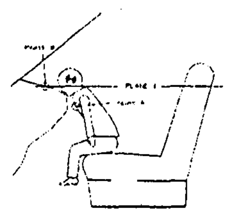

Figure 6. 3YO, Position 2.

These out-of-position test procedures were developed by, and tested extensively by VRTC over the past two years of air bag and dummy certification programs. Repeat tests were also conducted to confirm repeatability and reproducibility of test results.

NHTSA has also been working with Transport Canada in a joint research program to develop a low speed deformable offset barrier test procedure using belted 5th percentile female Hybrid III driver and passenger dummies. Figure 7 illustrates the crash test configuration, and Figure 8 illustrates the driver seating position for the 5th percentile female Hybrid III dummy. The combination of low speed

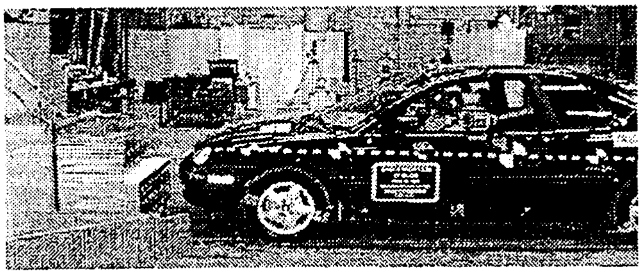

Figure 7. 40 kmph, 40% Offset Test Procedure.

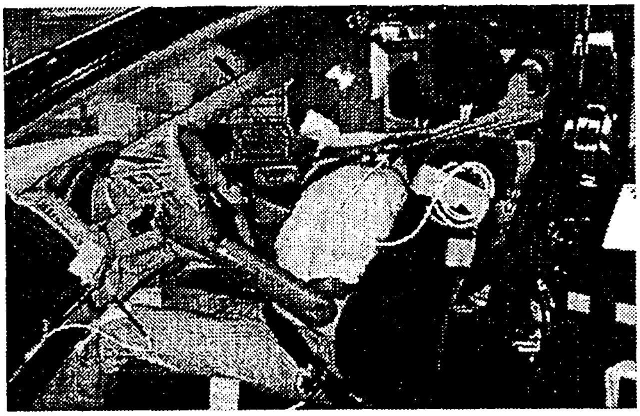

Figure 8. 5th Percentile Female Hybrid III Driver Seat Position.

and a deformable barrier result in generating a soft crash pulse just above the threshold for air bag deployment. This has the potential for presenting crash sensing challenges to some vehicle air bag systems. Vehicles that have difficulties discriminating between a "fire" and "no fire" condition in this crash mode tend to deploy the air bags late in the crash event. This results in positioning the belted 5th female Hybrid III dummies' head/neck very close to the air bag module (due to the crash forces already rotating the dummy torso forward). This test procedure has illuminated a need for reducing aggressivity to out-of-position occupants, and a need for improved low speed crash sensing to provide a more timely air bag deployment. It also aims at providing protection to small drivers, who conscientiously wear their safety belts and, by necessity, must position themselves close to the steering wheel to drive.

Associated research has also been conducted on establishing a uniform test procedure for seating the 5th percentile female Hybrid III driver and passenger dummies. The test procedure would ideally be repeatable in a single seat, reproducible amongst technicians, and be a realistic representation of the 5th percentile female seating position. NHTSA has been participating in the SAE Hybrid III 5th Percentile Dummy Seating Procedure Task Group meetings to help accomplish these goals.

Other test procedures that are in development in the advanced air bag technology research program include: static tests for air bag suppression, and dynamic tests for either air bag deployment or suppression. Static tests for air bag suppression test the advanced restraint systems ability to automatically turn the air bag off when an out-of-position adult driver or child passenger is pre-positioned close to the air bag module. For weight based sensing systems, it tests the ability of the sensor to discriminate between a child and a small adult passenger, and it tests the sensor functionality in a rough road environment (where seat loading forces can oscillate). For presence detection sensor systems, component test procedures are being developed to test the sensors ability to suppress air bag deployment based on an occupant dynamically entering a designated "keep-out zone." Dynamic test procedures are being developed that emulate crash conditions of the fatal crashes that have occurred in the real world. The test procedure involves a full scale crash test of low to moderate severity with pre-impact braking, and either benign air bag deployment or air bag suppression can be used to pass the injury criteria specified in this test. Initial research has involved hard braking tests in different vehicles and different initial seating procedures with the Hybrid III 6-year-old and 3-year-old dummies.

CRASH RECONSTRUCTIONS

NHTSA conducted crash reconstructions of real world injury and fatality cases involving children and air bag deployments from the National Automotive Sampling System (NASS). The main objective of the program was to compare the injury measures which resulted from the real world crashes to the injury measures recorded from the dummy instrumentation in the crash reconstructions. A secondary objective was to evaluate injury measures on the 5th percentile Hybrid III driver occupant. Six NASS cases were reconstructed in this program (three involved fatally injured children, one involved a seriously injured child, and two involved children with minor injuries.) Preliminary results indicate that neck injury measures recorded from the 6-year-old Hybrid III dummies were not always consistent with injuries to children of similar age and size in the selected NASS cases simulated by these tests. The reader is referred to a companion ESV paper for the specific details on the six reconstruction cases in the program [9].

EVALUATION OF NEXT GENERATION AIR BAG PERFORMANCE

Performance Testing

As a part of the advanced air bag research program, NHTSA is evaluating the performance of next generation air bag equipped vehicles. Since the introduction of 1998 model year vehicles, NHTSA's Office of Research and Development, Office of Vehicle Safety Compliance, and Office of Vehicle Safety Standards have conducted tests of 1998 model year vehicles that were certified using the unbelted sled test option of FMVSS No. 208.

NHTSA's Office of Research and Development conducted six 48 kmph rigid barrier crash tests with unbelted 50^{th} percentile male driver and passenger dummies in 1998 model year vehicles. Preliminary results indicated that all injury measures were below all current FMVSS No. 208 criteria with the exception of one test (the passenger chest Gs were slightly above 60 Gs). For these same six vehicle models, static out-of-position tests were also conducted with the 5^{th} percentile female Hybrid III adult dummy in two driver positions (Figures 1 and 2), and with the 6-year-old Hybrid III child dummy in Position 1 (Figure 3). Two additional static air bag deployment tests were conducted with the 6-year-old Hybrid III child dummy translated 100 mm and 200 mm away from the instrument panel. Preliminary out-of-position results indicate that, on average, chest and neck injury measures were slightly reduced from previous model year tests; however they still exceeded the injury assessment reference values.

In a joint research program with Transport Canada, ten 48 kmph rigid barrier crash tests and ten 40 kmph, 40% offset deformable barrier crash tests were conducted with belted 5^{th} percentile female driver and passenger dummies in 1998 model year vehicles [10]. Preliminary results from this program indicate that neck injury measures on the belted 5^{th} percentile female dummies continued to exceed NHTSA's injury assessment reference values in some of the 1998 vehicles. The problem of vehicle crash sensors firing late in the low speed offset deformable crash tests in some pre-1998 model year vehicles also continued to result in some of the 1998 vehicles. Therefore, improvements to reduce aggressivity to small belted females, and enhanced sensor performance in low speed crashes needs to further be achieved.

NHTSA's Office of Vehicle and Safety Compliance has also conducted unbelted sled tests and a small number of full scale vehicle crash tests (for vehicles that did not certify, or not fully certify, under the FMVSS No. 208 sled test option). Neck injury measurements were recorded in these tests; however they did not exceed the IARV's established for the 50^{th} percentile male Hybrid III dummy. NHTSA's New Car Assessment Program (NCAP) has also conducted rigid barrier frontal crash tests at 56 kmph with belted 50^{th} male Hybrid III dummies. Preliminary results indicate that many 1998 vehicles with next generation air bags performed satisfactorily in providing occupant protection for belted occupants in high severity collisions. The reader is referred to a companion ESV paper for information on NHTSA's frontal NCAP program [11].

Crash Investigations

In addition to crash testing, NHTSA's Special Crash Investigation (SCI) program is conducting investigations of real world crashes with next generation air bags. As noted earlier in the real world crash investigations section, NHTSA has implemented several early notification mechanisms to identify crashes, and has already initiated 56 investigations since April 1, 1998.

Initially, during the time period of October 1997 to January 1998, the SCI teams selected any case with a next generation air bag deployment. After January 1998, the following criteria was established to focus on cases of immediate interest to the agency.

- A child seated in a position where a next generation air bag has deployed.
- The crash was severe (delta V > 38.6 kmph)
- When a vehicle has driver and passenger in seat positions protected by a next generation air bag.
- When an injured driver or passenger are in a seat position protected by a next generation air bag and transported to a medical facility for treatment.

The agency anticipates investigating 100 crashes based on this criteria in fiscal year 1998 [3].

SUMMARY

Current regulatory steps toward reducing air bag aggressivity to out-of-position occupants fall short of eliminating the fatalities and serious injuries resulting from air bag deployment. NHTSA has initiated an extensive research program on advanced air bag technology to establish the technical basis for new vehicle performance requirements that lead to improved occupant crash protection. Tasks involve the development and certification of alternative test dummy sizes for incorporation into the Federal motor vehicle safety standards. Research is being conducted to establish corresponding injury assessment reference values for each test dummy, particularly in the neck and thorax regions. An advanced air bag technology assessment was conducted by JPL which projected the types of technologies that are being developed and may be available for model years 2001 and 2003. NHTSA conducted evaluations of some of these technologies through participation in the MVSRAC Advanced Air Bag Technology Working Group, and through other cooperative research programs. Test procedures have been developed for assessing overall air bag system performance and aggressivity issues for out-of-position occupants. Crash reconstructions were carried out to better understand and emulate the circumstances that occur in the real world and to enhance test procedure development. NHTSA has also evaluated the occupant crash protection afforded in 1998 model year vehicles with next generation air bags through various crash testing programs, as well as through static out-of-position tests.

FUTURE WORK

Future work in the Advanced Air Bag Technology research program will include improving test dummy biofidelity to support innovative sensor technologies, and the enhancement of injury criterion across the spectrum of occupant sizes. NHTSA will continue to test the performance of advanced air bag technologies, and refine test procedures and criteria to encompass a larger segment of the population, over a greater range of crash scenarios. NHTSA will continue to investigate real world crashes involving vehicles with next generation air bag systems and future advanced air bag systems, as they emerge. Finally, research will be continue to provide rulemaking support as needed.

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THE COMING REVOLUTION IN AIRBAG TECHNOLOGY

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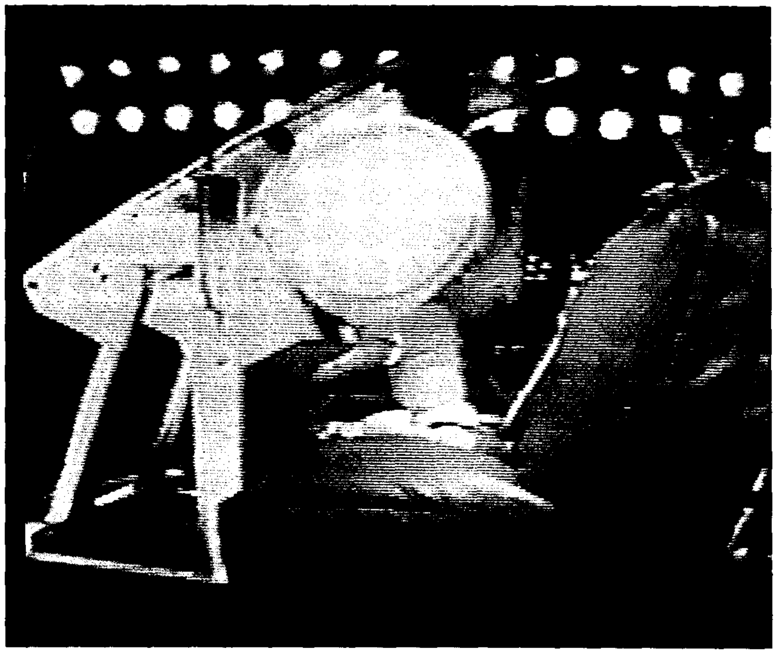
Paper Number 98-S5-W-30



ABSTRACT

There are now tens of millions of airbag-equipped vehicles on the highways. In vehicle collision accidents, thousands of lives have been saved, and tens of thousands of potentially severe injuries have been reduced. Yet, there are also injuries caused by various airbag systems, especially in low-speed to moderate-speed accidents in which no other significant injuries would likely have been caused.

Short-stature drivers and children passengers in the right-front seat, have been documented as the most vulnerable to airbag-caused severe to fatal injuries. There have therefore been incentives for motor vehicle manufacturers, airbag system manufacturers, and government agencies to move ahead in the development and implementation of safer airbag technology. This report examines the concepts, developments, and directions for airbag safety innovations.

A typical present-day airbag system is comprised of the basic elements of: (a) crash sensors to detect the sufficient deceleration that indicates a frontal collision is likely beginning, (b) a gas generator that instantaneously produces a sufficently high volume of gas, (c) a stored airbag in the center of the steering wheel and in the instrument panel that will become fully inflated in about 30-to-40 milliseconds, and (d) a diagnostic module that can monitor and validate the readiness of all the sysytem's component.

The criteria for airbags is no longer to simply offer automatic protection for the driver and front seat occupants in frontal crashes. More stringent requirements reflect the public's understandable concern after reports of airbag-caused fatal injuries to shorter drivers and children passengers. The airbag also must not create a risk nor cause injury to the shorter driver or others who may be too close to the stored airbag, such as with an unbelted or belted person moving forward during pre-crash braking. Nor should the airbag cause injury to small children passengers, who may be in a child safety seat or somewhat out of position (e.g., unbelted and leaning closer to the stowed airbag).

This may require airbag systems that have sensors or other means to detect the potentially adverse situation, and then restrict the particular airbag from deploying. This will also require automakers to verify compliance to test procedures that no longer focus on the 50th-percentile adult male test dummy, but will also include short-stature female drivers and child test dummies as well. Larger, tall test dummies should also be included in a more comprehensive test matrix of various individual sizes, weights, and seating positions.

While initial airbag systems have concerned occupant protection in frontal crashes, a second wave of airbag systems concerns occupant protection in side impact crashes and vehicle rollover accidents. Various designs offer protection for the torso, or for both the torso and also higher at the occupant's head level.

AIRBAG FATALITIES TO CHILDREN

A major airbag problem concerns the continuing epidemic of severe to fatal injuries to infants and young children who are in the right-front passenger seat of a vehicle equipped with a passenger-side airbag. At a National Transportation Safety Board (NTSB) hearing in September 1996, it was noted that there were 26 documented cases since 1993 in which infants and young children had been killed by passenger-side airbags in collision accidents that they otherwise would have likely survived with either minimal or no injuries. Many of the collisions were at very low speeds, in the 8 to 20 mph range. The tragic epidemic continues at the rate of one additional child fatality per week.

The evaluation of why children were being killed by airbags focuses on a few key issues, some behavioral and some technical. Though recommendations were typically expressed that children should always or preferably ride in the back seat, it was often difficult for the parent to place the infant where he or she was not immediately accessible next to them. As for young children, ages 5 to 12 years or so, it's understandable that parents would allow them to ride in the right-front seat, since the lap and shoulder belt appeared to be fit well enough... and they'd also enjoy *the added protection* of the passenger-side airbag, or so it logically seemed.

The passenger-side airbag bursts or explodes from the instrument panel at speeds from about 90 miles per hour to 210 miles per hour. The rapidly-inflating airbag can impact the passenger with a force as high as about 2,000 pounds. As it inflates, the airbag's maximum distance extending horizontally rearward from the instrument panel can be as much as 18 to 24 inches toward the child or safety seat.

Some airbags are stored in the front face of the instrument panel, and inflate *horizontally* directly toward the passenger. If it involves a small child or a rear-facing infant seat, the horizontal deployment airbag is aimed directly at the head of the small child or directly into the infant seat. Other airbag modules are located on the upper surface atop the instrument panel, and initially inflate *vertically* upward and then wrap over toward the seated passenger.

From evaluating the prior research and also the current knowledge about which *specific* airbag designs are causing fatal injuries to children passengers, it appears that some of the horizontally deploying airbag designs (e.g., Chrysler, Ford, GM) are the more injurious ones, while the top-mounted vertically deploying airbag designs (e.g., Honda, Toyota, Subaru) are significantly safer and non-lethal.

If pre-crash braking is involved, the child may also be moving toward the instrument panel. If the right-front passenger seat is not adjusted to its maximum rearward position, the passenger's closer proximity to the inflating airbag can lead to a greater risk of airbag-caused injury. Even if the child is wearing the lap-and-shoulder belt, a combination of poor belt performance (too much slack, slow lockup response), and possible forward adjustment of the seat, the airbag could nonetheless still cause a severe punch to the child. Yet, in many accidents, the airbag can also offer significant protection for the child passenger on the front seat.

TOWARD A SOLUTION: "SMART" AIRBAGS

The proposed solutions focus on what is called a *"smart airbag"* system, where the airbag inflation pressure, or even whether or not to activate, are automatically responsive or proportional to the speed of the crash and the weight of the person (child or adult) on the seat.

Some proposed "smart airbag" designs include occupant weight sensors in the seat cushion to detect whether the right-front seat is occupied, and by how much weight (child, small adult, large adult). Infrared detectors can also determine whether or not there's a child safety seat present. If the sensors detect a potentially dangerous situation, such as the close proximity of a rear-facing child safety seat, the airbag is disengaged and will not actuate in a crash.

Alternative proposals describe an airbag system able to inflate the airbag in proportion to the severity of the crash... with a ***"softer"*** inflation pressure for lower speed crashes, and a ***"firmer"*** bag for higher speed crashes. Some of GM's early-1970's dynamic sled tests and crash test studies using child dummies and live baboons indicated changes needed to reduce the potential injury to children. These improvements were incorporated in the GM ***"Air Cushion Restraint System"*** (ACRS) implemented in the 1973 Chevy Impala test fleet, making them the world's first cars with a "smart" airbag system.

Another desirable upgrade would be the development and mass implementation of *"smart"* airbag systems that can detect when a child or rear-facing child seat is in proximity to the passenger airbag, and cause softer inflation pressures in such instances, especially in low and moderate speed crashes. A parallel feature would sense when the seatbelt is being worn by the passenger (similar to a feature in some Mercedes airbag systems, which raises the airbag actuation speed threshold when the driver is belted).

As discussed above, it is also important to locate the stored airbag module in such a location that the initial burst-out forces will not be concentrated directly toward the head or neck of a seated child or small adult. Thus, the top-mounted vertically-deploying passenger airbags are a safer embodiment than the horizontally-deploying airbags that are located in the front face of the instrument panel.

THE 1973 GM DUAL-MODE AIRBAG... AND CHILDREN

The very first production airbag system, developed by General Motors and utilized initially in a test fleet of 1,000 specially-modified 1973 Chevy Impala 4-door sedans, did in fact have a "smart" two-stage inflation pressure. GM then offered their two-stage airbag system as a $235 extra-cost option in some models of the 1974-75-76 Oldsmobile, Buick, and Cadillac.

"Low speed detectors are designed to activate the total system in a frontal type collision with an immovable object, such as a wall, at about 11 m.p.h. When striking a comparable parked vehicle (which will move or crush), the low speed detector will activate the system at about 22 m.p.h."

"In more severe accidents the high speed detector will more firmly inflate the passenger system at about 18 m.p.h. when striking an immovable object, and about 36 m.p.h. when impacting a comparable parked car."

General Motors early-1970's concern about the airbag's deployment effects on children was described in a 1974 GM report:

"... work utilizing live baboons in laboratory experiments indicated a potential inflation hazard to small children who might be out of the normally seated position. The result of this program also stimulated the redesign program for the passenger restraint system."

"The possible inflation hazard experienced with the first generation design was reduced by providing dual sensing of impact severity and control of cushion inflation. During impacts of low severity, a low inflation of the cushion would be used. For high severity impacts, a faster deployment of the air cushion was provided."

"An additional series of tests... indicated the second generation air cushion restraint would reasonably control the inflation hazard to small children."

Thus, the 1973-1976 GM airbag system already had the safety benefits of a softer bag for lower speed crashes, and a firmer bag for more severe crashes. This is a 20-year-old feature that will soon likely be "re-invented" in order to help solve the dilemma of airbags that can and do kill children in the right-front passenger seat. The airbag's explosive dangers to children, described mostly as "out of position" children, was discussed in the '70's and '80's when some automakers were voicing concerns about airbags.

When it came time to implement airbags in the 1988 to 1996 era, most automakers did not include features that would make airbag inflation pressures proportional to the severity of the crash and the weight of the person on the seat. Some automakers made the crash sensor threshold or actuation speed very low, with a trigger speed as low as 8-to-12 miles per hour BEV (Barrier Equivalent Velocity).

AIRBAG INJURIES TO SHORT WOMEN DRIVERS

Short adult drivers, especially women, have been severely and fatally injured by the explosive force of a driver's airbag... even in low to moderate speed crashes. Because of their short stature, from perhaps 4'10'' to around 5'4", shorter drivers need to adjust their seat virtually to its full forward position. This places their chest and head in close proximity to the steering wheel. In the center hub of that steering wheel is the stored airbag, ready to inflate in a frontal impact. The powerful and instantaneous inflation can move the unfolding airbag toward the driver at 120 to 200 miles per hour, and generate a force of 2,000 pounds.

Some of the initial accident case examples concerned shorter women drivers, sitting very close to the steering wheel, who were fatally injured when the explosive force of the airbag fractured their ribs, which punctured and tore their aorta. The crashes were moderate in nature, and the airbag was the needless cause of death in what would have been a survivable collision. Some of the women were shorter, older, and more frail... making them more susceptible to the airbag inflation forces breaking their ribs, tearing their aorta, and causing fatal injuries.

The generally accepted precaution or recommendation, by NHTSA and most automakers, is for the driver to adjust their position so there is at least 10 inches of distance between their sternum and the center of the steering wheel. The vast majority of short-stature drivers should be able to position the seat and backrest, and the tilt and telescope steering wheel if so equipped, so that the recommended distance of at least 10 inches is attainable, without also compromising safe pedal reach and safe visibility.

HOW AND WHY AIRBAG HAZARDS OCCURRED

How could such a prominent safety technology as airbags been compromised, leading to needless deaths and injuries ? Airbags are not a new development, despite the general public perception that airbags are a technology of the '90's. In fact, the development of airbags goes back to the '50's and '60's, when the earliest dynamic sled tests and car crash tests by GM and Ford and Eaton Corporation showed their great promise to reduce traumatic injuries in collision accidents.

There was anticipation in the early-'70's that airbags would soon be installed. NHTSA had initiated rule-making, and the car companies in the U.S., Europe, and Japan were all developing airbag systems for their vehicles. However, top officials from Ford and GM and Chrysler went to the White House in 1971, and urged President Nixon to delay the then-pending auto safety standards, including the requirement for airbags.

The pending 1970's requirement for airbags was politically shelved, and languished in limbo into the mid-1980's. There was nothing preventing car companies from installing airbags on their own. After a United States Supreme Court decision in 1983 forced NHTSA to re-examine their latest cancellation, the rulemaking process began again. NHTSA and DOT responded with a 1984 plan to link mandatory buckle-up laws to a decision about requiring airbags. Without waiting for a NHTSA mandate, Mercedes introduced airbags in some models in 1984, and Ford offered a driver airbag option in the 1985 Tempo.

In 1988, Chrysler began to promote airbags as a standard feature in most of their cars. This was a major reversal by Chrysler CEO Lee Iacocca, who had opposed airbags for years... including his criticisms made in 1971 in the Oval Office to President Richard Nixon. In his 1984 autobiography, Iacocca was highly critical of airbags, even granting *"they'll work in 99.99 percent of cases"*. He feared the powerfully explosive airbags *"can also be dangerous"* and would also cause injury and death in some cases... and that airbags would therefore create a liability nightmare for the car companies.

In the 1989-1993 era, the news media began to report and dramatically illustrate that lives were being saved in head-on collisions, *thanks to airbags*, and the public demand for airbags began to gather momentum. With the simultaneous pressure from both a 1991 Congressional mandate and the upgraded Federal Standard, the race to install airbags swept across the auto industry through the 1990's.

Airbags are a well-proven live-saving and injury-reduction technology. Thousands of people have survived crashes, due to airbags, in which they otherwise would have likely died. The current estimate is that at least 500 vehicle occupants are saved from fatality injuries per year. As each year brings an additional 14 million airbag equipped vehicles onto U.S. roads, the value of airbags to prevent severe to fatal injuries will obviously increase the number of survivors.

Yet, the advent of millions of airbag-equipped cars, pickups, and vans has led to a combination of circumstances and accidents in which the airbag itself was the cause of the fatality. Examples have included short women drivers, perhaps somewhat slight of stature, sitting very close to the steering wheel, involved in 15 to-20 mph frontal collisions. Other examples include young children, such as a 7-year-old girl, safety-belted on the passenger seat of a Chrysler minivan, in a 10 mph frontal crash, Another concerns an infant in a forward-facing child safety seat, killed by the airbag in a minor parking lot accident.

OVERVIEW OF AIRBAG COMPROMISES AND OMISSIONS

Many of the fatal airbag accidents have been evaluated. The history of how airbags have been an on-again, off-again, on-again safety technology has been reviewed. The roles of the auto industry and the federal auto safety agency have been considered. Amidst the historical and present wealth of information, here's an overview of some basic compromises, omissions, and misjudgments that have caused life-saving airbag systems to also be occasionally hazardous to children passengers and short women drivers.

Failure to design and test airbags for smaller women and children, instead of only for an "average man". When airbags were required to comply with FMVSS 208, the basic test was and is a full-front impact of the vehicle into the concrete barrier at a speed up to 30 miles per hour, with injury limits specified for the head and chest of an unbelted 50th-percentile adult male dummy, about 5'9" tall and weighing 167 lbs. Even though the automakers and NHTSA could have *also* specified a range of test dummies, including shorter women dummies and child dummies, the desire for simplicity and economy prompted only a single crash test using just that 50th-percentile *"average man"*. And the driver's seat was adjusted accordingly.

Failure to set the airbag's actuation threshold speed higher, rather than as low as each vehicle manufacturer wants... sometimes too low. There was no actuation threshold speed specified below which the airbag should not inflate. At an auto manufacturer's discretion, the threshold speed could be as low as 8 to 10 miles per hour... or as high as 16 to 18 miles per hour In some cars, the crash sensor, which releases a magnetically-held steel ball, would therefore be very sensitive to low-speed deceleration.

Failure to have multiple inflation pressures, rather than just a single-mode high inflation pressure that's too high for the less severe crashes. Virtually all manufacturers adopted an airbag system that used sodium azide pellets to instantaneously generate a large amount of nitrogen gas that would immediately fill the stored airbag and burst it through its cover panel into a large, inflated, rigid pillow. The airbag would then deflate through side vents as the occupant loaded into the cushion. But once the ignition process began, the entire amount of sodium azide was activated, meaning the inflation pressure would always be the same... rather than a "softer" inflation for lower speed crashes, and a "firmer" inflation for higher speed crashes.

Failure to use airbag tethers and shapes that would ensure a greater distance between the inflating airbag and the driver or passenger. The speed of the inflating airbag is from 90 to 210 miles per hour, and can generate a force of 2,000 pounds. Tether straps are used inside the airbag to help shape the inflating bag and reduce the distance that the airbag inflates from its stowed position within the steering wheel hub and the instrument panel. Tethered driver airbag maximum distances from the instrument panel range from 12 to 15 inches, while untethered driver airbags range from 17 to 20 inches or more and are thus can dangerously impact into the chest and head of the short woman as the airbag explosively inflates.

A similar situation exists for the larger-size untethered passenger-side airbag... causing the airbag to explosively inflate and impact into the head of the child, causing severe to fatal brain and neck trauma. It is analogously important to consider the merits of tethers to control the inflation shape and excursion distance of the passenger airbag. The use of tethers would help make the passenger airbag inflate as a flatter pillow, rather than a rounded basketball shape, and would reduce the distance of the inflated airbag from the passenger.

Failure to include a "seatbelt-in-use" detector switch to raise the airbag actuation threshold to a higher speed. If the driver is wearing his or her lap-and-shoulder belt, then there's less need for the "supplemental" airbag to inflate, especially in low to moderate speed crashes. But some automakers have provided seatbelts that fit poorly, or that have too much slack, or that don't lock-up quickly enough in the crash. And most automakers don't want the extra cost of using a seatbelt detector that will raise the airbag's actuation threshold if it detects the driver is in fact wearing the seatbelt... such as from 12 mph if you're unbelted, raised to 18 mph if you're belted.

Failure to provide the safer seatbelt pre-tensioners to snug the belt at the start of a crash. Seatbelt pre-tensioners are devices that automatically take up any seatbelt slack, thereby snugging the lap belt and shoulder belt to the wearer's body at the start of a crash. Snug fitting belts serve as a more effective restraint, keep the occupant from excessive forward movement, and prevent a looser-fitting shoulder belt from slipping off the occupant's shoulder. Most seatbelt pre-tensioner systems also use a force-limiter feature that alleviates excessive loads on the occupant's body during the crash. Most European cars and upper-scale Japanese cars use seatbelt pre-tensioners. The only American brand that presently includes pre-tensioners is the new 1997 Cadillac Catera, which is essentially a restyled Opel that's imported from Germany.

Failure to recess the stored airbag a bit deeper, to allow more distance between the inflating airbag and the shorter driver. Recessing the stored airbag deeper below the plane of the steering wheel creates more distance between the explosively-inflating airbag and the driver, especially the shorter driver who sits very close to the steering wheel.

Failure to provide or offer a telescoping adjustment for the steering wheel. Include an adjustable telescoping steering wheel as a standard feature, so shorter drivers can adjust the steering wheel to be further away from themselves. This would create a safer distance between the explosively inflating airbag and the driver. Many steering wheels have a tilt feature, but not an ability for fore-and-aft telescoping as well.

Failure to provide or offer an adjustable pedal platform. Include an adjustable pedal platform for the accelerator and brake pedals, to accommodate shorter drivers, and thereby reduce their need to adjust the driver's seat to a full forward position. GM was rumored to have designed such a movable pedal platform, and was going to introduce it as an optional feature in some early-1970's Pontiac or Olds models. It may have been intended to help the airbag problem for shorter drivers. When GM abandoned its 1970's-era airbag program (after building about 11,000 cars in 1973-1976 with airbags for the driver and both front passengers.), this adjustable pedal platform feature never surfaced again. Pedal extenders can also help make the brake and accelerator more accessible to shorter drivers. Pedal extenders are also available at some of the companies that modify vehicles for handicapped persons.

Failure to provide sufficient warnings in highly-visible labels. Most vehicles lack the prominent display of highly-visible warning labels to alert the driver and passenger of the problems of sitting too close to the stored airbag, and of the need to always wear the lap-and-shoulder belt and keep it snug, and also to include the above-noted concerns about infants and children.

TEMPORARY MODIFICATIONS TO FMVSS 208

In efforts to alleviate the pending airbag problems, some auto companies urged NHTSA to modify the applicable safety standard, FMVSS 208. Ford Motor Company wanted the compliance crash speed reduced down from 30 mph to 25 mph, and also to allow the acceptance of chest injury forces to go from 60g's up to 80 g's. This would allow the automakers and airbag system suppliers to "depower" the airbags to make them 20-to-35-percent less forceful when they inflate. This could likely be accomplished by simply using less sodium azide propellant in the inflator cannister, for example.

General Motors also urged that a dynamic sled test, simulating a 30 mph vehicle-into-barrier crash test, be utilized as the only compliance test. Therefore, as Ford and GM urged, the lowered test requirements and more-permissive injury criteria would allow them to use an airbag that deploys with less force, which would supposedly reduce the injury potential to children.

Yet, reducing that particular FMVSS 208 crash test requirement may *increase* the injury potential for the larger adults. And using a sled test instead of an actual vehicle crash test, takes away the reality of evaluating the total vehicle's crashworthiness performance (e.g., how the windshield pillar moves toward the driver's head, or how the floorpan buckles at the driver's feet, or how the steering column re-orients upward toward the driver's neck).

Despite these actual and potential negatives, NHTSA has modified its rule to allow the depowering of airbags. Ford Motor Company announced that most of its 1998 models include depowered airbags.

FMVSS 208 still needs to be upgraded and made more inclusive toward protecting children and shorter drivers. NHTSA needs to expand the crash test matrix to include 5^{th}-percentile women drivers, and infants and small children on the front passenger seat. NHTSA needs to establish a minimum speed below which the airbags should not inflate. NHTSA needs to encourage airbag inflation pressures and expanding bag shapes that are proportional to the crash severity ("soft" and "medium" and "firm"). NHTSA needs to mandate or encourage adoption of seatbelt pre-tensioners, which automatically snug or tighten the lap and shoulder belts at the start of a crash. NHTSA needs to require frontal offest crashes, which is more realistic to actual accidents, rather than the car's entire front crashing into a flat-faced barrier.

TAILOR THE INFLATION PRESSURE TO THE SPECIFIC SITUATION: SEQUENTIAL AND MULTI-STAGE INFLATORS

It appears appropriate to *"re-invent"* an even better version of the 1973-through-1976 GM dual-pressure mode airbag system which had *both* a *"softer"* inflation and a *"firmer"* inflation, depending on the speed of the crash. The dual-pressure concept had merit back then, and the merits of the concept could be implemented again with the newer and superior technology that has been developed in the intervening years.

It is clearly feasible to develop an airbag system that automatically adjusts inflation rate and pressure proportional to the severity of the crash. The more severe the crash, the quicker the bag inflates and the firmer it gets. The ability to inflate the airbag proportional to the crash severity is similar to the two-stage capability of the General Motors dual-mode airbag system of the 1973-76 era. The current 1998 Lexus airbag inflator system, which uses a stored argon gas generator, appears to be close to having that capability.

Sensors are needed in the front seats and/or instrument panel to determine the weight of the occupant (or whether there's a child safety seat) on the seat and/or the occupant's proximity to the stored airbag. Sensors and stored algorithms should be used to determine the relative severity of the impact, and cause the airbag to inflate in proportion to that crash severity (soft, medium, firm), and relative to the weight of the occupant.

The inflation can be accomplished sequentially, such as by igniting an initial amount of sodium azide to begin filling the airbag. And then, about 10 to 15 milliseconds later, ignite the second amount of sodium azide. Thus, a more gradual build-up of inflation will take place... more like an "S" shaped curve, rather than an initial steep rise.

The inflation can be accomplished in multi levels, with multiple inflation pressures tailored to the severity of the crash. For example, a stored gas alone can provide a basic pressure, which can then be increased by also igniting sodium azide to boost the pressure with additional nitrogen gas. Also, multiple chambers of either stored gas or sodium azide (or other chemical propellant) could be selectively fired as needed to provide inflation pressures proportional to the situation of crash severity and occupant size.

CRASH SENSORS, THEIR LOCATION AND DEPLOYMENT THRESHOLD

Innovative crash sensors can lead to a slower-inflation rate airbag that is thus less explosive and less likely to cause injury. Present-day airbags require the sensing, actuation, and inflation to take place within about 30 to 50 millliseconds. The need for such rapid airbag deployment has led to various pyrotechnic gas-generating inflators that cause virtually an explosive inflation of the stored airbag, so the airbag can be fully inflated before the occupant moves significantly forward in the frontal collision.

The crash threshold for triggering a crash sensor should be related to the various velocities, accelerations, and decelerations that the vehicle experiences. The crash sensors and the supporting analytical electronics must detect and distinguish between crashes that require the airbag to deploy, versus low-speed incidents and non-crash jolts (hitting curbs, speed bumps, potholes) that should preclude the airbag from deploying.

The crash sensor triggering threshold has been from about 8 mph in some systems, to about 15 mph in others. The velocity is expressed in terms of the equivalent full-frontal crash of that same vehicle into a fixed barrier, thus "BEV" for Barrier Equivalent Velocity.

Most modern airbag systems include a computerized diagnostic module in which stored algorithms compare the incoming crash sensor signal characteristics with stored patterns. If the comparison shows that a valid crash is occurring, the airbag is caused to inflate.

If the sensing could take place even before the crash began to occur, that would allow more time for that sensing-to-actuation-deployment sequence to occur. That would enable a slower, safer rate for the stored airbag to become fully inflated.

Toyota had developed and tested such a pre-crash sensor system... back in 1970. The Toyota airbag system employed a radar sensor device and a small computer to sense and measure the distance between the car and the on-coming obstacle. The computerized decision to trigger the airbag allowing greater time to inflate the airbag... thus it could inflate with less explosive force. Toyota's car-into-barrier crash tests demonstrated the merits of such a pre-crash sensor.

It is important to locate and mount the crash sensors in the vehicle so they will respond to the vast range of frontal and front-angular crashes. The response time must be within 5-to-20 milliseconds, in order to allow enough time to complete the entire airbag inflation process before the occupant has moved too far forward into the airbag's primary deployment zone (typically the first five inches from the airbag cover, and the zone in which the "burst out" highest pressures occur).

Each vehicle has its own unique "crash signature" as to how the frontal structures will deform, buckle, and crush in various crash modes. The location of the forward crash sensors is typically near the front bumper or headlights, often mounted on a radiator cowl crossmember. The safing sensor, which must be activated simultaneously with a forward crash sensor, is typically mounted within the central cowl region (approximately adjacent to the driver's right knee).

If the locations of the forward sensors and safing sensor are not optimally selected, it can cause the inadvertent actuation of both sensors in such events as a low-speed impact into a parking lot curbing.

Analysis of one such incident showed the poor location of the right-hand forward sensor just above the front of the right-hand subframe member, and the safing sensor near the base of the right-hand windshield pillar and in-line with the same right-hand subframe member.

Thus, a very minor underbody contact between the curb and the subframe member was sufficient to trigger both the forward sensor and the safing sensor... and the airbag was fired in a situation in which it shouldn't have deployed at all. The short woman driver, wearing her seatbelt, was severely injured, including multiple major fractures of her jaw, and a shattered right wrist.

Crash sensors must be able to respond to impacts into flat walls, whether full frontal or offset involving only a portion of the vehicle's front structures. Crash sensors must be able to respond to car-to-car collisions, whether angular, offset, or full-frontal. Crash sensors must also be able to respond to vehicle impacts into a pole or tree, noting that such impacts could occur anywhere along the front of the vehicle... outboard near the headlights, possibly in-line with the front subframe members, or directly in the middle of the vehicle front.

Therefore, the precise location of the crash sensors, and how they are mounted to the vehicle, becomes important if the full array of potential collisions is to be taken into account. The fewer the sensors, the more difficult the challenge.

AIRBAG FOLDING PATTERNS AND MATERIALS

The airbag is typically folded into a very small package that enables it to be stored with the center of the steering wheel, and within the right-hand side of the instrument panel. In a frontal crash of sufficient severity to warrant deploying the stored airbag, a large volume of gas is instantaneously generated and routed to the stored, folded airbag. The airbag must then be unfolded as it rapidly inflates... all within about 20-to-40 milliseconds.

Since the unfolding, inflating airbag may contact the driver or passenger during the initial phase (the "punch-out" phase), it is imperative to avoid direct forces and uppercut forces to the neck, chin, or face.

Airbag folding patterns can also have an influence on the potential cause of injuries. Tests conducted by a major airbag system supplier appear to indicate that a "bias" folding pattern can help reduce the inflating airbag's interaction with the driver's neck. A more common "W-fold" pattern can increase the upward or uppercut forces under the driver's chin. A "star" folding pattern is preferable in that it appears to reduce neck shear, neck tension, and neck extension forces.

The airbag material itself can make a difference in the inflation pressure, the injury potential, and the ride-down venting. Nylon interwoven fabric, often with a thin neoprene inner-surface coating, has been common. Thinner weaves and other synthetic fibers have made airbags lighter and more easily inflatable.

AIRBAG TETHERS AND INTERNAL CHAMBERS

An airbag is basically a hollow fabric ball that gets quickly inflated by a burst of nitrogen gas... and it goes from folded to inflated in about 30 milliseconds. Most inflated shapes initially were like large rounded beachballs or basketballs. and the overall shape was determined by the sewn-together nylon fabric panels, and how it expanded outward under high internal pressure.

The use of internal tether straps, connecting the airbag module to the center portion of the fabric bag, enables a flatter pillow shape to occur, and the excursion distance toward the driver is also reduced. The flatter pillow shape can provide broader coverage in front of the driver, so the broader airbag would offer better protection in offset and angular crashes. And the greater distance from the driver means less injury potential. NHTSA tests have shown that tethered airbags have an excursion distance of only 12-to-15 inches from the steering wheel, while untethered airbags have a more potentially-harmful excursion distance of 17-to-20 inches.

While many automakers opted for internal tether straps to better shape and reduce the excursion of driver airbags, other automakers did not initially use tethers. Tethers for driver airbags are now common, but only a few passenger airbags utilize them... even though the merits of tethers would still apply to better shape the larger passenger-side inflated airbag and reduce its excursion distance toward the passenger.

The manner of inflating the airbag can be improved by constructing the airbag with multiple chambers. One approach is to initially fill an inner chamber and allow the nitrogen gas to then continue swirling into the outer chamber, thereby creating a "softer" outer bag and a "firmer" inner bag.

The reduction and control of the inflation gas, whether from the combustion of sodium azide or from stored argon gas, can be accomplished with internal gas diffusers and nozzles that direct the gas into the airbag in a circumferential manner or in an up-and-down or lateral manner. Thus, the burst of gas is directed in a safer manner, rather than directly toward the occupant.

AIRBAG MODULE COVERS

The cover over the driver's stored airbag module must serve multiple purposes, as a decorative yet resilient cover in the center of the steering wheel, yet allow the stowed airbag behind it to instantaneously inflate while moving the cover out of the way.

Thin cross-section lines, or partimg lines, allow the inflating airbag to "burst through" the cover in a pre-determined manner. Most are in an "H" shaped pattern, with two vertical parting lines and one horizontal parting line.

However, others are top-hinged and, with a cover that may be about 8 inches from top to bottom, allows a forceful upswing of the entire cover as the airbag inflates behind it. In a recent accident case example, involving a 1995 model luxury sedan, a 4'10" shorter woman driver received a severe uppercut punch beneath her jaw when the leather-covered cover pivoted forcefully upward.

DRIVER AIRBAG RECESS AND RETRACTION MECHANISMS

In respose to the airbag inflating outward toward the driver, there are various ways to help conteract the inflating airbag's initial burst-out forces. The airbag module could be mounted deeper within the hub of the steering wheel. The airbag module could simultaneously retract deeper into the steering wheel hub as the airbag inflates outward toward the driver.

Initially recessing the airbag module an inch or so deeper into the center of the steering wheel can have a notable effect of reducing the airbag-inflation "burst-out" injury potential to the driver.

Similarly, allowing the driver airbag module, as it inflates, to simultaneously move deeper or retract into the steering wheel, can also have a similar effect on reducing "burst-out" inflation injuries. This can be mechanically accomplished by a movable or deformable linkage or mounting bracket for the airbag module.

TOP-MOUNT PASSENGER AIRBAG WITH INITIAL VERTICAL DEPLOYMENT

The passenger-side airbag has been stored in many different locations: on the front face or angled face or top face of the instrument panel. Various crash tests, including those done by Minicars and by Honda in the early-1980's, indicated that top-mounted airbags that initially inflated upward, and then continued rearward toward the occupant, would reduce the injury potential to any children in the front seat area, including those who were out-of-position.

Thus, it is apparently safer to utilize a top-mount, vertical-deployment airbag for the passenger, since the airbag's initial burst-out forces are first directed upward toward and into the sloped windshield glass, and then the inflating airbag continues rearward with reduced force toward the seated passenger. The less desirable alternative is a front-mounted airbag that inflates directly horizontally rearward directly toward the seated occupant, who could be a small-stature adult or child, and who may have moved forward during pre-crash braking.

USE OF "ON-OFF" SWITCHES

Some automakers include or offer an available "on-off" switch to allow parents to turn off the potential activation of a passenger-side airbag. That would introduce the danger of their failure to turn the airbag back on, to protect larger children, teenager, and adult passengers, especially in the more severe frontal impacts when the combination of seatbelts and airbags is most critically needed.

A critical requirement for any airbag "on-off" switch would be to include a *lighted visible alert* on the instrument panel, with an amber or red light and wording and symbology to clearly indicate that either or both the driver's and passenger's airbags have been turned off. A green light would indicate that the system is ready for actuation when appropriate. It's also possible to design the airbag system so that it automatically re-sets to a ready mode each time the car is started.

SIDE AIRBAGS FOR TORSO AND HEAD PROTECTION

The latest airbag application is for side-impact protection. Volvo began utilizing side airbags in 1994, in a joint development program with Autoliv. The stored airbag was located within the outboard portion of the driver's seat and the right-front passenger's seat. Thus, the Volvo airbag protected the adjacent occupant's torso, and helped keep their head from being impacted by inward intrusion or lateral displacement.

The newest Volvo airbag system is the *"Inflatable Curtain"*, which is stored along the roof siderail, and inflates downward and longitudenally along the upper half of the side windows, and offers head protection to front and rear seat occupants in side impacts and rollovers.

BMW has recently shown their version of airbags for side-impact protection, including the mounting of one airbag within the upper door structure and another tubular-shaped airbag that inflates to offer protection from the windshield pillar to the mid-body pillar. Thus, this second or upper airbag more directly protects the head of the adjacent occupant.

Various side-impact airbags from Volvo, BMW, Mercedes, and Ford show alternatives for mounting the airbag... within the outboard portion of the front seat, or within the door just below the window level, or along the roof siderail (essentailly between the windshield pillar and the mid-body pillar).

The BMW design, first implemented in some of its 1997 models, is especially meritorious in having an upper-level tubular-shaped airbag that protects the head of the driver and right-front passenger. The front anchorage is at the windshield pillar, and the rear anchorage is at the top of the B-pillar. Once inflated, this head-protecting side airbag commendably stays inflated for a prolonged interval to help continue its effectiveness throughout what could be a more complex accident scenario, including a vehicle rollover.

It is apparent from crash testing demonstrations and from actual accidents involving Volvo, BMW, and other vehicles equipped with side airbags, that reasonable levels of injury reduction can be attained with side impact airbags. The technology is now available to have side impact airbags inflate within 20-to-30 milliseconds of the onset of a side impact to the subject vehicle. There are various storage cavities for the airbags that can be available by feasible redesign of the the seat, the door, or the roofrail. The crash sensors and gas generators have response and actuation times to ensure airbag inflation in sufficient time (e.g., within about 10-to-20 milliseconds).

Side impact airbags for front seat (and also rear seat) occupants are feasible in various designs.... as inflatable protective cushions for the pelvic, torso, head, and neck. The seat belt system will likely need to be integrated into newly-designed and strengthened front seats, rather than having the shoulder belt attached to the mid-body B-pillar, so as to avoid interfering with the inflation of side-impact airbags.

CONCLUSION

NHTSA's mission is to maximize motor vehicle safety, and issues Federal Motor Vehicle Safety Standards (FMVSS) to help encourage implementation of safety technology. While some automakers attempt to comply with the minimum FMVSS requirements, other automakers try to significantly exceed those minimum requirements. Some automakerts try to be at the forefront in developing safer vehicle technologies, including better airbag systems that significantly exceed the minimum requirements of the Federal Motor Vehicle Safety Standards.

Airbags are marvelous safety devices that will continue to save many lives, of adults and children, in collision accidents. The serious concerns about some airbag systems causing severe to fatal injuries to children and to shorter drivers must be expeditiously addressed and corrected.

So-called "smarter" airbags systems, many with features discussed in this paper, could and should have been implemented many years ago. They should now receive the highest attention by the auto manufacturers, the airbag system manufacturers, and the National Highway Traffic Safety Administration.

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Technical Session 6

Data Collection, Analysis, and Linkage

Chairperson: Claes Tingvall, Swedish National Road Administration, Sweden

AIR BAG CRASH INVESTIGATIONS

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ABSTRACT

The performance of occupant protection systems, especially air bags, is of high interest to the National Highway Traffic Safety Administration (NHTSA). Since 1972, the NHTSA has operated a Special Crash Investigations (SCI) program which provides the agency with the flexibility to acquire detailed engineering information quickly on high visibility traffic crashes of special interest. The SCI collects in-depth crash data on new and rapidly changing technologies in real world crashes. The NHTSA established the National Automotive Sampling System (NASS) in 1979 to provide a nationally representative sample of motor vehicle crashes, injuries, and deaths on our nations highways. A component of the NASS, the Crashworthiness Data System (CDS), collects statistical crash data on crashes involving passenger cars, light trucks and vans to help government scientists and engineers analyze motor vehicle crashes and resulting injuries. The NHTSA uses the data collected in these programs to evaluate rulemaking actions. The data are also used by the automotive industry and other organizations to evaluate the performance of motor vehicle occupant protection systems such as air bags.

This paper presents information from NHTSA's SCI and NASS CDS programs concerning crash investigations on air bag equipped vehicles. The paper's focus is providing information on data collection and findings in the NHTSA sponsored air bag crash investigations. Topics include: air bag related severe injuries and fatalities for belted and unbelted children, adults, adult females 157 centimeters (62 inches) or less in height, and pregnant women.

BACKGROUND

The NHTSA performs research and develops safety programs and standards in an effort to reduce the toll of deaths, injuries, and property damage from traffic crashes. Field investigations on crashes with an air bag deployment conducted in the NASS and the SCI programs under the auspices of the National Center for Statistics and Analysis (NCSA) play a vital role by providing data relative to real world events. The basic objective of NCSA's crash investigation and analysis of air bag deployments include the documentation of crash circumstances, the identification of injury mechanisms, the evaluation of safety countermeasure effectiveness, and the early detection of design and functional problems relative to air bags and vehicle occupants.

The NASS was established to collect a nationally representative statistical sample of motor vehicle safety data for the NHTSA. The NASS CDS is comprised of 24 data collection sites, called Primary Sampling Units (PSUs). The NASS data are collected by highly trained data collectors. The data collection follows a systematic format, including interviews, and scene and vehicle inspections.

The SCI program was established to collect detailed in-depth data on specific crashes of interest to the NHTSA. SCI cases are an anecdotal data set used to examine and evaluate the latest safety systems in real world crashes. The SCI data are used by NHTSA, automobile manufacturers, research engineers and scientists to explore ways to reduce the risks associated with motor vehicle crashes. In the SCI program, professional crash investigators perform an extensive examination of the vehicles and scene during which they secure and analyze the evidence necessary to reconstruct the pre-crash, at-crash and post-crash events.

The investigators follow up their on-site investigations by interviewing crash victims and other involved parties and by reviewing medical records to determine the nature, cause, and severity of the injuries. Each investigation provides extensive information about pertinent pre-crash, crash, and post-crash events involving the occupants, vehicles, rescue procedures, and environmental factors that may have contributed to the event's occurrence and/or resulting severity. Included in each report are analyses and determinations of occupant kinematics and vehicle dynamics.

The SCI program investigated all crashes reported to NHTSA for the early air bag vehicles. However, due to the rapid growth in the number of air bag equipped vehicles present in the marketplace in 1990 and thereafter, the SCI program shifted from investigating all air bag vehicle crashes to investigating special interest cases. These cases involve such issues as air bag related serious and fatal injuries, interaction between air bags and child safety seats, air bag non-deployment crashes, inadvertent air bag deployments, front right passenger air bag performance, side air bag performance, depowered air bag systems and air bag success stories. These SCI air bag cases have been utilized by the agency and the automotive safety community to acquire knowledge in real world performance of new and emerging air bag systems and have been instrumental in influencing subsequent second and third generation improvements to these new air bag technologies.

AIR BAG VARIABLE ENHANCEMENTS

The air bag related data variables coded in the NASS CDS and SCI have been modified extensively to collect more detailed information on occupant protection systems. Prior to 1991 both air bags and automatic belts were intermingled as passive restraint variables. In 1991, to collect more detailed information, the passive restraint variables were divided into subsets of automatic belts and air bags. Fourteen air bag related variables were added in the 1995 data collection year, including: air bag type, location, failures, previous deployments, replacement, service/maintenance, deployment status, specific deployment event, specific deployment speed change, damage, tethering, venting and all injuries related to the air bag deployment. In addition, the cover flap geometry, location and its relationship to injuries are also documented.

Additional air bag information became available in January 1997, with the introduction of the electronic data collection system (EDCS). The expanded data collection provides the ability to collect detailed information on the number of air bags per seating position. In addition, each specific air bag deployment is linked with detailed information on the crash event including: the event sequence number, Collision Deformation Classification (CDC), and crash severity indicator. These enhancements allow researchers to study multiple side and front air bag system deployments by sequence and severity.

A new variable was added to identify the class of air bag. The variable will identify whether the air bag system is pre-1998, depowered, or whether the vehicle is equipped with an advanced air bag system.

ELECTRONIC DATA COLLECTION SYSTEM (EDCS)

The EDCS is a paperless data collection system introduced into the NASS CDS and SCI for data collection year 1997. The investigators use pen-based computers in NASS, notebook computers in SCI, and digital cameras to collect field data in an electronic format. The field data are collected electronically on the pen based and notebook computers and then transferred via a wide area network for quality assurance to either the NASS CDS Zone Centers or from the SCI teams to NHTSA.

The SCI data will contain a complete automated variable set compatible with the NASS CDS. This will allow for clinical and statistical analysis on specific areas in air bag research.

The completed cases are stored in an electronic format and will be available in multiple formats including a hard copy print out, CD ROM, or by access through the Internet.

CONFIRMED AIR BAG FATALITIES

NHTSA has made an exhaustive effort through the SCI program to locate, document and confirm air bag deployment related life threatening and fatal injuries.

In October 1996, NHTSA began publishing summary tables for each confirmed air bag related fatality and seriously injured person on the first and fifteenth of each month. Beginning in December 1997, the tables are published during the first week of the month. These summary tables contain basic information about air bag deployment related serious injuries and fatalities sustained in minor, low and moderate severity crashes by:

(1) infants in rear facing child safety seats (RFCSS);
(2) children not in RFCSS;
(3) adult drivers; and
(4) adult passengers.

Serious injury has been defined as a level sufficient to be a threat to life. The injuries that are considered a threat to life have a significant effect on mortality rather than just a high Abbreviated Injury Scale (AIS). For example, a broken neck, while a significant threat to life is only an AIS-2.

Minor crashes include speed changes of 16 KMPH (10 MPH) or less, low is a range greater than 16 KMPH (10 MPH) to 29 KMPH (18 MPH), moderate speed changes are in the range greater than 29 KMPH (18 MPH) but less than or equal to 39 KMPH (24 MPH).

NHTSA has defined children as occupants 12 years of age and under. NHTSA recommends that no children be placed in a seating position equipped with a front deploying air bag. Children should always be properly restrained in a rear facing child safety seat (RFCSS) that is correctly secured in the vehicle until they reach at least one year of age and weight at least 9 kilograms (20 lbs). Children over one year of age and weighing more than 9 kilograms (20 lbs) but less than 18 kilograms (40 lbs) should ride in a forward facing child safety seat (FFCSS). Children that have outgrown their forward facing child seats or harnesses should ride in booster seats until adult safety belts fit them properly. A proper fit is when the lap belt stays low and flat across the hips without riding up over the stomach and the shoulder belt does not cross the face or front of the neck.

In an effort to create as close to a census as possible, the Fatality Analysis Reporting System (FARS) was queried for possible cases. All crashes that met a pre-determined criteria were then evaluated to determine if there was any potential to suspect the air bag may have been a contributing factor. A number of additional driver and child cases were identified and investigated. In addition, NHTSA asked the motor vehicle manufacturers to identify any and all cases they believed involved a potential air bag related fatality. These cases were reviewed and evaluated. In all but two cases, these were either under investigation or had been investigated by the SCI program. The SCI continues to monitor the FARS, NASS, law enforcement community and media for potential cases.

The SCI has confirmed, as of March 1, 1998, 94 air bag related fatalities as noted in Figure 1. Fifty four of the 94 air bag related fatalities were children. Forty-one were children not in a rear facing child safety seat (RFCSS), 13 were infants in rear facing child safety seats. There have been 36 adult driver and 4 adult front right passenger fatalities.

Air Bag Related Fatalities

As of March 1, 1998

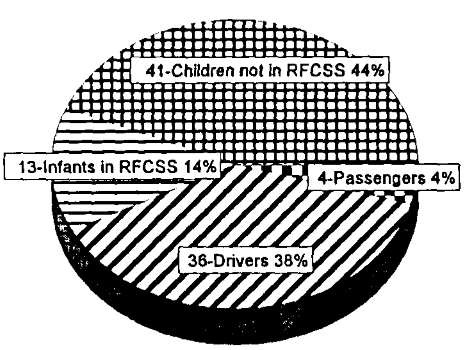

Figure 1. Percentage of Air Bag Related Fatalities.

CHILDREN CONFIRMED AS AIR BAG RELATED FATALITIES

There have been 10 cases with a child fatality in which the RFCSS was correctly secured to the vehicle with the child correctly secured in the child safety seat (see Figure 2). However, the RFCSS was secured in a seated position in which a front right passenger air bag deployed. In all 10 of these cases the air bag was the injury mechanism.

Children With Air Bag Related Fatalities

As of March 1, 1998

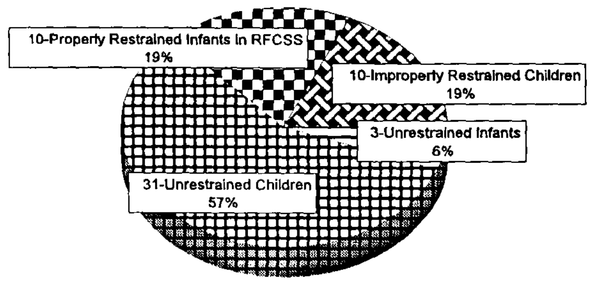

Figure 2. Children with Air Bag Related Fatalities.

Thirty four of the children were not restrained, while ten were improperly restrained. Of the 34 unrestrained (see Figure 3), seven children were being held in the lap of the right front occupant. Three of the seven children were infants in rear facing child safety seats being held on the lap of the right front passenger. Twenty seven children were not wearing the available lap and shoulder belts.

Unrestrained Children With Air Bag Related Fatalities

As of March 1, 1998

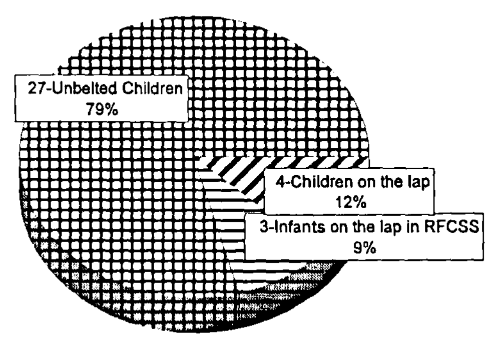

Figure 3. Unrestrained Children with Air Bag Related Fatalities.

Ten children were improperly restrained. Four children were wearing only the lap portion of the lap and shoulder belt. One child was belted with the lap and shoulder belt, but was leaning forward in the path of the deploying air bag. Three children were belted, however, the proper restraint for their physical dimensions is a child safety seat. Two children were restrained in forward facing child safety seats improperly secured to the vehicle.

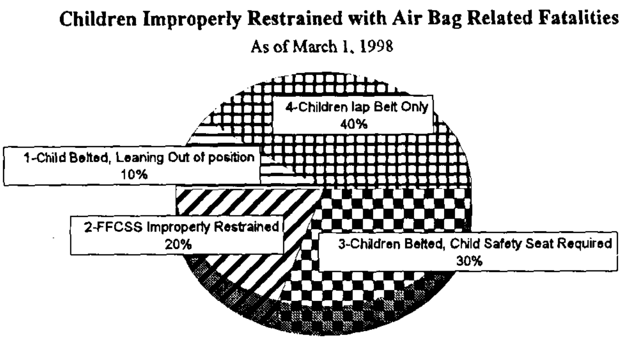

Figure 4. Children Improperly Restrained with Air Bag Related Fatalities.

NASS CDS AIR BAG INVESTIGATIONS

The NASS CDS has collected data on 3,058 crashes with air bag deployments from 1988 to 1996. Currently the NASS has 24 CDS teams with 60 field data collectors investigating an expected yield of 5,000 cases per year. As noted in Figure 5, the number of air bag deployment cases has increased year to year.

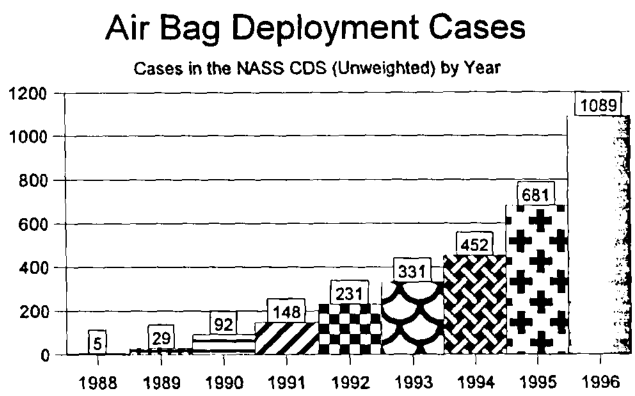

Figure 5. The number of air bag deployment cases represented by unweighted counts in NASS CDS.

The 3,058 NASS CDS cases, when weighted, represent 1,135,457 crashes with air bag deployments (Figure

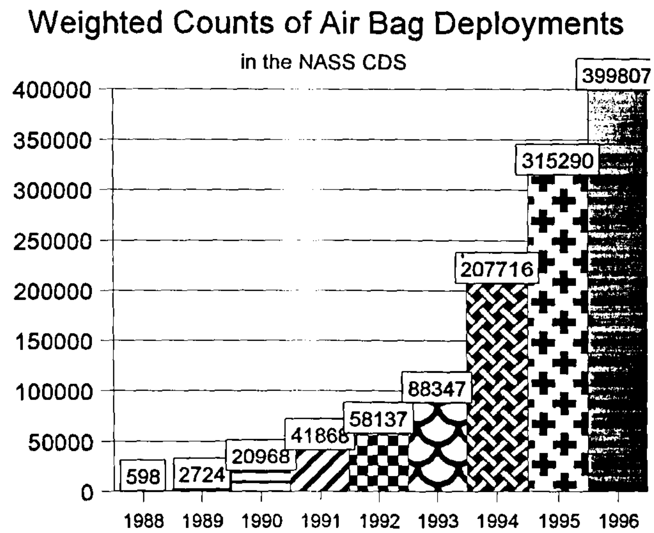

Figure 6. The number of air bag deployment cases represented by weighted counts in NASS CDS.

6).

In the unweighted (1988 to 1996) NASS CDS there are 34 children, 12 years old or less, seated in the front right occupant position where the air bag deployed with minor (AIS-1) or no injury. When the weighting factor is applied, these 34 children represent 11,783 occupants.

In the NASS CDS data collection year 1996, there were a number of cases of special interest involving children and air bag related injuries. Two children were seriously injured by a deploying air bag, while in a third case a child received minor injuries from a side air bag.

The first 1996 case involved a head-on crash which resulted in critical head injuries to a 3 year old front right child passenger of a 1995 Ford Escort. The Ford Escort was equipped with automatic shoulder restraints with manual lap belts and dual driver and passenger side air bags which deployed during the crash. The front right passenger of the Escort was a 3 year old male with a height of 107 cm (42") and weight of 15 kg (32 lbs.), seated in a forward position and restrained by the manual lap belt system. The motorized shoulder belt webbing was positioned behind the back of the forward facing child passenger. A booster seat was positioned in the rear seat area of the Escort, however, the child restraint was not in use at the time of the crash. The child responded to the frontal impact force by initiating a forward trajectory into the path of the deploying passenger side air bag. Based on the severity of his injuries, the child passenger was probably out of position in a forward direction with his head exposed to the inflating passenger side air bag. His involvement with the deploying passenger side air bag resulted in multiple soft tissue injuries of the scalp which included a right frontal/parietal contusion, a right scalp abrasion over the right ear, a left temporal laceration , and a contusion of the right earlobe. Internal air bag induced head injuries included cerebral edema (AIS-3), subarachnoid hemorrhage, and a diffuse axonal shear injury, with extreme loss of consciousness and non-responsiveness to pain . These injuries suggest an acceleration of the head from exposure to the inflating air bag. The child occupant came to rest on the right seat cushion of the Escort with his upper body and head slumped over the center console area of the vehicle. The child was transported to a pediatric hospital where he was admitted for a period of 28 days for evaluation and treatment of his injuries. He was discharged as an out-patient to a rehabilitation facility for occupational and physical therapy for motor function deficits.

The second 1996 NASS CDS case involved the front of a 1995 Plymouth Voyager minivan that impacted the left side of a 1990 Eagle Talon. The front right occupant was a six year old male, 132 centimeters (52 inches) tall and weighing 25 kilograms (55 pounds). This passenger was not wearing the available lap and shoulder belt. The unrestrained child responded forward during the pre-crash braking and contacted the front right passenger instrument panel and air bag cover flap. At impact the front passenger air bag deployed. The leading edge of the air bag cover flap and air bag contacted the occupant from the neck to the upper lip. The air bag contact produced severe abrasions from the neck to the upper lip. The inflating air bag contact also resulted in a subluxation of vertebrae C-2 over C-3 with spinal cord injury and a resulting quadriplegia. The child passenger was thrown in an upward motion and contacted the roof and rotated landing face down in the front right seat with his head against the front right door. The passenger was hospitalized until February, 1997 when he was transferred to a rehabilition institute.

The third 1996 case involved a 3-year-old male, 91 centimeters (36 inches) tall and weighing 14.5 kilograms (32 pounds), not using the available lap and shoulder belts who was sitting in the front right passenger seat of a 1997 BMW 528i. The BMW was equipped with driver and passenger side frontal air bags and supplemental side door air bags. Both front air bags and the right door air bag deployed as a result of the crash. At initial impact the front right occupant moved forward and to the right contacting the passenger side frontal air bag with no subsequent injury. The vehicle then rotated clockwise and side slapped the other vehicle. The side slap consequently deployed the right side door air bag. The child was contacted by the deploying air bag cover which is hinged at the bottom. The child sustained minor lacerations/contusions/avulsions to the right facial area from the deploying right side door air bag cover.

The NASS CDS recorded its first two child fatalities in 1997. The first crash involved a 2 year old male who was fatality injured when the front of his vehicle stuck the rear of another vehicle in a low speed impact. The child was seated on the lap of the front right seat passenger. Both occupants were unrestrained. As the deploying air bag inflated it expanded under his chin and jaw. The contact resulted in an abrasion across the chin and jaw that was approximately 1.75" wide. The contact to the top of the inflating air bag forced the head of the occupant upwards and the boy sustained a fracture/dislocation of the C1 and C2 vertebrae with a complete cord transection at the C1 level.

The second case was a three vehicle front to back chain reaction crash. A 3-month-old male was seated in a rear facing child seat (RFCSS) which was in the lap of the front right 17 year old female occupant. The child was not strapped to the child seat, nor was the child seat strapped to the vehicle in any way. The child seat was being held sideways so that the child would have been facing the driver.

The front of the case vehicle struck the rear of another vehicle. The case vehicle sustained a delta V of 26 km/h (16 MPH). At impact both air bags deployed. There were a total of 4 unbelted occupants injured in the case vehicle. The driver sustained contusions to the chest and the hand. The front right occupant sustained an abrasion to the left cornea. The rear seat middle occupant sustained a facial abrasion. The infant in the front right position sustained numerous skull fractures bilaterally with associated subdural and subarachnoid hemorrhage and cerebral edema.

Upon vehicle braking, the front right occupant moved forward and leaned her upper torso over the infant seat in a protective maneuver. This pre-impact occupant movement placed the front right occupant and the infant seat in a closer proximity to the instrument panel. The infant seat pitched laterally and moved forward due to this pre-impact occupant movement.

At impact, the front right seated occupants moved forward. The front right seat back was also being heavily loaded by a rear seated occupant. The infant seat impacted the instrument panel (right side) and the glove box door as evidenced by a straight edged vertical white mark left residually. This impact occurred simultaneously with the air bag deployment. Although the air bag made significant contact with the infant seat, there was some underriding effect with the infant seat-air bag interaction. The lack of frontal lobe injuries suggest that the child's head sustained forces from either side. The combination of air bag forces in conjunction with the instrument panel loading account for the numerous injuries sustained to the right side and parietal regions of the child's head. The left side (head) injuries are likely due to the front right seated occupant loading the infant seat with her torso.

The only NASS CDS driver fatality listed in SCI monthly counts occurred in data collection year 1996. The crash involved a 1995 Ford Escort that had multiple impact events with another vehicle, a stop sign, and a small diameter tree.

The driver of the Escort was a 79 year old male with a reported height of 175.3 cm (69.0") and weight of 81.6 kg (180 lbs.). He was restrained by the automatic 2-point shoulder belt webbing and the manual lap belt. The seat track was adjusted to a forward third track position. The initial right side impact sequence moved him laterally to the right and forward. The belt systems restrained the driver from contact with interior components and prevented him from contact injury. The minor secondary side slap configuration did not displace the driver to the right. He would have initiated a rebound trajectory to the left and was probably in an upright position as the front right corner area of the vehicle impacted the stop sign. Although the impact with the stop sign was minor, it displaced the driver forward. The inertia activated belts relaxed during the post-impact travel and locked at impact with the sign. The movement of the driver within the vehicle could have resulted in spool-out of the shoulder belt webbing which allowed him to move forward within close proximity to the steering wheel. As the vehicle impacted the small diameter tree, the driver air bag deployed.

The deploying driver's side air bag contacted the chest of the driver as he moved forward in response to the frontal impact with the tree. He subsequently loaded the belt webbing, however, his loading of the shoulder belt webbing was minimal due to the air bag expansion against his chest. As a result of the driver's involvement with the deploying air bag, he sustained multiple bilateral rib fractures with contusions over the hila of both lungs, a fractured sternum at the second intercostal space, a 1 cm laceration of the myocardium over the anterior surface, and a perforation (laceration) of the pericardium with 250 ml of blood . In addition to the internal injuries attributed to the air bag, the driver sustained numerous soft tissue injuries that were associated with air bag deployment. These soft tissue injuries included ecchymosis of the dorsum of the right wrist from probable contact with the instrument panel as the air bag expanded against his forearm, a 6 cm diameter contusion of the forehead from air bag contact, an abrasion of the left upper arm, an abrasion of the inferior nose, and two partial thickness linear abrasions of the right chin. The driver also sustained superficial lacerations of the left upper arm which were attributed to flying right side glass. There was no other mechanism visible within the interior of the vehicle to support the superficial lacerations.

His loading force against the shoulder belt webbing resulted in oblique linear abrasions that extended across the chest from the left shoulder to the right upper chest. The autopsy report noted that the abrasion pattern was indicative of shoulder belt usage. The hospital medical report noted a contusion to the left upper chest area that probably overlapped the abraded area. The driver's abdominal loading of the manual lap belt webbing resulted in a contusion over the lower portion of the falciform ligament of the liver and a 3 cm laceration of the medial portion of the anterior right lobe of the liver, interiorly, up to 2 cm in depth which is surrounded by a crush exhibiting injury, 400 ml of blood in the peritoneal cavity, and hemorrhage in the omentum and mesentery. The driver was removed from the vehicle by paramedics and transported by ambulance to a local hospital where he died in the emergency room following arrival.

SPECIAL CRASH INVESTIGATIONS

The SCI program has performed 1,659 in-depth crash investigations on air bag equipped vehicles since its inception in 1972.

The SCI program has been tasked with tracking and reporting NHTSA's list of confirmed air bag related life threatening and fatal injury counts. The SCI program has been significantly expanded in order to perform an investigation of all air bag related life threatening or fatal injuries. As a result, there are a significant number of active investigations. Cases are not listed as confirmed until the crash severity, injury and injury mechanism have all been confirmed. In the majority of the cases the time from case assignment to confirmation is lengthy due to the procurement of the official medical reports.

CHILDREN IN AIR BAG DEPLOYMENTS

Table 1 is a listing of the case counts by year of children (occupants 12 years old and under) confirmed as fatally injured by a deploying air bag. While it appears that the number of confirmed cases is on a downward trend, this in fact may not be the case. As previously noted, there are a number of cases under active investigation.

Table 1
Children Confirmed as an Air Bag Related Fatal Injury by Year
As of March 1, 1998

YEAR	Children in RFCSS	Children NOT in RFCSS	TOTAL
1993	0	1	1
1994	0	5	5
1995	3	5	8
1996	6	17	23
1997	3	13	16
1998	1	0	1
TOTAL	13	41	54

In October 1993, the SCI confirmed the first known air bag deployment related child fatality of the 1990's. The crash involved a 1993 Volvo 850 GLT, four-door sedan that was involved in a minor front-to-rear impact sequence. As a result of the crash, the Volvo sustained an estimated velocity change of 12 KPH (7 mph) which was sufficient to deploy the front driver and passenger air bags.

The front right occupant of the vehicle was the driver's six year old daughter. She had a reported height of 112 cm (44") and weight of 23 kg (51 lbs.). The investigation determined that she was not restrained by the available lap and shoulder belts.

Based on the location and severity of the child passenger's injuries and the associated contact points within the vehicle, it was presumed that the child was in a normal seated position and rotated slightly to her right, exposing her front left side to the instrument panel. Immediately prior to impact, the driver applied a rapid braking force in an attempt to avoid the impending crash. Due to the brake induced deceleration, the child passenger moved forward from the seat and against the right instrument panel and passenger side air bag module assembly. As the child contacted the involved components, the frontal area of the case vehicle impacted the rear of the stopped other vehicle which resulted in deployment of the driver and passenger air bags.

As the passenger side air bag deployed, the left lower edge of the module cover flap contacted her arm as the flap began to open in an upward direction. The initial contact resulted in a 3 x 1 cm hematoma over the anterior arm fold at the left elbow and crepitation of the elbow. The deploying passenger side air bag subsequently expanded across the child's chest as she was positioned against the module assembly. The left lower edge of the flap contacted the inferior aspect of the child's chin. The flap continued up into the left anterior aspect of her chin and into the lips and left side of the mouth area. As a result, she sustained a 10 x 5 cm abrasion to the anterior and inferior aspects of the chin, a 4 x 1 cm hemorrhagic area to the upper and lower lips, and a 3 x 1.5 cm abrasion at the left lateral aspect of the mouth.

The upward rotation of the module cover flap and contact with the inferior aspect of the occupant's chin, in combination with deployment of the passenger side air bag, accelerated the child in both a vertical and rearward direction. As the child was thrust upward and rearward, the superior aspect of the child's head impacted the right side of the rear view mirror and compressed the mirror into the overhead map light area. The impact fractured the mirror glass and separated the mirror from its windshield header mount. The subsequent contact from the mirror into the map light area resulted in multiple black plastic transfers to the lenses and switches of the lights. As a result of the contact, the child sustained a 5 cm diameter hematoma over the superior sagittal suture line of the scalp, a 0.7 cm hematoma of the front right scalp, fine, diffuse, acute subarachnoid hemorrhage, acute contusions of the superior aspect of the left and right temporal lobes of the brain anteriorly, uncal and cerebular tonsillar herniation, acute contusion of the inferior aspect of the pons on the right, and pronounced brain swellings. At the hospital, the child was stabilized before being transported by helicopter to a children's hospital. She was maintained on life support until she died, approximately 41 hours after the crash.

The extension injury pattern noted in this case has been seen in the majority of the unrestrained children not in a RFCSS cases performed in the SCI. During pre-impact braking the child slides forward into the path of the deploying passenger side air bag. As the air bag deploys it wraps under the chin against the neck lifting the child's head. The result is usually a severe anterior neck abrasion pattern. The internal injuries to the children have included severe brain, brain stem, spinal column and skeletal neck injuries. The most severe air bag induced injuries have been complete decapitations.

In a more recent confirmed case, the front right 11 year old male passenger received a blunt force trauma from the deploying air bag. The front of the case vehicle impacted the back of a stopped vehicle, causing the case vehicle's driver and front right air bags to deploy. Immediately prior to the crash, the front right passenger was bending forward in the process of retrieving a tissue out of the drawer underneath the front right seat. The crash severity to the case vehicle (Figure 8) was low.

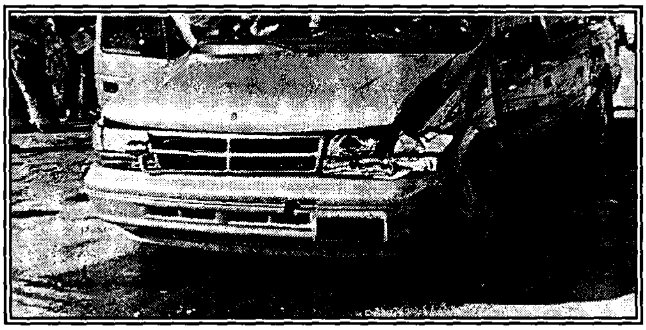

Figure 8 . Front of case vehicle's damage.

The front right passenger [152 centimeters and 32 kilograms (60 inches, 70 pounds)] was restrained by the three-point lap and shoulder belt. An inspection of the front right air bag revealed skin evidence on the bottom portion of the air bag. An inspection of the front right air bag module's cover flap revealed no evidence of contact. The front right passenger's use of his available seatbelt played no injury prevention role in the crash because of his close proximity to the front right air bag just prior to the crash.

The case vehicle's primary impact with the other vehicle thrust the front right passenger forward and slightly upward into the deploying air bag. The front right passenger's forward excursion put his head into the path of the deploying air bag. As the air bag deployed, the front passenger was raising up looking forward (i.e., sunglass lens has air bag material imprinted on it). The front right passenger sustained a non-anatomic brain injury, herniation of his brain stem (bilateral tonsillar and uncal), massive right subdural hematoma, massive cerebral edema, a subarachnoid hemorrhage, a contusion to the right lung with a small apical pneumothorax, an abrasion across the forehead, and a contusion to the upper chest. All these severe head injuries have been attributed to being struck by the deploying front right passenger air bag.

ADULTS CONFIRMED AS AIR BAG RELATED FATALITIES.

Since 1990, 40 adults (36 drivers and 4 passengers) have been confirmed as fatally injured by a deploying air bag (Table 2).

Table 2
Adults Confirmed as Fatally Injured by the Air Bag By Crash Year
As of March 1, 1998

YEAR	ADULT DRIVERS	ADULT PASSENGERS	TOTALS
1990	1	0	1
1991	4	0	4
1992	3	0	3
1993	4	0	4
1994	7	0	7
1995	4	0	4
1996	6	1	7
1997	7	3	10
1998	0	0	0
TOTAL	36	4	40

Thirty-five percent of the adult drivers and passengers in confirmed air bag related fatalities are 65 years of age or older. Only 5% are under the age of 25 years old.

Table 3
Adult Drivers and Passengers Confirmed as Air Bag Related Fatalities by Age of Occupant
As of March 1, 1998

Age in Years	Count	Percent
Under 25	2	5 %
26 to 39	8	20%
40 to 55	8	20%
56 to 64	8	20 %
Over 65	14	35 %

Fifty five percent of the drivers and passengers confirmed as an air bag related fatality were not belted.

Table 4
Adult Drivers and Passengers Confirmed as Air Bag Related Fatalities by Belt Usage
As of March 1, 1998

Belt Usage	Count	Percent
No Belts	22	55%
Yes, Lap & Shoulder	10	24%
Yes, Shoulder only	1	3%
Yes, Shoulder, Lap use	1	3%
Yes, Slumped forward	2	5%
Mis-used	1	3%
Unknown if used	3	7%

Thirteen of the thirty-six adult drivers are females 157 centimeters (62 inches) or less in height. The SCI has not confirmed any drivers (62 inches) or less centimeters in height in vehicles with a model year 1995 or newer. There may have been design changes and or the dissemination of information on sitting 10" from the air bag, that appear to have resulted in a decline in the number of female driver 157 centimeters (62 inches) or less in height, involvements. Both of the confirmed front right female 157 centimeters (62 inches) or less in height involve a passenger over 65 years of age that were not restrained by the available lap and shoulder belts.

Table 5
Females 157 Centimeters (62 inches) or Less in Height Fatally Injured by a Deploying Air Bag By Vehicle Model Year
As of March 1, 1998

YEAR	Drivers	Front Right Passengers	TOTALS
1989	1	0	1
1990	3	0	3
1991	4	0	4
1992	2	1	3
1993	0	0	0
1994	3	0	3
1995	0	1	0
1996	0	0	0
1997	0	0	0
1998	0	0	0
TOTAL	13	2	15

Of the 15 females 157 centimeters (62 inches) or less in height only 2 were using the available lap and shoulder belt correctly. Ten were noted as not restrained by the belts. In two cases it was not possible to determine belt usage. The remaining case is noted as belt mis-used.

Table 6
Females 157 Centimeters (62 inches) or Less in Height Fatally Injured by a Deploying Air Bag By Age
As of March 1, 1998

Age	Count	Percent
Under 25	2	13%
25 to 64	5	33%
Over 65	8	53%

The majority of the females 157 centimeters (62 inches) or less in height fatally injured by a deploying air bag were over 65 years of age. Of these 8 women, only one occupant was confirmed as wearing a lap and shoulder belt correctly.

PREGNANT DRIVERS AND AIR BAG DEPLOYMENTS

In October of 1994, a crash was investigated involving a women, in her thirty-fifth week of pregnancy, who was seriously injured as a result of a driver air bag deployment. The driver was a 29 year old female, 157 centimeters (62 inches) tall and having a weight of 74.8 kilograms (165 lbs). She was not wearing the available three point lap and shoulder restraint. The case vehicle was a 1992 Ford Taurus station wagon. The case vehicle was struck head-on by a pickup truck. At impact the driver's side air bag deployed in the case vehicle. The low impact speed resulted in a near threshold deployment. Due to the pre-impact braking and an extended time period between the point of contact and deployment, the driver's position had moved forward into the path of the deploying air bag. The cover flap and air bag struck the driver on the right side of her abdominal area which resulted in an abruption of the placenta.

The NASS CDS adjusted the occupant demographics on females in 1995 to include data on pregnancy. For 1995 through June of 1996, NASS reports 16 cases of pregnant women in seating positions involved in crashes in which the air bag deployed. None of these women experienced placenta abruption or uterine injuries.

These data do not suggest a conclusion that air bag deployment leads to an increased risk of injury and fatality to the mother or the unborn child. Of the 16 pregnant women, 13 were drivers and 3 were right front passengers. Nine used manual lap and shoulder belts, three used automatic belts and four were unbelted. These NASS CDS cases suggest that air bags are providing crash protection to pregnant females as well as to their unborn children.

"SAVED BY THE AIR BAG"

As of March 1998, the NHTSA estimates 2,536 drivers and 384 front right passengers lives have been saved by air bag deployments. The SCI has researched at least 46 crashes, where an occupant is reported to have been saved the air bag.

Figure 8. High speed frontal crash in which the driver was saved by the air bag.

One of the "saved-by-the-bag" crashes occurred when a law enforcement officer, driving his police cruiser, was impacted head-on by a pick up truck driving the wrong way on the expressway. The police car's Impact speed was about 60 miles per hour. The police vehicle pushed the pick up truck backwards more than 10 feet from the point of impact.

The law enforcement officer was wearing his lap and shoulder belt and was protected by the air bag. Although this vehicle sustained a speed change around 49 miles an hour, the driver received no life threatening injuries. His injuries included contusions and a right knee (patella) fracture .

Figure 9. The interior of the high speed frontal crash in which the driver was saved by the air bag.

SIDE AIR BAGS

The SCI has investigated 12 cases involving side air bag deployments. Ten of the twelve cases are side bag deployments related to a side impact. In all ten of these cases the air bag provided occupant protection.

The SCI has performed two investigations on 1998 vehicles equipped with an inflatable head protection system deployment. In both of these cases, the additional head protection reduced the potential for injury.

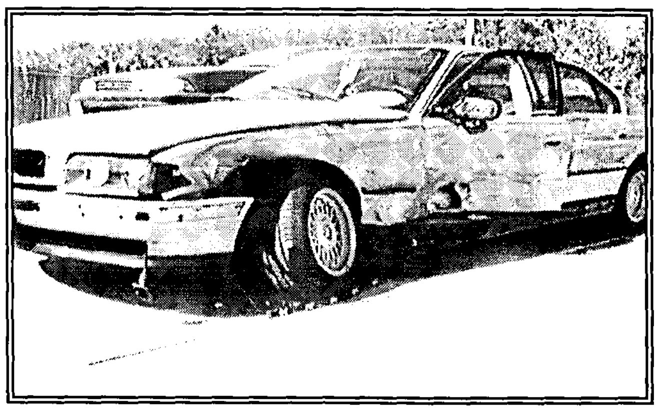

Figure 10 Exterior damage on a 1998 vehicle equipped an inflatable head protection system.

Two side air bag cases were performed as potential defects. The first of these was an inadvertent deployment in a vehicle equipped with a seat mounted air bag. A 15 year old male seated in the front right position placed his street hockey stick (plastic blade) with the blade forward of the

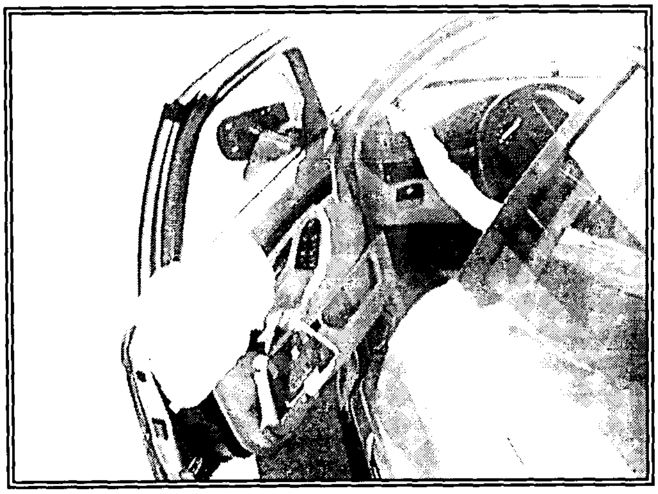

Figure 11. 1998 vehicle with deployment of the door mounted side air bag and the inflatable head protection system.

front seat with the handle extended along the right sill area and into the right rear area. The door was closed with sufficient force to drive the firing pin into percussion cap, deploying the seat mounted air bag. The handle was compressed into the seat at the location of the mechanical sensor located on the outboard aspect of the lower seat frame. The 15 year occupant sustained a severe contusion (AIS-1) on his right forearm.

The second case involved a 1998 vehicle struck in the driver's door. Our investigation determined the speed change to be slightly under the threshold for deployment. The manufacturer completed a diagnostic test on the system with no faults reported. The driver reported no injury.

DEPOWERED AIR BAGS

As of April 1998, the SCI has initiated 56 cases involving 1998 vehicles with a depowered air bag deployment. The SCI has screened over 325 police crash reports involving 1998 vehicles. From October 1997 to January 1998 the SCI was selecting any case with a depowered air bag deployment. In an effort to focus the depowered investigations toward cases of interest the agency established the following criteria for cases selected after January 1998:

- A child seated in a position where a depowered air bag has deployed.
- The crash was severe (Delta V > 24 MPH).
- When a vehicle has driver and passenger in seat positions protected by a depowered air bag.
- When an injured driver or passenger are in a seat position protected by a depowered air bag and transported to a medical facility for treatment

In FY1998, the SCI anticipates initiating field investigations on approximately 100 crashes in this category.

CONCLUSIONS

In the majority of frontal crashes air bags are highly effective in reducing fatal injuries. As of March 1, 1998, NHTSA has estimated 2,920 lives saved by air bags.

NHTSA recommends that no children be placed in a seating position equipped with front deploying air bag. There have been 54 children confirmed as fatally injured by the deploying air bag. However, in the unweighted (1988 to 1996) NASS CDS there are 34 children, 12 years old or less, seated in the front right occupant position where the air bag deployed with minor (AIS-1) or no injury. When the weighting factor is applied these 34 children represent 11,783 occupants.

Most occupants fatally injured by deploying air bags are not restrained by the lap and shoulder belt, using it improperly or are out-of-position at the time of deployment.

Acknowledgment of thanks are due to Seymour Stern and Ruth Isenberg of the NHTSA and to the Calspan Corporation, Indiana University, and Dynamic Science SCI Teams.

AIR BAG CRASH INVESTIGATION DATA AVAILABILITY

The NHTSA has a number of methods in which the air bag crash data is distributed. The 1979 through 1996 NASS CDS electronic files can be obtained by contacting the following:

Marjorie Saccoccio, DTS-44
DOT/Volpe National Transportation Systems Center
Kendall Square
Cambridge, MA 02142
USA

Summary tables are available to the public after the third business days of each month. Copies of the summary tables can be obtained by calling one of the following telephone numbers and requesting "Air Bag Fatality Reports for Special Crash Investigations" or by visiting the SCI on the National Highway Traffic Safety Administration's (NHTSA) Internet web site.

Toll Free 800-934-8517
Local Number 202-366-4198
SCI on NHTSA's Internet Web Site
http://www.nhtsa.dot.gov/people/ncsa/sci.html

Copies of completed hard copy NASS and SCI reports listed as available on the summary tables can be obtained from the hard copy storage facility at the address below. The reports contains slides and/or photographs and accordingly there is a cost associated with reproduction of the crash report.

Lyndra Marshall
Zimmerman Associates, Inc.
1815 North Fort Myer Drive
Suite 100
Arlington, VA 22209
USA

Completed SCI reports can be reviewed at the hard copy storage facility. There is a nominal cost for case retrieval and handling.

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PEDESTRIAN INJURY—ANALYSIS OF THE PCDS FIELD COLLISION DATA

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Paper Number 98-S6-O-04

ABSTRACT

The National Highway Traffic Safety Administration (NHTSA) has initiated the Pedestrian Crash Data Study (PCDS) to provide detailed information regarding vehicle/pedestrian crashes. The PCDS was implemented to focus on pedestrian crashes occurring after 1994, involving vehicle model years 1990 and later. NHTSA had previously conducted the Pedestrian Injury Causation Study (PICS) which focused on crashes that occurred between 1977 and 1980. However, vehicle designs have changed dramatically since that time, necessitating a new evaluation of pedestrian collisions with current vehicle models.

The PCDS study concentrates on several aspects of the pedestrian crash data including those proposed by the ESV/IHRA Project Pedestrian Safety Accident Survey Procedure (May, 1997) and several areas of the PICS study. The data used in the study was taken from pedestrians involved in frontal vehicle crashes in six major United States cities. The cases may involve more than one pedestrian but excludes persons operating motor-driven cycles or bicycles. Correlation and evaluation of the data will be based on age, impact speed, injured body regions and parts, and injuring vehicle regions and parts. A thorough comparison will be made between the PICS and PCDS results to evaluate the correlation between changes in vehicle geometry and the severity and location of injuries.

INTRODUCTION:

In 1994, there were approximately 40,700 traffic fatalities in the United States with a societal cost of over 150.5 billion dollars. In 1995, the number of fatalities increased by 2.7 percent to 41,798. For children between the ages of five and nine, more than one third of child traffic fatalities are pedestrians. According to the U.S. Department of Transportation's Traffic Safety Facts for 1996, 82,000 pedestrians were injured and 5,412 fatally injured in traffic crashes. Although this represents a 20% decline in pedestrian fatalities since 1984, the financial and emotional burdens associated with pedestrian crashes are substantial and cannot be overlooked.

NHTSA's implementation of the Pedestrian Injury Causation Study (PICS) program in the late 1970's was aimed at enhancing pedestrian safety and alleviating economic burdens as well as suffering and disabilities imposed on individuals as a result of pedestrian crashes. The study was conducted by evaluating almost 2,000 cases that were collected and reviewed by investigators in five U.S. cities. Trends and averages were used to evaluate areas of concern and initiate change in order to alleviate the number and severity of pedestrian crashes. One area of interest that resulted from the PICS study was the investigation into vehicle pedestrian interaction. Vehicle geometries were studied to identify pedestrian contact sources as well as injury severity caused by the contact.

Since the late 1970's, cars have "downsized" to accommodate demands for fuel economy, for instance hoods tend to be shorter and more sloped. There is also an increasing number of light truck and vans along with the introduction of front wheel drive on most types of vehicles. In addition, the vehicle materials have changed to make them lighter and safer. These changes prompted a new study, the Pedestrian Crash Data Study (PCDS) to evaluate vehicles manufactured in the 1990's and to assess the impact of geometrical changes and their relationship to the injuries inflicted onto the pedestrian. The following paper contains several areas in pedestrian research including a comparative analysis of the PICS study and the PCDS study, results from the PCDS study, and conclusions. (Isenberg et. al.)

METHODS

PICS/PCDS Program Comparison

The objectives set forth in the PICS and the PCDS programs are very similar. Both studies examine the factors that contribute to pedestrian injuries including their relationship to vehicle design. The PCDS study allows for an additional analysis of vehicle design changes over the past decade and its influence on injury profiles by focusing on changes in injury profiles. The study focuses on changes in injury severity and injury sources, with respect to vehicle changes since the collection of the PICS data.

The PCDS and PICS studies acquired the information through crash surveys by an investigation team, police reports, medical records and interviews with the pedestrian, driver and witnesses to the crash.

The data collection for the studies were very similar and only differed slightly in the criteria set forth for data collection. The PICS study included all fatalities in case collection but excluded pick-up trucks and vans greater than 6000 lbs. and sport utility vehicles (due to their non-existence at the time of the data collection) from the vehicle distribution. The PCDS study had a slightly different case collection profile. Fatalities were not a mandatory case collection and all vehicles were included in the study with a model year of 1990 or later. The pedestrian's first contact with the vehicle must have been forward of the top of the A-pillar and must have been the vehicle's only impact. Cyclists and pedestrians sitting or lying in the roadway were excluded from both studies.

The PICS data was collected over a 30 month period in five major United States cities: Buffalo, Palo Alto, Los Angeles, San Antonio and Washington D.C. Almost 2,000 cases were collected and the data was coded and recorded. Investigators for the PCDS study documented the information from six major U.S. cities: Fort Lauderdale FL., Dallas TX., Buffalo, NY, San Antonio, TX, Chicago IL., and Seattle WA. Almost 300 cases were available for this analysis although documentation will continue to achieve a goal of 900-1000 cases for evaluation.

Initial documentation for the PCDS crash data was required within 24 hours after the crash occurred. Some follow-up investigation was required to obtain additional information not available at the time of the collision (hospital stay, days of work missed, etc.). In addition to the coded information, the crash scene and the vehicle damage were recorded on videotape. After all of the necessary information was acquired, the final report was reviewed and recorded in the PCDS database.

The primary discrepancy in the PICS and PCDS data comparison exists in the methods used to assess injuries. The PICS study utilized two methods of injury assessment. The Occupant Injury Classification (OIC) System was used to describe injuries while the Association for the Advancement of Automotive Medicine (AAAM) Abbreviated Injury Scale (AIS) 1976 manual was used to assess the injury severity. The PCDS study used the AAAM AIS 1990 manual to indicate injury type and injury severity. The AIS 1990 introduced a more specific description of the injury and the possibility of different AIS values depending on the severity (for example, extreme blood loss is assigned a higher AIS value than the same injury with minimal blood loss).

The AIS values range from zero to six. Their description is as follows: AIS=0 "No Injury", AIS=1 "Minor Injury", AIS=2 "Moderate Injury", AIS=3 "Serious Injury", AIS=4 "Severe Injury", AIS=5 "Critical Injury", AIS=6 "Maximum Injury" and AIS=7,9 "Unknown."

The AIS codes will be used throughout the report along with the Maximum AIS (MAIS) to evaluate and summarize pedestrian injuries.

RESULTS

The following section contains several areas of pedestrian analysis. The first section discusses the differences between the PICS and PCDS data. The second section concentrates on the PCDS data only including a brief fatality analysis.

PICS/PCDS Data Comparison

Vehicle – Since the PICS study, improvements have been made to decrease the number of unknown variables through a more thorough data acquisition and coding system. The PCDS data coding resulted in less "unknown" or "other" classifications due to an increase of event selections in many categories. This incongruity will be reflected in some of the comparisons. For example, 22% of the PICS vehicle distribution were unidentified. In contrast, all vehicles were identified in the PCDS study. The changes that have occurred since the PICS study were in the redevelopment of the vehicle coding system. The NASS pedestrian coding manual for the PCDS study contains a code for every make and model vehicle manufactured for use in the United States. This helped eliminate the "other" and "unknown" category often needed in the PICS data.

Automobiles (passenger cars) were the most frequent vehicles in each study. The PCDS distribution included two additional categories that were not included in the PICS study. Since the 1970's, minivans and sport utilities have been introduced and made up approximately 20% of 1996's vehicle sales. The additional distribution may account for the decrease in the frequency of passenger cars since the PICS study. Eight-six percent of the PICS and 69% of the PCDS vehicles involved in the pedestrian studies were passenger cars.

The effect of vehicle geometry changes on injury patterns to the pedestrian has become a concern over the past decade. In addition to the introduction of mini-vans and sport utility vehicles to the types of vehicles driven, vehicle profiles have changed. Figure 1 is a schematic example that shows a comparison between a vehicle from

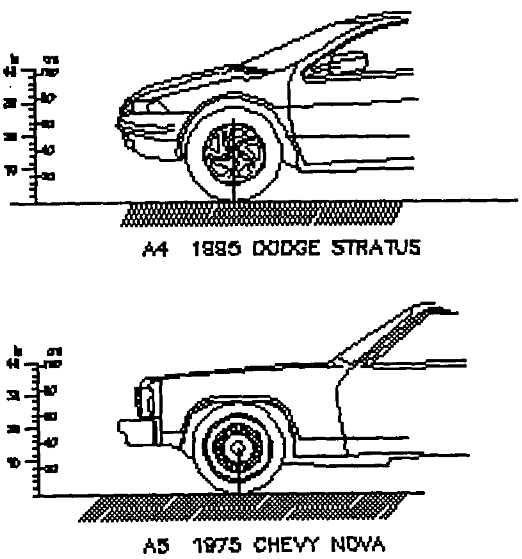

Figure 1. Vehicle profile changes.

1995 compared to a vehicle from 1975. Older vehicles tend to have a well-defined hood edge, vertical front end and horizontal hood as opposed to the sloped, curved features of newer vehicles.

Several aspects of the vehicle geometry have varied over the years. The vehicles in the PCDS study have changed significantly since the PICS study as follows: average curb weight (decreased 10.8%), the hood height (decreased 26.4%) and the hood length (decreased 26.3%). Another significant change in vehicle design is reflected in the bumper height, bumper lead and lead angles. The bumper heights have decreased approximately 16.5% as cars have taken on the lower profile designs decreasing bumper lead by 22%, hood length by 26% and lead angle by 8.7%. However, the PICS lead angle data had an exceptionally high number of unknowns (almost 50%) leaving the distribution notably subjective.

In conclusion, the types of vehicles involved in pedestrian crashes have not changed dramatically over the past decade, although vehicle designs have changed significantly. These changes have occurred to produce lighter, smaller cars to accommodate lower fuel consumption. In addition to the geometry changes, new materials have been utilized for weight, durability and occupant protection issues. This may also contribute to changes in pedestrian injuries caused by vehicle contact.

Pedestrian -- The following data represents profiles for the PICS and PCDS pedestrians including an injury assessment analysis.

The average pedestrian profile has changed since the PICS study. Average age (33 years old) has increased by 7 years while the height (161 cm) and weight (63 kg) have also increased by 16 cm and 15 kg. respectively. MAIS average values (approximately =2) have not changed significantly although ISS average value (14.6) has increased by approximately six points.

A more detailed look at the pedestrian age distribution can be seen in Figure 2. The PICS data has an evident peak at 6-10 years of age and tends to remain low for 40-75 years of age. The mean for the PICS age was 26 years old with a standard deviation of 23.3. The PCDS data has a minor peak at 6-10 years of age and again at 26-30 years of age. The mean PCDS age was 33 years old with a standard deviation of 21. The PCDS distribution remains higher than the PICS distribution between the ages of 20-55 years of age. It must be noted that the PCDS cases were collected during the case investigators' daytime working hours. Although the case can be recorded anytime within 24 hours of the crash, this may contribute to the lower frequency of child impacts because of their attendance at school during the majority of working business hours. It was found that among 184 PCDS cases involving children 18 years of age and under, 85% occurred between Monday and Friday, 16% occurred between six and nine AM and 50% occurred between three and ten PM.

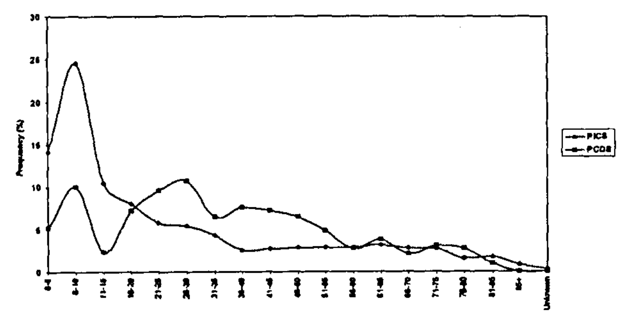

Figure 2. Age distribution.

According to the national statistics from 1996, over two thirds of the pedestrian fatalities were male. The PCDS data is not representative of this statistic or past historical data because it reflects an exact split between the number of males and females involved in pedestrian crashes as well as the number of male and female fatalities related to pedestrian crashes. The PICS study, on the other hand, indicates that males were more frequently involved in pedestrian crashes than females.

The pedestrian motion reflects the pedestrians actions prior to impact, such as running, jogging, stopped or other. The pedestrian motion distributions in the two studies were very similar. The majority of the pedestrians were either walking slowly across the road or running/jogging across the street before impact. As a result, both studies reflect a majority of all of the pedestrians standing (. PICS-97.8%, PCDS-99.0%) as opposed to kneeling, bending, crouching, sitting etc.

An avoidance maneuver is defined as any action or reaction the pedestrian took to avoid contact with the vehicle before impact. The distributions between the studies were very similar with approximately 60% of the pedestrians with no avoidance maneuver. The remaining pedestrian avoidance maneuvers were distributed among a variety of remaining maneuvers such as "braced against" (second most predominant at 8%), "jumped", "accelerated", "turned toward", "turned away", "accelerated" or "stopped".

Pedestrian orientation is the pedestrian's body, or chest orientation prior to impact relative to the vehicle. The orientations were very similar between the two studies. The most predominant body orientations were the left and right sides toward the vehicle. Side impacts accounted for approximately 70% of the total pedestrian crashes.

Vehicle-pedestrian interaction, as seen in Figure 3, describes the pedestrian's body projection after impact. The chart reflects how pedestrians in the PCDS study were more frequently carried by the vehicle, while pedestrians in the PICS were more often thrown forward or knocked to the pavement. In the PCDS study, the vehicle carried over 40% of the pedestrians after impact and had a secondary interaction of being knocked to the pavement (25%). On the other hand, the PICS study reflects that approximately 45% of the pedestrians were knocked to the pavement with a secondary interaction of being thrown in front of the vehicle (23%). Pedestrians carried by the vehicle accounted for less than 10% of the pedestrian interaction.

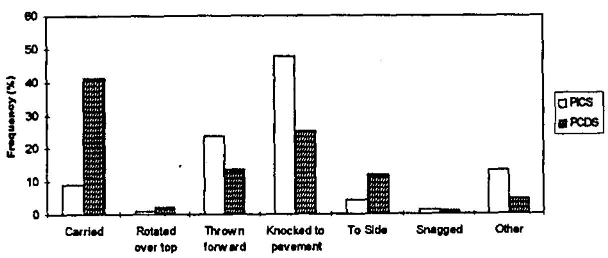

Figure 3. Vehicle pedestrian interaction.

This resultant interaction also relates to the injury source frequency distribution discussed in the injury section of this paper. Pedestrians in the PCDS study were more frequently carried by the vehicle and experienced injuries from the windshield, hood surface and the A-pillars. The pedestrians in the PICS were subject to injuries caused by the vehicle front end components (front fender, grille) and the environment corresponding to the interaction of being knocked to the pavement or thrown forward from the vehicle.

<u>Injuries</u> – Both studies reflected similar driver avoidance maneuvers with 40% of the drivers unable to perform any avoidance maneuver while 43% applied the brakes before contact with the pedestrian. Two peaks in the vehicle impact speed were prevalent in both the PICS and PCDS data. The first peak in the data occurred between 6-10 mph and 16-20 mph. In both studies, approximately 85% of the pedestrian impacts occurred at or below 35 mph and approximately 50% occurred below 15 mph.

Table 1 identifies sources that have caused AIS ≥ 2 injury. This was done in order to eliminate injuries that

Table 1.
Injury Sources for AIS ≥ Injuries

Injury Sources: AIS=2+Injuries				
Source	**PICS**		**PCDS**	
	N	**%**	**N**	**%**
Front bumper/valance	350	15.2	173	25.5
Front fender	161	7.0	13	1.9
Front grille/headlight	196	8.5	21	3.1
Hoof surface	280	12.1	98	14.4
Hood edge/trim/face	198	8.6	76	11.2
Cowl/windshield wiper mounts	9	0.4	23	3.4
Windshield glazing/trim	88	3.8	114	16.8
A-pillar	11	0.5	54	8.0
Wheels/tires	104	4.5	20	2.9
Side components	25	1.1	1	0.1
Rear components	12	0.5		
Non-contact	133	5.8	8	1.2
Environment	363	15.7	58	8.5
Unknown/other	375	16.3	20	2.9
Total	2305		679	

were very minor, such as small abrasions. The elimination of AIS 1 injuries resulted in a significant change in the distribution. The most evident change was the drastic decrease in the number of injuries caused by the environment. With the inclusion of AIS 1 injuries the environment was responsible for 37.6% and 24.7% (PICS, and PCDS respectively) while the elimination of the AIS 1 injuries decreased the environmental incidence by 21.9 and 16.2 percentage points, respectively. The remaining injury sources were distributed in a similar manor to the inclusion to AIS 1 injuries with the exception of the front bumper/valance in the PCDS study, which increased by 10.4%.

When focusing on injuries with an AIS 2 or greater, there is a significant difference in the injury trends between the two studies. There tends to be an increase in frequency of injuries caused by the front-end top components since the PICS study. The increase in frequency occurs with the bumper/valance, windshield glazing and trim, A-pillar and the hood and its components. There was a decrease in injuries caused by the environment, front fender, front grille/headlight, side components and non-contact sources.

The injury sources tend to correlate with the pedestrian and vehicle interaction where the pedestrian tended to be knocked to the pavement in the PICS data, correlating with a higher number of environment, non-contact and front end components. Similarly, the PCDS pedestrians were more often carried by the vehicle corresponding to the increase in bumper, windshield and hood components as predominant injury sources.

The body region injury distribution is given in Figure 4 and shows that the lower extremity represents the most frequently injured region. Approximately one third of all injuries were inflicted on the lower extremities followed by a high occurrence to the head, neck, face and upper extremities. The PCDS data showed considerable reductions in thoracic, abdominal, and pelvic injuries compared to the PICS study.

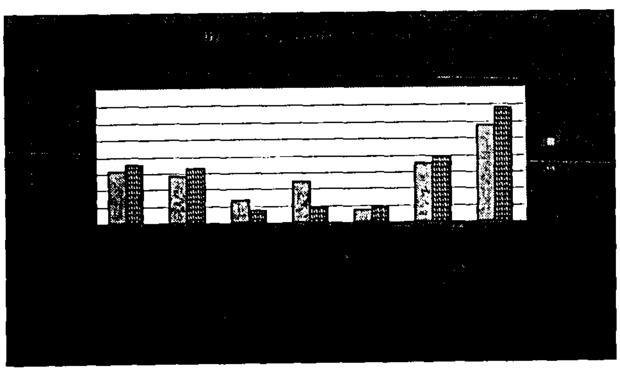

Figure 4. Injury by body region.

PICS/PCDS CONCLUSIONS

The analysis of pedestrian collisions has been performed over the years to identify areas of concern in pedestrian safety and determine changes in trends and patterns from previous studies. This section concentrated on trends from current vehicles sampled in the current PCDS study in comparison with the PICS study from the late 1970's and early 1980's. While there are many similarities, there have also been several significant changes among vehicle and pedestrians since the PICS study.

From the pedestrians sampled in both studies, the motions and maneuvers of both the vehicle and pedestrians were very similar. The most predominant pedestrian motion was either walking or jogging with their left or right side oriented toward the vehicle. The majority of the pedestrians did not attempt any avoidance maneuver (such as bracing against the vehicle, turning toward the vehicle, etc.). There is also a similarity in the driver's reactions. The majority of the drivers were not able to perform an avoidance maneuver to avoid hitting the pedestrian. The impact speed distributions were also very similar between the two studies with 85% of the impacts occurring below 35 miles per hour and approximately 50% occurring below 15 miles per hour.

In addition to the PICS and PCDS similarities, considerable changes have occurred in vehicle geometry and pedestrian profiles since the PICS study. Both studies were predominantly comprised of automobiles, but the average measurements indicate that the vehicles have changed in both size and shape. Current vehicle geometry has changed as much as 26% since the PICS study, including a decrease in bumper height, hood height, bumper lead, hood length and lead angle. In addition to the change in vehicle geometry, the average pedestrian in the PCDS study tended to be approximately 8 years older, taller and heavier.

Both of these influences (vehicle and pedestrian changes) have contributed to the changes in the pedestrian interaction with the vehicle and resultant injury patterns. The most evident difference between the two studies is the vehicle pedestrian interaction. In the PICS study, approximately 50% of the pedestrians were knocked to the pavement, while the vehicle carried 40% of the PCDS pedestrians.

The injury sources and resultant bodily injuries inflicted on the pedestrian seem to have a direct correlation with the vehicle interaction profile. In the PICS study the environment, front fender, front grille/headlight, side components and non-contact sources were more frequent than in the PCDS study. Also more prevalent in the PICS study were injuries to the thorax, abdomen and pelvis. In the PCDS study where pedestrians were often carried by the

the PCDS study where pedestrians were often carried by the vehicle, there was an increase in injuries caused by the bumper/valance, windshield, hood and A-pillars. Injuries to the head, neck, back, upper extremities and lower extremities were more frequent than in the PICS study.

PCDS Data

The following section will reveal information exclusively from the PCDS study that has not been discussed in the previous section. This section will include information on the vehicle, pedestrian and injuries from the cases sampled in addition to a fatality analysis.

Vehicle – Vehicles involved in the PCDS data included any vehicle equipped with original manufacturers' equipment only. Some vehicles involved were 1988, 1989 and 1997 model years, although the predominant model years were 1990-1996. There are currently 292 cases collected in the PCDS database, but collection is expected to continue until 900-1000 cases have been compiled.

The vehicles in the PCDS data were categorized in several different classes as shown in Figure 5. Utility vehicles make up almost ten percent of the total vehicles while vans and pick-ups make up about 10%-15%. The remaining 65% were passenger cars categorized by sub-compact, compact, intermediate, full size and largest according to wheel base width.

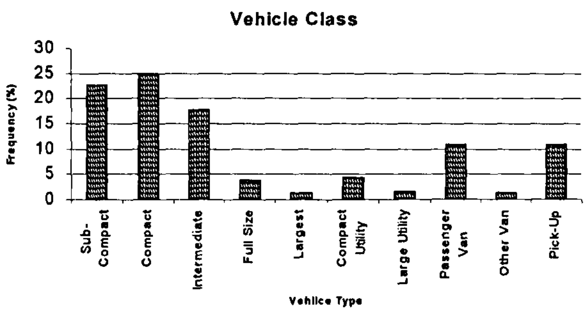

Figure 5. Vehicle Class

Injuries – The most predominant pedestrian body orientation before impact was with the left side (40%) and right side (32%) of the body toward the vehicle. Although turning accounts for 30% of the vehicle movement before hitting a pedestrian, almost half of the side impacts were while the vehicle was in a straight path of motion. Over 50% of the vehicles were traveling at speeds less than 30 miles an hour before the impact occurred. At impact, over 50% of the vehicles were traveling at speeds less than 20 miles per hour.

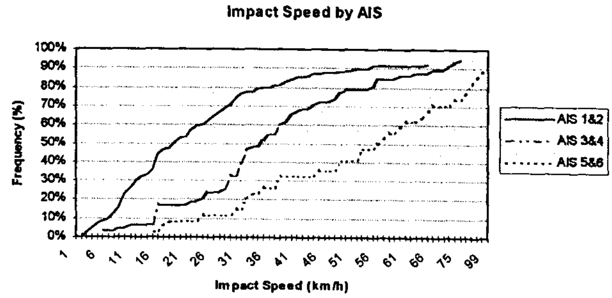

Figure 6. Impact speed by AIS.

One area of concern is how speed effects the severity of injury inflicted on the pedestrian. Figure 6 shows the relationship between vehicle velocity and AIS. The line representing AIS 1 and 2 rises sharply in the beginning because of the high frequency of injuries at lower speed, and begins to taper off at speeds above 35 km/h (22 mph). The AIS 3 and 4 injury frequency is below 30% until 30 km/h (19 mph), but rises to 70% by 45 km/h (28 mph). The AIS $\geq$ 5 injuries have few occurrances below 30 km/h (19 mph), with 30% being above 65 km/h.

A new area of pedestrian safety concern has been introduced with the recent popularity of vans, trucks and sport utility vehicles. As presented in the PICS/PCDS comparison section, approximately 70% of all vehicles involved in pedestrian crashes were automobiles. Figure 7 indicates the type of vehicle involved in the pedestrian crashes according to MAIS. The distribution indicates that automobiles are the most frequently involved vehicles among MAIS values equal to one through five. On the other hand, an MAIS equal to six is the most severe injury, most often resulting in a fatality. This MAIS=6 category was dominated by vans and pick-up trucks.

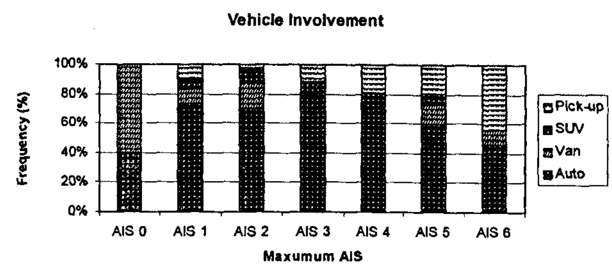

Figure 7. Vehicle involvement.

Figure 8 summarizes injuries by body area and AIS severity. The most often injured body regions were the upper and lower extremities, followed by the head and face. The neck, thorax, abdomen and spine had a lower incident of common injury, but were often the most serious. The injury regions are also categorized by AIS. The lower extremities are most often an AIS=1 injury followed by an

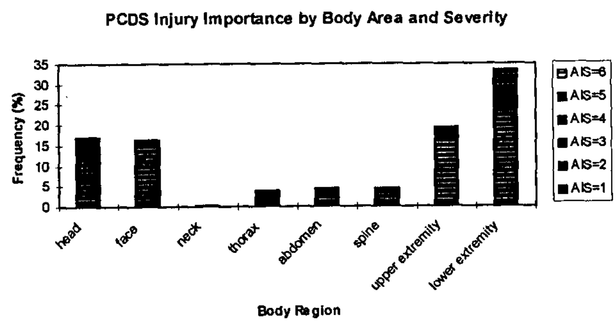

Figure 8. PCDS injury importance by body area and severity.

injuries. Most of the injuries are AIS=1 followed by AIS=2 and AIS=3. The head and the face also had very predominant injuries with an overall involvement of 17% and 16% respectively. Of those injuries, the face was comprised of mostly AIS=1 injuries. The head incurred more severe injuries with a significant involvement of all AIS values.

Fatalities – In 1996, traffic crashes were the cause of 41,907 fatalities in the United States. Approximately 13% (5,412) of all traffic fatalities were pedestrians, and over one fifth of all traffic fatalities under the age of 16 were pedestrians. This section contains results and information involving pedestrian fatalities only. Of the 292 PCDS cases, 28 resulted in a pedestrian fatality. NHTSA's Traffic Safety Facts for 1996 show that seven percent of police reported pedestrian crashes resulted in a fatality. According to the PCDS data, the fatalities are slightly over represented with an approximate fatality rate of ten percent.

Fatal age distribution differs slightly from the non-fatal distribution as shown in Table 2. The 1-12 year old age group represents children, 13-59 years old represents adults and 60 and above represents the elderly. In the fatality distribution the elderly are over represented by about 10%. The adult distribution is very similar and the child involvement is lower by approximately 8%.

Table 2.
Non-fatal/fatal Age Distribution

AGE GROUP	NON-FATAL % (N=263)	FATAL % (N=28)
1-12	19.0	10.7
13-59	69.2	67.9
60 +	11.8	21.4

The PCDS impact speed distribution for non-fatal and fatal crashes is represented in Figure 9. The majority of vehicles involved in non-fatal pedestrian crashes were at the lower end of the distribution, which tapered off at higher speeds. The frequency of pedestrian fatalities, according to the impact speed distribution, is more predominant at higher speeds where the two most predominant peaks are shifted by approximately 15-20 miles per hour. Over 40% of the fatalities occurred above 36-40 miles per hour, whereas only 7% of the total number of PCDS crashes occur within this range.

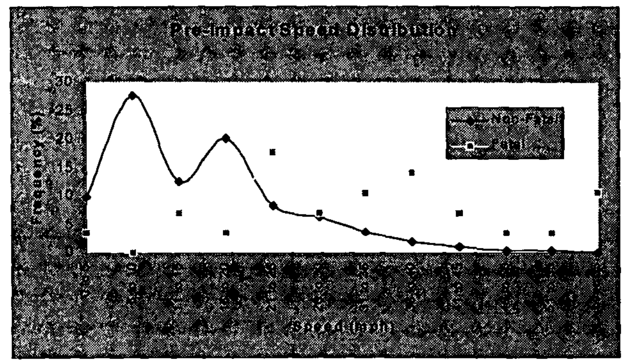

Figure 9. Impact speed distribution.

Pedestrians involved in fatal crashes had very similar body orientation as those involved in non-fatal accidents. Fatal and non-fatal had 70% pedestrians with left or right side toward the vehicle at impact; 65% had non-avoidance action. The main motion was walking or running with 80% fatal and 87% non-fatal crossing the road straight or in a diagonal manor.

The additional cases are needed prior to an assessment of how well the PCDS data represents the U.S. pedestrian collisions.

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UPDATE ON THE PEDESTRIAN CRASH DATA STUDY

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Paper Number: 98-S6-O-05

ABSTRACT

In July 1994, a Pedestrian Crash Data Study (PCDS) was initiated within the United States to collect detailed crash reconstruction data on pedestrian crashes. Information on the first eighteen months of data collection was presented in a paper titled "Pedestrian Crash Data Study - An Interim Evaluation" at the ESV Conference held in June 1996. This paper will report on the continued progress and data collection efforts of the PCDS. It will report on the procedures implemented to sanitize the video recordings which are part of the data collection process for vehicle and scene documentation, and report on the continued successful implementation of the pedestrian contour gauge for the documentation of the pedestrian's contacts with the vehicle. Additional analyses of the pedestrian crash circumstances, including pre-crash, at crash, and injury consequences will also be discussed for 292 crashes.

BACKGROUND

In 1992, a need was identified for the National Highway Traffic Safety Administration (NHTSA) within the United States Department of Transportation to collect pedestrian crash data through the Crashworthiness Data System (CDS), a component of the National Automotive Sampling System (NASS), formerly known as the National Accident Sampling System. The detailed pedestrian crash data that NASS had collected prior to 1987, when the Crashworthiness Data System (CDS) was implemented, had become obsolete and current pedestrian crash data were needed to ensure that pedestrian crash analyses capabilities were consistent with real world crash events.

Data collection for the Pedestrian Crash Data Study (PCDS) began in July 1994, and as of March 1, 1998, over 500 pedestrian crashes have been or are under active investigation. However, due to the conversion of the NASS CDS to a fully electronic and automated data collection system in 1997 at the same PCDS sites, time and quality control constraints have prevented the construction of an analysis file containing all 500 crashes. Hence, this paper will report on the analyses of 292 crashes that are in the current analysis file.

The previously mentioned published paper can be referred to for further detail on the background of the Pedestrian Crash Data Study and prior pedestrian crash data collection efforts as part of the National Automotive Sampling System.

SIZE AND NATURE OF THE PROBLEM

During the last four years, pedestrian injuries have continued to decline, whereas, pedestrian fatalities remain about the same. In 1996, pedestrian-vehicle impacts resulted in 5,412 pedestrian fatalities and 82,000 pedestrians injured (see reference number 5). These figures are a slight decrease from 1995 when 5,584 pedestrians were killed and 86,000 were injured. Generally, since 1993, pedestrian fatalities have hovered about the 5,500 mark, whereas in terms of injuries, there has been a consistent and definite decrease from 94,000 injures in 1993 to 82,000 injuries in 1996. Passenger car, van, and light truck involvements account for nearly 86 percent of the pedestrian fatalities and for nearly 96 percent of the pedestrians injured. One pedestrian is killed by a motor vehicle every 97 minutes and injured every 6 minutes in the United States.

Data on pedestrian injuries from the 1982-1986 NASS data files, the last pedestrian data files available for analyses, show that approximately 40 percent of the pedestrian injuries resulted from contact with the vehicle, 32 percent resulted from contact with the ground and 26 percent of the injuries were from unknown contact sources. Data collected in the PCDS will be used to determine if newly designed vehicles are creating the same or different types of injury patterns since the mid-1980's. These data are needed to determine the types of injuries sustained and the contact mechanisms involved in pedestrian impacts with late model year vehicles.

SCOPE OF PEDESTRIAN CRASH DATA STUDY

The PCDS continues to be operational at the six sites that were selected because of the number of pedestrian crashes that occur at these locations. The sites selected to participate in the PCDS are: Chicago, Illinois; Buffalo, New York; Fort Lauderdale, Florida; Dallas, Texas; Seattle, Washington and, San Antonio, Texas.

A pedestrian is considered as any person who is on a trafficway or on a sidewalk or path contiguous with a trafficway, or on private property and who is in contact with the ground. Persons in or on a nonmotorist conveyance are not pedestrians and are excluded from this study.

For a crash to qualify for the Pedestrian Crash Data Study:

- The vehicle must be moving in a forward direction at the time of the impact.
- The vehicle must be a late-model-year passenger car, light truck or van. Late-model-year is defined as being manufactured in the last 5 years. It also includes non-late-model-year vehicles where the exterior design is the same as late-model-year-vehicles (e.g. Ford Taurus 1988 to 1994).
- The pedestrian may not be lying down or sitting.
- The striking portion of the vehicle's structure must be original equipment manufacturer (OEM) without previous damage and/or parts removed in the impact area.
- The pedestrian impacts are the vehicle's only impacts.
- The first point of contact between the vehicle and the pedestrian must be forward of the top of the A-pillar.

The Pedestrian Crash Data Study will collect data on 900 - 1000 crashes for clinical analysis. In 1994, 15 cases were initiated, 77 cases during 1995, 190 cases during 1996, 205 cases during 1997 and 13 cases for the first two months of 1998.

OPERATIONAL PROCEDURES

The data are collected through on-scene crash investigations (or within 24 hours) of pedestrian crashes involving late model year passenger cars, vans, and light trucks. If a vehicle or pedestrian can not be located and interviewed, or the vehicle damage measurements can not be obtained within 24 hours of the crash, the case is dropped from the study.

Police cooperation has been established at each site to conduct on-scene crash investigations or follow-ups within 24 hours. Notification of the crash is facilitated through a variety of media including the telephone and monitoring of police and emergency medical services radio frequencies.

If an investigation is conducted on-scene, the researcher notifies the police of their presence immediately upon arrival at the scene and proper investigation protocols are followed so as to ensure there is no interference or disruption to any police investigation. Once a determination is made that the case meets the selection criteria, the crash investigation commences.

DATA COLLECTION FORMS

Data are collected and automated on 144 different variables in the Pedestrian Crash Data Study. Environmental, human, and vehicle data are collected for all phases of the crash. As shown in Table 1, there are 24 variables in the pre-crash phase, 38 variables in the at-crash phase and 82 or more variables in the post crash phase.

Additionally, there are six variables that are derived on the analysis files as they are created, such

Table 1.
The Distribution of PCDS Forms by their Relationship to the Crash Events

Number of PCDS Variables by Event Type			
	Pre-Crash	At-Crash	Post-Crash
Environmental	11	11	0
Human	11	16	47*
Vehicle	2	11	35

* add 13 variables per injury

as the Maximum AIS (MAIS), Day of Week, and Injury Severity Score (ISS). A complete listing of the automated variables by the five primary data collection forms is included in the appendix to this paper.

The Accident Form collects data on the general characteristics of the event such as the time of day, the vehicle class, and the general area of damage for the vehicle involved.

The Pedestrian Assessment Form documents data on the characteristics of the pedestrian (age, sex, height, weight), their avoidance actions, orientation at impact, alcohol and drug presence, and the consequences of their injuries such as their treatment, hospital stay, and injury severity. Height measurements include ground to knee, hip, shoulder and overall height.

The Pedestrian Injury Form contains thirteen variables for **each** injury that is documented from official or unofficial records. Each injury is coded according to AIS90 injury descriptors with modifications for NASS CDS. In addition to the injury description, additional data collected for each injury include: the contact source of the injury; the striking profile; the type of damage; and the damage depth. Injuries are documented sequentially on the form by order of occurrence as determined during the reconstruction of the crash.

The General Vehicle Form contains vehicle make and model data, official record data for the driver, such as alcohol and drug information, pre-crash data as to vehicle movement, environmental data, and reconstruction data for determining impact speed.

The Vehicle Exterior Form contains pedestrian contact data for both front and side pedestrian contacts, front and side pedestrian vertical and wrap measurements, detailed hood measurements, material identifications, and vehicle dimensions. Non-automated data include: the scene diagram; the crash case summary form; and, interview forms for the pedestrian and driver.

UPDATE ON NEW DATA COLLECTION TECHNIQUES

The two new techniques implemented for this study in 1994 included the use of video cameras to quickly document the on-scene crash data and the development of a contour gauge to quickly and accurately measure pedestrian contacts on the vehicles.

During the last two years of data collection, not only has the Hi8 video camera proven to be an expedient and effective method to capture important data, but the technology has been developed to quickly and cost effectively sanitize these videos for future distribution without loss of the quality of information documented on them.

When the study was initiated, the Hi8 video camera was compared to 35mm single lens reflex cameras. The study showed that the video camera was capable of quickly capturing physical evidence during an on-scene investigation. In addition, the field researcher provided an audio description of the video image. Evidence generated in a pedestrian crash is often very minor and barely visible. The Hi8 video camera is ideal for documenting this type of evidence because it is capable of viewing detailed physical evidence on the pavement left from the pedestrian at the point of impact, or even a tiny thread of fabric left on the vehicle. The slide photography, traditionally done in NASS CDS, is not as efficient in capturing on-scene evidence as the video camera. The video camera is capable of filming thirty frames per second which enables data quality reviewers to freeze frames of captured evidence and to make accurate assessments of the data collected.

With Hi8 video selected as the medium, a structured guideline for video taping each case has also been developed. The accident scenes are video taped to show actual paths of the vehicle and the pedestrian along with audio descriptions which associate the evidence with a scaled reference in the environment. The vehicle is also documented in a video format where each contact made by the pedestrian is viewed with various angles, closeups, and finally referenced with the contour gauge.

Before data is made available for analysis, each case must be sanitized. Sanitization is the procedure used to remove all personal identifiers contained in a case. Identifiers found on vehicles include the license plate, VIN, registration and inspection tags, along with any company names or phone numbers that might be found on commercial vehicles. Since on-scene investigations are conducted, the faces of all officials (e.g., police and EMT) as well as the pedestrian must be concealed. Street signs that identify the location of the crash must also be masked. In addition, audio must be sanitized whenever names or other identifiers can be heard.

Nonlinear editing technology is used in the video sanitization process. Each Hi8 video tape is digitized through a high quality video capture board to maintain video quality. Once digitized, the entire image can be viewed, frame by frame. The video technician identifies and marks each segment of the tape that needs sanitization. A custom mask is fitted over all objects requiring sanitization. Special care is taken to ensure that the mask covers only the object being sanitized. An audio message is inserted on the video tape reporting whenever important physical information is covered in the sanitization process. This becomes necessary whenever a license plate or other identifying object is contacted by the pedestrian.

A moving mask must be created whenever the object to be sanitized moves. Moving masks are also required whenever the camera pans across a stationary object. To accomplish this, a mask must be moved into proper position frame by frame. The result is a moving mask that continuously conceals the object in question.

After all video segments have been sanitized, a disclaimer is inserted at the beginning of each video. The disclaimer states "The audio portion of this video tape is the express opinion of the field researcher as perceived at the time of taping. Since all pertinent data are not available to the researcher at the time of taping, conclusions made might not represent the final determinations made during the quality control process." Also inserted is the case number along with video running time. At the end of the video an "End of Tape" title page is inserted.

The next step is to record the entire sanitized video onto a new Hi8 tape. In addition, the sanitized video is recorded onto a Beta tape for long term storage and possible future creation of MPEG video, written to CD-ROM or DVD. The final step is to label each Hi8 tape with the year and PCDS case number.

The contour gauge was created to provide a frame of reference on the vehicle for verifying the accuracy of the measurements and to provide an efficient and uniform method to document the pedestrian contact evidence. In addition, it provides an opportunity to reapply the exact locations of contacts on similar vehicles for simulation of impacts.

The contour gauge consists of two scaled ribbons which create an isometric coordinate system which wraps to the shape of each vehicle. The first scaled ribbon begins on the ground, below the center of the front bumper, and wraps over the vehicle along the longitudinal center which creates the "X" axis. This "X" axis wrap scale also assists in referencing the wrap orientation of the pedestrian with the ground. The "Y" axis is then placed laterally across the hood, or windshield with some vans, and referenced with the front axle of the subject vehicle. Scaled contact markers are then placed on the vehicle to identify the evidence and measured within the coordinate system created by the contour gauge. More than one marker may be used to identify the evidence when long streaks or large swiping areas and dents occur.

The contour gauge has proven to be a reliable source for data documentation and has been developed for use in computer reconstructions or actual simulations and examinations of pedestrian interactions with vehicles.

DATA ANALYSIS

Data from 292 pedestrian crashes were analyzed for this update on the PCDS. All cases were single vehicle and single pedestrian events with an equal number of drivers and pedestrians involved.

Pedestrian Characteristics

Males and females were evenly distributed with a count of 186 (50%) each. Two of the females who were involved were reported to be pregnant (in their first trimester) at the time of the crash. However, both women received only minor injuries (AIS 1). In terms of age, there were no pedestrians under the age of three. Fifty-three (18%) of the pedestrians were between the ages of 3 and 12, while 29 (10%) were between the ages of 13 and 19. The vast majority, 183 pedestrians or 63%, were between the ages of 19 and 65, with an additional 26 (9%) over the age of sixty-five. There was one pedestrian whose age was unknown. Figure 1 shows the distribution of the pedestrians by their age groupings.

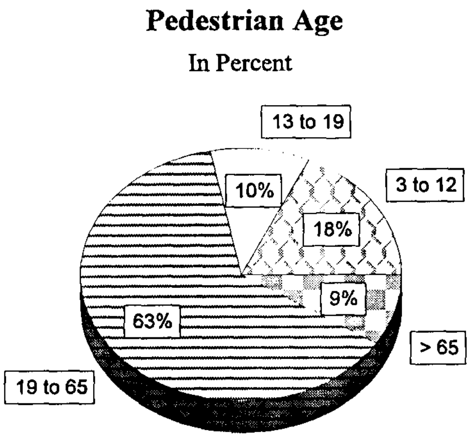

Figure 1. Percentage of involved pedestrians by age.

In regards to overall height, fifty-five (19%) pedestrians were 152 centimeters (5 feet) or shorter with the most predominant group 106 (36%) of pedestrians being between 153 and 168 cm (between 5' and 5' 6"). Eighty-one (28%) were between 169 and 183 cm (5'7" to 6 feet) and sixteen pedestrians (5%) were over 183 cm (six feet) tall. The height of the pedestrian appears to have some correlation to the Maximum AIS (MAIS) as seen in the Figure 2 below.

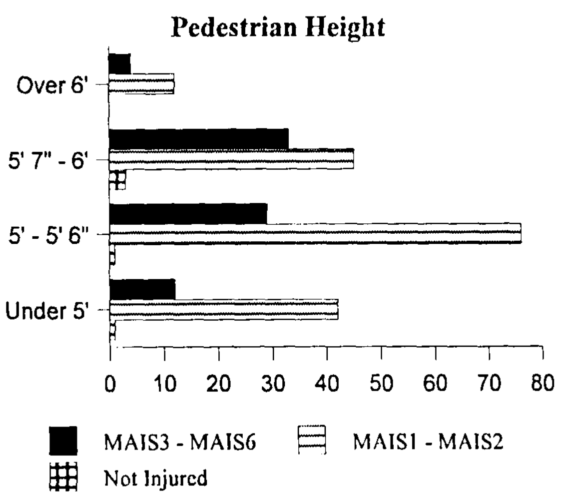

Figure 2. Distribution of MAIS by pedestrian height.

It appears from the population in the data base, that those individuals between 5'7" and 6' were more likely to receive a serious injury (MAIS3 - MAIS6) than any other population in the height distributions. This could be attributed to the likelihood of head contact on the vehicle's windshield or some other structure and could be worthy of further evaluation as more crashes are investigated and added to the data base.

Vehicle Characteristics

Figure 3 shows the distribution of the

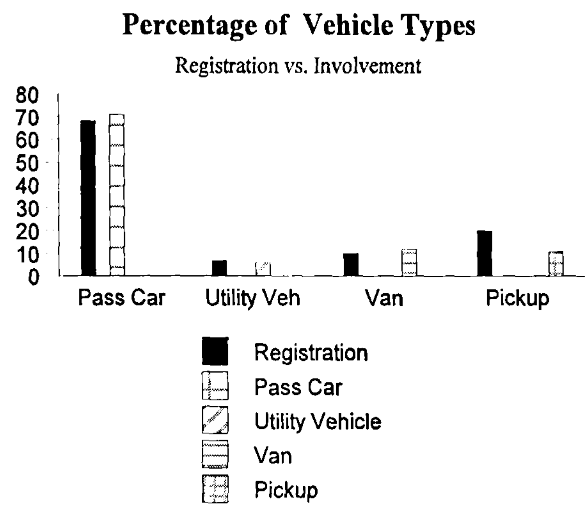

Figure 3. Percentage of vehicle types by registration and involvement.

vehicle types by overall registrations in the United States and their involvement in the PCDS.

Of the involved vehicles, 206 (71%) were passenger cars and 86 (29%) were other light vehicles, collectively referred to as light trucks (pickups), vans, and utility vehicles. This is nearly identical to the composition of vehicle registrations in the United States. However, within the "other" group, the mix of vehicles found in this study differs from registration data. The 18 utility vehicles in the study make up six percent of the data, closely matching the seven percent of registered vehicles. Overall, vans make up ten percent of registered vehicles, but 36 vehicles (12 percent) in the study were vans. Since the June 1996 Interim Evaluation, the population of registered minivans has increased

2 percentage points to 6% while full-size vans remained at 4%. In the present study, 9 percent of the vehicles were minivans, and 3 percent were full size vans. The remaining 32 vehicles (11 percent) were pickup trucks, which are 20 percent of registered vehicles. The present study differs from the registered vehicle fleet mainly by an over representation of minivans, and an under representation of pickup trucks.

Figure 4 shows the distribution of pedestrian injuries by vehicle type by crash involvement, involvement of vehicle type for all injuries and involvement of the vehicle types for serious injuries AIS3 - AIS6. There were a total of 2,180 injuries documented for the 292 pedestrians. Of these, 1,445 (66%) were from passenger cars, 323 (15%) were from pickup trucks, 164 (8%) were from utility vehicles and 248 (11%) were from vans.

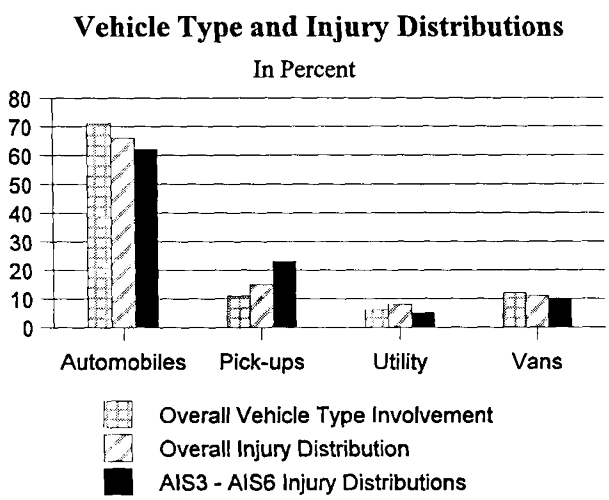

Figure 4. Percentage of vehicle types distributed by involvement and injury distributions.

When the serious injuries (AIS3 - AIS6) were examined the involvement by vehicle type changed significantly. There were 396 injuries coded at the AIS3 - AIS6 injury severity levels. Passenger cars accounted for 244 (62%), utility vehicles for 22 (5%), and vans for 39 injuries or 9%. However, pickup trucks accounted for 91 or 23% of the serious injuries which is far greater then their overall distribution of 11% in the crash population and their involvement in general injury causation.

Pre-Crash

Prior to the crash, the physical motions of the pedestrians indicated that 163 or 56% were walking, 11 or (4%) were not moving and the motions of 8 (2%) are not known. A significant number, 110 or 38%, of the pedestrians were running or jogging but it is not known if this is related to any type of intended physical exercise or activity.

In relation to the pedestrian's motion prior to any avoidance actions, 252 or 86% of the pedestrians were attempting to cross the roadway. This supports the fact that 227 (78%) of the pedestrians had their chest orientation either to the left or the right of the striking vehicle prior to the impact.

The vehicle driver's pre-crash attention to the driving task was reported as paying full attention for 224 (77%) crashes and distraction by other occupants or outside events accounted for 23 (8%) of the crash events. The driver's attention was described as other or unknown for the remaining crashes.

Prior to the critical event, 176 (60%) of the drivers indicated that the vehicle was moving straight. When a vehicle was involved in a turning maneuver, a pedestrian was more likely to be struck in a left turn 63 (22%) rather than a right turn 22 or 8%.

The critical crash event was reported as pedestrian in the roadway for 198 (68%) pedestrians. This would indicate that some of the vehicles had made their intended turns and then impacted the pedestrian. When examining the data, the number for the right turns 22 (8%) remains the same in relation to the pre-event movement and the critical crash event. However, the data for left turns, indicates that the vehicle made its turn and impacted the pedestrian after turning 51 (18%) and was moving forward.

Drivers made no avoidance maneuvers in 116 (40%) of the crashes. One hundred seventy-six (60%) of the drivers had the opportunity to attempt an avoidance maneuver. When a maneuver was undertaken, the drivers for 39 (13%) of the cases braked and also made a steering maneuver with about two thirds of them going to the left and one third to the right. The most likely avoidance maneuver consisted of braking only in 121 (43%) of the crashes. In these cases when only braking occurred, 74 had not brake lockup and 47 crashes did. When looking at MAIS levels for the vehicles that did and did not have lockup, there appears to be higher MAIS severity scores for the vehicles where brake lockup occurred. This appears in Figure 5 below. Data was also examined using impact speeds of less than and greater than 20MPH to see if this significance still

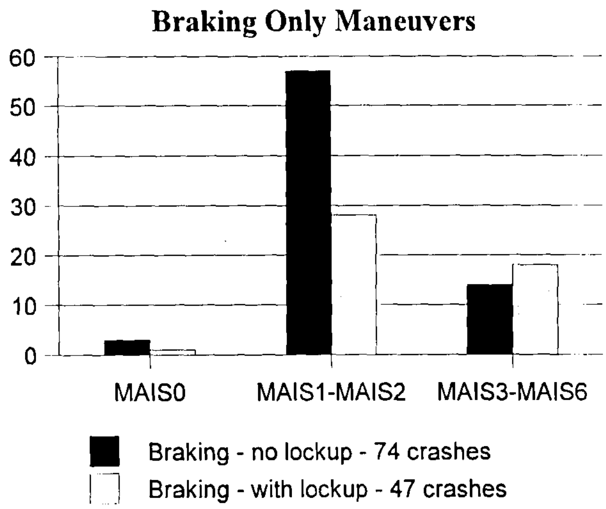

Figure 5. Distribution of vehicles that had braking only maneuvers.

existed. It appeared that even when impact speeds were taken into account there was an over representation of more serious crashes with brake lockups. As more crash data is collected, this will necessitate further examination in the future.

At Crash

One hundred seventy-one (59%) crashes were at or related to an intersection or driveway and the remaining were not. The weather was reported as being clear for 233 (80%) crashes, rain for 55 (19%) and snowing 4 (1%) of the crashes. However, wet roads accounted for 71 or 24% of the crashes. Sixty-two percent or 182 of the crashes occurred during daylight. The remaining were dark but lighted 73 or 25%, dark 14 or 5%, dusk and dawn 23 or 7%.

The variables describing the pedestrian's orientation at impact enables the examination of the pedestrian's body, as it interacts with the vehicle at impact. At various impact speeds the orientation of the pedestrian has contributed to the level of injury. The pedestrian is wrapped or carried by the vehicle in 120 (41%) of the cases. The pedestrian is knocked to the ground in 74 (25%) crashes, thrown in 40 (14%), shunted or pushed aside in 35 (12%), passed over in 7 (2%) and all other impact types account for the 16 (6%) remaining cases as noted in Figure 6.

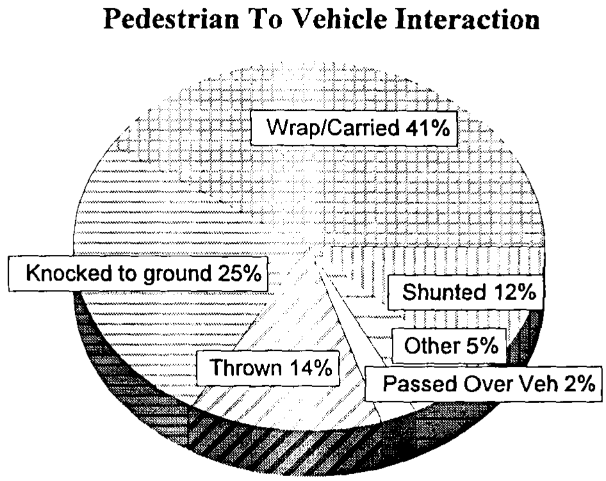

Figure 6. Percentage of crashes distributed by pedestrian to vehicle interaction.

The pedestrian's arm orientations at impact were almost evenly divided: 97 (33%) pedestrians impacted were holding something in their hands or arms, 89 (30%) were not holding anything, 74 (26%) had their arms extended, and the remaining 32 (11%) had their arms in an unknown or other manner The carrying of an object may contribute to or prevent an injury depending on the crash dynamics.

One pedestrian extending her arm while holding an umbrella received a fractured forearm when the leading hood edge of a sport utility vehicle struck her arm. If her arm had not been in this position it would not have been struck. A positive example of carrying an object was noted in a case with a child wearing a backpack. At impact she wrapped over the front hood of a vehicle with her back against the striking surface. Because her backpack absorbed most of the impact force, she received no significant injuries.

Figure 7 shows the distribution of impact speeds in the PCDS grouped in 15 KMPH (9 MPH) ranges . The impact speed is coded as a measure of severity in 271 of the 292 cases (93%). As previously mentioned the majority of the PCDS cases occur in urban areas with a high density of motor vehicle and

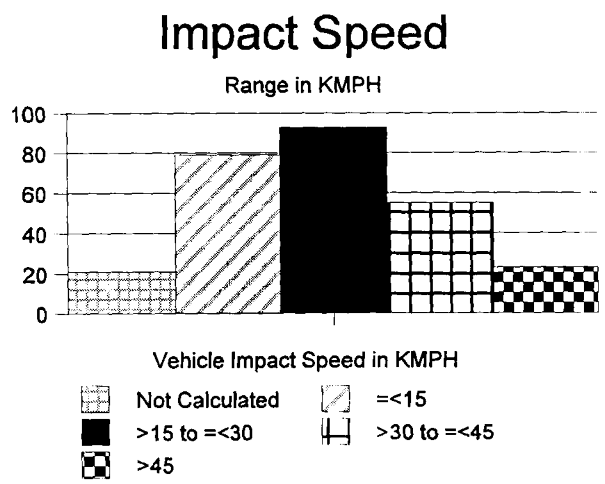

Figure 7. Number of crashes broken down by impact speed.

pedestrian traffic. As a result, the majority of the impact speeds include in the PCDS are in the 15 KMPH (9 MPH) to 45 KMPH (27 MPH) range.

The exterior of the vehicle that strikes the pedestrian is throughly documented, including 37 automated variables and detailed sketches of pedestrian contacts. The documentation is based on the plane of initial contact. The front plane contains data on 64 (86%) cases, while the side plane accounts for the remaining 10 (14%) cases.

Outcome vs. Injury

Of the 292 pedestrians involved in crashes, all but six pedestrians or 98% received some type of injury and 266 pedestrians or 91% received treatment at a medical facility. Only seven of the injured people did not receive any type of treatment for their injuries. Exactly half of those involved, 147 or 50% were treated at a trauma center and 104 or 36% were transported to a hospital for treatment. Although 102 pedestrians were hospitalized for their injuries, the number of days hospitalized is only known for 81 individuals. The average hospital stay for those 81 pedestrians who were hospitalized was 11 days.

Injury data were collected from both official and unofficial data sources (autopsy reports, hospital discharge summaries and emergency room reports, interview data, etc.) and coded to NASS injury coding protocols which are based upon AIS90. The AIS90 developed by the Association for the Advancement of Automotive Medicine is a systematic way to describe injuries by using a specific coded format. One major modification that NASS made to AIS90 was the inclusion of a single digit to account for the location or aspect of the injury on the body region (e.g. left leg, right arm, forehead, etc.) injured.

The overall distribution for Maximum AIS (MAIS), which is the highest single AIS code for a pedestrian with multiple injury levels, is shown in Figure 8 . The highest AIS severity sustained by any pedestrian in any crash was an AIS 6. Two hundred sixty-eight or 92% of the pedestrians involved in the crashes received more than one injury.

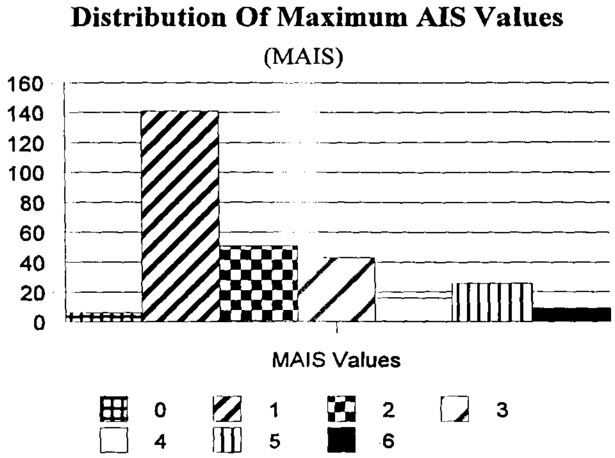

Figure 8. Number of crashes broken down by maximum AIS.

A total of 2,180 injuries were sustained by the 286 pedestrians that were injured. Lower extremity injuries accounted for 740 or 34% of the injuries followed by the upper extremities having 424 or 19% of the total injuries. The head and face were the next most frequent body regions injured having 370 (17%) and 359 (17%), respectively, of the injuries. The total injury distributions for all body regions are shown in Figure 9.

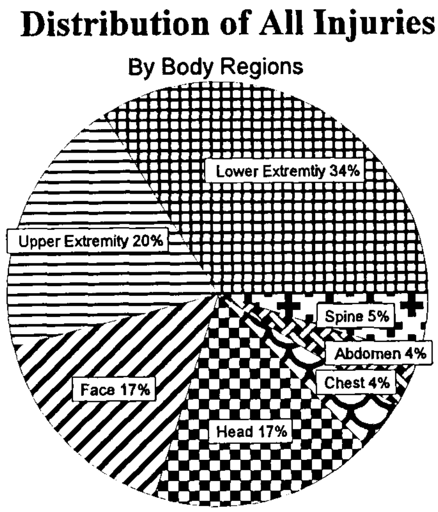

Figure 9. Percentage of all injuries distributed by body region.

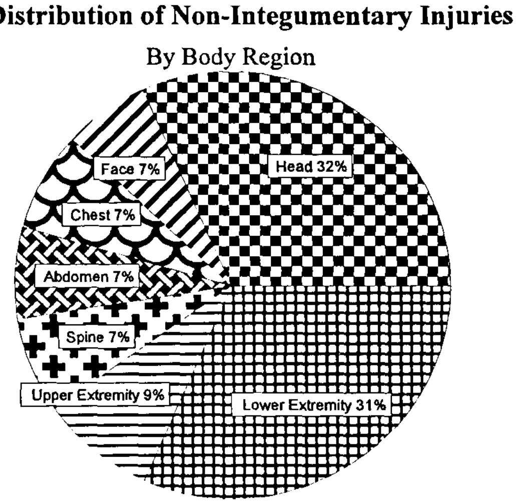

Figure 10. Percentage of all non-integumentary injuries by body region.

It is noted that overall injury distributions among body regions change when soft tissue or integumentary injuries are excluded from the total injury distributions. Distributions for the 767 non-integumentary injuries among body regions is shown in Figure 10. Lower extremity injuries remain the most frequent body region injured with 241 (31%) injuries. Of that number, 72% of the injuries were fractures to the lower extremity skeletal system. However, the head then represents 244 (31%) of the injuries, with the remaining injuries almost evenly divided among the remaining body regions. In regard to non-integumentary head injuries, it is noted that 29 injuries were skull fractures, 157 were injuries to the brain and 57 injuries involved loss of consciousness.

The 2,180 injuries that occurred actually represented 272 different types of injuries. Soft tissue injuries (AIS 1) accounted for 1,413 or 65% of the injuries and accounted for 43 of the different injury types by body region. Deleting these injuries due to their minor severity and outcome, the following is a listing of the five most frequent injuries that occurred along with the injury's count:

Injury	Count
Open Fx Tibial Shaft	34
Cerebrum - Subarachnoid Hemorrhage	33
Open Fx Lateral Malleous-Fibula	27
Fx Head/Neck/Shaft Fibula	22
Fx Femur Shaft	17

The wrap distance from the ground to where a head contact are shown in Figure 11. The ground to head contact is collected for both front and side planes. Previous studies have shown the head contact to be a significant source of injury. However, in the 236 front plane contacts, 110 (47%) had no head contact.

The data also show that 39% (93 of 236) of the cases have recorded a head wrap contact measurement to the vehicle long enough that the face or head contacted the hood or windshield. Sometimes these head contacts could result in no injuries, but this also clearly shows that, 39% of the time, the head or face did make contact with the vehicle. As noted in Table 2, the windshield accounted for 320 injuries, 26% of which were AIS 3-5. The hood surface was noted as the injury source in 206 injuries, with only 17% of hood surface injuries in the AIS 3-5 range.

Injuries are documented on the injury forms according to the sequence in which the body region contacted the vehicle or other injury component (e.g. ground) and there is no limit to the actual number of injuries that are coded for an individual. Lower extremity contacts accounted for 192 or 67% of the first injuries received for the 286 pedestrians that were injured. Other first contacts by body region included 38 (13%) contacts by the upper extremity, 20 (7%) contacts by the head and 20 (7%) contacts by the face. As the number of injury producing contacts increase, there is a reduction in the number of lower and upper

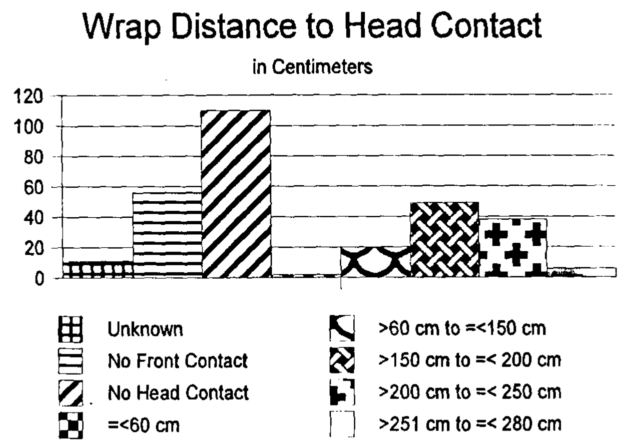

Figure 11. Number of crashes broken down by wrap distance to head contact.

extremity contacts and an increase in the number of contacts to the head and face. These data documents that head and facial injuries follow extremity injuries during the crash sequence.

Table 2.
Distribution of Contact Sources by AIS Levels

Contact Source by AIS Level			
Contact	AIS 1-2	AIS 3-5	Total
Front Bumper	236	75	311
Hood Edge	116	47	163
Reubfirced Hood	45	23	68
Front Grille	34	10	44
Front Header	12	9	21
Wheels	53	9	62
Side Mirrors	45	0	45
Other front	65	2	67
Wiper Blade	38	0	38
A1 Pillar	47	35	82
Hood Surface	170	36	206
Cowl Area	13	18	31
Front Fender Side	62	4	66
Windshield Glazing	237	83	320
Ground	490	33	523
Other	121	12	133
Total	1784	396	2180

The known injury mechanism sources were coded for 99% of the 2,180 injuries. Forty-two different contacts were coded as causing injuries with the most common injury contributors shown in Table 2. The ground was the most frequent injury contact with 490 contacts. However, 93% of the injuries from this contact were at minor AIS levels. Serious injuries (AIS 3-6) were more likely to be caused by contact with the front bumper, hood edge, cowl area or A pillar and it appears that if contact was made to one of these areas, there was a greater likelihood that a serious or life threatening injury would occur. This data is reflected in Figure 12 below.

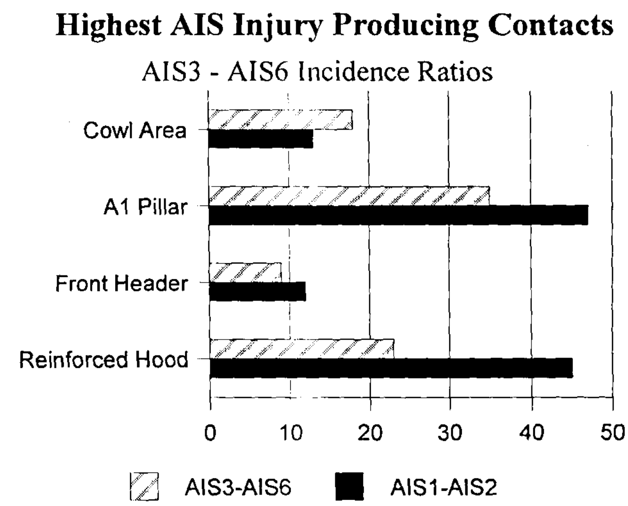

Figure 12. Relationship of the major AIS3-AIS6 injury producing contacts to AIS1-AIS2 injury levels.

The maximum AIS's (MAIS) were also tabulated against impact speeds. In Figure 13, it is clear that impact speed does affect the severity of the outcome. Approximately 89 of the 94 (95%) MAIS 3-6 injuries occur at impact speed greater than 15 KMPH. The vast majority of MAIS 1 injuries occurred at the two lowest groupings of impact speeds (below 31KMPH). MAIS2 injuries were retained as a separate MAIS injury group since many upper and lower extremity, and facial fractures are at the AIS2 level and could appear prior to the occurrence of more severe internal injury. It is clearly seen that MAIS2 injuries appear more frequently at this impact speed level. At impact speeds above 30KMPH the number of MAIS3-6 injuries rise substantially which is a clear indicator of speed having significant impact on MAIS severity and outcome.

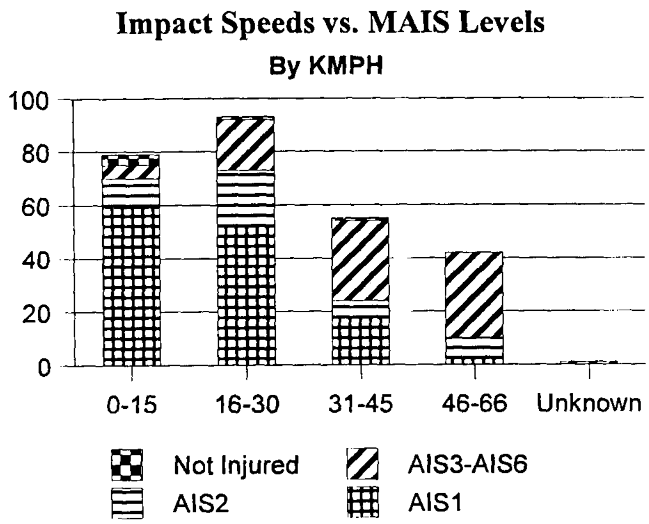

Figure 13. The distribution of impact speeds by MAIS levels.

CONCLUSIONS

The Pedestrian Crash Data Study (PCDS) is at the midway point in data collection since 500 crashes have been selected for investigation. This paper reports on some of the data collected for 292 of those crashes. The new data collection techniques that were implemented for the PCDS (video cameras and the contour gauge) have proven to be very effective means to collect scene and vehicle damage data and to accurately document contacts on the vehicle for reconstruction purposes and to ensure quality control. The success of the video sanitization efforts have ensured that the video tapes can be quickly and accurately sanitized without any loss to the quality of the tape or the information presented on the tape.

The analysis of the data thus far has shown several interesting points that will merit further exploration as more crashes are added to the data analysis file and as other crashes are initiated for investigation. These include additional analysis of pedestrian height in relation to the type of striking vehicle. In regard to vehicle type, the data showed that pickup trucks were over represented in causing serious injury (AIS3-AIS6) in relation to their overall distribution (11%) in the study.

As additional data are collected, further examination of brake lockup will be required to determine if lockup plays any role in causing more serious injury in relation to pedestrian crashes. The additional 400-600 new crashes for analysis should provide meaningful data to support or negate this issue.

The vehicle mechanisms producing serious injuries will also need further study. Additional injury contact data on the cowl area, A1 pillar, front header and reinforced hoods will be needed to determine if these areas are continuing to provide a disproportionate number of AIS3-AIS6 injuries in relation to their overall involvement in pedestrian crashes.

DATA AVAILABILITY

To obtain copies of the Pedestrian Crash Data Study file or individual cases contact:

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DOT/Volpe National Transportation Systems Center
Kendall Square
Cambridge, MA 02142
USA

REFERENCES

1 Abbreviated Injury Scale - 1990 Revision, Association for the Advancement of Automotive Medicine, Des Plains, IL, 1990.

2 Documentation for the Data File of the Pedestrian Injury Causation Study, U. S. Department of Transportation, National Highway Traffic Safety Administration, 1982.

3 Pedestrian Crash Data Study, 1996 Data Collection, Coding and Editing Manual, U. S. Department of Transportation, National Highway Traffic Safety Administration, 1996.

4 National Accident Sampling System, Crashworthiness Data System, AIS-90 Injury Coding Manual, U. S. Department of Transportation, National Highway Traffic Safety Administration, 1993.

5 Traffic Safety Facts 1996, A Compilation of Motor Vehicle Crash Data from the Fatal Accidnet Reporting System and the General Estimates System, U. S. Department of Transportation, NHTSA, 1997.

6. Isenberg R., Chidester C., and Kaufman R., "Pedestrian Crash Data Study (PCDS) - An Interim Evaluation", ESV Paper, June 1996.

APPENDIX 1

PEDESTRIAN CRASH DATA STUDY VARIABLE LIST

PEDESTRIAN ACCIDENT FORM

AC01	Primary Sampling Unit
AC02	Case Number - Stratum
AC03	Number of General Vehicle Forms Submitted
AC04	Date of Accident
AC05	Time of Accident
AC06	SS15 Administrative Use
AC07	SS16 Pedestrian Crash Data Study
AC08	SS17 Impact Fires
AC09	SS18
AC10	SS19
AC11	Number of Recorded Events in this Accident
AC12	Accident Event Sequence No.
AC13	Vehicle Number
AC14	Class of Vehicle
AC15	General Area of Damage
AC16	Vehicle Number or Object Contacted
AC17	Class of Vehicle
AC18	General Area of Damage

DERIVED VARIABLES

Day of Week
Year
Stratification
Month

PEDESTRIAN ASSESSMENT FORM

PED01	Primary Sampling Unit
PED02	Case Number - Stratum
PED03	Pedestrian Number
PED04	Pedestrian's Age
PED05	Pedestrian's Sex
PED06	Pedestrian's Overall Height
PED07	Pedestrian's Height - Ground to knee
PED08	Pedestrian's Height - Ground to Hip
PED09	Pedestrian's Height - Ground to Shoulder
PED10	Pedestrian's Weight
PED11	Pedestrian Attitude
PED12	Pedestrian Motion
PED13	Pedestrian's Action Relative to Vehicle
PED14	Pedestrian's Body (Chest)Orientation Prior Impact
PED15	Pedestrian's First Avoidance Actions
PED16	Pedestrian's Head Orientation at Initial Impact
PED17	Pedestrian Body (Chest)Orientation Initial Impact
PED18	Pedestrian's Arm Orientation at Initial Impact
PED19	Pedestrian's leg Orientation at Initial Impact
PED20	Vehicle/Pedestrian's Interaction
PED21	Police Reported Alcohol Presence
PED22	Alcohol Test Result for Pedestrian
PED23	Police Reported Other Drug Presence for Pedestrian
PED24	Other Drug Specimen Test Result for Pedestrian
PED25	Injury Severity (Police Rating)
PED26	Treatment - Mortality
PED27	Type of Medical Facility
PED28	Hospital Stay
PED29	Working Days Lost
PED30	Glasgow Coma Scale (GCS) Score
PED31	Was the Pedestrian Given Blood?
PED32	Arterial Blood Gases (ABG)-HCO3
PED33	Time to Death
PED34	1st Medically Reported Cause of Death
PED35	2nd Medically Reported Cause of Death
PED36	3rd Medically Reported Cause of Death
PED37	Number of Recorded Injuries for This Pedestrian

DERIVED VARIABLES

Maximum AIS
Injury Severity Score

PEDESTRIAN INJURY FORM

PI01	Primary Sampling Unit Number
PI02	Case Number - Stratification
PI03	Pedestrian Number
PI04	BLANK
PI05	Source of Injury Data
PI06	Body Region
PI07	Type of Anatomic Structure
PI08	Specific Anatomic Structure
PI09	Level of Injury
PI10	AIS Severity
PI11	Aspect
PI12	Injury Source
PI13	Injury Source Confidence Level
PI14	Direct/Indirect Injury
PI15	Striking Profile

PI16 Type of Damage
PI17 Damage Depth

PEDESTRIAN GENERAL VEHICLE

VEH01 Primary Sampling Unit Number
VEH02 Case Number - Stratum
VEH03 Vehicle Number
VEH04 Vehicle Model Year
VEH05 Vehicle Make
VEH06 Vehicle Model
VEH07 Body Type
VEH08 Vehicle Identification Number
VEH09 Police Reported Travel Speed
VEH10 Speed Limit
VEH11 Police Reported Alcohol Presence for Driver
VEH12 Alcohol Test Result for Driver
VEH13 Police Reported Other Drug Presence for Driver
VEH14 Other Drug Specimen Test Result for Driver
VEH15 Vehicle Curb Weight
VEH16 Vehicle Cargo Weight
VEH17 Vehicle Special Use(This Trip)
VEH18 Impact Speed
VEH19 Accuracy Range of Impact Speed Estimate
VEH20 Data Source of Impact Speed
VEH21 Driver's Attention to Driving
VEH22 Pre-Event Vehicle Movement
VEH23 Critical Precrash Event
VEH24 Attempted Avoidance Maneuver
VEH25 Precrash Stability After Avoidance Maneuver
VEH26 Precrash Direction Consequences of Avoidance Maneuver
VEH27 Relation to Junction
VEH28 Trafficway Flow
VEH29 Number of Travel Lanes
VEH30 Roadway Alignment
VEH31 Roadway Profile
VEH32 Roadway Surface Type
VEH33 Roadway Surface Condition
VEH34 Traffic Control Device
VEH35 Traffic Control Device Functioning
VEH36 Light Conditions
VEH37 Atmospheric Conditions

PEDESTRIAN EXTERIOR VEHICLE FORM

PEV01 Primary Sampling Unit
PEV02 Case Number - Stratum
PEV03 Vehicle Number
PEV04 Original Wheelbase
PEV05 Original Average Track Width
PEV06 Hood Material
PEV07 Hood Original
PEV08 Hood Length
PEV09 Hood Width Forward Opening
PEV10 Hood Width Midway
PEV11 Hood Width Rear Opening
PEV12 Hood/Fender Vertical/Lateral Crush From Pedestrian
PEV13 Windshield Contact Damage From Pedestrian Contact
PEV14 Front Bumper Cover Material
PEV15 Front Bumper Reinforcement Material
PEV16 Front Bumper - Bottom Height
PEV17 Front Bumper - Top Height
PEV18 Forward Hood Opening
PEV19 Front Bumper Lead
PEV20 Ground to Forward Hood Opening
PEV21 Ground to Front/Top Transition Point
PEV22 Ground to Rear Hood Opening
PEV23 Ground to Base of Windshield
PEV24 Ground to Top of Windshield
PEV25 Ground to Head Contact
PEV26 Ground Clearance
PEV27 Side Bumper-Bottom Height
PEV28 Side Bumper-Top Height
PEV29 Centerline of Wheel
PEV30 Top of Tire
PEV31 Top of Wheel Well Opening
PEV32 Bottom of A-Pillar at Windshield
PEV33 Top of A-Pillar at Windshield
PEV34 Top of Side View Mirror
PEV35 Centerline to A-Pillar at Bottom of Windshield
PEV36 Centerline to A-Pillar at Top of Windshield
PEV37 Centerline to Maximum Side View Mirror Protrusion
PEV38 Ground to Side/Top Transition
PEV39 Ground to Hood Edge
PEV40 Ground to Centerline of Hood
PEV41 Ground to Head Contact

CRASH TESTS TO RECONSTRUCT NASS CASES OF CHILD FATALITY/INJURY FROM AIR BAGS

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Paper Number 98-S6-O-06

ABSTRACT

This research program attempted to reconstruct cases from the National Automotive Sampling System (NASS) in which children, not in child seats, had been killed or seriously injured because of the deploying air bags and cases where there was minor injury with air bag deployment. The main objective was to compare injury measures from an instrumented child dummy to the actual injuries suffered by children in crashes and determine if a mathematical relationship exists between body region AIS level on the children and corresponding measures on the dummy. A secondary objective was to evaluate injury measures on the 5th percentile Hybrid III in the driver position, not necessarily as a simulation of the crash event. This paper presents the results of the test program and the comparison of measured dummy reponses to the actual occupant injuries in the crashes from the selected NASS cases.

INTRODUCTION

Cases from the NASS Special Crash Investigations (SCI) where children had been killed and the cause of death was attributed to air bag deployment were selected for reconstruction. In addition, cases of children with less severe injuries in a seating location with an air bag deployment were selected from the NASS Crashworthiness Data System (CDS.) In all cases the children were about 5 to 7 years old and were not in child safety seats. It was desired to select child passenger injuries of all levels, MAIS 1 through 6, hopefully, to allow for a wide range of dummy injury measures for comparison in the subsequent testing. The main objective of the comparison of injury measures from instrumented child dummies in tests to the actual injuries suffered by children in crashes is to determine if a relationship exists between body region AIS level on the children and corresponding measures on the dummy. A secondary objective is to evaluate injury measures on the 5th percentile Hybrid III in the driver position, not necessarily as a simulation of the crash event. The crash test program was conducted by Calspan Corporation in Buffalo, New York.

Six NASS cases were selected for simulation: specifically, the child passenger kinematics and interaction with the passenger air bag. It was desired that the selected case children injuries represent a range of AIS levels which may provide a mathematical relationship discussed above. The selection of cases was also limited to those in which the child was approximately the age, size and weight of the six-year-old Hybrid III test surrogate (48 pounds and 47 inches.) As shown in Table 1 all injured children were between 5 to 7 years old; however there was some variance in height and weight. It was felt however that the 6-year-old Hybrid III dummy would provide a reasonable representation of the children's kinematics and interactions with the deploying air bag.

CASE DESCRIPTIONS

The six NASS cases selected are shown below (3 child fatality cases are SCI, and 3 NASS-CDS cases, one with MAIS 3, and 2 with MAIS 1 level):

NASS Case	Outcome	Highest AIS
SCI 95-21	Fatality	5 - Brain
SCI 95-23	Fatality	5 - Brain
SCI 93-07	Fatality	5 - Brain, Neck*
95-43-154J	Serious Injury	3 - Brain
95-74-126J	Minor Injury	1 - Face
95-04-40E	Minor Injury	1 - Face

*Neck tension most probably caused brain stem injury

The descriptions of the occupants, seating positions, impact velocities and injuries, comparing the NASS case with the test are found in Tables 1 through 4. A short narrative of each NASS case is given below.

Case SCI 95-21 - A 1995 mini-van (subject vehicle) impacted the left side of a 1992 full size passenger car at about 9 o'clock and impact speeds of about 30 to 35 kmph on each vehicle. The seven-year-old female passenger, wearing only the lap belt portion of the belt system, was on the edge of the seat and was thrown forward due to pre-crash braking into close proximity to the deploying air bag. The driver was not injured.

Case SCI 95-23 - A 1993 mid-size passenger car (subject vehicle) rear impacted a stopped 1990 full size passenger car with about 50 percent left overlap on subject car and impact speed of about 29 kmph. The unbelted five-year-old female passenger was sitting normally in the seat and was thrown forward into close proximity to the deploying air bag due to pre-crash braking.

Case SCI 93-07 - A 1993 mid-size passenger car (subject vehicle) rear impacted a stopped 1986 subcompact passenger car with about 75 percent left overlap on the subject car and an impact speed of about 21 kmph. The six-year-old unbelted female passenger was sitting normally in the seat and was thrown forward due to pre-crash braking (ABS) into close proximity to the deploying air bag.

Case NASS-CDS 43-154J - A 1995 full size passenger car (subject vehicle) impacted the left side of a 1991 compact passenger car at about 9 o'clock and impact speeds of about 24 kmph on the subject vehicle and 19 kmph on the other vehicle. The five-year-old unbelted male passenger was sitting normally in the seat and was thrown forward due to pre-crash braking into close proximity to the deploying air bag.

Case NASS-CDS 74-126J - A 1995 subcompact passenger car (subject vehicle) impacted the left, front side of a 1994 full size passenger car at 9 o'clock and impact speeds of 43 and 24 kmph on the subject and other vehicle, respectively. The seven-year-old belted female passenger was seated normally and was essentially in this position at time of air bag deployment.

Case NASS-CDS 04-40E - A 1994 subcompact passenger car (subject vehicle) impacted the front of a 1987 subcompact passenger car at impact speeds of 24 and 67 kmph on the subject and other vehicle, respectively. The five-year-old belted female passenger was sitting normally in the seat and, although there was pre-impact braking, she was essentially in this position at time of air bag deployment.

TEST CONDITIONS

The driver position in the tests was occupied by an instrumented 5th percentile, female Hybrid III dummy. These were not to be simulations of the driver crash event but to give additional information on the 5th percentile dummy injury responses when interacting with an air bag. However, as it turned out some of the drivers in the NASS cases could, possibly, be represented by the 5th percentile, female Hybrid III dummy. A comparison of characteristics of test dummies and occupants of the selected NASS cases are shown in Table 1, with a judgement on whether the dummy was an adequate representation of the occupant. The driver dummies were positioned and restrained as described in the NASS case reports for all but case 1 (NASS-SCI-95-21.)

The specific make/model vehicles, impact angles and relative location of initial impact were replicated as described in the NASS case reports for the staged crash tests, except for test 4 (NASS-CDS-43-154J.) The schematic in this case report presented the impact as into the A-pillar/door of the struck vehicle; however, from the photographs it appeared that the A-pillar and door were virtually undamaged. Thus, the initial impact location was moved forward to replicate the photographic evidence.

In most cases the recorded impact velocities appeared too low to produce velocity changes sufficient to deploy the air bags. To provide a higher likelihood for air bag deployment, the target test velocities were slightly higher than reported in the NASS cases; however, an electronic firing circuit was also installed to induce deployment if the vehicles sensing system did not trigger deployment. The time to deployments were estimated based on the crash conditions and the switch for firing was set to a somewhat later time to give the vehicle sensor system the opportunity to fire before inducing deployment. It was necessary to induce deployment in 3 of the 6 crash tests. The Contractor's tow system configuration is able to develop velocities of one vehicle moving and one stationary or velocity ratio's of 1:1, 1:2 or other integer multiples at almost any angles of impact. Thus, if the two vehicles velocities are not in these ratios the closest ratio is used and the desired closing velocity is simulated (Table 3).

In the first 4 reconstructed NASS cases, the child passengers suffered serious or fatal injuries due to being in close proximity to the air bag at the time of deployment. These cases all involved pre-crash braking. Development of methods for simulating pre-crash braking were beyond the scope of the program. The NASS-SCI reports provide likely scenarios of the occupants motion throughout the crash event and this information was used to position the child at the time of impact for the first 3 SCI cases. NASS-CDS cases do not contain this level of detail on occupant motion; however a variable "posture" is given which describes how the occupant was seated prior to the crash. For case 4 (95-43-154J), the posture was listed as "unknown," but was assumed to be "normal" before braking; however, due to braking it was assumed that the unbelted child moved forward and was on the edge of the seat, a few inches from the instrument panel at initial impact. The last two cases were children who were properly belted and it was assumed that they were in essentially a "normal" seating position and posture at time of impact as was the assumption with all driver 5th percentile female dummies in the tests.

In the first test the child dummy was initially positioned forward in the seat and held in place by heavy fishing line which was to be cut at time of impact. During "run-up" the pull force of the towing system was erratic causing jostling of the dummy and eventually breaking the fishing line. Thus, at time of impact, not only was the impact velocity too high but the child passenger dummy was back in the seat in a position not simulating the child's position in the NASS crash. Because of the high speed and the position of the dummy this test was considered an invalid simulation for the child passenger. For the remaining tests the tow system performed more smoothly and steel wire was used to more securely position the dummy, and it appeared that the child dummy crash kinematics and position were probably a good representation of the NASS crash event.

TEST RESULTS

The maximum values of the recorded injury measures for each test and the corresponding case AIS levels for neck, head and chest are shown in Table 4 and graphically shown in Figures 1 through 6. None of the figures for the child passenger show a strong relationship between reported NASS injuries and recorded test measures. In general, the recorded injury measures in the test appeared higher than would be expected for the reported NASS injuries, especially on the neck for both the driver and passenger. The current injury assessment reference values (IARV's) for head, chest and neck are shown in Table 5 (NHTSA Report, "Development of Improved Injury Criteria for the Assessment of Advanced Automotive Restraint Systems", National Transportation Biomechanics Research Center, April 1998.).

6-Year-Old Child Dummy Results - Of the valid cases, the only serious or greater neck injury in the table (AIS 5 in NASS case CA93-07) was not listed in the case report but was assigned based on the mechanism of the type of brain injuries suffered by the child. Tension in the cervical spine could pull on the brain stem and cause the injuries listed. Relating NASS case injuries to neck tension shows minor injury up to about 3500 newtons and then AIS 5 at about 6000 newtons; however, in test 4 (case 43-154J) the 6-year-old child dummy experiences a tension of about 5500 newtons with no reported neck injury in the simulated case (Figure 1.) Extremely high flexion moments were experienced on the 6-year-old child dummy in three of the four valid simulation tests (from about minus 180 to minus 280 newton-meters or 4.5 to 7 times the IARV) with minor neck injury in two of the NASS cases but an AIS 5 in the third (Figure 2.) Head injury appears to show an expected trend; however, the child dummy with the highest HIC (1866) had the third highest head AIS in the corresponding NASS cases. Unlike the neck injury measures, which appear to be magnitudes higher than the corresponding NASS injury outcomes, the head injury measures appear to be in the "ball park" of the actual injuries, i.e., HICs from about 800 to 1900 corresponding to head AIS$\geq$3 (Figure 3.)

The agency is currently developing an injury criteria for the neck which combines the normalized forces and moments into a single indicator of neck injury.

Table 5.
Injury Assessment Reference Values for Body Regions

Body Region	Injury Criteria	6-Year-Old Child Dummy	5th-Percentile Female Dummy
Head	HIC (36 ms clip)	1000	1000
Chest	G's V*C (m/sec) [1]	65 1	60 1
Neck	Tension+ (N) Compression- (N) Flexion+ (N-M) Extension- (N-M)	3000 3000 140 40	3200 3200 210 60

[1] **V*C = Max. {1.3*V*[δ/(chest depth)]}**; where δ is chest deflection and V is sternum to spine velocity

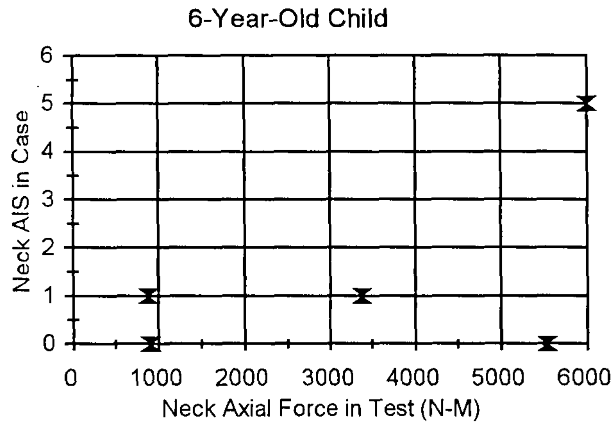

Figure 1. Neck Axial Force (Test) vs. Neck AIS in Case.

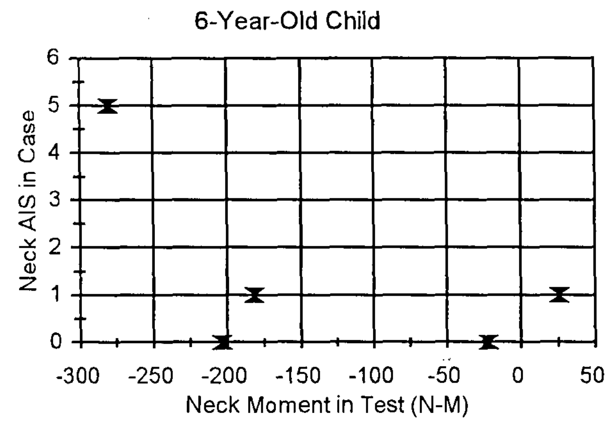

Figure 2. Neck Moment (Test) vs. Neck AIS in Case.

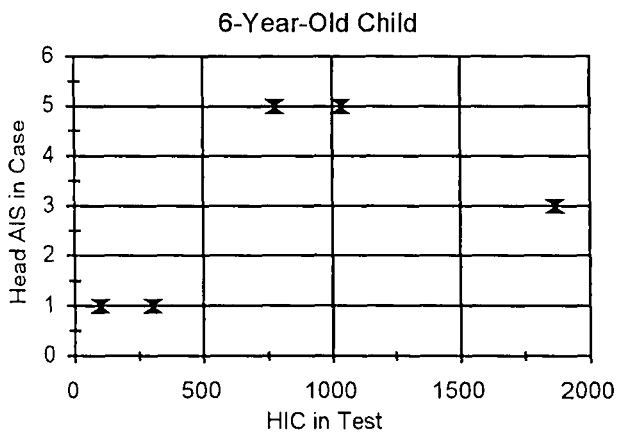

Figure 3. HIC (Test) vs. Head AIS in Case.

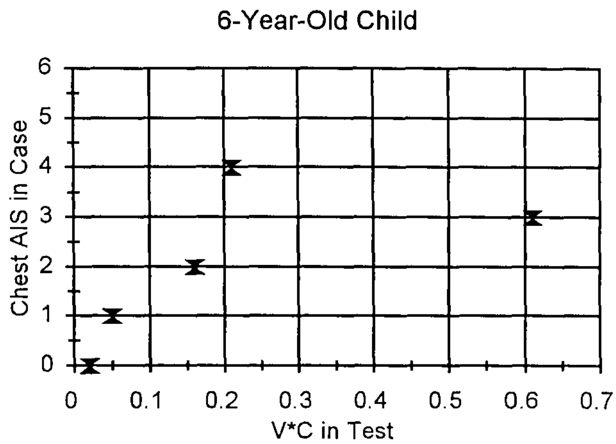

Figure 4. V*C (Test) vs. Chest AIS in Case.

The measure V*C is selected as the indicator of chest injury for the child dummies especially for out-of-position dummies where "blast" loadings occur. There appears to be a "weak" relationship between chest AIS and V*C from Figure 4; however, all values of V*C were relatively low and not indicative of the actual injury levels in the cases. Chest AIS was well distributed among the five NASS cases with an AIS 4, 3, 2, 1 and 0.

<u>5th Percentile Female Dummy Results</u> - All drivers in the NASS cases were either uninjured or suffered minor injuries, except case 5 (74-126J, Table 4.) The 5'4", 140 pound female in this case suffered an AIS 5 chest injury. However, for comparison, the chest G's and V*C in the test with similar restraint and position but a smaller dummy, were low (Chest G's of 29 and V*C of 0.3.) Since the test surrogate for the driver may not be a reasonable simulation of the NASS case driver, the driver tests should generally be viewed simply as evaluation tests of the 5th percentile female dummy interactions with air bags.

Except for neck moments, and one borderline neck tension, all injury measures on the 5th percentile female dummy in the tests were well below the IARV's shown above (the maximum HIC was 290 and chest G's were 29.) The driver dummy neck extension moments in two of the tests were magnitudes higher than the IARV of -60 newton-meters: the dummy experienced -156 newton meters in test 1 and -194 newton-meters in test 3 (Figure 6.) The dummy in test 2 also experienced a high neck

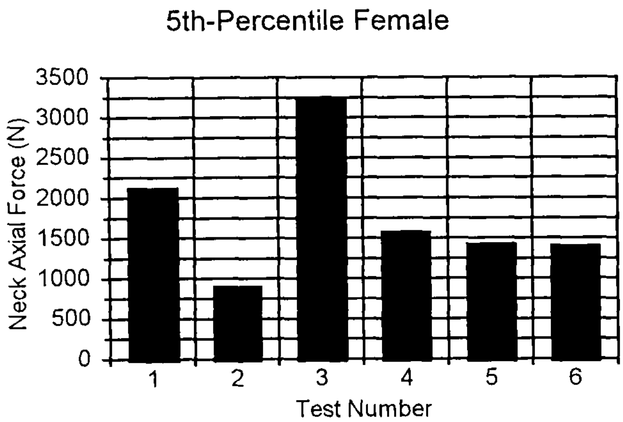

Figure 5. Neck Axial Force (Test) vs. Neck AIS in Case.

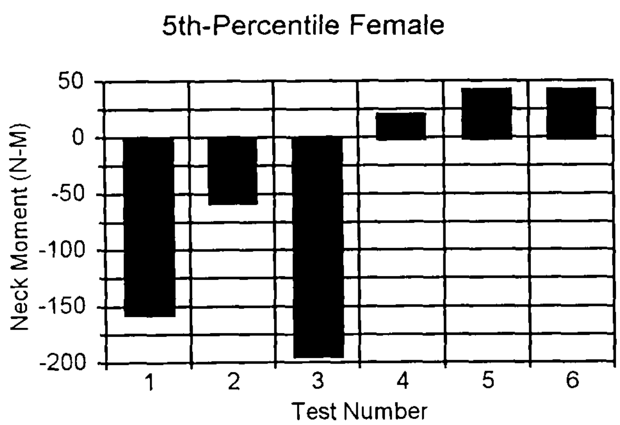

Figure 6. Neck Moment (Test) vs. Neck AIS in Case.

extension moment of 57 newton-meters. In tests 1, 2 and 3 the 5th percentile driver dummies were normally seated with the seat forward. Lap/shoulder belts were used in tests 1 and 2 and no belts were used in test 3.

CONCLUSIONS

Neck injury measures on 6-year-old child Hybrid III dummies in the tests were not always consistent with injuries to children of similar age and size in the selected NASS cases simulated by the tests. The simulation of the child with the highest neck injury (AIS 5) produced the highest neck extension moment (-280.0 newton-meters) and neck tension (6000 newtons) on the 6-year-old child Hybrid III dummy (SCI CA93-07, test 3.) However, one case (NASS 43-154J, test 4) reported no neck injury to the child but the neck injury responses on the 6-year-old child Hybrid III dummy were well above the IARV's for the neck: 5534 newtons neck tension and 204 newton-meters neck extension moment.

As discussed above no neck injury was reported in NASS case CA93-07 but was assigned an AIS 5 based on the mechanism of the type of brain injuries suffered by the child. This may also be true in some of the other cases of head injury where neck loading may directly, or indirectly, contribute to the brain injury. However, information to reach this conclusion was not evident in the other NASS reports.

The 5th percentile female Hybrid III dummy was placed in the driver position in the tests to evaluate the interaction with the air bag, and not, necessarily, as a simulation of the driver in the NASS case crash event. However, since several of the drivers were female, the NASS reported restraint, seat position and posture were simulated for the corresponding crash test. All injury measures on the 5th percentile female Hybrid III dummy were fairly benign, except with regard to neck injury and specifically neck flexion moments. In two of the tests the IARV's for neck flexion moment were exceeded and in one test the neck tension IARV was marginally exceeded, with the neck flexion moment being much higher than the IARV in two of the tests.

Table 1.
Comparison of Test Dummy to Case Occupant Sizes

Test # NASS Case	Driver: Driver Dummy	Driver: Case Driver	Passenger: Passenger Dummy	Passenger: Case Child Passenger	Valid Simulation of Occupant Size?: Driver	Valid Simulation of Occupant Size?: Passenger
1 SCI 95-21	5th% Female 4'11", 105 lbs	45 year-old male, 6'2", 173 lbs	6-year-old Child, 3'11", 48 lb's	7 year-old female, 4'3", 55 lbs	**N**	**Y**
2 SCI 95-23		33 year-old female, 5'6", 170 lbs		5 year-old female, 3'"10", 45 lbs	**N**	**Y**
3 SCI 93-07		34 year-old female, 5'0", 90 lbs		6 year-old female, 3'8", 51 lbs	**Y**	**Y**
4 95-43-154J		40 year-old female, 5'4", 130 lbs		5 year-old male, 3'4", 41 lbs	**?**	**Y**
5 95-74-126J		34 year-old female, 5'4", 140 lbs		7 year-old female, 4'0", 71 lbs	**?**	**Y**
6 95-04-40E		44 year-old female, 5'6", 165 lbs		5 year-old female, 4'0", 65 lbs	**N**	**Y**

Table 2.
Comparison of Test Dummy to Case Occupant Seating Positions and Belt Use

Test # NASS Case	Braking?	Occupant Position	Pre-Impact or Pre-Braking		@ Impact/Post-Braking	
			Case Driver	Case Passenger	Test Driver	Test Passenger
1 SCI 95-21	Y (ABS)	**Posture**	Normal	Vertical	Normal	20° forward
		Seat Pos.	Rear	Rear	Forward	Rear
		Occupant Pos.	Normal	Legs over seat	Normal	Edge of seat
		Belt Use	L/S Proper	Lap only	L/S Proper	Lap only
2 SCI 95-23	Y (12')	**Posture**	Normal	Normal	Normal	Vertical
		Seat Pos.	Forward	Mid	Forward	Mid
		Occupant Pos.	Normal	Normal	Normal	Edge of seat
		Belt Use	L/S Proper	None	L/S Proper	None
3 SCI 93-07	Y (ABS)	**Posture**	Normal	Normal	Normal	Vertical
		Seat Pos.	Forward	Mid	Forward	Mid
		Occupant Pos.	Normal	Normal	Normal	Edge of seat
		Belt Use	None	None	None	None
4 95-43-154J	Y (7')	**Posture**	Normal	Unknown	Normal	Vertical
		Seat Pos.	Mid/Fwd.	Mid/Fwd.	Mid/Fwd.	Mid/Fwd
		Occupant Pos.	Normal	Normal	Normal	Legs over seat
		Belt Use	L/S Proper	None	L/S Proper	None
5 95-74-126J	N	**Posture**	Normal	Normal	Normal	Normal
		Seat Pos.	Mid/Fwd.	Mid/Fwd.	Mid/Fwd.	Mid/Fwd.
		Occupant Pos.	Normal	Normal	Normal	Normal
		Belt Use	L/S Proper	L/S Proper	L/S Proper	L/S Proper
6 95-04-40E	Y (ABS)	**Posture**	Normal	Normal	Normal	Normal
		Seat Pos.	Mid/Rear	Rear	Mid/Fwd	Rear
		Occupant Pos.	Normal	Normal	Normal	Normal
		Belt use	L/S Proper	L/S Proper	L/S Proper	L/S Proper

Table 3.
NASS Reported Crash Speeds and Crash Test Speeds

Test # (Case #)	NASS Impact Speed (KPH)		Crash Test Speed (KPH)		Configuration	Type of Deployment
	Vehicle 1	Vehicle 2	Vehicle 1	Vehicle 2		
1 (SCI 95-21)	35	32	47	47	Front-left	Normal
2 (SCI 95-23)	29	0	39	0	Front-rear	Normal
3 (SCI 93-07)	21	0	28	0	Front-rear	Induced
4 (95-43-154J)	24	19	29	29	Front-left	Induced
5 (95-74-126J)	43	24	45	23	Front-left	Induced
6 (95-04-40E)	24	67	24	72	Angle front-front	Normal

Table 4.
Injury Responses in Tests Compared to NASS Case Injuries

	Case# (Test #)	HIC	Neck Tension (N)	Neck Moment (N-M)	Neck Shear (N)	VC (M/S)	Chest G	Maximum AIS Levels: Neck	Maximum AIS Levels: Head	Maximum AIS Levels: Chest	Comments
Child Passenger	CA95-21 (1)	56	-585	32.8	-374	0.12	20.8	3	5	4	Invalid speed, dummy position
	CA95-23 (2)	776	3374	-181.8	2932	0.61	49.9	1	5	3	
	CA93-07 (3)	1034	6000	-280.0	4512	0.21	16.9	5*	5	4	*Neck tension caused brain injuries
	43-154J (4)	1866	5534	-203.9	3883	0.16	34	0	3	2	
	74-126J (5)	100	879	25.8	438	0.02	29.1	1	1	0	
	04-40E (6)	302	904	-22	507	0.05	47	0	1	1	
Driver	CA95-21 (1)	200	2119	-155.9	1849	0.13	24.7	0	0	0	Invalid speed, dummy size
	CA95-23 (2)	38	897	-57.3	622	0.04	10.2	0	0	0	Invalid dummy size, 5'6", 170# F.
	CA93-07 (3)	290	3222	-194.2	3106	1.99	29	0	1	1	5', 90#, F
	43-154J (4)	23	1571	20.8	272	0.12	13	0	1	0	? dummy size, 5'4", 130#, F
	74-126J (5)	104	1420	42.3	657	0.3	26.7	0	0	5	? dummy size, 5'4", 140#, F
	04-40E (6)	108	1395	-42	-548	0.06	41	1	0	1	? dummy size, 5'6", 165# F.

AN UPDATE ON THE RELATIONSHIPS BETWEEN COMPUTED DELTA Vs AND IMPACT SPEEDS FOR OFFSET CRASH TESTS

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ABSTRACT

The Insurance Institute for Highway Safety evaluates some aspects of new vehicle crashworthiness based on performance in a 40 percent frontal offset test into a deformable barrier. The impact speed of 64 km/h used in this program has been criticized as being too high and not representative of real-world crashes. At the 1996 Enhanced Safety of Vehicles conference, the estimated crash severities of a sample of real-world crashes from the National Automotive Sampling System (NASS) were compared with the Institute's 64 km/h offset crash tests of 16 midsize 1995-96 model four-door cars. Injury likelihood from the NASS sample was related to the test speed through delta V using the CRASH3 damage-only algorithm. Results from that study suggest that a 40 percent frontal offset test into a deformable barrier conducted at a speed less than 64 km/h would represent a crash severity that is lower than a large number of real-world car crashes with serious injuries. The present study expands on the previous work by providing one additional year of NASS data and results from 41 additional crash tests of 1995-98 model cars, passenger vans, and utility vehicles. Delta V and injury data were collected for real-world offset crashes from NASS for each of the three vehicle types and separated by restraint use. Results indicate that for cars, the Institute's 64 km/h frontal offset test represents a crash severity that encompasses about 80 percent of all real-world crashes with AIS 3 or greater injuries (i.e., the remainder occur at higher crash severities) but only about 33 percent of all fatal crashes.

INTRODUCTION

Crashworthiness evaluations have become increasingly common as a means of providing consumers with information on the relative crash protection offered by different vehicles. One such program is the National Highway Traffic Safety Administration's New Car Assessment Program (NCAP), in which vehicles are tested in a fully-engaged frontal crash at a speed of 56 km/h (35 mi/h) into a rigid barrier. NCAP has been very successful at differentiating the extremes of good and bad restraint system performance, all but eliminating the poorest of performers in recent years.[1]

In 1995, the Insurance Institute for Highway Safety began evaluating vehicles in another type of crash test called the "frontal offset test." This same test has been adopted by both the European and Australian NCAP programs.[2-3] In this test, only 40 percent of the vehicle's width strikes a deformable barrier attached to a rigid barrier at a speed of 64 km/h (40 mi/h). Unlike the NCAP test, only part of the front structure absorbs crush energy, resulting in large front-end deformations and potential occupant compartment intrusion.[4]

The value of comparative crashworthiness information derived from new vehicle crash testing depends on both the test configuration and the test speed. Frontal offset crashes represent a significant portion of real-world crashes that result in serious injuries to occupants.[5] However, the choice of an appropriate test speed can be more complex. If the test speed is low, it will be equivalent to a real-world crash severity at which crash injury risk also is low, and consequently the test results would not differentiate performance in injury-producing crashes. On the other hand, to encompass virtually all serious injuries in real-world crashes, the test speed would need to be so high that there likely would be no good performers and as a result no useful consumer information. The key to meaningful evaluations is to select a test speed that encompasses a significant number of real-world serious injuries while ensuring that the designs required to perform well in the test are reasonably attainable in the current fleet.

REAL-WORLD CRASH SEVERITY

The Institute's frontal offset crash test program has been criticized for testing vehicles at too high an impact speed. Some cite estimates of crash severity from real-world crash databases as evidence that the Institute's impact speed is too high. However, these conclusions are based on data that require closer examination because, despite a widespread misconception to the contrary, for the overwhelming bulk of crashes delta V is not the same as impact speed. In an Institute study presented at the 1996 Enhanced Safety of Vehicles conference, delta V estimates for 16 frontal offset crashes were compared with the distributions of delta V by injury severity from NASS.[6] That study found that about 50 percent of fatalities and 75 percent of serious injuries occurred in real-world crashes at severities below the severity of the Institute's test. This study updates that analysis with results from 41 additional crash tests and an additional year of NASS data.

The first necessary step in selecting an evaluation test speed is to find a real-world measure of crash severity that can be compared with the chosen test speed. One of the most common measures used to assess the severity of real-world crashes is delta V, which is an estimate of the change in velocity of a vehicle during a crash. In the early days of crashworthiness research when belt use was extremely low, delta V was assumed to be an indicator of the impact speed with which unrestrained occupants impacted the interior structure in frontal crashes. However, delta V has continued to be used as an indicator of severity even as belt use has increased. For two-vehicle crashes, delta V can be used as a surrogate for vehicle acceleration. In a two-vehicle crash, the energy absorbed by both vehicles is combined and then apportioned to each vehicle in the form of delta V based on their mass ratio. This result is consistent with the underlying physics: The lighter vehicle will have a higher delta V and higher accelerations than the heavier collision partner. For single-vehicle crashes, delta V also can be used as a surrogate for vehicle acceleration to compare crashes provided the duration of the crashes is similar.

During the 1970s, a computer algorithm developed at Calspan for the U.S. Department of Transportation began to be widely used to compute delta V estimates. This program was capable of estimating both the impact velocity and change in velocity (delta V) of a vehicle in a crash based on information from the vehicle and the crash scene. The original algorithm was termed CRASH for Calspan Reconstruction of Accident Speeds on the Highway and contained two options that are included in today's version, damage-only and trajectory.

The resulting delta V computed from the damage-only algorithm represents the change in velocity of the vehicle's center of gravity at the time of maximum crush during the crash, and it does not include rebound velocity. The damage-only option computes delta V based on the conservation of momentum and the energy absorbed by the vehicle independent of any information from the crash scene. The energy absorbed during the crash is estimated by measuring the residual crush of the vehicle and applying an estimate of the stiffness to the measured crush area, which in the case of CRASH is done by selecting a stiffness category from a list. Each stiffness category contains stiffness coefficients that define a linear force-deflection curve for that vehicle category (mini cars, subcompact, compact, etc.). In an offset crash, the delta V calculated by the damage-only algorithm also is modified to account for rotation of the vehicle during the crash. Like the stiffness categories, CRASH contains generic size categories based on wheelbase whose coefficients are used to modify delta V in offset crashes.[7]

The second option for estimating delta V in the CRASH program is the trajectory option. This algorithm requires extensive information from the crash scene and multiple assumptions regarding the energy dissipated in tire-road friction, tripping forces, etc., to estimate post-crash energy dissipation. The laws of conservation of momentum are applied to the scene data to provide estimates of impact speed in addition to delta V. Because the damage-only estimate of delta V relies upon simple measures of vehicle damage, it has been used much more frequently than the trajectory option, which relies upon data collected at the crash scene that often is unavailable or questionable.

CRASH has been updated several time since its inception in the late 1970s. In the early 1980s, CRASH2 was changed to CRASH3 by updating the stiffness coefficients in the various categories used to calculate a vehicle's absorbed energy.[8] More recently, CRASH3 was changed to SMASH (Simulating Motor Vehicle Accident Speeds on the Highway), which includes another update in the stiffness coefficients and further allows the use of vehicle-specific stiffness coefficients in lieu of the preassigned stiffness categories used in CRASH3 to calculate absorbed energy.[9] SMASH also allows the user to input specific vehicle dimensions, such as overall length, wheelbase, etc., instead of relying upon generalized size categories. Prasad, who developed the SMASH program, cited significantly fewer errors when using vehicle-specific stiffness coefficients instead of the generalized stiffness categories in CRASH3.[9] Throughout these revisions, the basic equations used to calculate delta V have changed in form but not in substance.

NASS contains the largest sample of real-world crashes in the United States and frequently is used to relate crash severity to injuries in crashes. NASS is designed so that a sampling of crashes in various regions of the country can be scaled to represent the entire population. One data element in most NASS cases is an estimate of delta V for each vehicle involved in the crash as estimated by CRASH. (NASS has used various versions of CRASH over time and switched from CRASH3 to SMASH in January 1997). Approximately 90 percent of NASS cases that contain delta Vs from CRASH3 were calculated using the damage-only algorithm, and the remaining 10 percent used the trajectory model.[10] In this study, only results from the damage-only algorithm are used because the majority of NASS cases with computed delta Vs used this option.

METHOD

Using the NASS measurement protocol, delta Vs were calculated using the CRASH3 damage-only algorithm for the 57 vehicles subjected to the Institute's 64 km/h frontal offset test. The energy absorbed by the deformable barrier was determined using estimates of the deformed volume and the static crush strength of the barrier material. This estimate of energy absorbed by the deformable barrier was included in the delta V estimate for each vehicle. The average crash test delta V was tabulated for all tested vehicles within each vehicle type.

In addition to the delta Vs calculated by CRASH3, delta Vs also were computed using SMASH. All delta Vs calculated by SMASH were based on vehicle-specific size and stiffness properties. As much information as possible regarding size, overall length, wheelbase, and weight was entered into the program. The vehicle-specific stiffness coefficients were determined using the method developed by Prasad, which requires at least two points to define the slope and intercept of the $\sqrt{N}$ versus average crush line.[9] In this study, slopes were determined using NCAP or Federal Motor Vehicle Safety Standard (FMVSS) 208 test results for the vehicles along with a 12 km/h no-measurable-damage assumption. For some completely new models, SMASH delta Vs were not calculated due to lack of necessary NCAP or FMVSS 208 crash test data. Crash test data from previous model years were used to estimate stiffness coefficients for some redesigned vehicles considered not to have changed dramatically in structure. The energy absorbed by the deformable barrier was included in the delta V estimates.

Delta Vs from real-world crashes were extracted from the 1990-95 NASS data files for crashes that matched the conditions of the Institute's offset crash test. Cases were selected based on Collision Deformation Classification (CDC) coding, which includes impact angle, impact location, and amount of direct engagement. For this study, single- or multiple-vehicle towaway crashes coded as frontal, with one-third to two-thirds direct damage to the front-end and 11 to 1 o'clock principal direction of force, were selected. These data were reduced further by selecting only those cases where delta Vs were calculated using the CRASH3 damage-only algorithm (no trajectory cases or OLDMISS cases). The 1990-95 NASS data contain a total of 14,608 vehicles in frontal crashes (all clock directions, CDC code "Frontal"), of which 7,005 (48 percent) meet the Institute's offset conditions. Of the 7,005 vehicles, only 3,255 (46 percent) have computed delta Vs from the CRASH3 damage-only algorithm. These 3,255 vehicles were used in this study to relate CRASH3 delta V to injury levels.

RESULTS

Tables 1-6 list the delta Vs (including the deformable barrier energy) calculated by CRASH3 and SMASH for the Institute's frontal offset tests. CRASH3 delta Vs consistently are lower than actual impact speeds; the average CRASH3 delta Vs are 33 percent lower for cars, 22 percent lower for utility vehicles, and 10 percent lower for passenger vans. Overall, SMASH (using vehicle-specific stiffness properties) increases delta V, but SMASH delta Vs still are 3-12 percent lower than impact speeds.

The fact that delta Vs are lower than impact speeds should not be surprising. In a frontal offset test, the vehicle's center of gravity does not stop at the time of maximum crush because the vehicle rotates about the barrier during the crash. This rotation means that the computed delta V should be lower than impact speed. The large differences between delta Vs calculated using CRASH3 and SMASH result solely from the difference between the preassigned size and stiffness properties used in CRASH3 and the vehicle-specific properties used in SMASH. However, high-speed film analysis of the Institute's offset tests indicate actual delta Vs should be 2-3 km/h lower than impact speeds due to the effects of rotation, suggesting that CRASH3 is substantially underestimating delta Vs in offset crashes for most vehicle types.

Table 1.
Delta Vs Computed for Midsize Four-Door Cars in 64 km/h 40 Percent Offset Crashes, Including Deformable Barrier Energy

	Actual Impact	Delta V (km/h)	
Make/Model	Speed (km/h)	CRASH3	SMASH
Subaru Legacy	64	39	53
Volvo 850	65	44	58
Mazda Millenia	64	41	55
Toyota Camry (95)	64	48	58
Mitsubishi Galant	64	47	65
Honda Accord	64	40	49
Ford Contour	64	38	57
Chevrolet Lumina	64	42	56
Nissan Maxima	64	43	59
Ford Taurus (95)	64	44	68
Chevrolet Cavalier	64	37	45
Chrysler Cirrus	65	48	76
Volkswagen Passat (95)	64	43	52
Saab 900	64	46	60
Ford Taurus (96)	64	43	64
Toyota Avalon	64	44	54
Hyundai Sonata	64	48	56
Pontiac Grand Prix	64	42	61
Toyota Camry (97)	64	45	57
Toyota Avalon (98)	65	42	n/a
Nissan Maxima (98)	65	47	n/a
Honda Accord (98)	64	58	n/a
Volkswagen Passat (98)	65	37	n/a
	Average:	44	58

Table 2.
Delta Vs Computed for Small Four-Door Cars in 64 km/h 40 Percent Offset Crashes, Including Deformable Barrier Energy

Make/Model	Actual Impact Speed (km/h)	Delta V (km/h)	
		CRASH3	SMASH
Honda Civic	64	44	60
Mitsubishi Mirage	64	46	51
Kia Sephia	64	40	52
Saturn SL2	64	45	49
Ford Escort	64	39	51
Mazda Protégé	64	40	53
Volkswagen Jetta	64	43	53
Dodge Neon	64	48	59
Hyundai Elantra	65	38	46
Nissan Sentra	64	45	55
Toyota Corolla	64	40	n/a
	Average:	43	53

Table 3.
Delta Vs Computed for Luxury Cars in 64 km/h 40 Percent Offset Crashes, Including Deformable Barrier Energy

Make/Model	Actual Impact Speed (km/h)	Delta V (km/h)	
		CRASH3	SMASH
BMW 540i	64	41	n/a
Lexus LS 400	64	37	n/a
Cadillac Seville	64	44	n/a
Mercedes-Benz E420	64	40	n/a
Lincoln Continental	64	47	n/a
Infiniti Q45	64	37	n/a
	Average:	41	n/a

Table 4.
Delta Vs Computed for Passenger Vans in 64 km/h 40 Percent Offset Crashes, Including Deformable Barrier Energy

Make/Model	Actual Impact Speed (km/h)	Delta V (km/h)	
		CRASH3	SMASH
Chevrolet Astro	64	59	56
Nissan Quest	64	58	57
Honda Odyssey	64	42	59
Ford Aerostar	64	65	60
Dodge Grand Caravan	64	59	63
Toyota Previa	64	49	63
Pontiac Trans Sport	64	69	64
Mazda MPV	64	74	69
Ford Windstar	66	63	71
Toyota Sienna	65	46	n/a
	Average:	58	62

Table 5.
Delta Vs Computed for Utility Vehicles in 64 km/h 40 Percent Offset Crashes, Including Deformable Barrier Energy

Make/Model	Actual Impact Speed (km/h)	Delta V (km/h)	
		CRASH3	SMASH
Jeep Grand Cherokee	64	49	44
Toyota 4Runner	64	45	52
Ford Explorer	63	49	58
Land Rover Discovery	64	52	60
Mitsubishi Montero	65	45	61
Nissan Pathfinder	65	52	65
Chevrolet Blazer	64	64	66
Isuzu Rodeo	63	46	72
	Average:	50	60

Table 6.
Summary of CRASH3 and SMASH Delta Vs by Vehicle Type in 64 km/h 40 Percent Offset Crashes, Including Deformable Barrier Energy

Vehicle Type	CRASH3		SMASH	
	Delta V (km/h)	N	Delta V (km/h)	N
Cars	43	39	56	29
Passenger vans	58	10	62	9
Utility vehicles	50	8	60	8

Table 7 reports the differences between the coefficients contained within the CRASH3 pre-assigned stiffness categories (1-9) and the vehicle-specific stiffness coefficients calculated for the vehicles tested by the Institute. Values duplicated in the far-right column indicate that vehicles in the same Institute test category were assigned different stiffness categories according to NASS protocol.

For CRASH3, small and midsize cars are assigned stiffness category 2, 3, or 9; passenger vans are assigned category 7 or 4; and utility vehicles are assigned category 7 or 8. Note the difference in stiffness coefficients (slope)* for CRASH3 category 4 and the passenger van average vehicle-specific stiffness coefficients. Both the Honda Odyssey and Toyota Previa are assigned a category 4 stiffness and have CRASH3 delta Vs much lower than the other vans. The four utility vehicles assigned a category 8 stiffness have the four lowest delta Vs for those vehicles. Except for category 7 (vans and four-wheel drive vehicles), the pre-assigned stiffness coefficients are much lower than the vehicle-specific stiffness coefficients calculated for those vehicles. The lower stiffness coefficients result in lower estimates of energy absorbed by vehicle deformation and consequently yield lower delta Vs.

* The intercept is nearly the same for all vehicles.

Table 7.
Comparison of CRASH3 Pre-Assigned Categories and Vehicle-Specific Coefficients used in SMASH

Stiffness Category	CRASH3 Stiffness Category Description	CRASH3 Category Stiffness Coefficient Sqrt(N)/cm	Average Vehicle-Specific Coefficients Calculated for SMASH Sqrt(N)/cm
1	Mini-cars	5.7	
2	Subcompact	5.4	7.4 & 8.5 (small and midsize cars)
3	Compact	6.2	7.4 & 8.5 (small and midsize cars)
4	Intermediate	4.8	8.8 (passenger vans)
5	Full size	5.1	
6	Luxury	5.1	
7	Vans and four-wheel drive	9.3	8.8 & 9.2 (passenger vans and utility vehicles)
8	Pickup trucks	5.9	9.2 (utility vehicles)
9	Front-wheel drive	5.1	7.4 & 8.5 (small and midsize cars)

Table 8.
Median Delta-V (km/h) by Injury Level from NASS 1990-95, Weighted

	All Towaways		MAIS 2+		MAIS 3+		Fatalities	
	Delta-V	Raw N	Delta-V	Raw N	Delta-V	Raw N	Delta-V	Raw N
All passenger vehicles*	20	3,255	27	1,112	31	512	48	136
All passenger vehicles – belted	18	1,720	25	429	24	177	55	30
All passenger vehicles – unbelted	23	1,316	30	644	34	319	47	99
Cars and passenger vans	20	2,615	27	923	29	423	50	117
Cars and passenger vans – belted	19	1,381	25	352	24	144	55	23
Cars and passenger vans – unbelted	23	1,047	29	536	32	264	47	87
Pickups and utilities	21	571	32	169	40	81	40	18
Pickups and utilities – belted	18	306	30	68	32	31	43	7
Pickups and utilities – unbelted	24	235	34	97	48	49	40	11

*Passenger vehicles include cars, pickup trucks, utility vehicles, and passenger vans.

Table 8 shows the median delta Vs by vehicle type, restraint use, and maximum injury severity from the 1990-95 NASS data files. Injury severity measures presented are the maximum abbreviated injury scale (MAIS) code for either of the front-seat occupants of the vehicle. The delta Vs from NASS are weighted according to NASS guidelines. For reference, the raw (unweighted) number of samples are shown for each vehicle/restraint type. There were an insufficient number of cases with airbag deployments that met the selection criteria, and consequently airbag-equipped cars are not put in a separate category.

Figure 1 shows the cumulative distribution of delta Vs from NASS 1990-95 by MAIS level for passenger vehicles (cars, passenger vans, pickups, and utility vehicles) whose occupants were estimated by NASS to have been restrained during the crash.

Figure 2 shows the cumulative distribution of delta Vs from NASS 1990-95 by MAIS level for cars (cars and passenger vans) whose occupants were estimated by NASS to have been restrained during the crash. The average CRASH3 delta V for the Institute's tests (cars only) is 43 km/h. About 33 percent of fatalities and 80 percent of MAIS 3+ injuries in cars occur below delta Vs of 43 km/h.

Figure 3 shows the cumulative distribution of delta Vs from NASS 1990-95 by MAIS level for pickup trucks and utility vehicles. The average CRASH3 delta V for the Institute's utility vehicle tests is 50 km/h. About 80 percent of fatalities and 75 percent of MAIS 3+ injuries in pickup trucks and utility vehicles occur below delta Vs of 50 km/h. Note, however, that the sample includes both restrained and unrestrained occupants and that the sample size was limited for this vehicle category, with only 18 fatal crashes and 81 MAIS 3+ injury crashes.

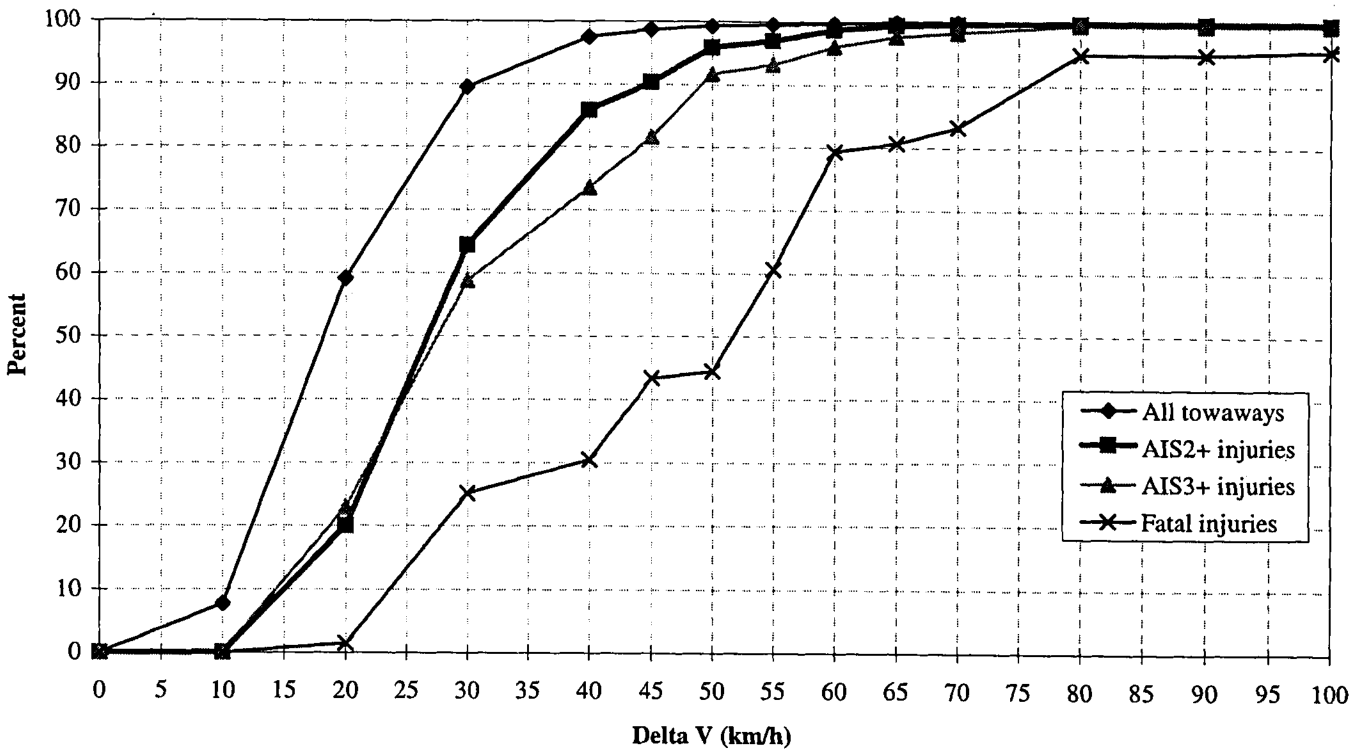

Figure 1. Cumulative Distribution of Delta Vs in Offset Crashes — Passenger Vehicles by Injury Severity, Belted Front-Seat Occupants.

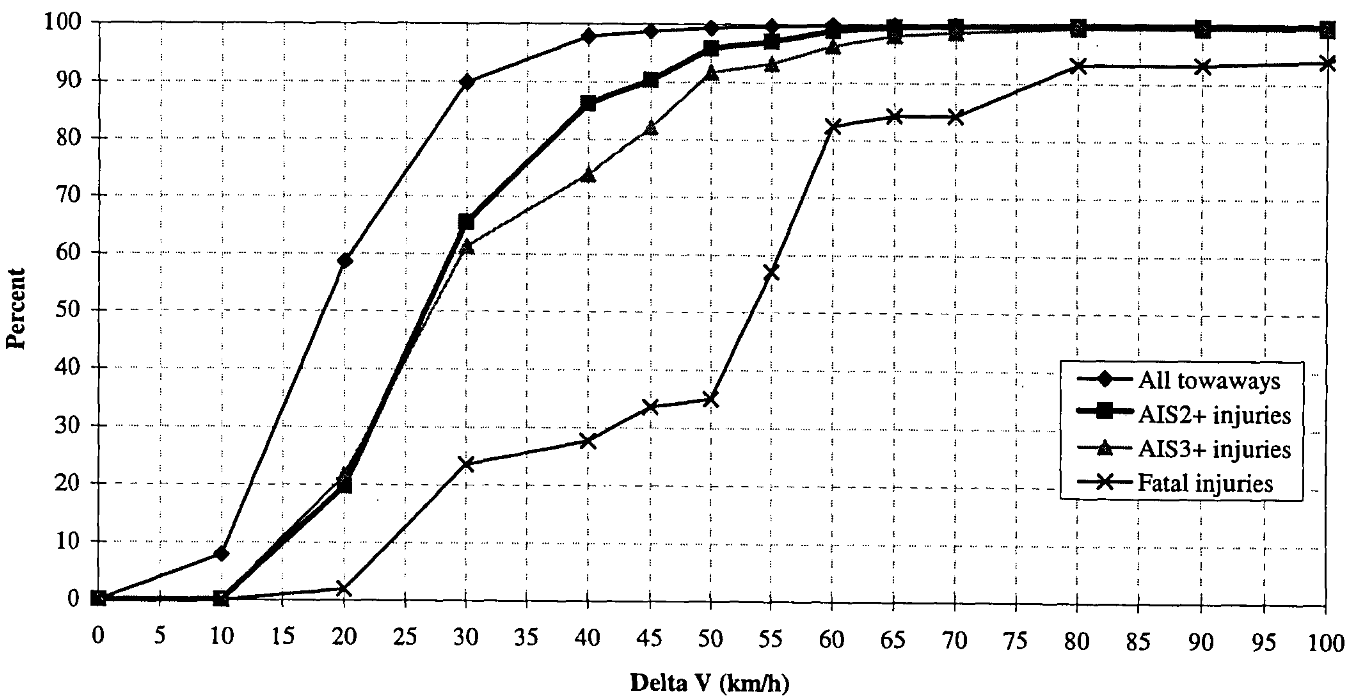

Figure 2. Cumulative Distribution of Delta Vs in Offset Crashes — Cars (Cars and Passenger Vans) by Injury Severity, Belted Front-Seat Occupants.

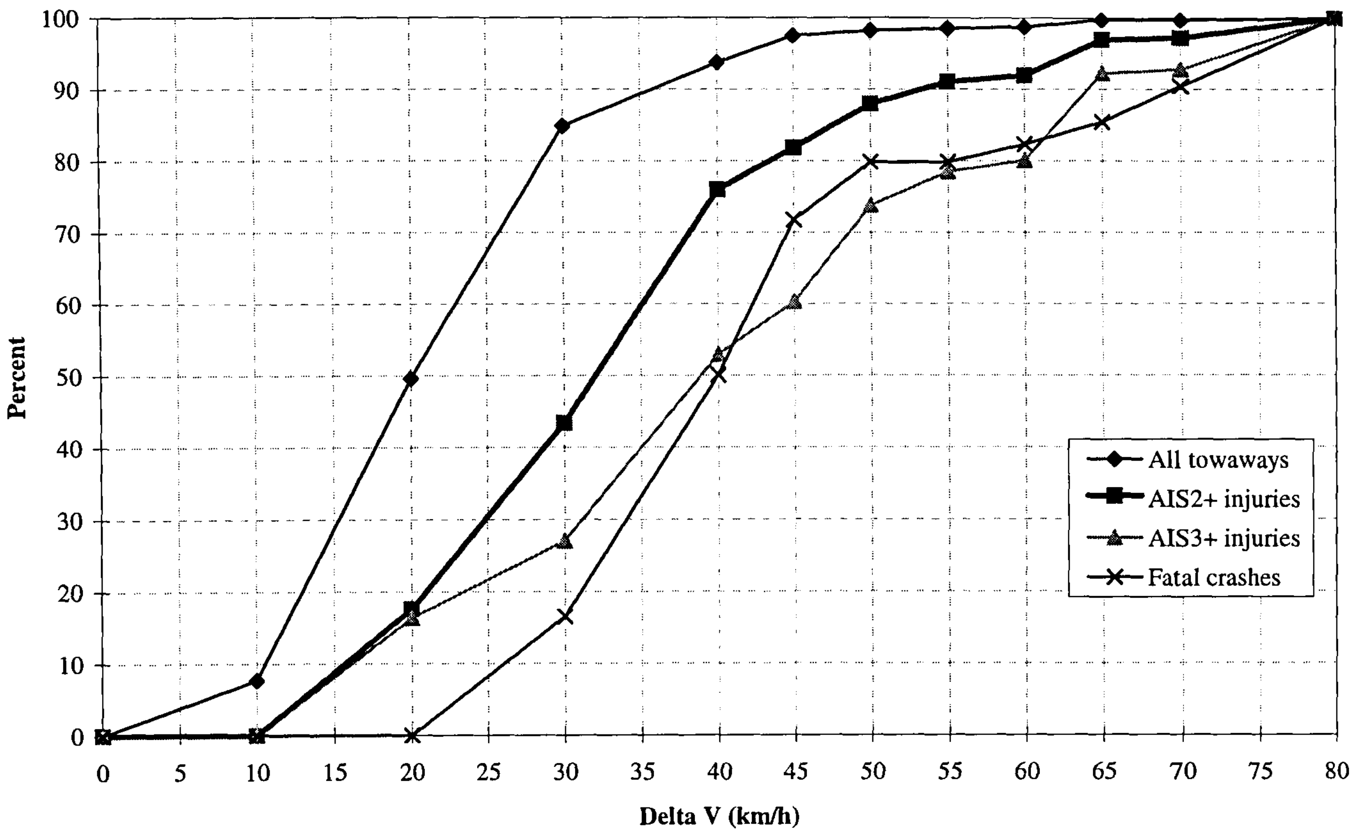

Figure 3. Cumulative Distribution of Delta Vs in Offset Crashes — Pickup Trucks and Utility Vehicles by Injury Severity, Belted and Unbelted Front-Seat Occupants.

DISCUSSION

Only in the special case of a full-width crash into a rigid barrier is delta V equal to impact speed. For a frontal offset crash, the delta V should be lower than the impact speed due to rotation of the vehicle. Even though delta Vs for offset crashes should be lower than the impact speeds, the estimates from CRASH3 are lower than the true delta Vs. Among new vehicles tested by the Institute, average CRASH3 delta Vs are 33 percent lower than impact speeds for cars, 22 percent lower for utility vehicles, and 10 percent lower for passenger vans. The delta V estimates obtained from SMASH, using vehicle-specific stiffness and size properties, are higher than the CRASH3 estimates, ranging 3-12 percent lower than impact speeds. The results from the SMASH program indicate that CRASH3 underestimates delta V because of poor pre-assigned stiffness and size category coefficients.

As offset crash testing becomes more common, it is imperative that investigators studying the relationship between such tests and real-world crashes be aware of the CRASH3 bias. For cars, about 80 percent of the significant injuries in real-world frontal offset crashes occur in crashes with severities at or below that represented by the Institute's frontal offset crash test. However, only about one-third of the occupant deaths in cars involved in frontal offset crashes occur with severities at or below that represented by the Institute's offset crash test speed. This latter estimate is lower than in the 1996 study (about 50 percent),[6] which may be due to the previous study's smaller sample size as well as the fact that the present study considered only NASS cases in which occupants were believed to be belted. These findings reinforce the conclusion that offset testing at a speed below 64 km/h would mean that new vehicle crashworthiness performance would be assessed at too low a severity level, and in effect would be a performance goal that would not address many of the serious injuries that occur in real-world crashes.

ACKNOWLEDGMENT

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THE ACCURACY OF CRASH3 FOR CALCULATING COLLISION SEVERITY IN MODERN EUROPEAN CARS

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ABSTRACT

CRASH3 is a computer program that enables a vehicle's change of velocity during a crash to be deduced from the observed damage to the vehicle(s) involved. Along with other programs that share similar mathematical techniques, it is widely used internationally, particularly by groups and individuals who have access to damaged vehicles but not the accident scene, and it is applied to a wide range of vehicles and accident circumstances. Crash tests conducted under controlled conditions provide an opportunity to assess the program's accuracy. In this paper CRASH3 is applied to vehicles tested during 1996-98 in the first three phases of the EuroNCAP program. This includes results from 26 models tested in 64 km/h offset frontal impacts and 50 km/h side impacts. On average, velocity changes were underestimated by 1 km/h for the side test and 7 km/h for the frontal test–this includes the effect of a special treatment of deformable barriers not available in the standard program.

INTRODUCTION

Improvements in car occupant protection rely on a close understanding of the events leading to injuries in real-world collisions. In-depth crash research aims to clarify the relationship between vehicle design, the injuries sustained by car occupants, and the injuries that are prevented. This relationship can be presented in the form of a dose-response model[1 2] with the injuries represented by the response. The dose is frequently a measure of the collision severity, i.e. some measure of the kinetic energy within the system.

Estimates of various collision severity measures provide a fundamental parameter for the assessment of the effectiveness of protection systems and are normally related to crash tests conducted for legal and vehicle design purposes.

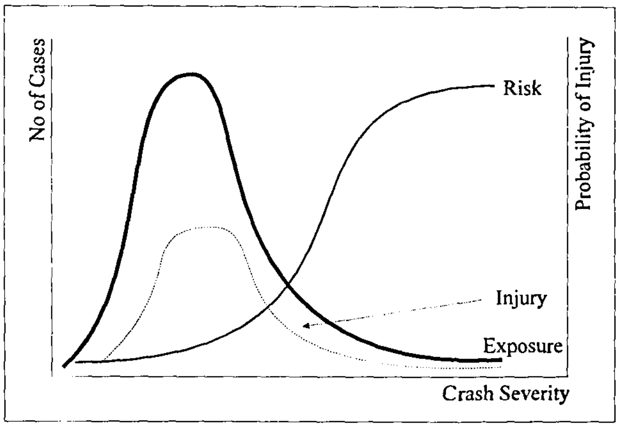


Figure 1. Characteristics of risk, exposure and injury curves.

A sample of real-world crash injury data can be collected either at the scene of the accident or by retrospective vehicle examination, and samples are most efficient statistically when the selection is made using stratified methods; additionally on-scene crash investigations can be highly expensive. Retrospective methods have been chosen by many crash injury data systems including the UK Co-operative Crash Injury Study, the US National Accident Surveillance System, Monash University in Australia and other groups. The main disadvantage of retrospective methods is that the opportunities for estimating collision severity are limited and the only possibilities are based on methods of assessing the energy required to cause the vehicle deformation. The CRASH3[3] programme was developed to provide such estimates using measurements of the vehicle damage, mass and force directions. The software includes a set of generic values of the stiffness of the vehicles that are used to calculate the deformation energy. These stiffness coefficients are based on a set of test collisions conducted in the late 1970s and early 1980s and the accuracy of the programme has been under assessment as vehicle design has progressed.

Smith and Noga[4] compared the predicted and measured results of the change of velocity during impact (delta-V) of 53 vehicles in 27 collisions with a variety of configurations and concluded that the 95% confidence limits lay within ±14% for collisions between 40 km/h and 48 km/h. Within the range 0-48 km/h CRASH3 underestimated the true value typically by 10% for the crashes examined.

The perspective of the crash reconstructionist, who may wish for accuracy in each individual crash, may be different from the safety researcher who deals with groups of crashes on a more statistical basis. Wooley, Warner and Tagg[5] reassessed Smith and Noga's work pointing out that some of the reconstructions could have an error exceeding 20% and therefore the accuracy of 10% could not be substantiated. This perspective was reinforced by Struble[6] who proposed developments in the programme to improve the accuracy in specific crashes.

Strother, Wooley and James[7] examined 402 NHTSA crash tests and concluded that CRASH3 overestimated the deformation energy of vehicles with low levels of crush and underestimated the energy required to cause higher crush levels. They suggested that the use of the generic stiffness coefficients could result in inaccuracies in the reconstruction of individual accidents. Neptune and Flynn[8] extended this view and suggested that the accuracy of the CRASH3 programme could be improved by the use of stiffness coefficients that related more exactly to the parts of the vehicle involved in the crush taking note of relatively stiff and relatively soft spots. Siddall and Day[9] also criticised the use of generic vehicle data that had not been updated since 1984 and proposed a revised set of vehicle parameters including stiffness coefficients.

The accuracy of CRASH3 has to be compared with that of other methods of collision severity assessment. Cliff and Montgomery[10] examined the accuracy of PC-Crash, a reconstruction programme widely used by reconstructionists in Europe. Using full scene and vehicle information to calculate pre- and post-impact velocities of 46 vehicles in 20 crash tests they estimated the pre-impact speeds and identified that PC-Crash typically underestimated the collision severity by 6%.

Alternative systems for the measurement of delta-V do exist. Kullgren[11] has developed a crash pulse recorder which employs photographic technology to record the acceleration of the vehicle over the crash phase. Integration of this data has been shown to provide a delta-V estimate with an error below 5%. Norin, Koch and Magnusson[12] have developed an equivalent system using the airbag module but no information has been published on its accuracy.

All of the assessments of the accuracy of CRASH3 have been conducted using vehicles within the US fleet. While some European vehicles may be included it is possible that the construction is different on account of the different legal requirements of the territories. Many European vehicles are not sold in the US and it is unlikely that they will have been considered in any US based assessment. The major driving factor in the performance of the vehicle structures for US vehicles are the requirements of FMVSS 208 and US NCAP. These are not requirements in Europe and vehicles may be designed with different criteria in mind. Since 1990, European consumer magazines[13] [14] have been regularly publishing the results of crash tests into a rigid barrier with only partial engagement of vehicle front. More recently the European Union has implemented a new Directive on frontal impact performance with effect from October 1998; this includes a collision into a deformable barrier at 56 km/h. Since 1997 the EuroNCAP consortium has been publishing crash tests into the same deformable barrier but at 64 km/h. At the same time the EU has also implemented a Directive requiring improved side impact protection. The performance of vehicles on European roads has perceptibly changed as a result, with the stiffness of the passenger compartment and the front end design adapted to the new tests. Consequently newer vehicles perform significantly differently from older vehicles. There is the implication that the stiffness coefficients within CRASH3 may no longer reflect the performance of European car design. This paper uses the available crash test data from EuroNCAP to evaluate the accuracy of CRASH3 with modern European vehicles.

METHOD AND TECHNICAL PREAMBLE

The Meaning Of Delta-V

A number of speed-related measures of impact severity have been introduced into the field of accident investigation over the years, including delta-V (ΔV), energy equivalent speed (EES), equivalent test speed (ETS), equivalent barrier speed (EBS), and barrier equivalent velocity (BEV). Unfortunately the literature betrays a lack of common understanding of these terms and it is therefore necessary to take care with their use. In this paper, only delta-V is discussed, and its meaning is drawn from the conventions of standard physics. Delta-V is a *vector*; in other words it is a quantity with magnitude (e.g. 50 km/h) and direction (e.g. northwards). More specifically, it is the *vector difference* between an initial velocity and a final velocity, as indicated in figure 2.

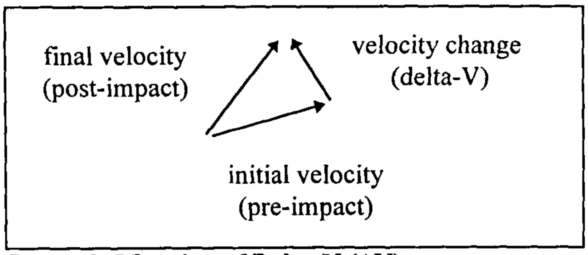


Figure 2. Meaning of Delta-V (ΔV)

The initial and final velocities are the *instantaneous velocities* of the centre of mass of the crash-tested vehicle immediately before and after impact with the deformable barrier. A definition of *instantaneous velocity* may be found in any physics textbook: the intuitive notion of travelling a certain speed in a certain direction at a certain time, e.g. 50 km/h northwards, is apropos. The beginning of impact is when contact is first made. The end of impact may be slightly vague, but when the vehicle separates from the barrier, or when the force on the vehicle from a side impact trolley is similar in magnitude to the frictional forces on the vehicle from the floor, the impact is over. In this sense, the impact is over before a side impact trolley and crash-tested vehicle come to rest.

The direction of delta-V is often not stated, especially when it may be implicitly understood. In the frontal EuroNCAP test, the moving vehicle is essentially brought to rest (possibly with some rebound and sideways deflection) by the immovable barrier, and so delta-V is "negative", i.e. directed opposite to the vehicle's original line of travel. In the side test a moving trolley pushes the stationary vehicle laterally, and so the vehicle's delta-V is directed along the trolley's line of travel. Throughout this paper, the focus on the magnitude of delta-V rather than its direction–this should not be interpreted as a departure from the vector nature of delta-V.

Test Delta-V and CRASH3 Delta-V

Test delta-V. The change of velocity, delta-V (ΔV), is the difference between a vehicle's immediate pre-impact and post-impact velocities. Ideally these would be directly measured during the test. No measurements of post-impact velocity were available for this paper. In the absence of better information, the frontal impact vehicles were assumed to be brought to rest by the barrier impact. This is accurate if any post-impact rebound or "glance-off" speed is negligible compared to the initial speed of 64 km/h. If the vehicles rebound, their true delta-V is higher; if they glance off (forwards) their delta-V is lower. It may readily be seen that our best assessment of a vehicle's true change of velocity in the frontal impact test is closely related to the pre-impact or test velocity: equal in magnitude, opposite in direction. Apart from this coincidence, the pre-impact velocity has no intrinsic importance for the evaluation of CRASH3. The damage-based algorithms of CRASH3 and similar programs are directed towards the estimation of delta-V, not the pre-impact or post-impact velocity.

The side impact vehicles are accelerated sideways by the trolleys. In the absence of direct measurements, an estimate of the velocity they attain may be obtained from the principle of *conservation of momentum*: the combined mass of the trolley and car multiplied by their (shared) velocity after impact equals the mass of the trolley multiplied by its initial velocity:

$$(m_{car} + m_{trolley}).v_{final} = m_{trolley}.v_{trolley}$$

The car is initially stationary, so:

$$\Delta V_{car} = v_{final}$$

This is accurate if the separation speed, if any, of the trolley and car after impact is negligible. If the car rebounds, its delta-V is higher. The value of delta-V obtained this way is referred to here as the *test* delta-V. For the purpose of evaluating the damage-based algorithm of CRASH3, it may be regarded as the true value of delta-V. Even if it is not exactly right, it is considerably more reliable and accurate than one can hope to achieve from vehicle damage. To illustrate, the test delta-V for a vehicle of mass 1100Kg in a EuroNCAP side impact test would be:

$$m_{car}.v_{car} + m_{trolley}.v_{trolley} = (m_{car} + m_{trolley}).v_{final}$$

$$0 + 950.50 = (1100 + 950).\ v_{final}$$

$$v_{final} = 23.1 \text{ km/h}$$

The car is initially at rest, so:

$$\Delta V_{car} = v_{final}$$

$$\Delta V_{car} = 23.1 \text{ km/h}$$

CRASH3 delta-V. CRASH3, like other similar programs, is designed to estimate a crashed vehicle's change of velocity during impact. It suffices to gauge the program by its success in accomplishing this goal. In this paper the term *CRASH3 delta-V* refers to nothing else but the estimate of a crashed vehicle's delta-V obtained using the damage-based algorithm of the program.

The Estimation Of Delta-V From Vehicle Damage

It is not the purpose of this paper to conduct a general review of the theory and practice of estimating delta-V from vehicle damage; however the wide range of opinions from critics and proponents of CRASH3 and similar programs warrants a few remarks. The program enables delta-V to be calculated from vehicle damage and other data not pertaining to the scene of the accident. It is essential to distinguish (a) the scientific or physical *principles* of CRASH3, (b) the *scope* of CRASH3–the range of crashes to which it may be applied–and (c) and the *accuracy* of CRASH3.

The basic principles upon which CRASH3 is founded are sound: mathematically, scientifically, technically, and to whatever other high standard one would wish to nominate. The principles may be found in elementary physics books covering Newtonian mechanics. If the 'inputs' are known for all vehicles or objects involved in the collision, it is possible to obtain a calculation of delta-V, properly defined as the vector difference between the vehicle's immediate pre-impact and post-impact velocities. The program must have some means of assessing the total energy dissipated in the collision–for this it uses crush profile–and it must be given the direction of impact force, among other things. The program does not require any specification of the pre-impact or post-impact velocities, either in direction or magnitude.

There are limitations to the scope of CRASH3, and the program has been misused by both its proponents and detractors. Two requirements are (a) that the vehicle damage provides a suitable basis for assessing the energy dissipated and (b) that the contacting surface of the vehicle reaches a common velocity with the surface of the object struck. Under-runs, sideswipes, and highly offset or highly oblique impacts, among others, may violate these conditions. If so, the program should not be run at all. It is no criticism of the program to point out that it delivers inaccurate results for crashes to which it is inapplicable. Except for not containing a model of the deformable barriers, the program is applicable to the EuroNCAP test configurations.

The accuracy of CRASH3 is the accuracy of its estimates of delta-V, i.e. the closeness of the calculated velocity change to the vehicles' true change of velocity (in practice, not usually known). The program's accuracy is highly influenced by its 'built-in' model of the relationship between vehicle damage (crush profile) and energy dissipated. Much of the point of checking the accuracy of the program against crash-tested vehicles is to assess whether modifications need to be made to this relationship. The results described in this paper bear upon the accuracy of CRASH3 and in particular upon the accuracy of the deformation-energy relationship. Such investigations have been reported before, but changes in vehicle fleets over time and in different places demand a continuing effort. It would be laudable if all methods of estimating delta-V were subjected to the same rigours.

Energy Dissipated By Deformable Barrier

When programs such as CRASH3 are used to calculate delta-V for any given vehicle, the energy dissipated or absorbed by *all* vehicles or objects involved in the collision must be taken into account. For the EuroNCAP tests, this means the energy dissipated by the deformable barriers must be included in the calculation of delta-V. The standard version of CRASH3 has no capacity to model the EuroNCAP deformable barriers. This was done separately and the result, energy dissipated, was entered to a modified version of the program. The method used was to take crush profiles of the barrier blocks still available from the crash tests, and integrate (pseudo-static) force-deflection curves to obtain estimates of the energy dissipated by the barriers. This technique is very similar to the method used within the program to deduce the energy dissipated by the vehicles. Where the blocks were no longer available, an average value was used as the best estimate.

EuroNCAP Deformable Barrier Elements					
	Height (m)	**Width (m)**	**Depth (m)**	**Crush strength (kN/m²)**	
Front: main block	0.65	1.00	0.45	342	
Front: bumper element	0.33	1.00	0.09	1711	
				Stiffness coefficients*	
	Height (m)	**Width (m)**	**Depth (m)**	**a (kN)**	**b (kN/m)**
Side: lower (centre)	0.25	0.50	0.50	0	380
Side: lower (outer)	0.25	0.50	0.50	3	160
Side: upper (centre)	0.25	0.50	0.44	0	81
Side: upper (outer)	0.25	0.50	0.44	0	69

Figure 3. EuroNCAP barrier properties. **Valid to crush of 0.30 m; for the lower (centre) block, 0.16 m.*

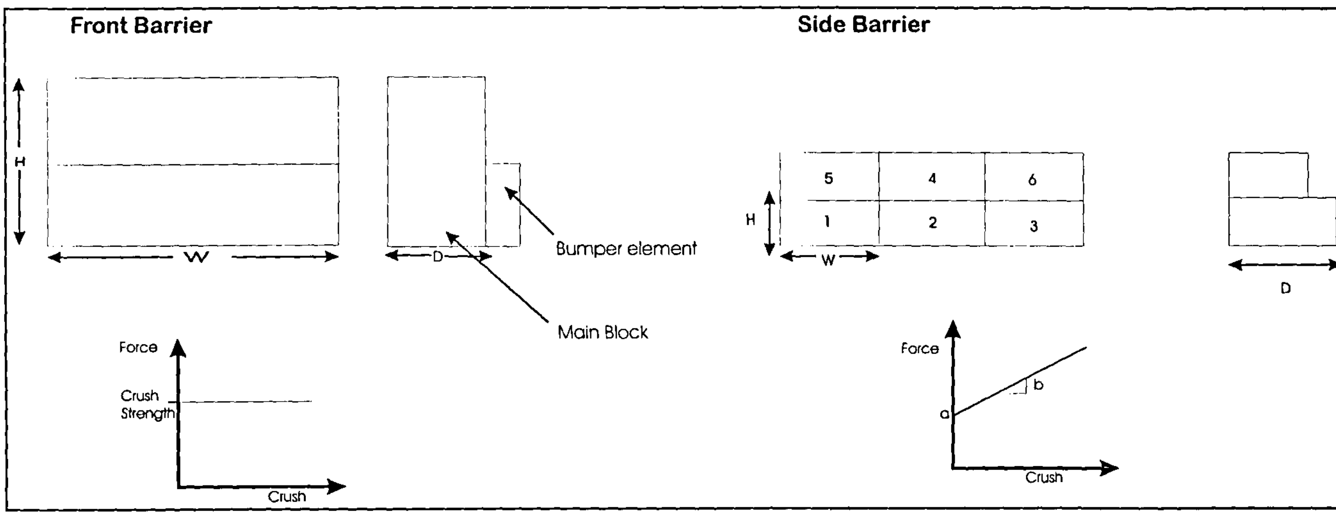


Figure 4. Schematic views of front and side impact blocks with schematic force-deflection curves

The properties of the deformable barrier elements used for estimating the energy dissipated by the barriers are shown in figure 3. These express pseudo-static force-deflection characteristics.

The constant crush strength characteristic of the two frontal barrier components are represented by the flat curve of figure 4. For these components, only the volume of crush is required for an estimation of energy dissipated (E):

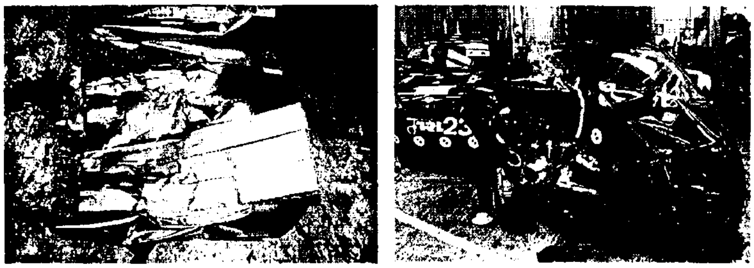
$$E_{barrier} = (\text{crush strength}) . (\text{volume of crush})$$

The volume of crush was determined by taking crush measurements at a number of points over the surface of the deformed barrier elements.

The force-deflection curves of the side impact barrier blocks have a linear slope, and more complicated equations are needed to ascertain the energy dissipated. (These are the same as CRASH3 applies to the vehicles.) Energy is represented by the area under the force-deflection curve. The energy dissipated between two points with crush C_1 and C_2 is given by:

$$E = (a\,(C_1+C_2)/2 + b\,(C_1^2 + C_1C_2 + C_2^2)/6)\,d$$

where d is the distance between the measures and the stiffness coefficients a and b are scaled to a 'per unit length' value. Further details of the method are available in the literature. Three-point crush profiles of each of the six side barrier components were measured and used to obtain an estimate of the energy dissipated by the side impact barriers.

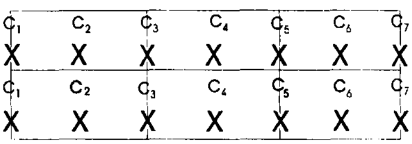


Volume of crush of Main Block = 40%, Energy dissipated by Main Block (E_M) = 40kJ

Volume of crush of Bumper Elements = 5% , Energy dissipated by Bumper Elements (E_B) = 2.5kJ

Total Energy dissipated by Frontal impact barrier = $E_M + E_B$ = 42.5 kJ

Figure 5. Frontal impact EuroNCAP vehicle and corresponding barrier with sample barrier energy calculation



	C_1	C_2	C_3	C_4	C_5	C_6	C_7
Upper Blocks	0.28	0.18	0.13	0.17	0.16	0.14	0.22
Lower Blocks	0.24	0.15	0.11	0.13	0.15	0.23	0.25

Crush to Energy relationship: $E = (a\,(C_1+C_2)/2 + b\,(C_1^2 + C_1C_2 + C_2^2)/6)\,d$

	Block 1	Block 2	Block 3	Block 4	Block 5	Block 6	Total Barrier
Energy (kJ)	1.6+0.7 = 2.3	1.1+1.4 = 2.5	0.8+1.5 = 2.3	0.4+0.5 = 0.9	0.9+0.4 = 1.3	0.4+0.6 = 1.0	10.3

Figure 6. Side impact EuroNCAP vehicle and corresponding barrier with sample barrier energy calculation.

RESULTS

The EuroNCAP frontal test specifies a 40% offset impact into an immovable deformable barrier, with a vehicle impact speed of 64 km/h. In the side impact test, a 950 kg trolley fitted with a deformable front block moves parallel to the lateral axis of the car and strikes the passenger compartment with a speed of 50 km/h.

Table 1. Energy absorbed by vehicles and barriers

	Vehicle (kJ)		Barrier (kJ)	
NCAP	Average	Range	Average	Range
Front	116	55-176	45	37-56
Side	33	18-51	13	6-18

Table 1 shows the calculations of the energy dissipated by the vehicles and deformable barriers. In both tests the barriers absorb about 30% of the total impact energy.

Figure 7 shows CRASH3's estimate of velocity change against the 'true' test value. Points above the diagonal line are overestimates of delta-V while points below the line are underestimates. The higher cluster of points are results from frontal impact testing and the lower cluster of points are from side tests. The average of the frontal test estimates is 7 km/h low with a scatter of ±10 km/h. The centre of the side test estimates is 1 km/h low with a scatter of ±5 km/h.

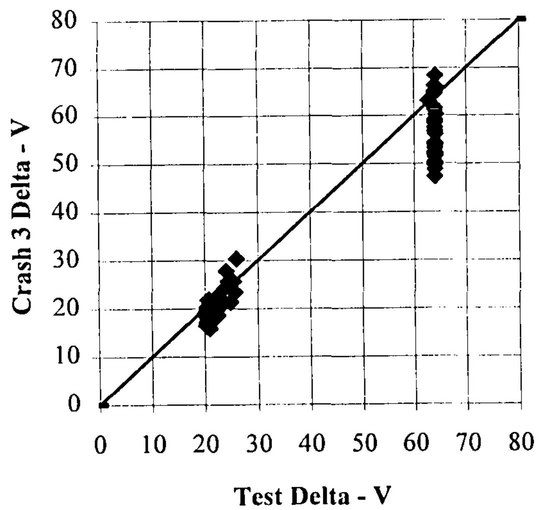


Figure 7. True velocity change vs Crash3 estimate

DISCUSSION

The side impact results are as accurate as one could realistically hope to achieve, and call for no remedial action. The main question here is whether additional side impact calculations at other speeds and with other objects will also work out well.

The underestimation of delta-V for the frontal vehicles indicates that there is more energy around than CRASH3 'realises'. To be more precise, the program underestimates the total amount of energy dissipated by the crashed vehicle and deformable barrier. Part of the discrepancy may lie in the estimation of barrier energy, which was calculated independently of CRASH3 and entered into a modified version of the program. It would be helpful to have the dynamic force-deflection or crush-energy characteristics of the deformable barrier elements determined directly by impact tests. Even without this, there are techniques used in branches of engineering that may assist in extrapolating from pseudo-static tests to dynamic performance. Some of the barrier elements crushed in a manner most unlike their pseudo-static response, with tearing, gouging, and swaying–for these cases any analytic method is subject to a considerable degree of uncertainty.

The shortfall in estimated energy could of course also arise from the relationship between vehicle damage and energy implicit in the program. This relationship is currently expressed by stiffness coefficients, as described above, although if better correlations could be found, CRASH3 could be modified to adopt them. Underestimating delta-V implies that one or both of the stiffness coefficients used by CRASH3 is too low. The coefficient *a* referred to in figure 4 expresses the degree of elastic rebound of the vehicle's front end (the difference between maximum dynamic crush and post-impact residual crush) and the coefficient *b* expresses the vehicle's increasing resistance to deformation; so the vehicles with delta-V calculated too low are either more elastic or stiffer than CRASH3 assumes.

The stiffness values of the vehicles tested could be adjusted–either individually or as a group–to align the CRASH3 estimate of delta-V with the test value. Calibrating CRASH3 in this way would improve the assessment of energy dissipation for crashed vehicles that resemble EuroNCAP frontal impact vehicles, with correspondingly favourable implications for the program's estimation of velocity change. Work is continuing, however, to check the accuracy of CRASH3 against a considerably wider variety of crash tests; and a better basis for modifying the front (and other) stiffness coefficients of modern European cars should exist in the relatively near future.

Even without introducing custom stiffness coefficients, the results obtained in this paper may still be used to interpret data from CRASH3 and similar programs. It is likely that the energy calculated for vehicles from real crashes that resemble the EuroNCAP vehicles in damage is systematically underestimated by the equivalent of about 7 km/h for frontal impacts, but fairly accurate for side impacts. This applies to modern European vehicles. The likely scatter of CRASH3's estimation of delta-V under these circumstances is about ±10 km/h for the frontal impact and ±5 km/h for the side impact. As more crash test results are incorporated into the continuing work being carried out for the UK Co-operative Crash Injury Study, it will be possible to comment on a wider range of impact types.

The crush profiles of the damaged vehicles tested under EuroNCAP were collected by a number of investigators, working under time pressure and circumstances comparable to those in the field. The scatter of CRASH3 results is therefore representative of data collected under normal working conditions rather than the best that could conceivably be achieved from inspecting vehicles under 'laboratory conditions'.

CONCLUSION

Under conditions of a 40% offset, 64 km/h frontal impact into a immovable deformable barrier, the accident reconstruction program CRASH3 underestimates the change of velocity for modern European vehicles by about 7 km/h with a scatter of ±10 km/h. For a side impact from a 950 kg movable deformable barrier at 50 km/h, the CRASH3 estimate is about 1 km/h low with a scatter of ±5 km/h. This includes the effect of providing the program with an estimate of the energy dissipated by EuroNCAP deformable barriers, which is not within its normal capability. Further work progressing for the UK Co-operative Crash Injury Study will broaden the scope of these conclusions to a wider diversity of crash test types.

ACKNOWLEDGEMENTS

The Co-operative Crash Injury Study is managed by the Transport Research Laboratory on behalf of the Department of Environment, Transport and Regions (Vehicle Standards and Engineering Division) who fund the project with Ford Motor Company Ltd, Rover Group, Toyota Motor Europe, Nissan Motor Company, Honda R&D Europe, and Daewoo Motor Company. The crash injury data was collected by teams at the Vehicle Safety Research Centre at Loughborough University, the Accident Research Centre at the University of Birmingham, and from the Vehicle Inspectorate. Crash test data was provided by EuroNCAP and other funding organisations.

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A REVIEW OF CRASH SEVERITY ASSESSMENT PROGRAMS APPLIED TO RETROSPECTIVE REAL-WORLD ACCIDENT STUDIES.

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Paper Number 98-06-O-09

ABSTRACT

In-depth, retrospective accident investigation studies provide a means to understand how car occupants are injured in road traffic accidents. In most retrospective studies, crash severity is estimated using the CRASH3 computer program.

This paper gives a brief description of CRASH3, and sets out how it is used by retrospective accident investigation studies. The effects of variations in the data input by accident investigators on results from CRASH3 were investigated. Variations in vehicle damage profile measurements and the application of a single stiffness class to front wheel drive vehicles involved in frontal impacts were looked at specifically. Based on the findings of these investigations, recommendations for the use of CRASH3 in retrospective accident investigation are then given.

INTRODUCTION

Many scientists, engineers and legislators are working towards reducing the frequency and severity of injuries to motor-vehicle occupants involved in road traffic accidents.

In-depth, retrospective accident investigation studies provide a means to understand how car occupants are injured in crashes. In these studies, detailed examinations of the accident damaged vehicles are correlated with occupant injury records. This is done to determine the causes of injury to car occupants.

It is important to gain a measure of crash severity. In most retrospective studies, this is done using a computer program.

Crash Severity Assessment Programs

There are various computer programs available that can be used for the purpose of assessing crash severity, for example, CRASH3, EDCRASH, SLAM for Windows, PC-CRASH and AiDamage. CRASH3, EDCRASH and SLAM for Windows are similar programs, and are discussed in this paper. Although capable of crash severity assessment, PC-CRASH is more focused on accident reconstruction, and is therefore not discussed in this paper. AiDamage is a crash severity assessment tool, and was developed in the UK. This program is not discussed in this paper because it will be reviewed at a later date.

CRASH was developed to assist investigators to assess the severity of motor vehicle crashes. "CRASH" is an acronym for "Calspan Reconstruction of Accident Speeds on the Highway". It was developed throughout the 1970s, on behalf of the United States' Government. By the 1980s, the CRASH program was developed to its third revision - CRASH3 [1].

Data relating to the damage sustained by the vehicle are entered into the program. These data consist of a code describing the damage location and type, and measurements of the damage profile. The program then calculates estimates of crash severity.

CRASH3 has been criticised because the stiffness coefficients and other default data used by the algorithms are considered very much out of date. The program does not have a facility to substitute for the default data. This does not allow proper interpretation of the crash severity estimates to be produced.

EDCRASH is an up-to-date version of the CRASH3 program. This is part of a suite of crash and accident reconstructional aides developed by the Engineering Dynamics Corporation. As computers developed, so too did the CRASH program. The program was no longer tied to a mainframe computer - desktop computers became a viable medium for the program. As a result, graphics and more streamlined calculations were introduced [1], but to calculate estimates of crash severity, the same algorithms as CRASH3 are used.

SLAM for Windows is another version of the CRASH3 program. This was developed by AR Software. SLAM uses a Windows based rather than a DOS based environment. It, too, uses the same algorithms to calculate estimates of crash severity.

The use of the CRASH3 Program in European Accident Investigation Studies

The Co-operative Crash-Injury Study (CCIS) is the UK's largest retrospective accident investigation study. It has been in its current form since 1983. Its sixth phase begins on 1st June, 1998.

The study is funded by the UK's Department of Environment, Transport and the Regions (DETR), and is currently co-sponsored by six motor manufacturers: Ford, Rover, Honda, Toyota, Nissan and Daewoo.

The study is managed by the Transport Research Laboratory, in Berkshire, England. Data are collected, from various locations around England, by five teams from the Vehicle Inspectorate Executive Agency and two University based teams - the Birmingham Accident Research Centre (BARC), Birmingham University, and the Vehicle Safety Research Centre (VSRC) of the Institute of Consumer Ergonomics, Loughborough University.

The study has used CRASH3 as a tool to provide an estimate of impact severity throughout the lifetime of the project.

Recently, work was undertaken to investigate the possibility of harmonising crash investigation within Europe. Those aspects which were common to Europe's three main studies - the Co-operative Crash-Injury Study (UK), BASt (Germany) and INRETS (France) - were sought. CRASH3 and PC CRASH were identified as the crash severity assessment tools used. The results from each program are comparable with the other as each program uses the same algorithms to calculate Delta-V and ETS [4].

Purpose of this paper

Since it forms the basis of most crash severity assessment programs, this paper gives a brief description of CRASH3, and sets out how it is used by retrospective accident investigation studies. The data input to CRASH3 by accident investigators will have an effect on the results it produces. Two sources of data input are investigated: variations in damage profile measurement and the application of a single stiffness class applied to front wheel drive vehicles involved in frontal impacts. Recommendations for the use of CRASH3 by retrospective accident investigation studies, particularly those in Europe, are then given.

A DESCRIPTION OF CRASH3

The basic function for which the CRASH3 program is used in retrospective accident investigation studies is to calculate the linear impulse that each vehicle involved in a crash experiences. This is calculated by assuming the conservation of linear momentum. In addition, the amount of energy used in damaging the vehicle(s) is calculated using a relationship between the stiffness of the vehicle, the amount of deflection and the area over which the damage is sustained. A complete explanation of the exact calculations used are given in the CRASH3 user guide and technical manual [5].

Data Application

The following are the assumptions made by the CRASH3 program. These must be understood if the program is to be used effectively [3]:

1. The effects of road incline and camber and are ignored by the program.
2. Transfers of load distribution within the vehicle and suspension effects during acceleration are ignored
3. the driver is assumed not to control the vehicle (steering and braking).
4. The force - deflection characteristic of the vehicle is assumed to be linear.
5. The crush profile measurement points are taken at single heights; this means that the program does not account for vertical variations in crush profile.
6. The vehicles are assumed to reach a common velocity during the impact; this means that the program is not appropriate for sideswipe impacts.
7. There is negligible ground friction force, between tyre and ground, or vehicle structure and ground, during impact.
8. Vehicle data for a particular size of vehicle is based on the averages of crash test results from a range of vehicles of that size classification.
9. There is negligible elastic recovery of the vehicle structure.

Data Input

Scene data, e.g. impact and rest positions of vehicles, cannot be collected for use within retrospective investigation studies. This means that for use within such studies, the CRASH program has only vehicle damage data available to use in its calculations. The program has been designed so that this is possible. The algorithm that makes use of vehicle damage data is called the DAMAGE algorithm.

Data required for the DAMAGE algorithm of the CRASH program are:

- A Collision Deformation Classification (CDC) - a seven character code which describes the principal direction of force applied to the vehicle, the location of the damage, the type of impact, and a zone in which the damage was sustained. SAE J224 Mar 80 describes this coding system in detail.
- Measurements of the vehicle damage profile (six measurements known as C1 to C6) - this profiles the amount of damage sustained by the vehicle.
- The stiffness classification of the vehicle - these are selected according to the vehicle's size, which is based on the vehicle's wheelbase.
- The mass of the vehicle.

Data Output

The outputs from CRASH3 are Delta-V and ETS. A description of each of these follows.

Delta-V has been defined as "the change in velocity of a vehicle's occupant compartment during the collision phase of a motor vehicle crash (i.e. from the moment of initial contact between vehicles until the moment of their separation)" [2]. Delta-V can be calculated by CRASH3 when data for two vehicles that have crashed with each other are available.

ETS has a similar definition to Delta-V. However, it is calculated when data for only one vehicle are available. In this case, the results given by CRASH3 are intended to be those equivalent to the vehicle being crashed into a rigid barrier. These results have various references: ETS - Equivalent Test Speed; EBS - Equivalent Barrier Speed; EES - Equivalent Energy Speed. They all refer to the same output produced by CRASH3. For the remainder of this paper, this particular output will be referred to as ETS.

Interpretation of Delta-V and ETS

It is desirable to calculate an ETS even when a Delta-V is calculated. Hence, the ETS provides retrospective accident investigation studies with a consistent estimate of crash severity, regardless of whether all collision partners were seen.

Users of data which contain reference to crash severity estimated by the CRASH3 program should be aware that the outputs, Delta-V and ETS, are indeed only estimates. The principles used by the program when calculating Delta-V and ETS are correct, but have limitations.

As already stated, the program makes assumptions on which to make its calculations feasible. One of these assumptions states that, for a particular size class, the vehicle data used by the program is based on the averages of crash test results from many vehicles of that size classification - it is applying its calculations to a 'typical' vehicle.

These data, such as vehicle stiffness, are based on 'typical' vehicles in the United States from the 1970s, when the program was developed. These are inevitably different to vehicles in the 1990s. The user must be aware of this when applying the CRASH3 program today, particularly to European vehicles. This topic is not dealt with in this paper, but is dealt with in the paper, "The accuracy of CRASH3 for calculating collision severity in modern European cars" [6].

The output will also be influenced by the data input by investigators - i.e. the CDC, stiffness class, size class, vehicle mass and the damage profile measurements. The data output can only be as good as the data input.

APPLYING CRASH3

The following sections detail how measurement and stiffness class can affect the accuracy of results given by the CRASH3 program.

Effect of variations in measurement on Delta-V and ETS

In order to investigate the influence of measurement on Delta-V and ETS, a frontal, more than two-thirds distribution impact, applied to the stiff structure level of the vehicle, with a moderate amount of deformation was selected. This was represented by a CDC of 12FDEW3. Measurements representing different size classes of vehicle were applied, along with the CDC to the CRASH3 program. The measurements were then adjusted varying up to ±25cm. Table 1 shows the measurements that were used.

Table 1.
Nominal Input Data for Assessing CRASH3 Data Output from Toleranced Measurements

Size class	Damage width (cm)	C1 (cm)	C2 (cm)	C3 (cm)	C4 (cm)	C5 (cm)	C6 (cm)
1	175	0	6	12	18	24	30
2	180	0	8	16	24	32	40
3	185	0	10	20	30	40	50
4	190	0	12	24	36	48	60
5	195	0	14	28	42	56	70
6	200	0	16	32	48	64	80

For a tolerance of -5cm to +10cm on the nominal measurement, the variation in ETS is less than 1km/h per cm variation in measurement. This is illustrated in Figure 1.

Variation in ETS due to stiffness class

Many European vehicles have front wheel drive transmission. For frontal impact configurations, the CRASH3 program assumes a single stiffness category for such vehicles, regardless of their size. This is because the transmission is assumed to become involved in the deformation phase of the impact. The effect that this categorisation makes to ETS was investigated.

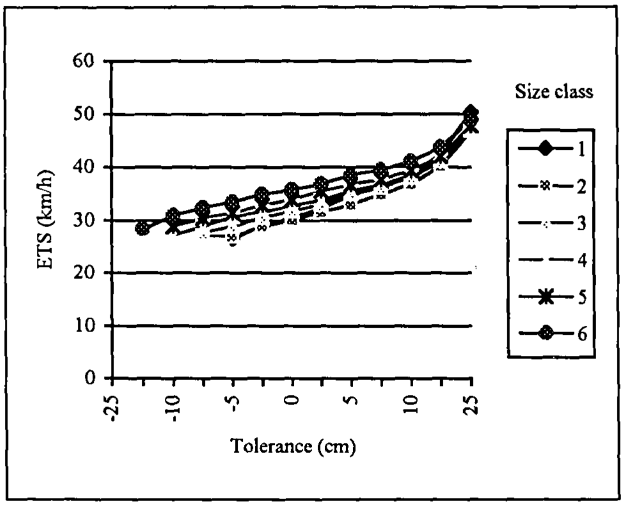

Figure 1. Results from CRASH3 using a range of measurements.

A CDC representing a frontal, more than two-thirds distribution impact, applied to the stiff structure level of the vehicle was selected: 12FDEW_. CRASH3 was run, using the CDC only, for increasing amounts of deformation, represented by each extent code: 1 to 9.

This was repeated for the smallest size vehicles, i.e. size class 1, medium sized vehicles, i.e. size class 3 and large vehicles, i.e. size class 6, using default data from the program. The comparison was made for stiffness class for the size of the vehicle, and for the stiffness class representing a front wheel drive vehicle.

For a large, front wheeled drive vehicle in a frontal impact, the results show a higher ETS from CRASH3 than a rear wheel drive vehicle, of the same size, with the same CDC. This is illustrated in Figure 2.

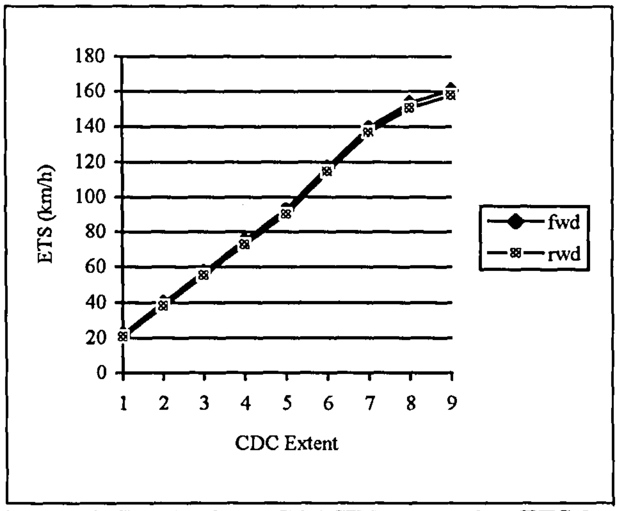

Figure 2. Results from CRASH3 comparing ETS for front wheel versus rear wheel drive vehicles, size class 6, with a CDC of 12FDEW_.

This suggests that a large, front wheel drive vehicle is slightly more stiff than the equivalent rear wheel drive vehicle. The shape of the curves up to extent zone 5, which corresponds on a vehicle to the bulkhead / bottom of the windscreen, show a linear increase in ETS. This illustrates the program's assumption that the force - deflection characteristic of the vehicle is linear. For extent zone 6, which represents the section of the vehicle defined by the windscreen, the gradient of the curves increase. This suggests that the vehicle is assumed to become stiffer beyond the bulkhead. The gradient decreases again for extent zones 7 to 9 (representing from the header rail to beyond the B pillar).

For a medium size vehicle, and a small vehicle, the shape of the curves are identical to that for a large vehicle. However, for a medium size vehicle, the results suggest that the front wheel drive vehicle is slightly more stiff than the equivalent rear wheel drive vehicle for zone 1 - which corresponds to one fifth of the length of the bonnet, at the front of the vehicle - only. Beyond this zone, the equivalent rear wheel drive vehicle is more stiff than the front wheel drive vehicle.

A similar effect is seen for a small vehicle, with the change occurring beyond zone 3. Figures 3 and 4 illustrate these results.

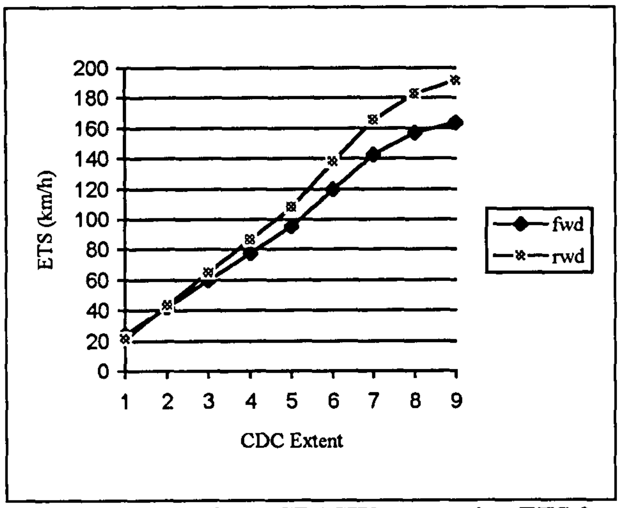

Figure 3. Results from CRASH3 comparing ETS for front wheel versus rear wheel drive vehicles, size class 3, with a CDC of 12FDEW_.

CONCLUSIONS

1. Within the tolerance range of -5cm to +10cm on nominal vehicle measurements, CRASH3 gives less than 1km/h variation in ETS per cm variation in measurement.

2. CRASH3 assumes front engined front wheel drive vehicles involved in frontal impacts have a single stiffness category . If the equivalent rear wheel drive vehicle is compared with a front wheel drive vehicle, following this rule, the following are observed:

- Large vehicle (size class 6) - a front wheel drive vehicle appears to be more stiff than an equivalent rear wheel drive vehicle for any amount of deformation.
- Medium vehicle (size class 3) - a front wheel drive vehicle appears to be more stiff than an equivalent rear wheel drive vehicle for a small amount of deformation, i.e. up to extent zone 1, only. Beyond this, the equivalent rear wheel drive vehicle appears to become considerably stiffer than the front wheel drive vehicle.
- Small vehicle (size class 1) - a front wheel drive vehicle appears to be more stiff than an equivalent rear wheel drive vehicle for a moderate amount of deformation, i.e. up to extent zone 3. Beyond this, the equivalent rear wheel drive vehicle appears to be slightly stiffer than the front wheel drive vehicle.

An important note to make here is the significance of entering damage profile measurements into the CRASH3 program. The program will make an estimate of Delta-V and ETS from a CDC alone. In this case, the program will call upon its default data. As the default data has been compiled as data for a 'typical' vehicle, it is advantageous to be able to enter more relative information. Hence, taking and entering damage profile measurements will inevitably improve the accuracy of the estimate from CRASH3.

3. The CRASH program has been used by the CCIS since it began in 1983. To change to a program with different approach to calculation of Delta-V and ETS would make any future data less compatible with data already held.

4. The three main crash investigation studies in Europe all make use of the same algorithms to calculate Delta-V and ETS, and hence estimate crash severity.

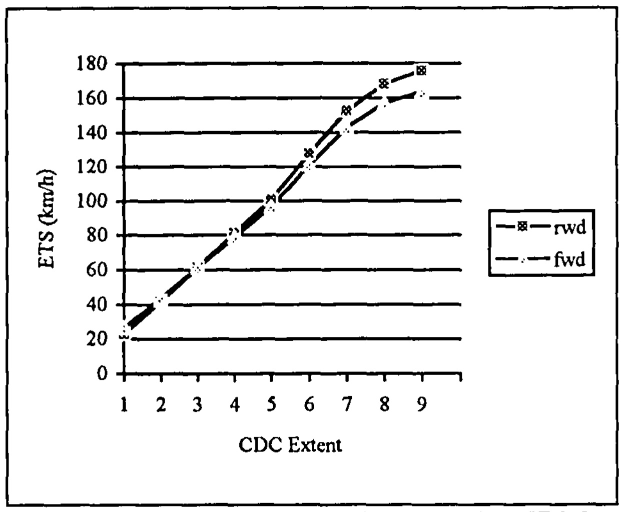

Figure 4. Results from CRASH3 comparing ETS for front wheel versus rear wheel drive vehicles, size class 1, with a CDC of 12FDEW_.

RECOMMENDATIONS FOR THE USE OF CRASH3 BY RETROSPECTIVE ACCIDENT INVESTIGATION STUDIES

1. Keep the DAMAGE algorithm as the crash severity assessment tool for retrospective accident investigation studies. It has been demonstrated that a tolerance for measurement of vehicle damage in the field can be specified. Further work will confirm, or redefine, which specific tolerance will be most appropriate. The CRASH3 program has been used by the CCIS since it began in 1983, and the DAMAGE algorithm is used throughout European accident investigation studies. Changing to a different method of assessing crash severity may produce a step in continuity of data. With regard to assigning a single stiffness class to front wheel drive vehicles, involved in frontal impacts, there does not appear to be a need to change away from this rule. The results have shown that there is no significant difference in results between front and rear wheel drive vehicles, and, to change now would, again, produce a step in the continuity of data held. It would be beneficial to consider the situation for different impact configurations, and for the 3 remaining size classes of vehicle.

2. Alongside CRASH, the CCIS should review EDCRASH and SLAM in terms of (a) consistency with the CRASH DAMAGE algorithm, (b) updated crash test data and (c) application to European vehicles. EDCRASH has been identified as the leading contender for updating the CRASH3 principles. It has a more user-friendly working environment, it can be 'fine tuned' to specific vehicle parameters, and is a modular part of a suite of accident investigation and reconstructional aides. It also provides access to more up-to-date vehicle stiffness data. These should also be assessed as to their appropriateness to European vehicles. It may be the case that EDCRASH contains the same default data as CRASH3. If this is the case, it will be compatible with existing data.

3. Review other crash severity assessment programs available, such as PC-CRASH and AiDamage. This is a basic requirement of accident investigation to ensure that the most appropriate tools are being used to make best use of the data available.

ACKNOWLEDGEMENTS

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CRASH PULSE RECORDERS IN REAR IMPACTS - REAL LIFE DATA.

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ABSTRACT

AIS 1 neck injuries have become the most common injury in vehicle crashes, especially rear impacts. Reserch has shown that there are variations in rear impacts causing initial symptoms and residual disability to the neck. Therefore impacts in which the duration of symtoms differ need to be separated in analyses. Concerning AIS 1 neck injury, crash severity is usually measured as change of velocity. The correlation between injury risk and impact severity parameters based on acceleration levels is to a high extent unknown. In this study, the results from crash recording of real life rear impacts are presented where the change of velocity and the crash pulse is measured. Out of 22 impacts, it was shown that most of the occupants that sustained symptoms the shape of the crash pulse varied considerably and the peak acceleration varied from 2.7g to 14.7g. In one impact the occupant had whiplash symptoms six month after the collision (peak acceleration 14.7g) and in another impact , two months after, when this article was written (peak acceleration 12.6g). Also, high change of velocity (>20km/h) does not have to cause disability to the neck at least when the mean acceleration is less than 7g and no clear peaks exist.

INTRODUCTION

The main public-health problems concerning neck injuries AIS 1 are those leading to long-term consequences. Nygren (1984) and Norin et al. (1996) found that 1 out of 10 occupants sustained medical disability a year after a collision. The need of preventive measures against long-term disability outcome are important since accident data collected for the initial symptoms of neck injuries AIS 1 seem not to predict the risk factors for long-term consequences (Krafft, 1998; Ryan et al, 1994). A new mathematical model that predicts neck injuries has been proposed. The Neck Injury Criterion (NIC) includes parameters such as seat-back design, change of velocity and crash pulse (Boström et al, 1996, Boström et al, 1997).

Neck injuries in rear impacts mostly occur at low impact-velocities, typically less than 20 km/h (Romilly et al 1989, Olsson et al 1990). Mc Connel et al (1995) performed a series of low-speed rear-end crash tests with seven male volunteers, with velocity changes of up to 10.9 kph, but the crash pulse was not mentioned. No one sustained neck injury symptoms after a few days. In another study with volunteers (Eichberger et al, 1996) where the sled impact velocities were 8-11 km/h and the mean decelerations 2.5g, the volunteers suffered whiplash symptoms for approximately 24 hours. In one of these test, the volunteer sustained symptoms for about two weeks. Olsson et al (1990) showed that the duration of neck symptoms caused by rear end collisions seems to correlate with the degree to which the impacted vehicle is deformed, provided that one of the rear side bumper was activated.

Descriptions in the literature of the influence of the crash pulse and stiffness of the structure in low-speed rear-impacts are rare. It has been shown that for vehicles equipped with a tow-bar, the pulse and the risk of disability to the neck increase compared to vehicles without. Also, the disability risk increases in the struck vehicle if the striking vehicle has a longitudinally mounted engine instead of a transverse one (Krafft, 1998). The link between injury risk and impact severity parameters based on acceleration levels remains unknown, since such measurements require on-board measurement techniques. This paper presents results from real-life rear impacts with vehicles equipped with a low-cost one dimensional crash recorder, the Crash Pulse Recorder (CPR), (Kullgren et al, 1995).

The aim of the study was to present crash pulse and change of velocity measured in real life rear impacts related to short- and long-term consequences from AIS 1 neck injuries.

MATERIAL AND METHOD

Since 1996 the crash recorder has been mounted in 10,000 vehicles in two different car models. The recorder was mounted under the driver seat. All rear impacts within this period were reported to the insurance company Folksam, irrespective of repair cost. However, only twenty-two rear impacts have been evaluated due to uncertain reporting procedures. All 22 crashed vehicles were inspected where the extent of seat-back deformations were investigated. Injury details were obtained from medical notes, and questionnaires were sent to the occupants. A follow-up of possible medical symptoms was done at least six months after the collision. Symptoms that still remained after half a year are referred to as "long-term consequences" and earlier recoveries are referred to as "short-term consequences".

The CPR is based on a spring mass system where the movements of the mass in a rear impact is measured. The displacement of the mass is registered on a photographic film. The circuit has its own power cell and does not need an external power unit. The CPR has a trigger level of approximately 3g.

When the characteristic parameters for each CPR have been measured, such as spring coefficient and frictional drag, and with knowledge of the displacement time history, the acceleration time history can be calculated. The crash pulses are filtered at approximately 100 Hz. Change of velocity and mean and peak accelerations were calculated from the crash pulse.

The accuracy of the CPR was validated in 21 frontal full-scale crash tests (Kullgren et al, 1995). The average standard deviation for change of velocity in tests below 30km/h was 2.0 km/h. The standard deviation concerning mean acceleration was 0.5 g, and for peak acceleration it was 1.4 g.

RESULTS

Out of 22 cases of rear impacts, there were 11 cases where a crash pulse could not be fully determined, cases L-V in Table 1. They did not reach the trigger level, but the inidividual trigger levels were measured. In this group three out of eleven sustained short-term consequences. In cases G-K the trigger levels were reached, but the displacement of the mass was too short for determination of a crash pulse. However, it was possible to measure the peak acceleration. In the impacts where a peak acceleration was calculated, cases A-K, the g-level reached from 2.7g to 14.7g. In nine of these cases, the occupants sustained short-term consequences and in one impact (case B) the occupant sustained long-term consequences. The occupants in case D still had symptoms from the neck, two months after the collision when this article was written, and may sustain long-term consequences.

Table 1.
Results from 22 rear impacts with Crash Pulse Recorder

Case	Change of velocity	Trigger level or peak acceleration	Collision partner/ object	Occupants Female, Male	Initial symptoms	Symptoms after 6 months.
A	28.2 km/h	10.1g	Truck	F+M	Yes	No
B	23.3 km/h	14.7g	Volvo 244 -82	F	Yes	Yes
C	14.7 km/h	9.0g	Skoda Pickup	M	Yes	No
D	26.0 km/h	12.6g	Ford Scorpio	M+4F	Yes	*
E	4.3 km/h	3.7g	BMW 530 -87	M+F	Yes	No
F	6.1 km/h	6.1g	Chrysler Voyager -89	M	No	No
G	-	2.9g	BMW 318 -81	M	Yes	No
H	-	3.3g	Volvo 245	M+F	Yes	No
I	-	4.3g	Toyota Carina -97	M	No	No
J	-	3.4g	VW Passat -97	M+F	Yes	No
K	-	2.7g	BMW 750 -88	M	Yes	No
L	-	3.3g	Nissan Sunny -93	M+2F	No	No
M	-	3.3g	Pole		No	No
N	-	3.2g	Pole	M	No	No
O	-	2.8g	Volvo 140	F	No	No
P	-	3.0g	Volvo 760 -83	M+F	Yes	No
Q	-	3.0g	Trolley	2 M	No	No
R	-	2.8g	Ford Fiesta -90	M	No	No
S	-	2.8g	Ford Escort -88	M	Yes	No
T	-	2.4g	Honda Accord -88	F	Yes	No
U	-	2.7g	Volvo 944 -92	M+F	Yes	No
V	-	2.8g	Tree	F	No	No

Deformation/collapse of the seat backs were only found in case B and D.
* The occupants still had whiplash symptoms 2 months after the impact when this paper was written.

In the six cases A-F, where the crash pulse and change of velocity were recorded, A-D is shown below in figure 1 to 4 and cases E and F are shown in the appendix.

Case A.

Changeof velocity:	28.2 km/h
Mean acceleration:	5.8g
Peak acceleration:	10.1g
Striking vehicle:	truck 28 000kg
Driver:	belted male, 26 years
Front passanger:	belted male, 26 years
Symptoms:	Initial whiplash symptoms; both occupants recovered within a month.

Other:
The driver was aware of the impending impact and leaned forward just before the collision. The front passenger was unaware. Both front seats were intact after the impact. No collapse or deformations were found on the back rests.

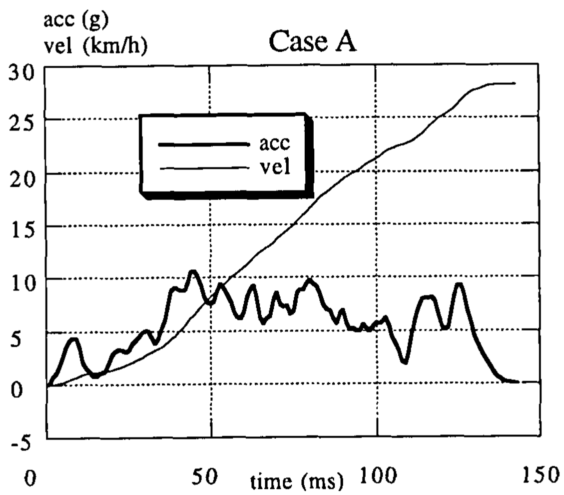

Figure 1. The change of velocity and acceleration in a rear impact, case A.

Case B.

Change of velocity:	23.3 km/h
Mean acceleration:	6.7g
Peak acceleration:	14.7g
Striking vehicle:	Volvo 244, 1400kg
Driver:	Belted female, 58 years
Symptoms:	After six months, there was still neck pain and headache.

Other:
The back rests collapsed and the front doors were jammed.

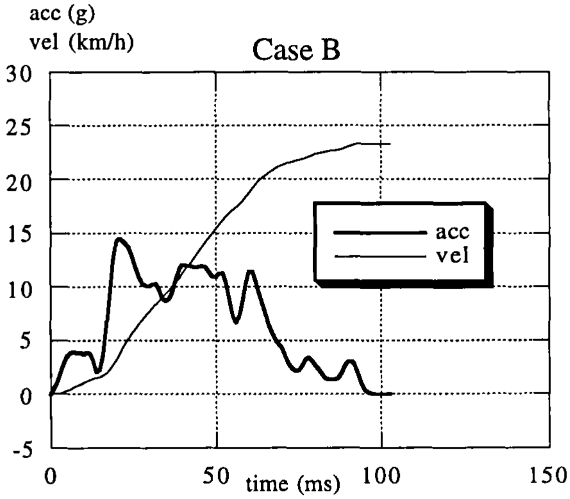

Figure 2. The change of velocity and acceleration in a rear impact, case B.

Case C.

Velocity change:	14.7 km/h
Mean acceleration:	5.5g
Peak acceleration:	9.0g
Striking vehicle:	Skoda Pickup-97, 1000 kg
Driver:	Belted male, 35 years
Symptoms:	Initial whiplash symptoms; recovery within a month.

Other:
The driver was not aware of the impending impact. The back rest was intact after the collision.

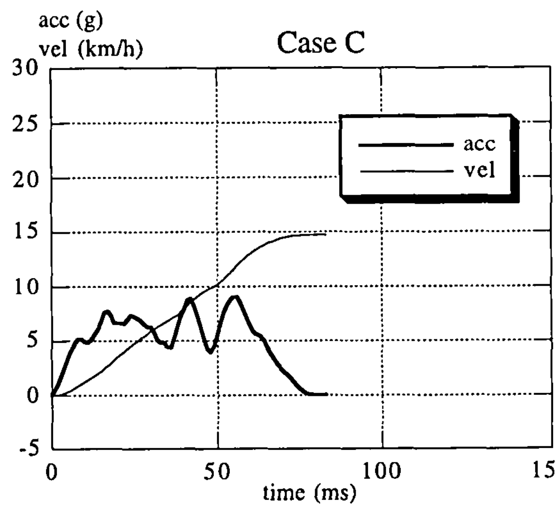

Figure 3. The change of velocity and acceleration in a rear impact, case C.

Case D.

Change of velocity:	26 km/h
Mean acceleration:	6.4g
Peak acceleration:	12.6g
Striking vehicle:	Ford Scorpio, 1500kg
Driver:	Belted male, 57 years
Front passanger:	Belted female, 57 years
Rear passengers:	Two children under 5 years of age and one female, 33 years. They were all belted
Symptoms:	All adult occupants still have typical whiplash symptoms two months after the collision.

Other:
The front passenger turned her head before the impact, to check on the passengers in the rear seat.

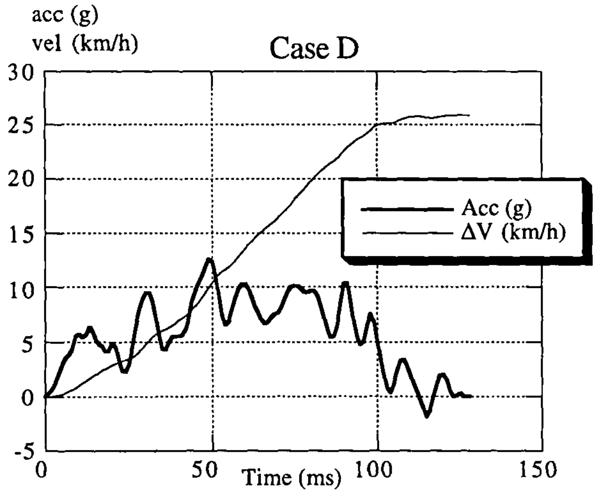

Figure 4. The change of velocity and acceleration in a rear impact, case D.

DISCUSSION

In reconstructions of rear impacts causing AIS 1 neck injuries, change of velocity is a commonly used parameter to decide the relevance of the occupants' symptoms. However, it is still unknown whether change of velocity is a relevant predictor for long-term consequences to the neck. It does, however, seem to be a risk factor in rear impacts causing short-term consequences (Eichberger et al 1996; Krafft et al 1995; Ryan et al 1994).

The impact severity parameters used in most studies are often chosen because of the possibility to measure and estimate them. Since the majority of real-world accident data describing acceleration time histories are not available, it is rare that crash pulse characteristics are mentioned as a possible risk factor.

The CPR makes it possible to relate injuries to the measured crash pulse and change of velocity. The method is unique in traffic safety research where such on-board measurement devices have been mounted in normal traffic. Also, the CPR-mounted vehicles in this study represent only two different models from one car make which limit influencing factors on the results.

The accuracy of change of velocity calculations in frontal impacts have in several tests been shown to have large random errors, sometimes exceeding 25%, (O'Neill, 1994; Stucki and Fessahaie, 1998). In rear impacts, the accuracy can be expected to be even lower since the elastic properties of vehicles in low regions of impact severity might produce a higher change of velocity than what was previously anticipated (Romilly et al, 1989).

It is shown in this study that the shape of the crash pulse varies considerably between rear impacts. Also, relatively high changes of velocity do not have to be critical to sustain disability to the neck. In case A, the velocity change was 28 km/h and the mean acceleration was nearly 6g with no clear peaks. The occupants recovered after a few weeks. In case B, however, the change of velocity was 23km/h and the mean acceleration was nearly 7g but there were early peak acceleration of nearly 15 g after 20ms. The occupant in case B still had typical whiplash symptoms six months after the collision. Out of eleven impacts in which the peak acceleration was determined (2.7g-14.7g), few sustained long-term consequences. Most occupants recovered within a month.

The crash pulse measurments available from earlier studies are from volunteer tests where the average acceleration was 2.5g (Eichberger et al, 1996), which seems to be in the lower region compared to those reported in this study, and therefore would not be expected to lead to any serious whiplash symptoms. Boström et al (1997) presented a mathematical model (NIC) where squared shaped acceleration pulses above 2.5g reached the injury tolerance limit which is also in the lower segment compared to this study. In sled tests, Svensson (1993) used a peak acceleration of approximately 7-8g which seems to be more representative.

New anti-whiplash devices have been coming out on the market, namely active head restraints moving forward and yielding seat back rests where a controlled angular deflection occurs during the rear impact (Wiklund and Larsson, 1998; Lundell et al 1998). Since the injury mechanism is still unknown, even if different hypotheses exist, there is a need to evaluate such new solutions by looking at real-life data. There might be technical solutions that cover more than one conceivable injury mechanism, but where the injury tolerance limit is remains unknown.

It is necessary to implement more advanced measurement technique of crash severity, taking both change of velocity and acceleration measurements into account when evaluating different anti-whiplash devices. Crash recording could show the distribution of Delta-V and crash pulse characteristics for neck injuries which cause short- or long-term consequences.

This study has focused on rear impact, since it is the most common impact direction in terms of AIS1 neck injuries. Replication of these results should be sought in a larger sample. The injury also occur in frontal impacts (Ryan et al 1994; Krafft, 1998) but there is very little documentation describing injury mechanism and risk factors in this direction, and more research is necessary for all impact directions to prevent injury more effectivly in the future.

CONCLUSIONS

From twenty-two Crash Pulse Recorders, the following conclusions can be drawn:

- The crash pulses where occupants sustained initial AIS 1 neck injury varied widely.
- Out of eleven rear impacts (31 occupants) with peak accelerations from 2.7g to 14.7g, occupants from nine impacts sustained short-term AIS1 neck injuries and at least one sustained long-term consequences.
- A peak acceleration of 14.7g may cause long-term AIS 1 consequences to the neck.
- High change of velocity (28 km/h) does not have to cause long-term AIS1 consequences to the neck , if at least the mean acceleration is less than 6g and there are no clear peaks.

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APPENDIX

Case E

Change of velocity:	6.1 km/h
Mean acceleration:	2.3g
Peak acceleration:	6.1g
Striking vehicle:	BMW 530 -87.
Driver:	Belted male, 68 years
Front passanger:	Belted female, 52 years
Symtoms:	The passanger had only initial symptoms
Other:	The back rests were intact

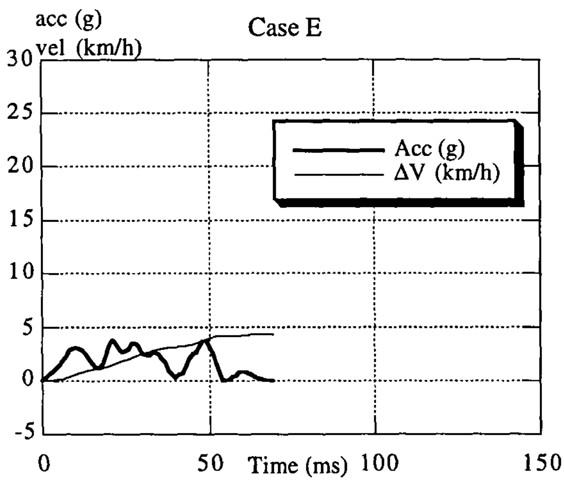

Figure I. The change of velocity and acceleration in a rear impact, case E.

Case F.

Change of velocity:	4.3 km/h
Mean acceleration:	2.1g
Peak acceleration:	3.7g
Striking vehicle:	Chrysler Voyager -89
Driver:	Belted male, 54 years
Symtoms:	No
Others:	Back rest were intact.

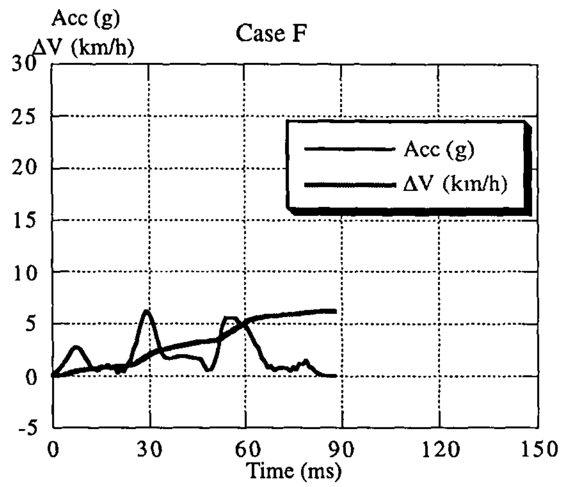

Figure II. The change of velocity and acceleration in a rear impact, case F.

Figure III. The vehicle in CaseA.

Figure IV. The vehicle in CaseB.

Figure V. The vehicle in CaseC.

Figure VI. The vehicle in CaseD.

THE ROLE OF MOTORSPORT SAFETY

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Paper Number: 98-S6-O-12

ABSTRACT

Motor sport is an activity in which accidents are expected to occur, but in which the driver and spectators expect a very high level of protection. Much of the physics and biology are the same as those involved in highway accidents, and the motorsport safety research being carried out in both Europe and the USA can make a significant contribution to road safety. Because many motorsport accidents are recorded on video, data is recorded in on-board Accident Data Recorders and detailed post accident analysis is carried out, motorsport provides an excellent environment for vehicle safety research.

The FIA has researched and implemented changes to vehicle design regulations, circuit design and circuit safety features, driver equipment, race control procedures, and medical intervention standards, to reduce the fatalities and serious injuries per accident by over 90% since the early 1970's. Its target is zero fatalities and serious injuries.

The parallels between this approach and Sweden's Vision Zero policy are clear. In both, the responsibility for road safety is taken away from the driver and handed jointly to the Administration, and to the system (vehicle and highway) suppliers. Motorsport has been carrying out a similar policy for nearly 30 years and the lessons learned could, with due care, be applied to new approaches to road safety.

INTRODUCTION

Motorsport is just over 100 years old, a few years younger than the automobile itself. For many years, apart from steps taken to protect spectators, little was done to protect participants from fatality or serious injury as a result of accidents, until the late 1960's. While drivers raced largely for the glory rather than monetary reward, and automobile manufacturers participated as part of their R&D effort rather than marketing, death and injury were accepted as part of the risk. Just as public attitudes to road safety changed in the late 1960's, it was the drivers, now professionals earning substantial incomes from motorsport, who campaigned for greater safety.

It is the nature of motor racing that drivers are encouraged to drive their vehicles at the limit of control, and both inevitable and accepted that accidents will occur. Accidents are a necessary part of motorsport providing spectator and TV entertainment. However, it is the responsibility of the governing or sanctioning body to ensure that accidents do not result in fatalities or serious injuries so an adequate level of safety is required not only for the drivers and spectators, but also for team participants and officials involved with the staging of events.

In 1994, after 11 years without a single fatality in Grand Prix events, two fatalities occurred during a single Grand Prix weekend. Because one of them involved triple World Champion Ayrton Senna and was covered world wide by live TV, the reaction of the Press, public, governments, sponsors, and even the Vatican was so adverse that it became apparent that international motorsport could be threatened unless even greater levels of safety were achieved. The FIA, as the governing body of international motorsport, immediately took wide-ranging steps to improve safety, including new regulations for car construction and circuit design, and initiated R&D into improved systems and standards for the future. It is clear that the only acceptable safety objective is zero fatalities and serious injuries.

In the USA, the major automobile manufacturers participating in the prime racing series, such as Champcar, IRL, NASCAR and IROC, are working closely with the sanctioning bodies to research and improve safety. Oval racing, with it's high speeds and rigid containment walls, provides a unique opportunity to research high delta-V, high-g impacts and to investigate human tolerance of these conditions. Impacts generating 80g frontal, 120g lateral (Ref.1.), and 135g rear have been recorded, and are under detailed investigation to determine why no g-related injuries were sustained by the drivers involved in the accidents.

Because every aspect of motor racing is so controlled, and the technology now exists to enable accidents to be monitored and analysed in detail, it presents a valuable opportunity to research automobile safety *in extremis*. The physics and biology of racing accidents and injuries are almost the same as for road car accidents. Motorsport safety can show what is possible in terms of human protection and tolerance if there are no constraints on the level of technology applied, nor on the costs involved. While the lessons learned cannot always be directly or economically applied to the road system, much of the data and experience gathered is relevant.

Historical Aspects

In the 1960's, 1 accident in every 8 in Formula One events resulted in a fatality or serious injury (defined as an injury that prevented the driver from continuing to participate in the event or subsequent events), with some years as high as 1 in 4 (Figure 1).

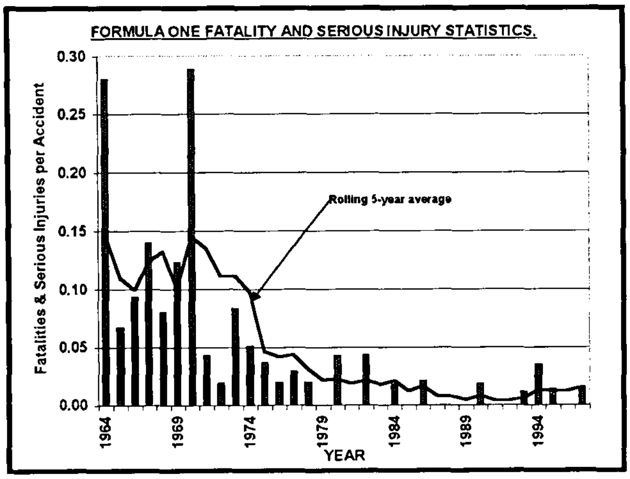

Figure 1. Fatalities and serious injuries per accident in Formula One, from 1964 to 1997.

Figures 2, 3 and 4, and the following passage (Ref.2.) illustrate the conditions which gave rise to this.

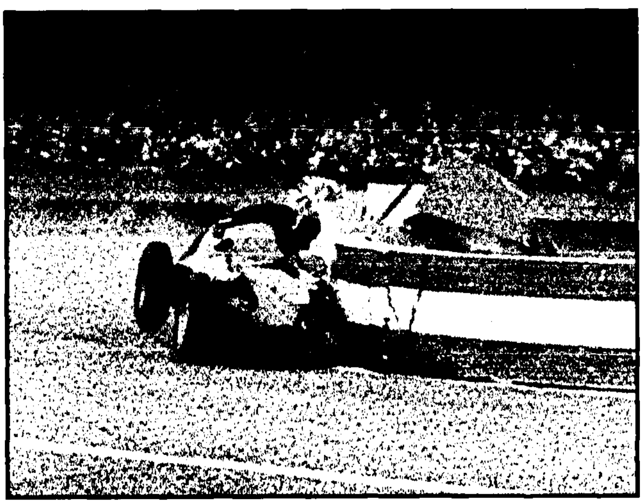

Figure 2. Jean Behra. 1958. Goodwood.

Figure 3. Tony Brooks. 1956. Silverstone.

Figure 4. Barriers and Marshals. 1962. Monaco.

"In the race it began to rain heavily on the far side of the circuit, so as the leaders came down the hill to the Masta Straight, Jackie (Stewart) aquaplaned off, striking amidships a large stone buttress of an even larger and very solid stone barn, and wrapped the car round the buttress like a banana. It then bounced off into a ditch with Jackie trapped in the car with a crushed tank leaking fuel all round him. Graham (Hill) and Bondurant went off in the same area for the same reason a few seconds later but without such disastrous consequences. Just as Graham was getting back on the road he saw Jackie's car and stopped to help him. It took nearly ten minutes to get him out of the car and another 20 minutes before the ambulance arrived. He had been sitting up to his waist in petrol, so the drivers helping him stripped off his fuel-sodden clothes and wrapped him in a spectators rug."

It was this accident involving Jackie Stewart that started the driver led movement for greater safety in motor sport. The first steps taken were:

- To reduce the risk of fire.
- Establish circuit safety criteria, including arrestor areas.
- 6-point harness restraint systems and driver protective clothing.
- Standardisation of signalling and marshalling procedures.

These were followed during the 1970's by:

- Structural specifications for the cars chassis.
- Medical centres at race circuit.
- Tyre barriers.
- Graded driver licensing.

The effect of these measures was to reduce the number of accidents causing fatalities or serious injuries to an average of 1 in 40 accidents - a 5-fold improvement in less than 10 years.

Between 1980 and 1992, a further steady decline in fatalities and serious injuries per accident resulted in the rate falling to less than 1 in 250 accidents - a further 6-fold reduction.

Safety Regulations

To achieve this further reduction, all aspects of motorsport that influence safety were scrutinised and measures introduced to minimise the threat to participants and spectators.

The Technical (Ref.3.) and Sporting Regulations (Ref.4) governing Formula One set the highest standard and provide a proving ground for safety measures prior to introduction into other international racing classes.

<u>**Car Construction**</u> - The prime objectives are:

1. To protect the driver from intrusion injuries.
2. To generate a deceleration pulse, in any impact direction, that can be accommodated by the driver restraint system within his deceleration and load tolerances.
3. To restrain the driver from impacting the inside of the car or any solid object or, where that is not possible, to provide a means of attenuating the resulting impact to below a level that would cause injury.
4. To avoid fires.
5. To ensure that the driver can exit the cockpit quickly and easily.

The Technical Regulations take the approach of defining a driver survival cell and stipulating a series of structural integrity demonstration tests, rather than laying down construction methods and materials.

The chronological development of the structural tests is shown in Table 1.

Table 1.
Chronological Development Of Formula One Survival Cell Structural Tests

Formula 1 Technical Regulations – Structural Integrity Demonstration Tests

Year	Frontal Impact Test					Lateral Crush		Floor Push	Roll-over Load (kN)		Nose Side	Side Impact		Rear Impact		Steering Wheel	
	Speed (m/s)	Max. Av. ('g')	Structure	Damage Zone (In front of)	Dummy Peak ('g')	Positions	Load (kN)	Load (kN)	1.	2.	Load (kN)	Speed (m/s)	Max. Av. ('g')	Speed (m/s)	Max. Av. ('g')	Speed (m/s)	Peak ('g')
1985–88	10 39 kJ	25	Front only Stationary	Pedal line													
1988	"	"	"	Axle line		2	19.62										
1990	"	"	"	"		"	"			72.1	19.62						
1991	11 47 kJ	"	Full chassis Stationary	"		4	"	9.81		"	"						
1992	"	"	Full chassis Moving	"	60	3	25	12.5		"	30						
1994	"	"	"	"	"	"	25 + 30 + 10	"		"	"						
1995	12 56.2kJ	"	"	Survival cell	"	"	"	"		"	40	5 9.8kJ	10				
1996	"	"	"	"	"	4	"	"		"	"	"	"				
1997	"	"	"	"	"	"	"	"		"	"	"	"	12 56.2kJ	35	7	80
1998	"	"	"	"	"	"	"	"	75	76	"	7 19.1kJ	"	"	"	"	"

Figures 5 and 6 illustrate the current tests.

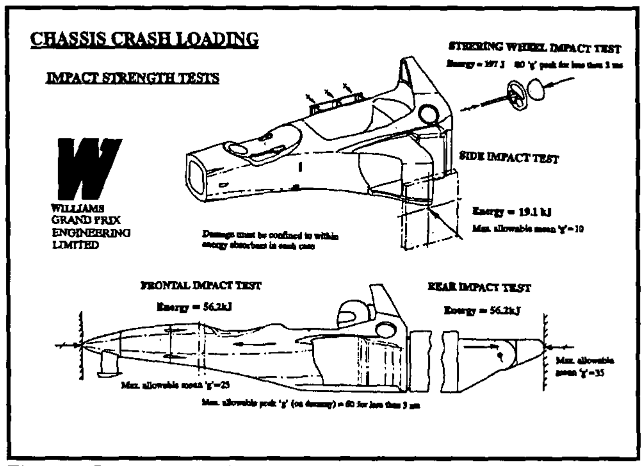

Figure 5. Impact strength tests.

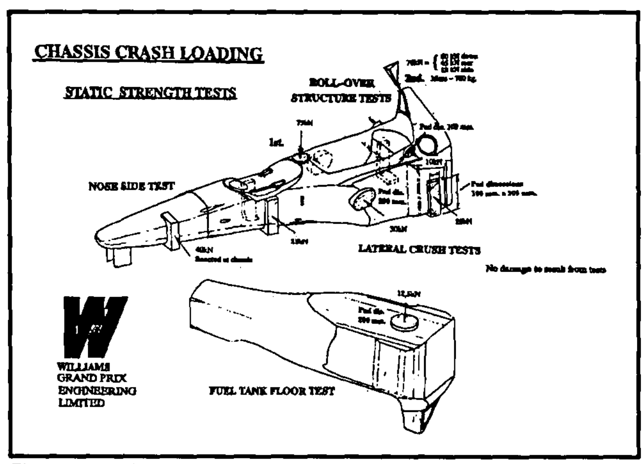

Figure 6. Static strength tests.

The driver must wear a 6-point harness employing 75 mm wide webbing. Parts of the safety cell that may be struck by the driver's head are padded with energy absorbing foam.

Drivers must demonstrate that they can get out of the car within five seconds, wearing full racing equipment and unaided.

Detailed specifications relating to fuel systems and fire extinguishing equipment are set down, as is the location of the fuel tank in the centre of the car.

Circuits - Closed-circuit racing tracks are licensed by the FIA according to the classes of cars to be raced on them. Circuits are inspected according to the FIA Internal Guidelines for Motor Racing Course Construction and Safety (Ref. 5.), which lays down standards and guidelines for all aspects of circuit construction, including:

- Track design and construction
- Run-off areas and kerbs.
- Deceleration and arrestor areas.
- Barriers - guard rail, concrete walls, tyre barriers, spectator protection fences.
- Service and access roads
- Marshalling and signalling posts and equipment
- Track-side signs and all other potential obstacles

Drivers - Drivers are licensed to participate in racing classes according to their experience. The licensing system also provides a means of sanctioning drivers for actions that are considered prejudicial to safety.

Standards for driver equipment, including helmets and overalls, are set and regularly checked.

Medical - The philosophy behind the medical service standard laid down by the FIA, is based on providing timely and expert medical attention within seconds of an accident occurring, through to transfer by helicopter of an injured driver or other participant to an approved receiving hospital.

Much has been written about the critical "golden hour" in the treatment of trauma but it is intervention, reduced to minutes or even seconds in Grand Prix racing, that is deemed most important (Ref.6.). Rapid response in the event of an accident is provided by fully equipped, rapid intervention medical cars stationed around the circuit and able to reach the scene of any accident within 30 seconds. These are backed up by doctors and paramedics on foot, stationed at intervals around the circuit. At a circuit such as Monaco where access is difficult, 3 intervention cars backed up by 100 doctors and paramedics are required to provide this level of intervention performance.

In a number of accidents in the last few years, rapid intervention undoubtedly saved the lives of drivers with obstructed airways.

At every circuit there are also two or three trained extraction teams, equipped to extract a driver with possible spinal injuries from a damaged car. These teams practice on actual Formula One cars and familiarise themselves with potential problem features. Following extraction and stabilisation, and injured driver will either be taken to the Medical Centre by ambulance, or direct to the receiving hospital by helicopter.

FIA regulations demand a high level of equipment at the circuit Medical Centres. Staffing levels are a minimum of two consultant anaesthetists, a consultant general and orthopaedic surgeon, a spinal or neurosurgeon and a burns specialist. Intensive resuscitation rooms and an operating theatre equipped to University Hospital standards are a minimum requirement. Only when the injured person is deemed stable enough to travel to the receiving hospital for more specialist treatment or care are they transferred.

Driver fitness is monitored, particularly post-accident. Random drug tests to IOC standards are carried out regularly.

Race Control - A permanent FIA Race Director controls the running of major international motorsport events. Race Control is in radio contact with all medical facilities, race officials, marshals, and signallers, and is able to survey the whole track and Pit Lane via closed circuit TV. The Race Director is thus able to assess the seriousness of an accident and either stop other cars running or control their pace using the Safety Car. These measures enable medical intervention teams to gain unencumbered and safe access to the scene of the accident. If the driver is not injured, his stationary car can be removed from an exposed position without putting track marshals in danger.

Race Control also monitors the speed of cars in the Pit Lane and reports offenders to the Stewards of the Meeting, who administer penalties to those who exceed the limits set down on safety grounds.

Future Developments - In 1992 the safety record of Formula One approached zero fatalities and serious injuries per accident, a level where individual incidents have a disproportionate effect on the statistics. The events of 1994, when two drivers were killed and one seriously injured, focused sharply on this effect. The FIA responded by initiating a series of R&D programmes to investigate where further safety measures could be effective. The objective of meeting and maintaining the target of zero fatalities and serious injuries was confirmed. Programmes which have been carried out or are currently under way include:

- Investigations into measures to control the speed of the cars, particularly in high speed, high lateral acceleration corners carried out in co-operation with the participating teams. A number of restrictions on aerodynamic downforce, power and tyre grip have been introduced.
- Head protection around the sides and behind the driver's helmet has been made mandatory.
- Increased severity structural tests have been introduced for the driver's survival cell, which has also been increased in size.
- A mandatory Accident Data Recorder, to provide both impact data and information on the performance of circuit safety features (gravel arrestor beds, kerbs etc) was introduced in 1997.
- Research is being carried out into the performance of existing, proprietary and increased performance impact barriers.
- A major R&D programme is underway into restraint systems for the protection of the drivers head and neck in a frontal impact.
- More severe crash helmet test specifications are being developed.
- Accident reconstruction, using helmet damage for correlation, is performed on accidents in which injuries have occurred.
- Close co-operation with national motorsport safety researchers in different countries is being undertaken.
- In-cockpit signalling systems are being developed.
- Wheel retention systems are being investigated.
- Minimum safety standards for private testing have been established.
- Software for the analysis of safety features on proposed new circuits and changes to existing circuits, are being further developed.

Safety Regulation - The FIA governs international motorsport through the World Motor Sport Council. This body is assisted in its tasks by specialised Sporting Commissions and Working Parties. Those relevant to safety are:

- Medical Commission
- Technical Commission
- Circuit and Safety Commission
- Formula One Safety Commission

plus a number of Working Groups that involve technical experts from the teams, circuits, the medical profession and organising bodies.

It is through this system of close co-operation between the FIA and all those involved in organising and participating in motorsport, that fast responses to new safety issues are possible. Safety measures can, if necessary, be introduced within weeks.

Road car safety legislation in Europe lags many years behind best available technology. For this reason, the FIA became a founder member of EuroNCAP in order to provide motorists, who are members of associated motoring clubs, with up to data safety information and to put pressure on all manufacturers to sell cars that demonstrate state of the art safety performance.

Vision Zero - The Swedish Ministry of Transport and Communications has proposed a radical Vision Zero road safety strategy which was approved by the Swedish Parliament in 1997. Vision Zero is conceived from the ethical base that it can never be acceptable that people are killed or seriously injured when moving within the road transport system. It is the long term goal is that no-one will be so affected. (Ref.7.)

For many years, the emphasis in traffic safety work has been in trying to encourage the road user to respond in an appropriate way, typically through licensing, testing, education, training and publicity, to the many demands of a man-made and increasingly complex traffic system. Traditionally the main responsibility for safety has been placed on the user to achieve this end, rather than on the designers of the system.

The Vision Zero approach involves an entirely new way of looking at road safety and of the design and functioning of the road transport system. It involves altering the emphasis away from enhancing the ability of the individual road user to negotiate the system to concentrating on how the whole system can operate safely. Also, Vision Zero means moving the emphasis away from trying to reduce the number of accidents to eliminating the risk of chronic health impairment caused by road accidents.

Vision Zero accepts that preventing all accidents is unrealistic. The aim is to manage them so they do not cause serious health impairment. The long term objective is to achieve a road transport system which allows for human error but without it leading to serious injury.

While the concept envisages responsibility for safety amongst the designers and users of the system, the designer has the final responsibility for 'fail-safe' measures:

- System designers are responsible for the design, operation and the use of the road transport system and are thereby responsible for the level of safety within the entire system.

- Road users are responsible for following the rules for using the road transport system set by the system designers.
- If the users fail to comply with these rules due to a lack of knowledge, acceptance or ability, the system designers are required to take the necessary further steps to counteract people being killed or injured.

CONCLUSION

The parallels with the way in which motorsport safety is managed and the strategy of Vision Zero are many. While accidents in motorsport are accepted as being part of motor racing, they will always be actively discouraged on the road. However, in both approaches prime responsibility for accidents occurring and the resulting fatalities or injuries, is taken away from the vehicle drivers. In its place the administration takes responsibility and sets down standards of safety performance for the vehicle manufacturers and highway (circuit) operators to achieve. It also ensures that users obey regulations concerning use of the system.

Close co-operation between the parties involved is essential for the fast introduction of safety initiatives and the monitoring of the effects of safety measures. Motorsport has demonstrated that if this close co-operation exists, significant reductions in fatalities and serious injuries can be achieved within a short time scale. Vision Zero is a state of mind. Within motorsport it is foreseeable that a sustained record of zero fatalities and serious injuries is achievable in the near future. On the way to this target motorsport can demonstrate many techniques and procedures that can contribute to achieving the same goal on the road.

ACKNOWLEDGEMENTS

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THE AGING OF THE AUSTRALIAN CAR FLEET AND OCCUPANT PROTECTION

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Paper Number 98-S6-O-13

ABSTRACT

Concerns have been raised over the ageing of the Australian car fleet and the effect that this might have on occupant protection provided in crashes by these older vehicles. This paper outlines best estimates on the factors influencing occupant safety in older vehicles. It also suggests research areas that need investigation to better quantify the expected safety effects of a younger fleet.

Investigations in other international countries show what has been achieved elsewhere when action has been taken to reduce the age of the passenger car fleet and the action necessary to implement the change. From the study several factors emerge that could be used to change the age mix of the fleet in Australia , and how this could be achieved by financial, regulatory or other action.

One section of the paper presents data on the present Australian passenger car fleet age. Another section investigates some of the many options available together with future scenarios and their broad impacts on fleet characteristics. Finally the policy options are outlined that reduce the age of the fleet plus a study to quantify the improvement with benefits to the community.

INTRODUCTION

Australia has reached a level of vehicle use per 1,000 population and is second to the United States as shown in figure 1. However the rate of increase in vehicle ownership has slowed and is now relatively static. New vehicles less than one year old make up a surprising low percentage of the fleet and in Australia at less than 6%, compared to many European countries up to better than 20%.

Table 1.
International VehicleOwnership. 1997

	Motor vehicles per 1,000 population
USA	770
Australia	595
France	500
United Kingdom	475
Japan	475
Canada	385

One significant reason is the low corrosion rates for Australian cars that do not operate in severe winter conditions when compared to Europe and in North America. Consequently scrap rates remain low across Australia at 3 to 3.5 percent out of a total fleet of 8.6 million. Stringent vehicle inspection programs are not in force in most regions, allowing the few badly corroded vehicles to remain in service. Not all of the vehicles that are scrapped are the oldest in the fleet, crashes can mean near new vehicles can be scrapped, a factor which aslo contributes to the ageing of the total fleet.

New vehicle sales have remained relatively static in absolute numbers between 400,000 and 500,000 new passenger vehicles each year (5.5%) for the past decade, with the net result that the age of the fleet has increased slowly.

Using Australian Bureau of Statistics data the Australian fleet profile has been drawn in figure 1 to show the fleet age is growing at the rate of almost one quarter of a year every year.

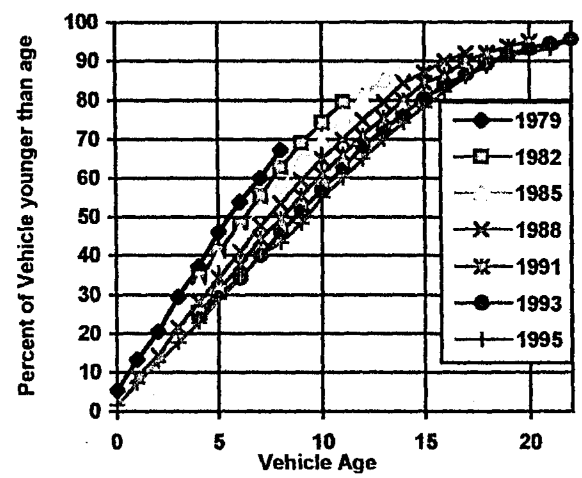

Figure 1 Australian Fleet Age 79-95

RELATIONSHIP TO OCCUPANT SAFETY

Firstly it is acknowledged that there is debate about how occupant safety should be measured, and there is no universal way that manufacturers, legislators or consumer interest groups have agreed to determine occupant safety. Many factors make a contribution to vehicle occupant protection level: Vehicle Mass, build date and therefore legislated occupant safety design level of equipment and vehicle, manufacturers specification of equipment that may significantly exceed the legislated safety level, personal use of restraint systems, deterioration of safety equipment over long time periods, overall design specification of the vehicle plus active and passive safety features, maintenance level of the vehicle at the time of the crash.

Crashworthiness and the risk of injury

Monash University has used data from many crashes to publish the risk of hospitalisation or death as a percentage for a wide range of vehicle models operating on Australian roads. As an example, the poorest performing small cars made in the same year, have three times the risk of serious injury or hospitalisation as the best small cars.

Table 2.
Percent risk of serious injury

Honda Civic	% risk of serious injury (hospital)
year 82-3	2.64
84-87	3.78
88-91	2.90
91-94	2.57

Table 2 demonstrates as one example, the variation which can occur for a particular model over a decade

For large cars models the worst rated have twice the risk of the those with the best rating for death, serious injury or hospitalisation. These are large changes when all of the vehicles are made to meet the same legislated level of safety performance. The data can be seen in Figure 2 which shows the Vehicle Crashworthiness by year of Manufacture. More detailed specific model data is also available in consumer friendly formats for vehicles made since 1982.

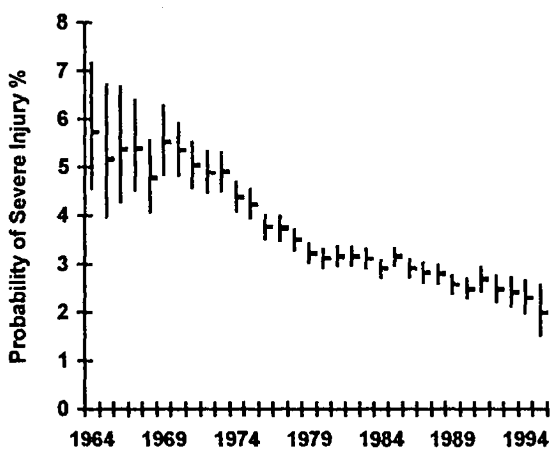

Figure 2. Crashworthiness by Year of Manufacture

ANCAP and Changes in Occupant Protection

An active ANCAP publishing and distribution program commenced in Australia in 19993 when the first crash test results were made available to consumers. Later programs have been able to document the improvements that been made to new vehicles since starting ANCAP in 1993. Large family sized cars have improved with significant reductions in head and chest injury, but even greater reductions are available if the consumer options the vehicle with a driver and passenger airbag. For small cars significant improvements have also been achieved but there still remain many models that are at a very poor level of occupant protection. The consumer quest for lowest cost purchase price means that most of the low cost products are sold without driver airbags with lower levels of occupant protection. The mixture of models in the market place will make the task of statisticians more difficult in the future as the year of manufacture of a vehicle means that there were several levels of occupant protection available for that particular vehicle.

Table 3.
Injury Risk Improvements from ANCAP Tests

Year vehicle built	Driver Injury Risk	Passenger Injury Risk
1993	59	47
1994	53	36
1995	44	28
1996	31	20
1997	29	29

The results in Table 3 show the risk of injury declined steadily over the years, for the driver the introduction of more airbags in models made up a significant proportion of the gain in years 1996 and 1997. There were no passenger airbags fitted in any of the ANCAP vehicles tested in ANCAP over this time period.

Another source of data on the occupant protection safety of older vehicles is the USA NCAP results. These results need to be treated with care, as the vehicle specification of a Honda Civic in the USA in 1978 the year testing commenced may be considerably different to the Australian specification vehicle. We are also not sure how many of the changes that were subsequently made to USA vehicles were also made to other international market vehicles.

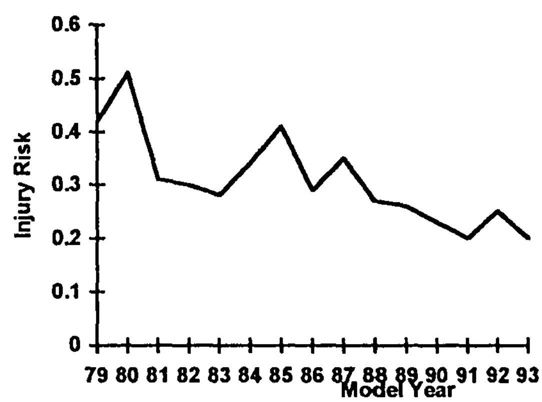

Figure 3. USA NCAP Combined Head & Chest Injury Risk

Figure 3 shows the improvements to combined head and chest injury risk measured by NHTSA in the NCAP test results. There is a significant downward trend from 1979 to 1993 when the risk of a serious injury was down to half that at the commencement of the program. This is a real benefit to consumers that may have a vehicle crash.

Older Vehicle Safety Data

One source of vehicle safety data that is not available on older models is manufacturers test data on models. This is possibly due in Australia to the fact that most of the data was generated overseas up to the 1990's and there was no consumer group publishing material or significant demand for knowledge for improved safety. There was no legislative requirement for dummy crash test data until a version of FMVSS 208 was introduced in 1996 and before then, the only frontal crash requirement was the limit on rearward movement of the steering column to 127mm in a 48 km/h crash introduced in Australia in 1973. It is interesting to note that was no dummy in the vehicles used to show compliance with this test requirement. Researchers are therefore unable to make accurate occupant protection level predictions of older vehicles.

Consumers and Crashworthiness

Consumers are seeking the continued involvement of motoring organisations in running car safety crash tests as a worthwhile activity to obtain independent comparable safety material. However there are continuing misconceptions about what makes a car safe. Although those equating car strength with safety in an accident have declined, over one half of surveyed motorists continue to place undue emphasis on strength. Accident prevention features such as good brakes, and impact absorption features are minority mentions. References to safety features such as airbags and seatbelts have increased, however, and they are now mentioned by two thirds of Australian motorists.

Table 4.
Crashworthiness, A Consumer Perspective

What Helps to Make a Car Safe in a Crash	
Top Features	1997
Safety features. Airbags, Seatbelts, Headrests.	66%
Strong body. Bigger cars.	54%
Reinforcing bars. Side reinforcement strength.	19%
Accident prevention features. Brakes	19%
Impact Absorption. Crumple zone	13%

While the use of airbags is a commonly nominated safety feature, airbags are a vexed and often misunderstood issue among motorists. Fewer that half of motorists say they want an airbag in the next car that they buy. The main concerns about airbags are that they can cause injury, especially to children and they go off too easily. This data follows bad US press of US airbags. Australian airbags, given the high seat belt usage, are more user friendly.

Policy Changes to Reduce the Fleet vehicle Age

New Vehicle Taxation - *Reduce the Government net tax take so that the benefits to Government and community are in excess of the loss of revenue.* The benefits to government need to be calculated to realise the long term safety from this change in policy as many of the benefits may only be realised over the life of a motor vehicle, possibly ten to twelve years.

Government to increase the rate of depreciation allowed for new vehicles. This policy change would have a significant positive effect on the fleet market by making it more financially attractive to change fleet vehicles at regular intervals. An innovative approach to allow private buyers to be able to claim depreciation would also improve the attractiveness of more frequent turn over of vehicles. The benefits would need to be revenue neutral to government to be acceptable.

STRATEGIES TO REDUCE THE FLEET AGE

New Vehicles Benefits Task Force - A task force of industry, academia, government and motoring club representatives has been convened to review possible actions to reduce the Australian fleet age to improve occupant safety, emissions and reduce fuel usage. It is evident that reduction in the age of the fleet will take many years to accomplish and require many interventions to be successful. Economic costing of each proposal is essential to show the net benefits to the total Australian economy.

Recent qualitative opinion surveys have shown a strong dislike for 'cash for clunker' schemes as users of older vehicles see no potential, even with cash incentives, to purchase new vehicles.

The Taskforce is likely to look at what information consumers receive in terms of the benefits of newer vehicles to ensure positive messages on safety and environmental benefits are being received. These could include more specifically:

Increase Awareness of benefits of new cars - A major awareness program would need to be introduced to change the perception of owners of older vehicles with the benefits of owning a newer vehicle. Research to complement this program would be needed to measure the effectiveness. Much more must be done to make the information available to consumers more comprehensive and easier for consumers to interpret and use. This could include integration of manufacturer, regulator and consumer safety information.

Programs need to be introduced to measure and publish the benefits of newer vehicle ownership. This may include the NCAP testing of some older models similar to the EuroNCAP tests on some old vehicles.

Introduce financial incentives - Many European countries have offered significant financial incentives to scrap older vehicles, Germany, France and Italy have recently provided cash incentives to scrap old vehicles with varying success. For example, in Germany a cash incentive of $3,000 incentive was allowed for a ten year old car. A program would need to be revenue neutral to be politically acceptable, with benefits emanating from the lower fuel use, emissions and safety benefits that would result in lower hospital admissions.

CONCLUSIONS

The Australian fleet is ageing with the average vehicle over ten years old. There are significant community costs associated with this trend, that will increase if no action is taken to reverse the trend. Newer vehicles are safer for occupants which means less hospital admissions with serious injury per crash. There are considerable savings to government health costs as road crashes contribute a large percentage to the health rehabilitation of injured occupants. Considerable evidence from the Australian and United States NCAP programs show the trend to improved occupant protection packages. Injury risk in Australian vehicles which lagged United States equivalent vehicles in 1993/4 now show signs of approaching the same level of occupant protection. The low rate of small cars fitted with driver airbags remains a concern and price sensitive buyers are not ordering the airbag model.

Strategies to reduce the age of the vehicle fleet will depend on a collective approach from manufacturers, regulators and consumer groups. Cost incentives to encourage older vehicle owners to trade up to a new model have only been partly successful when tried overseas, and to be successful would need to be funded for many years.

ACKNOWLEDGEMENTS

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THE RISK OF SKULL/BRAIN INJURIES IN MODERN CARS

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ABSTRACT

Skull/brain injuries to car occupants are still a major problem in road accidents, as they are a dominating cause of death, and for survivors, as they often lead to permanent problems. Many of the preventive actions in passive safety have therefore been directed towards injuries to the head.

In Sweden, it is since 1997 possible to link medical data coded according to ICD (International Classification of Diseases), and police reported accident data, for all cases where an injured person has been admitted to hospital. This provides an opportunity to study the influence of the car design on injuries.

In this study, a material from the police and the hospitals on the national basis has been used to study the influence of new car design. The method used was predominantly paired comparisons, which can control the influence of accident severity and other problems associated with exposure.

It was found, that there has been a dramatic reduction of skull/brain as well as facial injuries in the last years that can be related to the design of the cars. The reduction was in the order of 50-60% when comparing cars from 1984 with cars from 1995, involved in car to car impacts.

INTRODUCTION

Injuries to the skull and brain are the leading causes of death among car occupants involved in road traffic accidents (1). They are also the origin of severe and disabling injuries (1,2), and has therefore been of major concern for the protection of injuries to car occupants. Several preventive systems have been developed mainly to prevent from injuries to the skull and brain, as well as legislative actions.

There are mainly two injury criteria for brain injuries, measured in crash tests; peak acceleration and HIC (Head Injury Criterion). Dynamic impact tests have shown that there has been a positive development of the risk of receiving a skull/brain injury, based on HIC measured in frontal crash tests (3,4). The introduction of airbags is one measure that has proven to give positive effects.

The possibility to discover any positive impact on injuries in real life accidents is limited, due to the problem to collect large scale materials with enough depth of the medical data and technical data on vehicles. Nevertheless, positive effects can be seen if sound statistical methods can be applied to materials where medical diagnoses are available.

Several attempts have been made to study the impact of increased crash protection, also when single car models have been studied. Generally, it has been complicated to find a correlation, model by model, with crash test results, but on an aggregated level, such relationship has been found (5,6).

The objective of this paper was to study if there is a positive development on injuries to the head for newer car models compared to older cars, when exposure is kept under control.

MATERIAL AND METHOD

Two different materials were used; A and B.

A. To study the general development of fatal, serious and minor injuries to car drivers, police records from 1994 to 1997 were used, where the injuries were classified by the police.

B. To study the development of skull/brain injuries a database of injured persons admitted to all hospitals in Sweden during 1992-95, linked to police records, was used. ICD-codes on three-digit level were used to identify different kinds of injuries to the head. For the analysis of risks, only injuries to drivers in car to car impacts were used. In all 10 170 injured persons with known diagnose, were included in the study.

To obtain the risk figures on skull/brain and facial injuries for cars of different age, the paired comparison method was used, where the exposure base was all cars on the market colliding with the study population. A 3-year moving average was used.

The paired comparison method for car to car collisions (2) is a method where the accident severity is controlled for, and therefore, the risk figures are only sensitive, apart from the passive safety, to systematic differences in seat belt use and accident types, which does not seem to be likely to be sources of error.

RESULTS

Table 1 shows the number of injuries among car drivers admitted to hospital 1992-95. Skull fracture shows a consistent decreasing trend, where the proportion in relation to all injuries has been reduced by approximately 20% from 1992 to 1995.

Table 1.
The number of injured persons by main diagnose.

	1992	1993	1994	1995
Skull Fracture	109	108	90	83
Other head injury	897	868	809	841
Fracture, upper extr	168	138	166	151
Fracture, lower extr	272	224	214	222
Other injuries	1184	1093	1284	1249
Total	2630	2431	2563	2546

Figure 1 shows the relative risk of minor and fatal/serious injuries to drivers in cars from year model 1985 to 1997. While there has been only a small reduction of minor injuries, the risk of fatal and serious injuries have dropped by approximately 40% over the period, where the major reduction has taken place for cars of model year 1990 and later. To some degree this is associated with a vehicle weight increase during the period.

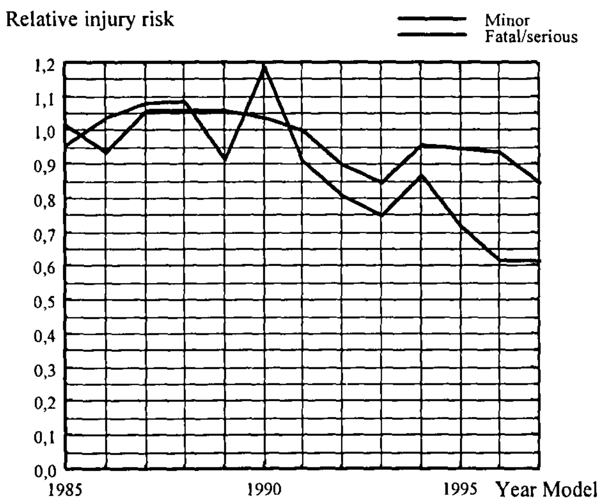

Figure 1. The relative risk of police reported minor and fatal/serious injuries to drivers of cars of different year models 1985-1997.

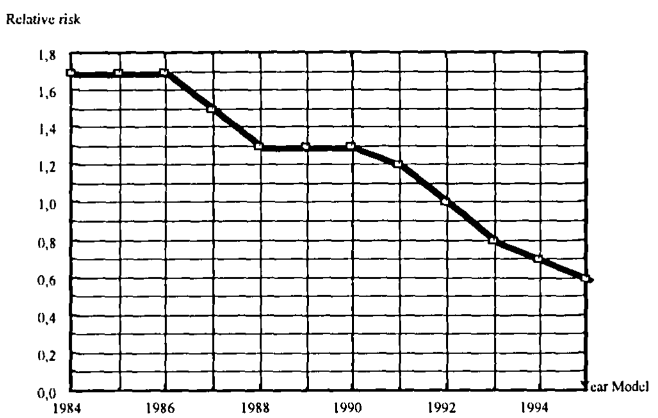

Figure 2. The relative risk of minor/moderate head injuries (ICD-coded) to drivers in car to car collisions with cars of different year model. n=1462.

The reduction of minor to moderate head injuries, mainly consisting of commotion, was 76% from year model 1984 to 1995. The major reduction occurred after 1990, where the relative risk fell by approximately 50%.

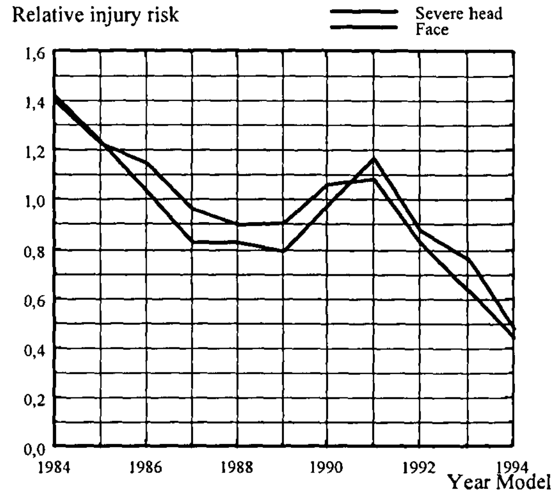

Figure 3. The relative risk of severe skull/brain injuries and facial in car to car collisions with cars of different year model. Facial injuries = 390, skull/ brain injuries = 347.

Both severe skull/brain injuries as well as facial injuries have been reduced by approximately 60% from 1984 to 1994. There was an increase for both types of injuries in the late 80-s and early 90-s, but since 1991, there was a continuos decrease.

DISCUSSION

Skull/brain injuries is one of the major causes to the public health problem due to traffic accidents, being both the dominant causes of death, and often leading to permanent medical disability. It is therefore natural, that many efforts to reduce the harm caused by road accidents are directed towards injuries to the head (1).

It is of great importance that all these efforts that have been made during the last few years in terms of upgrading the safety performance of cars, are followed up. The investments made by the car industry and the consumers in safety are probably the largest ever, and it is therefore interesting to see whether this has lead to changes in real life accidents.

In crash tests, especially those made for the consumers, it is quite clear that the key values have undergone a positive trend. HIC values in full frontal as well as offset impacts are much lower for cars that have entered the market recently, and they can be tested at higher velocities than ever (3).

The possibilities to study the effectiveness of crash protection in real life accidents, are limited. Often, the safety impact of the design of the car is confounded by factors not associated to the car, but to the use of the car, the exposure and the accident severity. Such confounding factors can be controlled by using in-depth study technique. Such a technique is, however, hard to combine if a large number of accidents are to be used, and, furthermore, reconstruction of accidents might give a too low accuracy of accident severity variables (7). A matched pair technique offers the possibility to control several confounding factors. In this study, such a technique was used on a material with very good medical information, which is unique. The reliability as well as the validity of the data and results are therefore relevant. One factor that was not controlled for, was the use of seat belts. It is, however, not expected that the seat belt use could vary to such extent for cars of different year model, that it could alter the findings significantly.

One factor that might explain the somewhat surprising high effectiveness of safety development, is the fact that speeds and speed limits in Sweden are low, probably leading to that a smaller proportion of accidents are at a level, where the accident severity is higher than the segment where crash protection can act. This factor is also increased due to that only car to car collisions were included in the analysis. Accidents with trucks, lorries and buses, often leading to high accident severity would probably lead to somewhat other results. The increased weight of cars also can explain to a small part, the positive development.

The general positive development that can be seen during the 90-s, has also been seen in other studies taking place earlier. It is though important to realise, that there are major differences between individual car models. Probably, there are cars, that have a risk situation that is even better than shown by the present results. The reduction was not constant, and there were even signs of an increase in the early 90-s. This remains to be explained, but one fact is that several cars at that moment were prepared for, and also outside Sweden, equipped with driver side airbags.

The positive development as seen in crash tests would not be of any use if they did not address major part of those accidents where occupants would gain from crashworthiness development. It is, however, important to stress, that car safety, crashworthiness and occupant restraint protection, cannot solve accident outcome with very high severity, Those accidents must be addressed with other measures. If, on the other hand, such accidents are modified by infrastructure means, such as energy absorbing guard rails etc, the benefit from better crashworthiness could probably be larger than today.

The more or less constant risk of minor injuries can at first be considered as a small problem. It should, however, be stressed, that among these injuries, there is a large number of injuries to the neck, often causing long term consequences(2).

The positive development of head protection in cars, is a gradually increasing reason for the total decline in road deaths. It is, however, important to stress that the positive impact can only be fully used if seat belts are worn. The use of seat belts must therefore be 100% if all investments into passive safety should use its full potential.

Nevertheless, it is clear that the public health has gained significantly from the development of passive safety of cars. The total potential is, though, only used, if all cars in the population have the high safety level shown here. These results contrast to other findings, where the potential of increased crash protection has been estimated to be low(8).

The process behind the positive development seems to be the increased demand from consumers rather than newly introduced regulation. This process should be further stimulated, as there also seems to be a further potential in passive safety.

CONCLUSION

There was a high and consistent decrease of head and facial injuries in cars of model years in the 90-s compared to cars from the 80-s.

In car to car impacts, the reduction of injuries to the head, was in the order of 50-60%.

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AIS UNIFICATION: THE CASE FOR A UNIFIED INJURY SYSTEM FOR GLOBAL USE

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ABSTRACT

The Abbreviated Injury Scale (AIS), developed by the Association for the Advancement of Automotive Medicine (AAAM) is the most widely used anatomic injury severity scale in the world. However, different user groups have modified the AIS system to fit their needs, and these modifications prevent ready comparison and trending of data collected in these systems in the US and throughout the world. The US currently has 5 AIS based severity systems (NASS-88, NASS-93, AIS-85, AIS-90, NTSB) and two AIS based impairment systems (IIS and FCI) in use, with additional revisions forthcoming. Other modified AIS systems are known to be in use in the U.K. and Japan. The data collected in these systems cannot be accurately combined or compared without re-coding or the use of complex "mapping" programs.

With the increasing use of severity mapping of statewide hospital discharge data (ICD-9-CM and soon ICD-10-CM) and linking of country wide mortality data (ICD-9 and ICD-10) for engineering use, the relationship of the AIS severity systems to ICD-9/10, ICD-9-CM, and the proposed ICD-10-CM becomes more important. The recent creation of the national FARS-MCOD database for fatal motor vehicle (MV) injuries, and the mapping of statewide CODES data to NASS format are indicators of future data directions.

This paper compares five severity systems and two impairment systems in terms of purpose, code structure and use and discusses the reasons for the user modifications to these systems. With global "harmonization" encouraging greater sharing of international data, the paper also presents the relationship of the AIS worldwide to the larger scope of worldwide mortality (ICD-9/10) and US reimbursement (ICD-9-CM/10-CM) classification systems.

To resolve compatibility issues resulting from multiple injury systems, the authors propose a "unified" system for global use, configured by inputs from major AIS "data owners", users and analysts. Six key attributes of the unified system are: (1) Backward compatibility with historical data through "maps" so no data is lost. (2) "Scalable" to allow a simple level of use for developing countries, a more complex level for crash research and a detailed level for clinical hospital use, all with data compatibility. (3) Satisfy the needs of the engineering community for injury location information and aspect, and also the clinical requirement for precise injury description. (4) Integrated interface for overall severity scores, such as MAIS, ISS and NISS*. (5) Coordination with other injury data systems such as the ICD-9/10 mortality systems and ICD-9/10-CM reimbursement systems.** (6) Establish a structured process to maintain and upgrade the system, on a data compatible basis for the 21st century.

The authors believe that a "unified" system is critical to the preservation of the AIS as a worldwide standard. Unified data can provide a pool of consistent international data to support a variety of important research, prevention and treatment efforts and is essential to satisfy the global needs of the medical and engineering communities.

OVERVIEW OF ANATOMIC INJURY SYSTEMS

In order to propose a unified system, it is first necessary to understand why the users of each system developed it in a unique way. Five broad types of systems important to clinicians, engineers, regulators and vehicle researchers are listed in Table 1, along with the names of the systems falling under each type. Unless a unified system meets the needs of all intended users, it will not stay unified for long. To accomplish this goal, an understanding of the different system uses is required. The following is an overview of the various types and characteristics of systems in use in the US.

Table 1.
Types of Injury Systems

1. Severity / Location - NASS-88, NASS-93, NTSB
2. Severity / Identification - AIS-85, AIS-90
3. Mortality - ICD-9, ICD-10
4. Reimbursement - ICD-9-CM, ICD-10-CM, OIICS
5. Impairment / Identification - IIS, FCI

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*MAIS - Maximum AIS, ISS - Injury Severity Score, NISS - New Injury Severity Score

**ICD - International Classification of Diseases

Injury Severity/Location Systems

These systems have three basic goals: locate the injury on the body, assign a threat to life rank to the injury and identify the source of the injury, if possible. They are currently used for collecting injuries relating to MV transport and aviation crashes. Injury location systems are of primary use to vehicle designers, regulators, manufacturers and researchers. To analyze the safety of vehicles or design safety interventions, the location and severity of occupant injuries is necessary. With this information, injuries can be matched with the source in the vehicle that caused the injury, and counter-measures developed.

A six point scale, (Table 2) based on a revision of the AIS (with some modifications to be discussed later) is used to rank threat to life in all location systems known to the authors. However, the part of the code that locates the injury varies between systems. To insure no injury location information is lost, location systems permit the coding of the location of an injury, even if the exact injury and its severity is not known. This requires an additional ranking level not used in AIS, usually designated as level 7 (Table 2).

Location systems do not need to identify an injury in terms of organ or system to a **clinical treatment level of detail** for the system to be useful. Information of the type necessary to assess quality or cost of care is not needed. As a result, some of the systems (NASS-88 & NTSB) do not uniquely identify an injury, i.e. several clinically distinct injuries may share the same injury code. However, it is imperative that the organization of the classifications permit computer parsing of the injury by body area, system, organ, etc. Injury severity/location systems include NASS/CDS-88, NASS/CDS-93, NTSB and modifications of these systems in use outside the US.

Injury Severity/Identification Systems

These systems have two basic goals: identify the injury in sufficient detail for treatment review and assign a threat to life rank to the injury. Injury identifier systems are of primary use in clinical settings or by medical researchers. Data coded with these systems is used to assess injury trends, quality of care and outcome. Precise definitions of the injuries are required in order to assess the treatment provided and outcome obtained.* As a result of this requirement, injury codes are unique; no injuries share the same code. A six point AIS severity scale, (Table 2) is used to rank threat to life. Coding of unknown injuries is discouraged, although a "9" severity level is allowed in cases for injuries where the severity is unknown.

Location of injury is not a major requirement of the users of these systems. The location in many cases does not affect the care or outcome and therefore is extraneous information. For example, an identification system might precisely specify which arm bone is broken, (i.e. radius or ulna) but will not identify whether it is the left or right arm. Identification systems are used by hospitals and researchers for all type of injuries, regardless of cause, including MVCs, falls, GSWs, etc. Perhaps as a result, these systems are less oriented towards collection or analysis of the source of a vehicle occupant's injuries. Injury sources are not captured for each injury, and the system is not generally organized to permit analysis for sources based on the location of the injury on the body. Injury identifier/severity systems include AIS-85, AIS-90 and modifications of these systems in use outside the US.

Table 2.
AIS Injury Severity Levels (Threat to Life)

0 = not classified as an injury (NASS and NTSB)
1 = minor
2 = moderate
3 = serious
4 = severe
5 = critical
6 = maximum
7 = injury, severity unknown (NASS)
88 = injury, severity unknown (NTSB)
9 = injury, severity unknown (AIS)
unknown if injured (NASS)
99 = other, (NTSB)

Mortality Systems

Mortality systems are the oldest of the five types of systems, with origins dating back more than 200 years. A mortality system has a single goal: to classify all **causes** of deaths for storage and statistical analysis. To meet this objective, less injury detail is required than that recorded in severity, impairment or reimbursement systems. Additional information, which might be useful for care or treatment of injuries is not required. The source of each injury is not recorded and no severity information is recorded, perhaps since all individuals are deceased. Injuries of different severities in other systems, and injuries with different sources may be coded under the same code in a mortality system. The World Health Organization's (WHO) International Classification of Diseases, 9[th] revision (ICD-9), is an international standard currently used to report US

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*Injury identifier codes "Pre-dots" began with AIS-85. AIS-80 and earlier AIS revisions did not include injury codes, only severity digits, but were used for outcome analysis.

mortality data.* Injuries are not defined as "**causes**" of death according to ICD-9 and ICD-10. Injuries are "nature of injury" (N-codes) and are only recorded when associated with a specific cause. As a result, two types of codes are recorded for an injury in the ICD-9 mortality system: a single code for cause of the injury (i.e. motor vehicle crash) and from one to twenty nature of the injury codes (i.e. crushed skull, broken ribs, etc.).

Reimbursement Systems

A reimbursement system has a single purpose: to classify and store conditions and procedures so that charges can be assigned and utilization reviewed. Injuries are a subset of all possible conditions including diseases, poisoning, burns, related complications and procedures. One major reimbursement system in the US is the ICD-9-CM (clinical modification).**

The ICD-9-CM is an expanded and altered version of WHO's ICD-9 mortality system. The "CM" includes more detail, organized in a different way, in order to capture the information required for billing and utilization. In spite of its name, the ICD-9-CM is **not** an international standard and is not under the exclusive control of the WHO. The similar names but different purposes and details of the ICD-9 and ICD-9-CM can cause confusion. ICD-9-CM coding is required by the US government for reimbursement for Medicare or Medicaid and is also required by states with rate setting systems. Many states make publicly available statewide hospital discharge data in ICD-9-CM format, and similar census data is available for the national Medicare database. Diagnoses and procedures coded in ICD-9-CM determine the DRG (Diagnostic Related Group) that specifies the reimbursement level used by U.S. Public Health Service and the Health Care Finance Administration.

No severity, impairment or source of injury information is part of the ICD-9-CM nature of injury code. The code cannot be "parsed" to give the location of the injury. Only the most significant injuries (from a reimbursement standpoint) are generally recorded by coders, and the coding may be affected by reimbursement considerations. As with mortality systems, injuries with different severities in other systems and injuries with different sources may be coded together under the same reimbursement code.

Another classification system is the Occupational Illness and Injury Classification System or OIICS, administered nationally by the Bureau of Labor Statistics. The creators of this system considering using the ICD-9-CM system for their data, but found it too complex. The OIICS system is designed to capture data on occupational injury or illness. The system includes codes for the nature of injury or illness, part of body affected, source of the injury, manner of event or exposure causing the injury and the secondary contributing injury source. No severity or impairment information is included in the code.

Impairment/Identification Systems

An injury with low severity (threat to life) does not necessarily have low impairment, either as measured by a quantitative scale or by public perception. Bilateral eye injuries causing permanent blindness may have a severity of AIS-1 or 2 (minor or moderate) in terms of threat to life, but have a large effect on lifestyle and long term impairment. Impairment is the complement to severity, and while this is a developing area, the use of impairment systems will undoubtably grow.

The Injury Impairment Scale (IIS) and Functional Capacity Index (FCI) are two different impairment systems, both based on the AIS-90 identification/severity system. They are designed to use the same injury code structure as the AIS-90, but instead of severity assign an extension to the code that corresponds to the loss of function resulting from that injury after healing has occurred. The IIS and FCI each map into their own subset of all the AIS-90 codes.

INJURY SYSTEM DETAILS

Each system contains a dictionary of injury descriptions, at least one code to represent each injury, and other attributes of the injury, which may include severity, impairment or location data. These characteristics are described for each of the main systems.

AIS-85

The AIS-85 was the first AAAM system to combine the six point severity scale with numeric codes to designate specific injuries. AIS-85 uniquely identifies 1224 injuries with a 5 digit numeric "pre-dot". Injury aspect information (left, right, central, bilateral) is only included for a few bilateral codes. There are eight body chapters that could be used for injury location, except that all skin injuries are grouped in a ninth chapter, essentially preventing easy computerized location analysis. In contrast to ICD-9-CM, AIS requires the coding of **all** injuries for an individual, not just the most severe or costly. A sample code appears in Table 3.

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*The US has announced the intention to shift to the ICD-10 revision in 1999.

**A preliminary version of the ICD-10-CM was released for review in late 1997.

Major Uses of AIS-85 - Some hospitals have not converted to AIS-90 and continue to compile hand coded trauma registry data in AIS-85. However, the widest use of AIS-85 is output from the automated "mapping" program used to compute severity from ICD-9-CM hospital discharge data. Other uses include numerous studies in the literature, NHTSA Study Center crash cases and MVC data bases in parts of the UK and Australia.

Table 3.
AIS-85 Code Dissection

Code Number = 32305.4
Description = Le Fort III maxilla fracture
- 3 = AIS-85 body chapter (total of 9) - Face
- 23 = organ or specific area - maxilla
- 05 = injury succession number (5th listed)
- 4 = AIS-85 Severity, 1 to 6, or 9 (injury of unknown severity), 4 specifies a severe injury

Note: The Body chapter digit is partly amenable to computerized parsing for location analysis, but this analysis is confounded by the collection of all skin injuries in a separate body chapter. Organ & injury succession numbers are not configured for parsing.

AIS-90

The AIS-90 is a revision of the AIS-85. Extensive changes were made to the injuries included, particularly in the head chapter. There are 1315 injuries uniquely identified. The injury description code was expanded from 5 to 6 digits, and was therefore changed for all injuries. Injury aspect information is included only for a few bilateral codes. Injury location is limited to eight body chapters, with an additional chapter for "other". Skin injuries, with the exception of burns and some other injuries, were put into the body chapter in which they occurred. This allowed computerized injury analysis by body chapter location for most injuries. Organization by type of anatomic structure was introduced so that computer analysis could be carried out below the body chapter level. As with AIS-85, AIS-90 coding rules require the coding of **all** injuries.

Table 4 displays the same injury shown for AIS-85 in Table 3. Note that all parts of the code are different from AIS-85, including severity. However the severity of the injury could be the same if a >20% blood loss occurred. However, blood loss information was not collected in AIS-85, so a direct comparison between the codes is not possible.

AIS-90 Use - Hand coded AIS-90 data exists in a few state-wide trauma systems for about 18,000 individuals per year. The AIS-90 data is sometimes mixed with AIS-85 data because coders may not record, or users may delete the injury identification code "pre-dots". AIS-90 is also used in individual hospitals' trauma registries which typically contain less than 2,000 cases per year, NHTSA Study Center crash cases and numerous studies in the literature. Modified versions of the AIS-90 are used in MVC databases in parts of the UK and Japan. Unlike AIS-85, relatively less "mapped" data exists for AIS-90, since the mapping computer program was just released in late 1997.

Table 4.
AIS-90 Code Dissection

Code Number = 250808.3
Description = Le Fort III maxilla fracture
- 2 = AIS-90 body chapter (total of 9) - Face
- 5 = type of anatomic structure (6 types) - skeletal
- 08 = specific anatomic structure (19 types)
- 08 = level (consecutive number, 00 or 99)
- 3 = AIS-90 severity, 1 to 6, or 9 (injury of unknown severity), 3 specifies a serious injury

Notes: Body chapter parsing analysis confounded for burns and degloving injuries, since these injuries are not coded in the body chapter where they occur. Anatomic structure parsing analysis confounded for burns.

The code 250810.4 is used (+1 to severity) rather than 250808.3 if blood loss >20%.

NASS-88

In the middle 1980's NHTSA required an injury location and severity system to correlate occupant injuries and severities with injury sources for its Crashworthiness Data System (CDS) database. At the time, the AAAM system, AIS-80, did not record any injury information beyond the severity digit. Therefore, to provide injury location information, NHTSA adopted another system, known as the Occupant Injury Classification, or OIC. This permitted the analysis of the location of skin contacts and other injuries relative to the sources of the injuries, a vital part of MVC injury prevention. The authors refer to this system as NASS/CDS-88 or NASS-88 and it was used for data collected by NHTSA between 1988 and 1992.

As a location system, NASS-88 focuses on location information, not treatment detail. The injury code consists of four alphabetic characters and one severity digit. There are 20 body chapters, versus 9 in the AIS-85 system, to permit finer resolution in the location of injuries. Unlike AIS-85 and AIS-90, skin injuries are always coded in the body chapter and with the detailed aspect in which they occur. Injury codes are not unique and may be used to specify different injuries at the same location with different severities. As a result, there are 5,698 injury descriptions, but only 3,192 unique injury codes. NASS coding rules require the coding of all injuries, even when severity is not known. This is done to retain body contact point information. To accomplish this, NASS created a new severity level of 7 for these injuries. The recording of injuries of unknown severity makes the calculation of ISS different for NASS and AIS cases. AIS prohibits the calculation of ISS for patients with unknown severity, NASS allows it.

Table 5.
NASS-88 Code Dissection

Code Number = FCFS-4
Description = Le Fort III maxilla fracture
- F = NASS-88 body chapter, Face (total of 20)
- C = aspect/location (max of 10 aspect codes) - central
- F = lesion (19 types) - fracture
- S = system/organ (22 types) - skeletal
- 4 = Severity, 1 to 6, or 7 (injury of unknown severity), 4 specifies a severe injury

Note: All parts of the code (body chapter, aspect, lesion, organ, severity) are amenable to computerized location analysis.

The NASS-88 system was designed to be easy to code and analyze, and all parts of the injury code are designed to parse for computer analysis. The coding manual relies on the use of "wildcards" to specify the code structures, with the permissible values for the wildcards varying by body chapter. This approach makes it necessary to first "expand" the manual in order to determine all of the defined injuries. It also makes it difficult to identify errors in coding, as a listing of all the defined codes after expansion is not included. In contrast, neither AIS-85 or AIS-90 use wildcards.

NASS-88 Use - NHTSA's NASS/CDS crash database contains 50,000 individuals and 158,000 injuries, collected by NHTSA's investigators over the period 1988-1992. **This is likely the largest uniform hand coded severity database in the world.** Using the mapping programs developed by two of the authors it is possible to combine the NASS-93 and NASS-88 databases to produce a unified database with 80,000 individuals and 250,000+ injuries. NASS-88 is also used in numerous U.S. MVC studies in the literature.

NASS-93

Starting with the 1993 CDS data year, NHTSA ceased using the NASS-88 injury system and changed to a system the authors call NASS/CDS-93, or NASS-93. This system is based on the AIS-90. Since the AIS-90 is an injury description system, NHTSA modified the system to collect location information. The modifications included changing injury codes for skin injuries by placing burns and other injuries in the body region in which they occur, and adding an aspect digit (up to ten aspects) to every code to specify injury location.

Table 6.
NASS-93 Code Dissection

Code Number = 250808.3,4
Description = Le Fort III maxilla fracture
- 2 = NASS-93 body chapter (total of 9) - Face
- 5 = type of anatomic structure (7 types) - skeletal
- 08 = specific type of anatomic structure (19 types)
- 08 = level (consecutive numbers, 00 to 99)
- 3 = AIS-90 severity, 1 to 6, or 7 (injury of unknown severity), 3 specifies a serious injury
- 4 = aspect (10 types), central

Notes: Modifications made to original AIS-90 codes allows parsing for body chapter, anatomic structure, type of structure and severity.

The addition of aspect resulted in some conflict with original AIS-90 codes. These have largely been eliminated by successive modifications to NASS-93.

The code 250810.4,4 is used (+1 to severity) rather than 250808.3,4 if blood loss >20%.

These modifications nearly tripled the number of AIS-90 codes, from 1315 to 3176. However, unlike NASS-88, the codes are unique. The injury manual added "wildcard" codes (like NASS-88) to the original AIS-90 structure to designate which aspects are applicable to each code, and which body chapters apply to burn codes. This requires the manual to be "expanded" to locate undefined injuries. Even with the NHTSA modifications to enhance location, the drop in the number of body regions (to nine) makes the system less sensitive for computer analysis of injury location than the 20 chapters in NASS-88. For example, it is not possible to identify skin injuries to the "lower leg" - all leg injuries are now in "lower extremities" and could be located in the upper or lower leg, knee, ankle or foot. NASS-93 coding rules require that all injuries be coded, and like NASS-88, there are special injury codes of severity 7 for injuries of unknown severity. As with NASS-88, this results in different calculations for ISS than in the AIS system.

NASS-93 Use - NHTSA's NASS/CDS crash database expands by about 10,000 individuals and 30,000 injuries each year. The total for 1993 to 1996 is more than 100,000 injuries. Within two years, the NASS-93/CDS database will replace the NASS-88/CDS database as the largest uniform hand coded injury database in the world.

Using the authors' "Crashmap" program, NASS-93 injury codes and severity levels can be produced from statewide hospital discharge linked Crash Outcome Data Evaluation Study (CODES) data. This process can assign NASS codes and severity levels for tens of thousands of injuries for the thousands of individuals hospitalized from MVCs in the CODES states each year.

Other uses include 100-200 cases per year from NHTSA's Special Crash Investigation (SCI) group, 500 - 1000 cases a year from NHTSA CIREN study cases and numerous studies in the literature. The Transport Canada national MVC data base is also reported to use NASS-93.

NTSB

The National Transportation Safety Board (NTSB) has the charter of oversight of aviation, pipeline, marine and interstate truck crashes. The NTSB maintains a database of all commercial and general aviation crashes exceeding an injury and damage threshold. In the 1980's the NTSB began to use an AIS based system to record injuries for some of these crashes. The system is an injury location system using an 8 digit numeric injury location with a two digit AIS severity. The source of the injury is also recorded and attached as an extension to the code.

Table 7.
NTSB Code Dissection

Code Number = 0299040103
Description = Le Fort III maxilla fracture
02 = Body chapter (total of 24) - Face
99 = Aspect (total of 4) - Other
04 = Lesion(19 types) - Fracture
01 = System Organ (24 types) - Skeletal
03 = AIS severity, 00 to 06, 88 (injury of unknown severity), 99 Other, 03 specifies a serious injury

Note: All parts of the code are amenable to computerized parsing for location analysis

The NTSB system is similar in concept to NASS-88, but uses numeric rather than alphabetic identifiers. It does not uniquely identify codes. The definitions of body chapter, aspect, lesion and system/organ are different than the NASS or AIS systems. The sample case in Table 7 shows the same injury used previously.

NTSB Use - The system is designed for use in the national database of all aircraft crashes with significant damage or injury. This includes 37,000 crashes for the period 1983-96. Injuries and seating information for crash occupants are compiled in supplements K & L, but not for every crash.

ICD-9

ICD-9 is an outgrowth of what was originally a mortality only system. It includes morbidity, but in the US the largest use is to present national mortality data. In this classification system, injuries are assigned numbers, basically in sequence. The code numbers are not organized to allow parsing for body region as in the NASS or NTSB systems. The ICD-9 system is often confused with ICD-9-CM, which is a US system used for reimbursement. The two systems are not identical.

Table 8.
ICD-9 Code Dissection

"N" or Nature of Injury Code Number = 874.9
Description = Open wound of neck, other and unspecified parts, complicated
874 = Three digit numeric disease/injury identifier
9 = One digit detail qualifier after decimal
No aspect, severity or impairment information

In the context of ICD-9 mortality data, this code is used for **decapitation.** In unlinked FARS, this injury would be represented only by "K" for killed.

Note: ICD-9 codes cannot be parsed for computerized location analysis.

In 1998, the ICD-9 began a new and prominent role in crash research with the linkage of nationwide Fatal Crash Reporting System (FARS) and Multiple Cause of Death (MCOD) mortality data. FARS-MCOD provides more detailed causes of death (in ICD-9 format) for MVCs. **FARS-MCOD is the first US database with injuries coded in an international standard, and will likely replace unlinked FARS because of the increased injury information the ICD-9 codes provide.** When linkage of all FARS years is complete, FARS-MCOD will contain ICD-9 injury codes for more than a million persons.

ICD-10

The ICD-10 is a major revision of the ICD international standard. Such revisions occur every 10 or 20 years. The US is scheduled to adopt this system for reporting of mortality data in 1999. The code structure, injury organization and coding rules are changed from ICD-9.

Table 9.
ICD-10 Code Dissection

Injury Code Number = S18
Description = Traumatic Amputation at Neck Level
S18 = 3 digit alphanumeric disease/injury identifier
May have one digit detailed qualifier after decimal, but none in this case
No aspect, severity or impairment information

Note: ICD-10 codes cannot be parsed for computerized location analysis.

ICD-9-CM

The "CM" or clinical modification of the ICD-9 was developed in the US to expand the morbidity part of the ICD-9 to capture information important for the US national reimbursement systems. It is not an international standard, but is used by virtually every US hospital. It is a classification system where injuries are assigned numbers, basically in sequence. The code numbers are not organized to allow parsing for body region as in the NASS or NTSB systems. However, codes for skin injuries contain more location information (although not Aspect) than the 9 body chapters in NASS-93 can record.

Table 10.
ICD-9-CM Code Dissection

Diagnosis Injury Code Number = 874.9
Description = Open wound of neck, other and unspecified parts, complicated
Code looks like ICD-9
874 = Three digit numeric disease/injury identifier
90 = One or two digit detail qualifier after decimal
No aspect, severity or impairment information

Table 8 and 10 show the same code. **In ICD-9-CM this is a "bucket" code** and may contain unspecified open wounds to the neck, as opposed to decapitation in ICD-9 mortality data.

Note: ICD-9-CM codes cannot be parsed for computerized location analysis.

The ICD-9-CM is becoming increasingly important to crash researchers as conversion programs, such as "Crashmap", are used to convert CODES statewide ICD-9-CM discharge and ED data to the NASS-93 injury code format familiar to crash engineers.

ICD-10-CM

The ICD-10-CM is a major revision of the ICD-9-CM US reimbursement system. This revision is currently under review, and may be introduced in 2001 or 2002. The code structure, injury organization and coding rules have all changed from ICD-9-CM, and while it is based on the ICD-10 there are many differences, including codes that are not used and the inclusion of limited Aspect information for laterality (left, right). The code numbers are more organized than ICD-9-CM, but still do not allow parsing for body region as in the NASS or NTSB systems. Codes for skin injuries contain more location information than the 9 body chapters of NASS-93, and include aspect. CODES ICD-10-CM data may in the future supply more skin contact location information for MV researchers and engineers than NASS-93.

Table 11.
ICD-10-CM Code Dissection

Injury Code Number = S11.80
Description = Unspec. open wound of other parts of neck
S11 = Three digit alphanumeric disease/injury identifier (open wound of neck)
.80 = One or two digit detail qualifier after decimal - in this case unspecified wound to neck
Aspect is third digit to right of decimal (not this code)
No severity or impairment information

There is no code in ICD-10-CM equivalent to the S18 decapitation code in ICD-10 shown in Table 9, as this is not currently a treatable condition.

Note: ICD-10-CM codes cannot be parsed for computerized location analysis.

FCI

Impairment scales attempt to assess the long term effects of injuries after healing has occurred. The Functional Capacity Index (FCI) is an impairment scale based on the AIS-90 system, jointly proposed by NHTSA and The Johns Hopkins University. The FCI uses a subset of the 1315 AIS-90 codes, and assigns a non-zero impairment to 324 of those codes. Impairment is measured by function in 10 dimensions: eating, excretory, sex, ambulation, hand/arm, bending, vision, hearing, speech and cognitive. Each dimension has its own set of limitation levels (a-f). A continuous rating of whole body impairment is computed from the dimensions (WBFCI) and assigned a value between 0.00 and 100.00. The FCI is currently under review.

Table 12.
FCI Code Dissection

Injury Code Number = 250808.3aaaaaaaaaa00.00
Description = Le Fort III maxilla fracture
"Predot" and Severity = 250808.3 same as AIS-90
2 = AIS-90 body chapter (total of 9) - Face
5 = type of anatomic structure (6 types) - skeletal
08 = specific anatomic structure (19 types)
08 = level (consecutive number, 00 or 99)
Ten Dimension Limits aaaaaaaaaa = no impairment in eating, excretory, sex, ambulation, hand/arm, bending, vision, hearing, speech, cognitive areas
WBFCI = 0 on continuous scale of 0 to 100.00, no whole body impairment
No Aspect

IIS

The Injury Impairment Scale (IIS) is an impairment scale developed by the AAAM based on the AIS-90 system. It uses an ordinal 0-6 scale to indicate impairment. Of the 1315 AIS-90 codes defined, the IIS assigns impairment codes to 508. It is also currently under review.

Table 13.
IIS Code Dissection

Injury Code Number = 250808 2
Description = Le Fort III maxilla fracture
"Predot" = 250808 same as AIS-90
2 = AIS-90 body chapter (total of 9) - Face
5 = type of anatomic structure (6 types) - skeletal
08 = specific anatomic structure (19 types)
08 = level (consecutive number, 00 or 99)
Impairment = 2, compatible with most but not all normal function
No Aspect

SYSTEM DIFFERENCES

Code and System Structure

The authors, Bradford et al and the IIHS have presented papers on the differences and incompatibility of the AIS, NASS, ICD-9 and ICD-9-CM systems. Tables 3 through 13 have shown some of the differences in the code structures for the AIS, NASS, ICD, FCI, IIS and NTSB systems.

Table 14 illustrates the differences between the NASS and AIS systems in terms of the number of codes and the distribution of the codes by severity. The total number of injury descriptions varies from 1224 in AIS-85 to 5,698 in NASS-88. The percentage and number of codes at any severity level are also different between the systems. Examination at a finer level will uncover many other differences, including injuries which are not included in all systems, different body chapters for the same injury, and major variations in the way skin injuries are recorded. Of particular interest are the many changes in the head body chapter injuries between AIS-85 and AIS-90. Also, identical injury descriptions including "one bilateral" versus "two left/right" aspects in different revisions or systems can cause double counts. These details are covered in the authors' other papers.

Table 14.
System Severity Level Distributions and Total Injury Code Counts

Severity	AIS85 No Aspects		AIS90 No Aspects		NASS88 Aspects Expanded		NASS93 Aspects Expanded	
0	0	0.0%	0	0.0%	1	0.0%	1	0.0%
1	166	13.6%	246	18.7%	1538	27.0%	955	30.1%
2	289	23.6%	399	30.3%	2139	37.5%	971	30.6%
3	374	30.6%	343	26.1%	1213	21.3%	771	24.3%
4	217	17.7%	156	11.9%	415	7.3%	248	7.8%
5	151	12.3%	144	11.0%	200	3.5%	193	6.1%
6	27	2.2%	22	1.7%	38	0.7%	22	0.7%
7	0	0.0%	0	0.0%	154	2.7%	15	0.5%
*9	0	0.0%	5	0.4%	0	0.0%	0	0.0%
Totals	**1224**	**100.0%**	**1315**	**100.0%**	**5698**	**100.0%**	**3176**	**100.0%**

Notes: Total for unique codes in NASS-88 is 319?
AIS-90 and AIS-85 use 9 for "Injury, Unknown Severity"
NASS-88 and NASS-93 use 7 for "Injury, Unknown Severity

Table 15 summarizes other characteristics of the systems. Differences include a wide range in the number of body chapters for location of injuries, (none to 24) the

Table 15. Table of System Characteristics	AIS85	AIS90	NASS88	NASS93	NTSB	ICD-9	ICD-10	ICD-9-CM	ICD-10-CM
Body Chapters	9	9	20	9	24	No	No	No	No
Aspect	No	No	Yes	Yes	Yes	No	No	No	Proposed
Injury Code	5 numeric	6 numeric	4 alpha	6 numeric	8 numeric	4 numeric	4 alphanum	5 numeric	6 alphanum
Severity	1 digit	1 digit	1 digit	1 digit	2 digits	No	No	No	No
# Injury Desc.	1224	1315	5698	3176	unknown	>800*	963*	2030*	>2030*
Unique Injuries	Yes	Yes	3192	Yes	No	Yes	Yes	Yes	Yes

*Note: Includes codes in injury section only ICD-9/9-CM 800-959, ICD-10/10-CM S00 to T69

number of characters in the injury code (four to eight) and whether they are numeric, alpha-numeric or alphabetic, and whether the system includes aspect information (left, right, central, etc). The NASS-88 and NTSB location systems assign the same injury code to several injury descriptions at the same location, and hence have more injury descriptions than unique injury codes.

Threat to Life Baseline

Another important issue is the compatibility of the severity scale between these systems. The AIS severity scale is not "static". As medical technology advances, the threat to life of a given injury can diminish. An injury that 10 years ago in NASS-88 was a "3" level (serious), and under AIS-85 was a "2" level (moderate), may under the revised AIS-90 be a "1" level (minor). This type of change is illustrated in Tables 16 and 17. Although these adjustments in threat to life are appropriate for clinical use, they confound analysis of injury severity over time.

The time frame in which injury severities were assigned establishes the baseline of medical technology used. The authors call this factor the TLB or Threat to Life Baseline.

For severity system data users who wish to compare or trend data collected from different revisions of AIS systems, differences in the TLB make analysis complex. For example, it may not be possible to determine whether reductions in injury severity of MVC occupants over time is caused by vehicle safety interventions or the change in severity of injuries due to a TLB revision. Table 16 illustrates this point for a MVC occupant with the same injuries measured in AIS-85, AIS-90, NASS-88 and NASS-93. **The result is that the Maximum AIS by ISS Body Region, overall MAIS and the ISS for the individual varies with the recording system used.** The individual shown might rank as "major trauma" (e.g. ISS>15) in one system and not in another.

Table 16.
Comparisons of Severity Levels

An 11 year old child sustains a fractured femur, a dislocated knee and a LeFort III fracture of the maxilla (with ≤ 20% blood loss), and an eyelid laceration in a motor vehicle crash in a snow storm.

Injury Description	AIS-85	AIS-90	NASS-88	NASS-93
ISS Body Region - Extremities or Pelvic Girdle:				
Right femur fracture, NFS, (age <12)	92601.3	851802.2	TRFS-3	851802.2,1
Right knee dislocation, NFS	91805.3	850806.2	KRDJ-3	850806.2,1
Mais for Body Region:	3	2	3	2
ISS Body Region - Face:				
LeFort III fx of maxilla (with blood loss ≤ 20% by volume), aspect is central	32305.4	250808.3	FCFS-4	250808.3,4
Left eyelid laceration	10301.1	210600.1	FLLO-1	297602.1,2
Mais for Body Region:	4	3	4	3
ISS Body Region - External:				
Hypothermia, 33-32 C	(no code)	919604.2	(no code)	(no code)
MAIS for Body Region	N/A	2	N/A	N/A
MAIS Overall	**4**	**3**	**4**	**3**
ISS	$3^2+4^2=25$	$2^2+3^2+2^2=17$	$3^2+4^2=25$	$2^2+3^2=13$

Table 17.
Example of Variation in Threat to Life Baseline

Injury Description	NASS-88	NASS-93	AIS-85	AIS-90
	Injury Codes			
Heart laceration, NFS	CCLH.5	441008.3,4	51703.5	441008.3
Left elbow dislocation	ELDJ.2	750630.1,2	81504.2	750630.1
(two codes in NASS-88)	ELDJ.3			
Injury Description		**Injury Severity**		
	NASS-88	NASS-93	AIS-85	AIS-90
Heart laceration, NFS	5	3	5	3
Left elbow dislocation	2 or 3	1	2	1

Simply because severity data is ranked using a code with a 6 point AIS scale attached does not make it automatically comparable. The threat to life baseline must also be the same between the systems. **This point is not well known or understood.** If the TLB is not the same, then a "map" is required to adjust the severity of each injury code before comparisons between systems can be made. Examples such as shown in Table 16 illustrate the importance of having a way of normalizing the TLB between systems before comparing or trending severities or overall body scores, such as MAIS, ISS or NISS.

Table 17 illustrates how variations in the Threat to Life Baseline can cause differences in severity of one and two points across the AIS and NASS systems. Since ISS uses the square of the severity level, it amplifies these differences. For example a two point change from a 3 to a 5 changes the ISS by 16 points (3 x 3 =9 vs 5 x 5 =25). The heart laceration code shown in Table 17 illustrates the importance of this issue. This code, with a two point severity change, comprises 20% of all the AIS-5 level injuries in NHTSA's NASS-88 database.

Table 17 also demonstrates the related issues of code counts and "numerical consistency". For example, to answer the question, how many elbow dislocations were in the NASS/CDS data base between 1988 and 1996, Table 17 shows it is necessary to count two "pre-dot" codes in NASS-88 for the data from 1988-1992 and one pre-dot code in NASS-93 for the data from 1993-1996. Further, the appropriate aspect codes must also be accounted for, in this case: left, right and unknown. The AIS based systems lack rules for diagnosis or code counting, so each case must be considered individually.

Before answering the question, "Did new driver side arm rests introduced in 1994+ model years reduce the number of left elbow dislocations of AIS-3 compared to prior years?", it is important to recognize that the NASS coding system eliminated all AIS-3 elbow dislocation codes when it was revised in 1993. Therefore, there would be zero AIS-3 elbow dislocations in 1993+ data to compare to prior years.

The only current method to systematically address the above issues is the use of a NASS-93 to NASS-88 conversion map, which identifies the relationships between the old and new codes and severity levels so that proper data queries and analyses can be conducted.

SYSTEM CONVERSION BY MAP

One way of dealing with the incompatibility issues presented in this paper is to keep data from each system and revision separate and re-code any data necessary for trended analysis. This is an expensive and time intensive approach. Another approach is to develop computerized conversion "maps" that convert between the injury descriptions in the systems. The authors have created or worked on many of

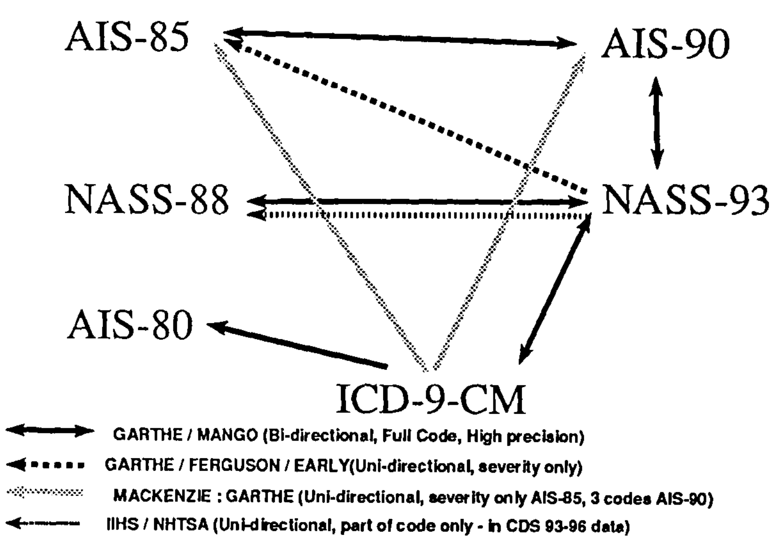

Figure 1. AIS-NASS-ICD Conversions

the maps currently in use, which are illustrated in Figure 1.

Maps can help to resolve issues caused by code, severity and injury count differences. However, as the number of revisions of each system grows the number of required conversions grows geometrically. If each of the AIS, NASS, ICD and ICD-CM systems shown in Figure 1 are revised, then the total number of maps required to convert between all systems grows to 36. With revisions forthcoming for ICD-10, ICD-10-CM and AIS, this possibility looms in the near future. Constructing the conversions becomes an untenable task; an effort larger than revising the base system. Even if the additional conversions were constructed, it is doubtful that most users would be able to keep on hand and apply all the maps that might be necessary to adjust their data.

A further complication is that maps perform more precisely going from the system with the most detail (typically the latest revision) back to the system with less detail (the earlier revision). Therefore, to obtain the highest precision, combined data must be converted to the "old" format, partially defeating the purpose of revising the systems in the first place.

The difficulties with the expanding number of conversions, and the confusion experienced by users of data collected in different systems is one of the primary reasons the authors propose the creation of a unified injury system.

HAND CODED VERSUS MAPPED DATA

Another major factor in considering a unified system is the evolution in the type and use of injury data. Hand coded data is most familiar to clinicians. To produce the data, coders assign a set of severity codes from a severity dictionary to a case after reviewing information from medical records and other primary sources. An experienced, trained coder can code 3-4 cases per hour. The detail and accuracy produced is high, but the process is relatively expensive. The expense limits the amount of data that is coded this way to thousands of cases.

At one time, the pure AIS system was used to collect the largest databases, which generally belonged to regional, or sometimes statewide trauma systems. However, Figure 2 shows that this is no longer the case. While individual hospitals may have thousands of hand coded AIS cases in their trauma registries, this data is rarely combined with other hospital's data and made available for public analysis. Meanwhile, the requirements of vehicle engineers and policy makers has resulted in massive hand coded national databases for MV crashes. NHTSA's NASS-88 & NASS-93 CDS databases contain over 80,000 persons with 250,000 injuries for the period 1988-96, and are growing at the rate of 30,000 injuries per year.

Mapped data is becoming more popular, especially for the engineering community. Hospital inpatient, observation stay and ED data, collected in reimbursement formats are available statewide and in some cases nationally for millions of individuals. By converting the data from these formats to a severity format using a computerized "map" or conversion, information on large numbers of cases can be obtained at a low cost compared to hand coding.

In most cases, the precision of the maps is not at present equal to re-coding the cases by hand; however, the database sizes are so large that the data remains useful even with the lower level of precision. Of particular importance in this area are the conversions to severity data from the ICD-9/10 mortality and ICD-9/10-CM reimbursement systems. One area that maps now may be superior to hand coded NASS/AIS data is in the analysis of skin contact injuries. NASS-93 and AIS-90, with only 9 body chapters are limited in the ability to precisely locate extremity injuries, as mentioned earlier. ICD-9-CM and to a greater extent, ICD-10-CM (with aspect) contain more information on the location of skin injuries than NASS-93 and AIS-90, and nearly as much as the 20 body chapter NASS-88. As a result, data mapped from ICD-9-CM/10-CM systems (such as CODES data) can produce data with better location resolution than the NASS-93 system. This is another factor which may contribute to the expanded use of mapped data.

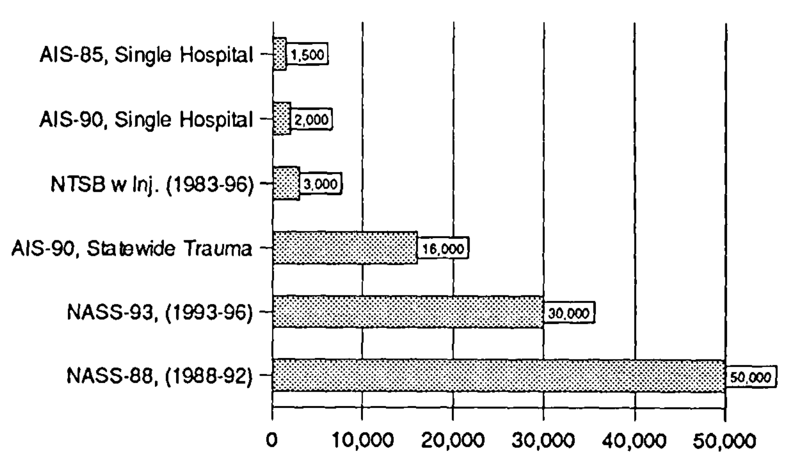

Figure 2. Hand Coded Database Sizes, (cases).

The driving force behind the refinement of the mapping approach is the magnitude of the data that can be converted with it. Figure 3 illustrates how the mapped dataset sizes dwarf even the massive NASS/CDS database, with 380,000 individuals in MV crashes and tens of thousands of injuries available from one CODES state for one year. If the precision of the maps can be improved enough, the sample sizes offer whole new areas for researchers, regulators and engineers to study.

SUMMARY OF CURRENT SITUATION

There are at least five variations of the AIS severity system in use, none of which collect data that is directly compatible with the others. Further, computed scores, such as ISS, cost (HARM) or impairment weights cannot be applied between the systems without adjustment.

Engineering users require injury location type systems, while clinical users require injury description systems. Currently, no single system combines enough information for both groups. Hospital users tend to use their data within their hospital or center, while engineering users want to combine and analyze data on a national basis. The need for data has resulted in the development of engineering based databases (NASS-88, NASS-93), which are much larger and more accessible than the hospital (AIS-85, AIS-90) injury description type databases. The multitude of severity systems in use makes the comparison or trending of data difficult, and can lead to mistakes in analysis when data is combined without corrections.

With the increasing use of severity mapping of statewide CODES hospital discharge data (ICD-9-CM and soon ICD-10-CM) and linking of country wide mortality data (ICD-9 and ICD-10) for engineering use, the relationship of the AIS severity systems to ICD-9/10, ICD-9-CM, and the proposed ICD-10-CM becomes more important. The recent creation of the national FARS-MCOD database for fatal MV injuries, and the mapping of statewide CODES data to NASS format are indicators of future data directions.

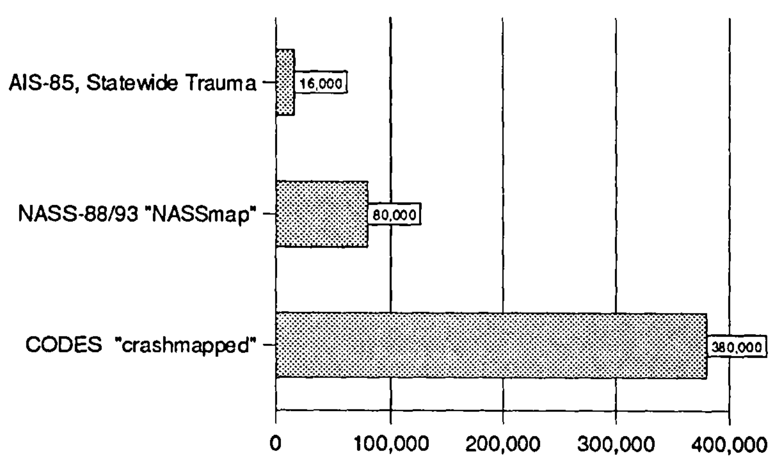

Figure 3. Mapped Database Sizes (cases).

The proposed adoption of aspect by ICD-10-CM leaves the AAAM's AIS as the only severity system without this feature, a feature which is vital for engineering use.

The various modifications to the AIS encompassed in AIS-85, AIS-90, NASS-88, NASS-93 and NTSB have been developed to satisfy the needs of their user groups. A unification of AIS data, and coordination with the other injury systems can only occur if the needs of all users can be satisfied within a unified system. Without satisfaction of user requirements, any new system will once again be subject to modifications by individual groups.

CONSIDERATIONS FOR A UNIFIED SYSTEM

From the study of the existing systems described above, the authors have identified key factors which are critical for the success of a unified system. The factors, in no particular order are:

1. To join the engineering and medical communities and unify AIS, NASS and NTSB, both **location** and **identification** features must be included. Location data from 20 to 24 main body regions has proved necessary for engineering purposes, with supporting **structure that allows computerized injury sorting by System, Structure, Organ, Lesion and Aspect.** Aspect is a key part of future databases currently missing from ICD-9, ICD-9-CM, AIS-85 and AIS-90. The location information must be included in a way that keeps the injury codes **defined uniquely** for clinical use.

2. The injuries described by the system must be **adequate in detail and coverage** to satisfy severity, impairment, mortality and reimbursement uses. Failing to include injury descriptions to cover each of these areas will result in "holes" in the system that prevent effective computerized interface with other major databases.

3. The system must be **"scalable"** so that it can be used at several levels. The simplest level, which might encompass a hundred codes or less, would be available for developing nations, and for

applications where detail is not important. The next level upward can include sufficient detail for engineering, mortality or reimbursement uses, with 2-3,000 codes. The highest level would be available for clinical uses and research and might contain 5,000 codes. Each level can "nest" or expand into the other, as depicted in Table 18.

4. The basic injury description and location information must be **independent** of the severity, impairment, charge or other factor that is coupled to the injury. This allows for periodic updates of the severity or impairment, an important consideration for clinical use. Conversely, the independence also allows users who wish to combine multiple years of data from multiple revisions to "normalize" the severity or impairment to a specified baseline by attaching the corresponding threat to life levels for the period desired.

Table 18.
Example of Injury Code "Nesting"

18 year old driver injured in MVC- found to have a swollen right ankle and difficulty walking.

Level of Detail	Injury Description
Low	Ankle fracture
Medium	Tibia fracture, NFS
Medium	Closed tibia fracture
High	Closed tibia medial malleolus fracture
High	Right closed & displaced tibia medial malleolus fracture

5. The system must be flexible enough to allow the inclusion of new injuries as the need arises. A formalized method is required to add new injury codes to the system and resolve the compatibility and historical data issues that added codes produce. The system must have the property of **"numerical consistency"** so that diagnoses can be counted at some level. The simplest level is counting injuries only by maximum severity by body chapter. A properly designed unified system can allow counting below the body chapter level by type of anatomic structure and specific anatomic structure, and in some cases perhaps individual codes. The property of numerical consistency thus accounts for the cases where one injury may in the future be counted as two or more injuries or vice-versa. Without rules and organization for numerical consistency corrections, trend studies can produce incorrect comparison counts of injuries.

6. Medical panels are needed to review and assign severity and impairment factors on a periodic basis to reflect changes in current medical technology, and organize and recommend new injury descriptions for inclusion.

7. The new system must have accompanying computerized "maps" to convert data from each of the current systems to the new system so that **no existing data is lost.**

8. **Overall scoring systems** (severity and presumably future impairment) such as MAIS, ISS and NISS, and their component variables should be integrated with the new system to make their calculation easy. These overall criteria would be normalized and adjusted as each review of the severity and impairment levels proceeds. In this way these tools stay "in sync" with the system in the future.

9. **Uniform interfaces** with other systems such as mortality and reimbursement.

10. The system needs the support and input from the **major data owners and users** in the US and around the world, and should be set forth as an international standard.

A UNIFIED INJURY SYSTEM (UIS)

The authors make the claim that a system with characteristics as outlined above is not only possible, but is both more desirable and less burdensome than the alternative. The alternative in this case is to allow the AIS, NASS and NTSB systems to go in their own directions with non-compatible revisions. This would lead to greater divergence of the NASS with the AIS, and as NASS is now the largest hand coded severity database in the world, it is likely NASS would become the engineering standard. The revisions to ICD-10 and ICD-10-CM will force another round of conversions from these systems, and these conversions will be more than likely written to NASS, not AIS, because AIS lacks aspect. Failure to develop a unified system would force the creation of a large set (20 or more) of additional, technically difficult conversions to allow comparison or trending of AIS, NASS, NTSB, ICD-10 and ICD-10-CM data.

The authors believe that the need, and benefit of a unified system is obvious. To demonstrate the feasibility of such a system they hope to produce a demonstration chapter of the new system for review in the near future.

CONCLUSION

The authors have presented a brief overview and examples of the codes used for many of the injury systems in both the United States and the world. The systems include two mortality systems, two hospital reimbursement systems, five severity systems and two impairment systems. None of the systems is directly compatibility with the others without electronic conversions or "maps". As the number of revisions of the systems grows, the number of maps required to analyze the data is becoming large. At the same time the trend toward the use of large statewide or national samples is causing more and more severity and impairment data to be created with maps. This trend makes the performance of the maps increasingly more important, and encourages the development of a unified system that would that enhance map precision.

Further, the increasing sophistication of research in the US and other countries is encouraging the collection of more complex injury information. At the same time, vehicle crashes are predicted to become major sources of economic expense in growing nations that require a simpler system for their use. A unified system that can satisfy both requirements is needed.

The authors propose a Unified Injury System (UIS) to satisfy both the engineering need for location information and the clinical need for detailed injury information for treatment. The system proposed is also "scalable" so that more detail can be used by clinicians, but the codes can be "collapsed" to a simpler level for use where the detail is not required.

Data created in past systems will be compatible with the UIS through the use of "maps" so no prior data will be lost. The linkages between the UIS system and the reimbursement and mortality systems can be improved to provide more accurate electronic conversion of hospital and mortality data.

Finally, the UIS separates the description and location of injuries from the threat to life, impairment, and reimbursement attributes. This allows the injuries to be collected and stored separately from these characteristics. Review boards (e.g. AAAM) can adjust the severity or impairment levels on a regular basis, and the injuries can be adjusted to correspond with the medical impairment level or severity level appropriate for either the present or a time in the past. This will permit trending, combining and comparison of injury severity and impairment over long time periods.

The authors believe that a unified system will greatly benefit clinicians, researchers and policy makers on a national and international level, and will allow the AIS severity system to reach a new level in use and acceptance.

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A COMPREHENSIVE SURVEILLANCE SYSTEM TO INVESTIGATE TARGETED ISSUES IN CHILD OCCUPANT PROTECTION

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ABSTRACT

Current databases relating information about children in vehicle crashes are not comprehensive due in part, to the small sample sizes of these studies. This limitation has led to a focus on case series analyses, which have in turn produced few statistically based recommendations for vehicle and child restraint design changes. The magnitude of the problem of child occupant protection is not clear and limited mechanisms currently exist by which to systematically and thoroughly investigate critical questions in the field.

To address these issues, we have created a comprehensive surveillance system devoted exclusively to children riding as occupants in motor vehicles through the utilization of current insurance claim settlement procedures. This surveillance system will provide a mechanism for the prompt identification of important "targeted issues" that require more detailed investigation and analysis. These targeted issue studies will utilize crash investigations and telephone interviews to learn more details about crash circumstances, occupant kinematics, and restraint system performance. The unique combination of the surveillance system with these focused investigations will result in a statistically based sample with valid and generalizable results.

INTRODUCTION

The majority of automotive safety research has focused on the adult driver (1-4). Laboratory crash test data have typically studied the "50th percentile" male (5-7). The best real-world data available on the effectiveness of various restraint systems, such as lap belts, lap-shoulder belts, and air bags, are almost entirely on vehicle drivers. It is not known how data on driver protection may apply to vehicle passengers, particularly children.

Recently, child deaths associated with air bags (8) have focused attention on the fact that children are not just small adults and that research efforts must continue to concentrate on the specific needs of our smallest passengers (9-19). The data collected on how and why adults are injured in vehicle crashes do not always apply to children, who have smaller body frames, are proportioned differently, and have different injury patterns and tolerance levels to injury than do adults.

Many studies that have examined child occupant protection have looked primarily at mortality as the measured outcome. Death is easy to define and mortality data appear in a variety of readily available sources, including the National Center for Health Statistics, and the Fatal Analysis Reporting Systems (FARS) maintained by the National Highway Traffic Safety Administration. As a result, many studies that have identified child-specific risk factors, examined the effectiveness of restraints, and measured potential deficiencies in current restraint system-vehicle interactions have largely used mortality as the outcome of interest (2,4,20-23). However, because child occupant mortality is relatively rare (9.4 deaths per 100,000 children), examining only mortality as an outcome fails to capture the full impact of childhood injury and its potential long-term consequences (24).

Existing research that has focused on child occupant protection using injury as an outcome can be broadly categorized into three types, each having its own unique strengths and limitations: laboratory-based research, hospital-based research, and research using large databases.

Laboratory-based research explores restraint systems and vehicle design features as they pertain to child occupant protection under well-controlled laboratory conditions (6,7,25,26). Child dummies or other surrogates are placed in simulated crash situations in order to measure both the forces of impact on the child occupant and the related kinematics. The strength of these studies is their ability to provide detailed information on the occupant kinematics as well as their capacity to base design specifications on engineering principles. However, these studies are often limited by their lack of a comparison group and by the artificial nature of the laboratory environment, in particular, the limitations of child-sized test dummies (27). The real-world relevance and applicability of these studies is, therefore, largely unknown (28).

Hospital-based research is conducted at one or possibly a small group of hospitals, typically designated trauma centers, and generally focuses on how a limited number of factors, such as seating location and restraint use, affect risk of injury (29-34). The strength of these studies is their ability to control the quality of data obtained, but the inherent biases in studying populations of children referred for specialty care often challenges the validity and limits the generalizability of these studies' results and conclusions. In addition, hospital-based research typically examines a relatively small sample, making it difficult to account properly for the complex nature of motor vehicle collisions and the many potential predictors of injury to children.

Research using large, existing databases, most notably in the United States, the National Highway Traffic Safety Administration's National Automotive Sampling System (NASS), has attempted to overcome the biases associated with hospital-based research by including a sample of individuals from all types of crashes, independent of where the crash occurred and whether health care was received (35-37). However, because NASS is a probability sample of all police-reported crashes in the United States and includes everything from truck- to motorcycle- to automobile crashes, children are underrepresented in the database, limiting its utility. For example, the emerging issue of child air bag-related mortality was not identified through NASS due to the relatively small number of children represented. The small sample size of children in NASS results in large sampling errors both with regard to determining the incidence of significant injury to children and the circumstances of any given type of crash (38). In addition, a significant limitation of studies utilizing NASS data is the reliance upon police reports of injury, which have been documented to be unreliable, particularly for children (39).

Both hospital-based studies and research using large existing databases utilize crash investigations as a methodological tool. During a crash investigation, investigation teams are dispatched to the scene to measure and document the crash environment, damage to the vehicles involved, and occupant contact points according to a standardized protocol. The on-scene investigations are supplemented by information from witnesses, crash victims, physicians, hospital records, police reports, and emergency medical service personnel. From this information, a report is generated that includes estimates of the vehicle dynamics and occupant kinematics during the crash and detailed descriptions of the injuries sustained in the crash by body region, type of injury, and severity of injury. Although these investigations provide detailed information regarding injury mechanisms and occupant kinematics, because of the limitations discussed above, the global context of these studies is unclear. Often these investigations do not include adequate control groups and the source population of the chosen cases is not known. Consequently, it is not known whether the results are representative of the underlying population of children in motor vehicles.

In summary, child-specific transportation safety research has been conducted, and has resulted in a significant decrease in motor vehicle-related mortality to children over the past 20 years (21). However, more recently, progress has slowed (40, 41), due in part to the more complex nature of modern child occupant protection problems such as misuse of child safety seats, side impact protection, and air bag-restraint system interactions. As a result, conflicting masses of information are given to parents, child restraint devices are often recalled, and public-policy decisions are based on tragic anecdotes of injured children rather than on sound, generalizable data.

The Child Occupant Protection Surveillance System is designed to build on the foundation of child-specific automotive safety research that has been conducted to date, and to address current gaps in our knowledge. This surveillance system provides the infrastructure to identify and conduct individual focused research studies or "targeted issues" that utilize telephone interviews and crash investigations as the research method. The unique combination of the surveillance system with the focused investigations provides a global context that combines epidemiological and engineering analyses using accepted methodology from each field.

METHODOLOGY

Overview

The research approach of "Biomechanical Epidemiology" was applied to the development of the surveillance system. In this approach, bioengineers, clinicians, epidemiologists, health educators, medical information systems specialists, professional crash investigators, and others developed a partnership with experts in insurance industry data collection for the inception, design, and implementation of the system. By integrating the expertise of multiple disciplines from the outset, the final results will be useful to the widest possible audience. An Advisory Board of experts from multiple disciplines was created to provide guidance to the partnership.

The surveillance system involves identification of a census of children involved in crashes reported to State Farm Insurance Company. After consent is obtained by the claims representatives, a minimal dataset of information about these crashes, including contact information, crash location, driveable status of the vehicle, an initial description of the damage to the vehicle, the Vehicle Identification Number, and the age and treatment status of all child occupants, is obtained from the initial claimant. Following quality assurance review of the data at State Farm, the data is electronically transferred on a daily basis to the Children's Hospital/University of Pennsylvania Research team (the Research Team).

From this population, a representative sample of children with minor to severe injuries, in all types of crashes, from minimal to extensive vehicle damage, will be chosen according to a stratified sampling strategy. Contact information on the selected study sample will be electronically transferred to a telephone interview service. Drivers and parents of selected children will then be interviewed regarding the circumstances surrounding the crash and the nature and severity of the child's injuries. Completed interviews, devoid of personal identifiers, will be transferred back to the Research Team for analysis.

This surveillance system will provide a mechanism for the prompt identification of important "targeted issues" that require more detailed investigation and analysis. These targeted issue studies will utilize information obtained from the telephone surveys and crash investigations to learn more details about crash circumstances, occupant kinematics, and restraint system performance. These cases will be selected and analyzed using traditional epidemiological methodologies such as cohort studies in which cases will be chosen based on the presence or absence of a particular crash or vehicle characteristic and case control studies in which children with no significant injury will be paired with children with significant injury.

Study Population

All children between the ages of 0 and 15 years, riding as occupants (non-drivers) in crashes reported to the State Farm Insurance Companies from 15 states and the District of Columbia will comprise the population eligible for inclusion into the surveillance system. Only crashes involving model year 1990 and newer vehicles will be included in order to focus on state-of-the-art vehicle safety design features and to make results of the project applicable to the most relevant fleet. It is estimated that approximately 50,000 children per year are riding as occupants in eligible crashes reported to State Farm. Data collection will run for approximately 3 years for a total number of telephone interviews with the parents of approximately 20,000 children. From these interviews, approximately 600 crashes will be selected for targeted issue crash investigation analysis.

State Farm is the largest automobile insurance carrier in the United States, with over 35 million insured vehicles and 2 million crash claims annually. The regions of study chosen (East, Upper Midwest, West) represent 50% of the claims received by State Farm annually and a mixture of urban and rural populations and tort and no-fault states. The study was limited to these areas to minimize the number of State Farm personnel necessary to conduct the study and to centralize the locations of crash investigation teams.

Identification of Children in Crashes

The surveillance system will be initiated by insurance claims representatives through the systematic identification of children who were occupants in crashes reported to State Farm. The claims representatives function as initial field data collectors and obtain consent to release information to the Research Team about the child and the crash as part of the normal claims investigation process. In order to enhance the data collection and interpretation, information will be stored in the electronic claim file using objective measures. On a daily basis, a minimal dataset regarding the child and the crash is electronically transferred to the Research Team typically within 24 hours of the crash. For those crashes in which consent is not granted to release the information, State Farm keeps summary information.

Sampling Scheme for Surveillance System

For the cases that are transferred to The Children's Hospital of Philadelphia, a two-stage cluster sampling technique is used in order to efficiently identify the greatest number of injured children from among a representative population of crashes of all severities. In the first stage of sampling, each crash (i.e., vehicle) is assigned a value that corresponds to the worst treatment status of any child occupant. In this manner, crashes are stratified into four groups representing those crashes in which no child occupant received treatment, crashes in which at least one child occupant received outpatient/ emergency department treatment, crashes in which at least one child was admitted to the hospital, and crashes in which one child died. Once crashes are clustered this way, a random sample of crashes from each cluster is selected in order to ensure adequate representation of crashes of all severities. All child occupants from selected crashes are included in the final study population. Sampling weights are assigned to each cluster to ensure inclusion of a broad range of crash severity as well as increase the proportion of child occupants in the final study sample that have a significant (AIS $\geq$2) injury. For example, a 100% sample of crashes in which at least one child was admitted to the hospital or died, a very small sample (e.g., 2%) of crashes in which no child occupant sought treatment, and an intermediate proportion (e.g., 50% sample) of crashes in which a child sought emergency department and/ or physician's office treatment will be selected.

The second stage of sampling is applied only to crashes that were assigned to the emergency department/ outpatient stratum in the first stage. Cases selected from this stratum undergo a brief screening telephone interview designed to rapidly identify those cases in which at least one child occupant suffered a significant (AIS $\geq$ 2) injury. All cases that screen positive for such an injury immediately proceed to a full interview on all child occupants described below. Contacts that screen negative are subject to random sampling to identify a small number that proceed to full interviews. The final surveillance system population is expected to consist of approximately 15,000 children with ten percent of the population < 1 year, thirty percent 1-4years, forty percent 5-9 years, and twenty percent 10-15 years of age.

Telephone Interview Tool Development

Cases selected for study have a minimum of data electronically transferred to Response Analysis, Co., a professional telephone survey company, for completion of an *Injury and Crash Circumstance Survey Tool* that was developed by the Research Team in conjunction with State Farm. The process of survey development included writing of interview scripts, pilot testing, evaluation of pilot interview results, and revision of scripts.

The survey has been designed to last approximately 25 minutes and ascertains information on the crash circumstances; driver behavior; trip circumstances; characteristics of restraint system used; size, weight and position of the occupant (exposures of interest); as well as the nature and severity of injuries to each child occupant (outcomes of interest). The injury outcome portion of the survey tool has been designed to allow classification of the body region, nature, and severity of injuries according to the Abbreviated Injury Scale (AIS) score. This portion of the survey has undergone validation in a pilot study conducted on injured children evaluated in the Emergency Department at The Children's Hospital of Philadelphia. Responses given by parents regarding the nature and severity of injuries were compared to information documented in the medical record. Throughout the period of data collection for the project, the circumstance portion of the survey will be validated by comparing information on the circumstances of the crash given by the driver with evidence gathered during on-site crash investigations.

Targeted Issues Studies

The surveillance system provides a mechanism for the prompt identification of key issues for which further research and study are needed to answer critical questions related to child occupant protection. Two methodological approaches will be utilized to address these "targeted issue" studies.

One method of addressing "targeted issue" studies is through the use of the crash investigations conducted by Dynamic Science, Inc. This method of data collection is used to address those study questions that require verification of interview data and more detailed information about the crash circumstances, occupant kinematics, and performance of restraint systems than is available through the surveillance system.

Whenever possible, cases selected for crash investigation-based targeted issues are chosen using two traditional epidemiological methods in order to provide a scientifically sound framework for the interpretation of data. One study design is the case-control study in which investigations will be selected based on whether a crash resulted in significant occupant injury (cases), or no child occupant injuries (controls). This type of design is particularly well suited for the efficient examination of a number of potential risk factors for significant injury. For example, to identify the independent contribution of several restraint characteristics, vehicle characteristics, and child characteristics to risk of significant injuries for the 6 to 9 year old population, a case control study design would choose crashes in which a 6 to 9 year old was injured (cases) and crashes of a similar nature in which a 6 to 9 year old was not injured (controls).

Another study design that is employed for crash investigation-based targeted issues is the cohort study. In this study design, crashes are selected for investigation based on the presence or absence of a particular characteristic, typically of the vehicle or crash. For example, to identify the effect of side impact protection on the severity of injuries to children, the cohort of cases is all side impact crashes. Crashes are then classified into two groups based on the exposure of interest, the presence or absence of side impact protection on the case vehicle. Investigations compare the nature and severity of injuries to children in vehicles with and without the exposure of interest. In most cases, the exposure parameter is a variable received from State Farm in the initial transmission of data to ensure the timeliness of the crash investigation.

The second methodology for the targeted issue studies is an in depth telephone survey to enhance the data collected in the surveillance system described above. These surveys would occur following the initial surveillance systems survey. Examples of these directed telephone targeted issues include parental risk assessment, trip characteristics, and parental decision making.

In summary, the surveillance system and these two targeted issue methodologies will be conducted concurrently. Approximately 600 in-depth crash investigations will be conducted and an appropriate sample size from the 20,000 telephone interviews will be chosen for each targeted telephone survey. This unique combination of epidemiological and engineering methodologies will ensure high quality and comprehensive data on both crash circumstances and injuries to child occupants.

CONCLUSION

A motor vehicle crash surveillance system that focuses exclusively on children has been created and will address many of the limitations of current child occupant injury databases. The surveillance system consists of a probability sample of children from 0-15 years of age identified from all motor vehicle collisions reported to State Farm claims representatives in 15 states and the District of Columbia. The surveillance system using telephone interviews with involved drivers and parents of children provides the global context for individual focused "targeted issues". These specific research studies use crash investigations and directed telephone interviews. By performing these investigations within the framework of sound epidemiological studies, the results will be representative of the underlying source population of children in motor vehicle crashes. This study combines an insurer's capability to identify large numbers of motor vehicle collisions of research interest with timely investigation by an academic research team resulting in a research infrastructure designed to address current and emerging challenges in child occupant protection.

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AN APPROACH TO THE STANDARDISATION OF ACCIDENT AND INJURY REGISTRATION SYSTEMS (STAIRS) IN EUROPE

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ABSTRACT

STAIRS is a European Commission funded study whose aim is to produce a set of guidelines for a harmonised, crash injury database.

The need to evaluate the effectiveness of the forthcoming European Union front and side impact directives has emphasised the need for real world crash injury data-sets that can be representative of the crash population throughout Europe. STAIRS will provide a methodology to achieve this. The ultimate aim of STAIRS is to produce a set of data collection tools which will aid decision making on vehicle crashworthiness as well as providing a means to evaluate the effectiveness of safety regulations. This paper will disseminate the up-to-date findings of the group as they try to harmonise their methods.

The stage has been reached where studies into the diverse methods of the UK, French and German systems of crash injury investigation have been undertaken. An assessment has already been made of the relationships between the three current systems in order to define the areas of agreement and divergence. The conclusions reached stated that there were many areas that are already closely related and that the differences were only at the detailed level.

With the emphasis on secondary safety and injury causation, core data sets were decided upon, taking into account: Vehicle description, collision configuration, structural response of vehicles, restraint and airbag performance, child restraint performance, Euro NCAP, Pedestrian and vehicle occupant kinematics, injury description and causation. Each variable was studied objectively, the important elements isolated and developed into a form that all partners were agreeable on. A glossary of terms is being developed as the project progresses which includes ISO standards and other definitions from the associated CAREPLUS project, which addresses the comparability of national data sets.

A major consideration of the group was the data collection method to be employed. The strengths and weaknesses of each study were investigated to obtain a clear idea of which aspects offered the best way forward. The quality of this information and transference into a common format, as well as the necessary error checking systems to be employed have just been completed and are described.

In tandem with this area of study the problem of the statistical relationship of each sample to the national population is also being investigated. The study proposes a mechanism to use a sample of crash injury data to represent the national and international crash injury population.

INTRODUCTION:

Researchers, manufacturers, insurers and regulatory bodies all have a role to play in the area of vehicle crashworthiness. Each has an individual approach to this area and uses similar information as a base for their judgements. However, none of the parties has the benefit of all the information that could be available. Three separate levels of collection systems are currently in place in several EU countries.

The first represents the National crash injury population - the accidents that occur throughout a country that meet certain criteria for inclusion. These criteria are different for each country and are not necessarily comparable. The second level forms a specialist database; insurance companies are the largest of this group and can include data from more than one country. However, a lot of the information is self reported and the quality of the information, including injuries, may not be of the required standard. The final level is derived from In-depth investigation systems. These include a high degree of detail, but consequently they may be more limited in number of cases. They also are derived from a set of inclusion criteria initially based on the crash notification process, plus other additional sampling variables (e.g. the presence of an injury).

It would obviously be preferable if all these systems were in some way compatible so that a better view of the overall situation could be observed. The aim of STAIRS is to give help and guidance at the in-depth level and to produce a set of data collection tools for:

- Research based vehicle safety policy-making,
- Measuring the effectiveness of vehicle safety regulations,
- Measuring the effectiveness of new safety systems,
- Identifying the need for new/revised vehicle safety regulations,
- Identifying areas requiring further research.

In order to progress this task, three of the largest in-depth investigation studies in Europe are being used: The Medical University of Hannover (Germany), The Co-operative Crash Injury Study (UK), and INRETS (France). Two areas of study were identified. The first concerns the actual data collection process; the second is the statistical problem of linking the in-depth sample to the national dataset.

The first work package has seven tasks to complete (See Figure 1), and deals with the collection process. Initially the three different systems of each country were assessed in order to find the strengths and weakness present, as well as looking at the initial level of compatibility that already existed between them. Following this, a nucleus of data had to be identified along with the collection methodology to be used. Relevant, practical quality checks were then identified concerning the accuracy of the data. A small pilot database was then collected in order to validate the previous steps, and finally the handling of sensitive data within the confines of each country's data protection laws was developed.

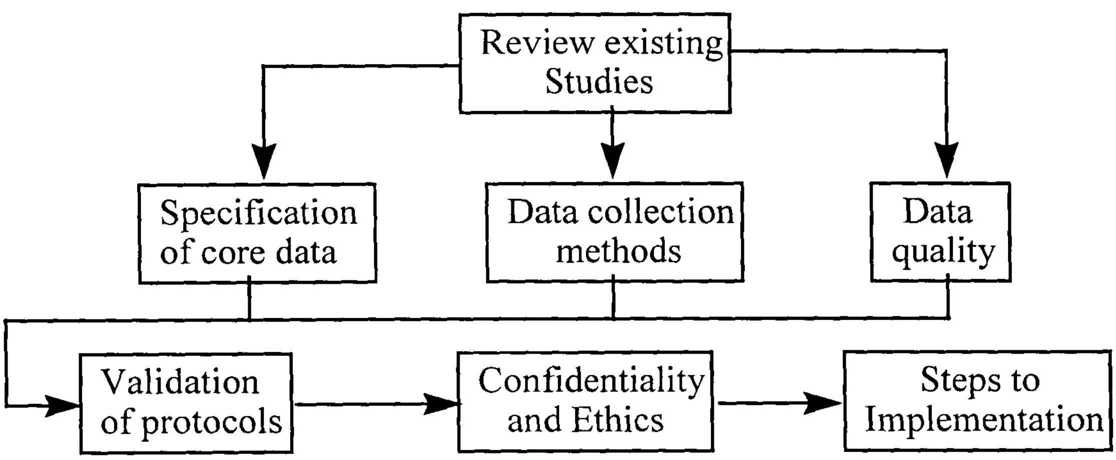

Figure 1. Work package one flowchart.

The second work package is designed to draw up a protocol so that a generalisation of the results from in-depth investigations can be related to the National database. The same three studies are being used to formulate this linkage. The tasks to complete in this work package are:

- Sampling and case selection,
- Comparability of data
- Correct usage of the databases.

The initial problems to overcome is the statistical relationship between the in-depth, local and national databases. A methodology is to be devised to take into account the biases between each of these databases so that a link can be made to national level, the limit of STAIRS.

There will be, within the overall strategy of this package, a connection to the CAREPLUS system so that a link between the National and International databases will be feasible.

WORK PACKAGE ONE.

Work Package 1.1 - Review of existing In-depth studies:

Germany has the longest running, consistent, single programme having commenced in 1973, collecting full 'in-depth' data from1985. The collection area is bound by the common border of Hannover, approximately 2,289km^2. It has a population of 1.2 million and is fairly representative of the national population in terms of its percentage of urban to rural areas. The study uses an on-scene, in-time collection methodology and has specialists in the injury, vehicle mechanics and road environment fields to collect the data.

The UK study CCIS (The Co-operative Crash Injury Study), began in 1983 although previous in-depth studies had been in existence since the sixties. There are two main collection teams based at Loughborough University (The Vehicle Safety Research Centre), and Birmingham University (Birmingham Accident Research Unit). There are a series of six smaller groups, the Vehicle Inspectorate, in other areas around the country. The project is managed by the Transport Research Laboratory (TRL). All information is collected in the same manner retrospectively. This entails going to investigate the vehicle at a recovery yard some days after the crash and taking all the necessary measures. This information is then collated with the injury information from the hospitals.

France has had different collection systems in place ever since the sixties. However the current large scale project only began in 1993. It consists of four teams. Two belong to The Institut National de Recherche des Transports et de leur Sécurité (INRETS), at Salon-de-Provence, and Lyon., the other two belong to the Centre Européen de Sécurité et d'Analyse des Risques (CEESAR), and are located in Amiens and Evreux. All the teams collected their data in the same way until recently. The methodology used is on-scene, in-time and includes a strong Primary Safety element with information on driver behaviour collected by a psychologist. Recently, the centre at Lyon has begun to collect its data retrospectively, although the information collected is similar. The impact of this change has yet to be assessed.

All three studies have common objectives, in particular, regarding the assistance given to policy makers and industry. This includes assessing the need for new regulations as well as the efficiency of the current laws. Each of the separate databases are also used to monitor new safety mechanisms, such as airbags or side impact bars, to see if they have affected the injuries sustained in different types of crashes. However, each study does have its own individual aims and objectives. The German study concentrates on the injury pattern and considers the efficiency of the emergency services in handling injuries and their outcome, while the French have a deep interest in the drivers psychological behaviour, and the UK study focuses on secondary safety and injury causation.

Although there are these divergent areas of interest, there is immense potential for convergence as collecting detailed descriptions of deformations and injuries and other main methods are entirely compatible, with the differences being in the detail. This is due to the individual aims of each study and need not be compromised to achieve compatibility. A series of variables are common throughout the studies, but the interpretation of the exact meaning is slightly different. If a glossary of terms could be agreed as well as the method of collection, then there are no reasons why steps cannot be made towards compatible systems within each country.

Work Package 1.2 - Variables and values:

This work package seeks to define a group of variables, upon which all partners agree, and which are essential for a detailed accident database. The data is a minimum set and it is expected that groups will add extra details or extra variables to reflect particular interests. However it should be possible to reduce any enhanced dataset down to the STAIRS level without ambiguity.

Initially each partner put forward a list of the variables they deemed necessary for the above. Discussion took place until there was consent as to the exact interpretation of the variables meaning. This has, on certain occasions, necessitated the variable to develop into a new form that none of the current systems collect, but with the ability to be compatible with the old formats in each of the databases. If an international standard was already in place then it was, if possible, adopted and integrated into the lists. The intent is not to re-invent the current collection systems, but to provide the opportunity of developing a new one.

The document is set out in a logical manner beginning with: accident configuration, followed by the vehicle description, pre- and post-crash measurements, seats (including child restraints), intrusion, pedestrians, casualty and finally the injury section (See Table 1)

VARIABLE	VARIABLE
Accident Details	Number of Vehicles
Number of People	Vehicle Description
Pre-crash Measurements	Post-crash Measurements
Doors	Seats
Restraint Details	Airbag
Child Restraint Evaluation	Measurement of Intrusion
Pedestrian	Casualty
Occupant and Injury Details	Single Injury Description

Table 1 Document Variable Headings

The collision partner list includes a wide range of vehicles, most of which are not covered in the body of the work.

It is envisaged that the variables used are transferable and can be enhanced to suit whatever area of interest is being investigated. Similarly, the list is seen as modular, with headings to be omitted or new ones added or enhanced as the user requires. The list will also develop with time, and is not to be taken as a rigorous, defined system. New areas are being added all the time, and the current list includes Euro NCAP variables and other current EU-Commission research projects such as CREST, COST 327.

Variables have been added in the 'accident configuration' section which relate to those collected at national level. This is to enable a link between the in-depth investigations and the national databases. Many variables that are extremely helpful in defining collision types could not be used as there was no comparable equal across the participating countries. An example is that of 'type of road'. The definitions within each country were based on completely different lines, from traffic flow to whether the road lies within a town boundary or not. These disparities were too great to overcome, but work is being done within the CAREPLUS programme that may help in this area in the future.

The Collision Partner Configuration table (See figure 2) was developed to enable a quick reference to the type of vehicles involved. This idea of using a grid or matrix to refer to certain pieces of information which may include a number of variables has been used throughout the work package; from an intrusion 'matrix' to the locating of pedestrian contacts on the exterior of a vehicle's bonnet.

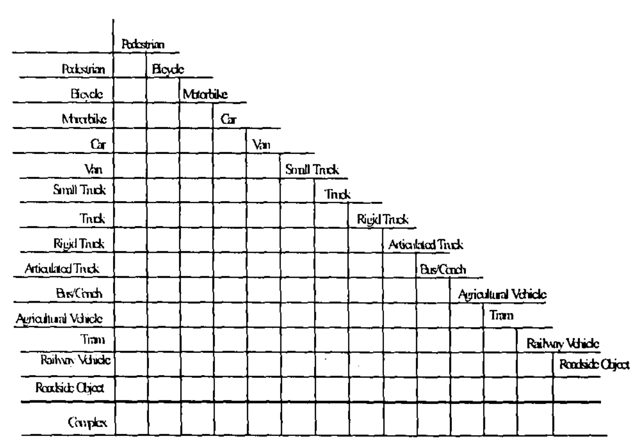

Figure 2 Collision Partner Configuration Table

Many areas which are currently very contentious were examined with a view to developing a new paradigm. However, it was accepted that some areas, such as refined methods to estimate collision speed, were too large a subject for the STAIRS project to cover and outside of its remit. In other areas the current practice was developed and extended to produce a hybrid. The extra digits in the collision deformation measurements and in the AIS injury descriptions are examples of this. Others, such as intrusion, were developed to a lesser degree but do give a starting point to work from.

Essentially STAIRS is concerned with secondary safety, and as such deals mainly with investigating the crashworthiness of the vehicle. Particular emphasis was placed on the presence of safety components and their effectiveness. This has necessitated taking into account current and proposed standards. Euro NCAP variables are included throughout the document and consideration was given to the new side impact tests when the collision deformation measurements were discussed. Details of child restraints were also included as this was deemed an area that will require more investigation in the future.

The body of the document is laid out with the variable on the left, followed by the attendant values, and finally by a notes section (See figure 3). The notes section is intended to clarify the meaning of either the variable or the value or explain the protocols to be used when collecting the data. This is particularly relevant within the new systems detailed for intrusion, injuries and pedestrian contact location.

There is a copy of the complete document on the World Wide Web at the URL www.ice.co.uk/stairs.

Variable	Value	Notes
Post-crash measurements: Collision condition		
Number of collisions	Number	Total number of collisions for the considered vehicle in the crash
Chronological collision number	Number	Collision number in the chronological series of the collision sustained by the vehicle
Collision number (by severity)	Number	The ordering is dependant on the severity, 1 being the most severe (in terms of deformation).
Collision partner		See previous list in section.
Mass of collision partner		In Kilograms
Overlap	In percent (%)	Percentage of the area of the concerned vehicle in contact with the obstacle in the crash
Collision angle	In hours	Angle formed by the longitudinal axes of the vehicle and the obstacle at the time of collision. Longitudinal axis to the front refers to 12 o'clock. See figure 6.
Direction of force	In hours	Give the direction of the main force sustained by the vehicle. Longitudinal axis to the front refers to 12 o'clock.
Rollover	Yes/No	In case of 4-wheeled vehicle including overturning to the side
Under-run	Yes/No	Main impact is to the upper area of the vehicle where it is mostly glazing .
Final position	On wheels Left side Right side Roof	This is the vehicle position after the crash

Figure 3 Example of a page from the Variables and values document

WORK PACKAGE TWO.

Combining the datasets from several countries is complex. If the analysis of the data were just used for linking injury outcome with vehicle performance, then sampling methods would not be a problem. However, STAIRS is to be used as a tool for a better understanding of the European crash population. In order to achieve this the case selection process must produce representative data. To link in-depth data to a subset of the local accident population, and from there link to a subset of the national population, will involve using weighting factors through a two stage process.

Currently only working documents have been produced, but the following is a synopsis of the current situation. Both France and the UK are planning the linkage between their respective in-depth databases and the appropriate local/national databases by use of common variables (see figure 4). In Germany the linkage to the local accident database is possible, but it may not be possible to represent the national accident database due to the special features of the local sample area.

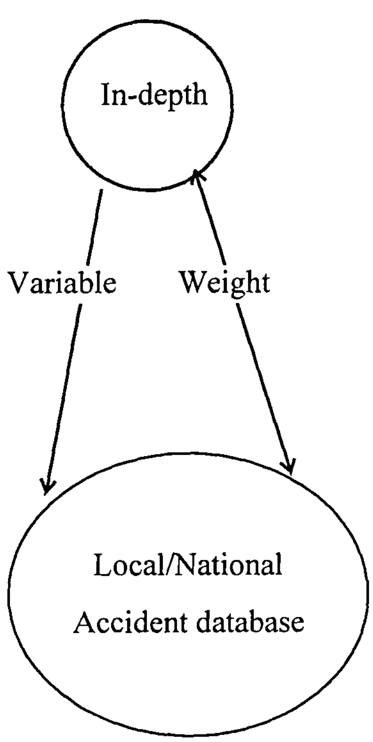

Figure 4 Linking in-depth to local/national databases.

If a variable of interest is only collected within the in-depth database and an estimation of its' distribution is required at national level, the in-depth distribution will be weighted by one (or more) variables which will scale the distribution to estimate the local and then the national distribution. The weighting variable(s) must be in common with the in-depth and local/national databases. Further, the weighting variable will reduce the sampling biases which may be in the in-depth database. A check at each level of the process should be made using a known outcome from a closely related variable to ensure accuracy of the estimate.

The following assumptions are made:

- In-depth database accidents are included within the local/national database.
- The local database may be a biased sample of the national database.
- The in-depth database may be a biased sample of the local database.

The question is then:

- Is there any weighting variable (wi) to reduce the bias from the in-depth to local database.
- Is there any weighting variable (wj) to reduce the bias from the local to the national database.
- Is the weighting variable the same in each case? (wi) = (wj).

We expect w_i and w_j to be functionally related to the variable of interest. The problem is to identify those weighting variables which are required for the variable of interest and to demonstrate that their use reduces bias.

The following points arise:

- The need to identify key variables for weighting purposes.
- To identify types of variables which would use the same set(s) of weighting variables.
- To use substitute weighting variables when necessary, e.g. δV is not a linking variable so one could use speed limit instead as the best available.
- To accept that there may not be suitable weighting variables and/or data in the in-depth database to provide an estimate.
- It is essential to estimate the confidence interval on any estimate.
- Weighting from a small in-depth database to a national estimate may be imprecise

OTHER WORK PACKAGES.

Further work in other areas is occurring simultaneously but have not yet reached their conclusions. **Work Package 1.4** deals with **data quality** and covers the areas of: Data collection, compilation of data, initial processing of electronic data, and comparison of data from several sources. The emphasis of the quality aspect in this package is to ensure accuracy of data and does not mean that the data is necessarily available to answer certain questions.

There are three levels within the data quality process:

- Collection of the data.
- Coding of the collected data into an accepted format.
- Analysis of the data

A set of flow diagrams have been produced that relay the primary principals explored within these three categories(See example figure 5).

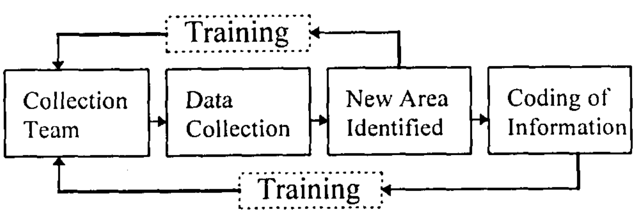

Figure 5 The Collection Loop

These diagrams relate to an established group and identify the feedback loop necessary to ensure that the changing environment of vehicle design and safety systems are identified at an early stage. From this the appropriate training can be given to the investigators. This includes any changes that may occur within the coding systems.

The accuracy of data is the most important at the collection phase. Crash investigators should be proficient in the areas of impact kinematics, biomechanics and vehicle examination. They should also understand fully all the tools at their disposal, and the circumstances in which each one is the most practical, efficient and accurate. The advent of electronic forms of collection will help in this area, but only insofar as the time taken and there will be fewer transposition errors. The physical collection process and its' inherent quality problems will not be solved by the use of computers.

Concentration of the quality management procedures should be directed at the collection end of the process to ensure the least degradation of information. In order to ensure that this happens the following recommendations should be applied:

- A balanced team should be selected, with the appropriate specialists in place.
- Training and a constant updating of skills necessary to ensure the high quality of information collection should be a main priority.
- A similar process for the coding of the information should occur.
- A glossary of terms, updated as necessary, should be in place with a clear, precise understanding of the terminology and conventions used.
- An objective method of recording data, such as photography, should be used either as the primary or secondary tool for investigation.
- Putting the case together should have at least two stages:
    1. The initial methodology of bringing together all the separate parts; vehicle information, injury details etc., and which should include a manual logic check for self consistency throughout.
    2. A second, more objective check made by personnel not directly associated with the collection process.
- Checks should be used to ensure that the data is transferred into an electronic format correctly.
- A check for self-consistency within the coding of the electronic data should occur.
- There should be a management check.

Data also has to have a certain level of 'user quality'; that is the ability to answer questions that may be asked of it. This area of quality is determined by the prevalent areas of investigation at the time, which is in turn dictated by the overall aims of the funding body concerned. In order to be of use, a common database must have datasets from its contributors that cover all the relevant areas of interest, both political and social, to such a level that it can provide useful information on any query that may arise. To ensure that this happens in a controlled manner rather than in a haphazard fashion, regular reviews of the core datasets should occur.

Work package 1.6 - Confidentiality and Ethics, is now at the stage whereby all the necessary information concerning the working practices in each country have been identified. Each country has its own set of laws at local and national levels, dealing with this type of data. European legislation does exist and has been used as the foundation for this work package. There is however, broad consensus as to the handling of the sensitive information collected. The transfer and storage of confidential data is subject to strict guidelines concerning the availability, access and confidentiality of the information. All partners provide for the secure storage of the written data. Electronic data has to be anonymous and each system has in place a means of removing direct references to the persons involves in the crash and the vehicles they occupied.

From this a set of protocols can now be developed to set down best practise within this area; but with the flexibility to allow for the local differences that are present.

A workshop is being organised for **Work Package 1.5** in order to validate the protocols established and receive feedback from other interested parties. The date will be within the week commencing 15th June 1998 at the European Commission buildings in Brussels.

Work Package 3 involves the dissemination of the information from the STAIRS project as a whole. This has been achieved by the development of a wide ranging database of companies, institutes, working groups and research establishments that have an interest in the field of vehicle safety. The deliverables from the work packages are distributed amongst these groups and feedback requested. Replies from this diverse section will give an excellent range of replies as to the practicality of the proposals and help in the further development of them.

As any list will never be totally comprehensive, especially in such a large area as vehicle safety, an avenue of contact has been provided in the shape of a world wide web site at:

http://www.ice.co.uk/stairs

This site is intended to hold all the up-to-date information on STAIRS and also the points of contact in each relevant country.

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NEW "ELECTRONIC" DATA COLLECTION METHODS in the NATIONAL AUTOMOTIVE SAMPLING SYSTEM CRASHWORTHINESS DATA SYSTEM

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ABSTRACT

The National Automotive Sampling System (NASS) Crashworthiness Data System (CDS) was established in 1979 to help analyze motor vehicle crashes and injuries. It collects data with research teams at 24 sites that study about 5,000 crashes annually involving passenger cars, trucks, and vans. Historically, trained researchers have collected NASS CDS data on paper data encoding forms.

Recently, the NASS program took a giant step forward into the world of electronic crash data collection. Researchers started collecting data using electronic digital methodologies in January of 1997. In this "paperless" system data go directly into the database in the field, rather than on paper forms.

All case data are transferred electronically to quality control centers, central data depositories, and NHTSA. An interface is being designed for users to access data and digital images. This paper will describe the process of converting from a paper to an electronic crash data collection system. This new system gives NHTSA the capability to provide quick electronic access to cases. Eventually the data will be accessible through the Internet.

INTRODUCTION

In 1991, NHTSA first began the process of investigating the possibility of scanning NASS CDS cases to provide easy access for clinical analysis. This was followed with an investigation into the current state-of-the-art in still video and digital cameras. In 1995, NHTSA reassessed the future needs and began design work on a total electronic system for acquiring crash data, not just a conversion of conventional data collection efforts. Objectives were set for an electronic data file to be made available to the public in late 1998 containing data, images, and photographs for crashes occurring during calendar year 1997.

Increasing the accessibility and timeliness of Agency data was part of Goal 4 of the Strategic Execution Plan for the agency. An objective of this goal was to "develop software for user-friendly, direct access to NHTSA's major data files through the Internet and other electronic media." This was set as a milestone for the year 1999. The new NASS electronic data collection system is the vehicle that will allow the agency to achieve that milestone and continue to provide responsive and timely service to data users throughout the United States and the world.

HARDWARE / SOFTWARE

Field Computers

In June 1996, the NASS development team purchased the hardware that would become the electronic "tools" necessary to implement the paperless data collection system. Fujitsu Stylistic 1000 pen-based computers were purchased for all field researchers, for the NASS training instructors, for NASS headquarters and for the development team. A depot of spare units is maintained to replace units out of service.

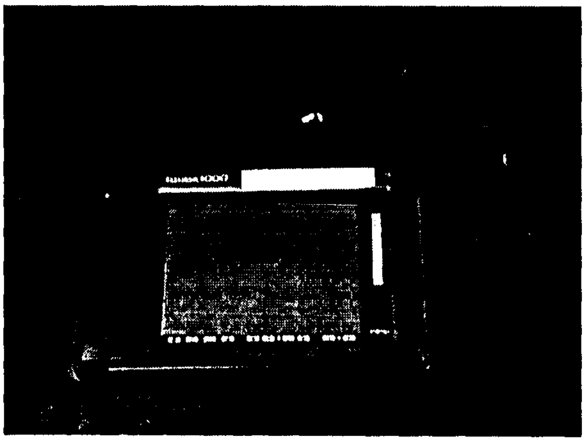

Figure 1. This is the Fujitsu Stylistic 1000 pen-based computer that is used for data collection.

Digital Cameras

To replace the old system that recorded information on 35 mm slides, the development team began in early 1992 to look at alternative imaging techniques. Initially it was thought that still video imaging would be the best method. However, the advent of the digital camera around 1995 provided a convenient format to capture and record electronically the data that had traditionally been gathered through 35 mm slides. The number of digital cameras available at that time was limited. After reviewing the available models, the development team chose the Fujix DS-220 based on cost, color resolution, its wide angle/close up features, its LCD screen preview, and its available PC card storage media. The digital cameras were purchased at the same time as the pen-based computers, and each researcher and other team members who had a pen-based computer also had a camera. A depot of spare cameras is also maintained.

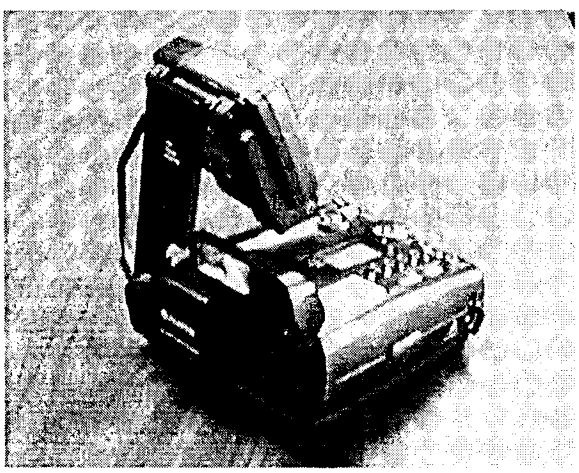

Figure 2. The Fujix DS-220 digital camera with LCD monitor attached.

Because the technology continues to improve in the computer and camera marketplace, the NASS team is continuously reviewing the available products so that when the system hardware needs replacing, appropriate replacements can be specified. Laptops and pen-based computers are being considered, and the latest digital camera technologies that permit increasingly more sophisticated digital imaging and storing possibilities are being reviewed.

Data Storage

Gathering of the data electronically was only half of the equation. Plans had to be made for storage and retrieval of vastly larger amounts of data, larger than the previous data collection efforts. The average annual number of cases collected in the NASS did not change from the previous system to the new 1997 start of the electronic data collection methodology (5,000). However, the data to be stored increased, specifically the number of variables and the number and size of the digital images recorded. Previous electronic "flat" file storage per case was 3 kilobytes or approximately 15 megabytes per year. With the new electronic data collection and storage, the text and digital images total approximately 30 megabytes per case or 125 gigabytes for the year. Consequently, a relational database was required to ensure that the data variables and all associated images could be stored and easily retrieved. Therefore, an Oracle database was developed and several sub programs were developed for getting information from the pen-based computers into the database. For example, programs were developed to enter the Police Accident Report (PAR) data into the main program, to enter the field data collected by the researcher, to import and organize the digital images, to create scaled scene diagrams, to import scanned images, to provide for injury coding, and to permit monitoring and data management.

Work continues developing mechanisms to provide continuous data access to analysts and researchers who have in the past used the NASS Crashworthiness Data System (CDS) and General Estimates System (GES) data, and new groups of users. NHTSA has implemented a DARS (Data Archival and Retrieval System) group to test and evaluate methods of using the data from the relational database. Results of this test and the programs being designed by the development team are expected to bring the data to the public in the summer of 1998. The data collection will continue to be upgraded and improved in future NASS electronic data collection years.

PSU TEAM FUNCTIONS

Sampling

The basis for the NASS is its sampling algorithm by which each Primary Sampling Unit (PSU), or research team, lists each PAR and selects the appropriate ones for further investigation. A team member goes to the jurisdiction and lists information for each valid NASS CDS PAR filed since their last visit. This was previously done using paper and pencil. The researcher then returned to their office and entered this information into a desktop computer where it was then uploaded to another computer.

Now the information is entered at the police jurisdiction into a pen-based computer. A check for errors and duplicate entries is made at the time of the original listing (instead of later at the office). When the listing is complete, the researcher returns to the office, uploads the information into the local computer system and sends it through a Frame Relay connection to a computer at our software support contractor where the sample is selected and down loaded.

The police report for the selected crash is obtained and scanned. The scanned report is used for quality control and kept separate from the case information.

Scene Documentation

The crash scene is required to be documented, photographed, and have a scene diagram drawn for each crash researched. Photographs and scene diagrams have always used conventional 35mm slides and paper and pencil diagrams. We now use a Fujix DS-220 digital camera for all photography. This camera permits previewing and reviewing all photos. The digital images are all stored on PC cards and uploaded into the pen-based computer back at the office where they are categorized and labeled. Rough sketches of the scene are done in the field. These documents are then used to produce Visio® diagrams of the scene at the office. The field sketches are scanned and included as case documentation.

Coding Of Data

As with sampling, previous procedures involved coding data on paper forms in the field and returning to the office to enter the information into the computer. The pen system is now used for direct field entry of the information. It especially facilitates the sketching of vehicle damage on an outline of the vehicle on the pen-based computer. The field researcher is led through the process of entering data and can never run short of forms. This information is then uploaded back at the office into the local system where edit checks on the data can be run anytime. Photos of the car are taken with the digital camera. The camera permits the researcher to photograph out-of-the-reach locations and preview the image. Its instant feedback of information produces increased opportunities for quality control and assurance of adequate photographic coverage.

Interviews

Interviews are still recorded on paper forms. When interviews are conducted in person, the paper can be less intimidating then a computer to the person being interviewed. Paper also simplifies the rapid documentation of information even when the interview is conducted over the phone. The completed form is then scanned and included with the case materials.

Medicals

Official medical records are obtained and shipped to the quality control zone centers. There information is recorded and coded by experts. Afterwards, the medicals are scanned and the originals destroyed. The originals are used for this coding process as the quality of the handwriting has always been an issue.

ZONE CENTER FUNCTIONS

Coding Of Injury Data

The "zone centers" are the quality control center for a set of PSUs. Their expertise permits them to code the injury data for all crash involved persons. They review the hard copy of the medical report received from the PSU, placing injury codes and descriptions directly on mannequins of the human body at the place of injury displayed on the computer screen. This permits not only an automated review of the data coded, but also a clinical review of the injuries and their locations on the body. After the injuries have been coded and checked, the hard copies of the medical reports are destroyed, having already been scanned at the relevant PSU.

Case Quality Control

The zone center reviews each case and its components at different times during the case review process. Corrections to the case are made directly on-line and reasons for the change are documented at the same time. This permits summary reports and tracking of the progress and problems for individual researchers and teams.

Productivity and Timeliness

The zone centers also use the system to track the timeliness and productivity of interviews, scene and vehicle inspections, and case throughput. The date of the interview, inspection, etc., is automatically recorded in the system, where previously it had to be manually entered. This permits a rapid and up-to-date review of the progress of all field personnel.

Case updates are made each night from the PSU to the zone center, to the central files in Cambridge Massachusetts at the software contractor, and to NHTSA offices in Washington, D.C. This permits the review and monitoring of any case at anytime.

Expertise

The zone centers are considered our experts in field crash data collection. If a researcher has a question about data coding, collection, or crash reconstruction the zone center now has the capability of looking directly at the same case. This permits an easier and more helpful way of aiding experienced researchers who encounter a confusing situation, a novice researcher who has not had much field experience, and any researcher who needs help with new procedures, protocol, or variables.

NHTSA FUNCTIONS

Quality Control

NHTSA regularly examines the file looking for ways to improve the data. Previously when a case was found where data were in question and the case had already been finished and shipped to Washington, D.C. (for storage), the case had to be shipped back to the zone center for review and modification. Now the zone center or NHTSA can review the case anytime and verify it for correctness.

All cases are available to quality control staff at NHTSA anytime in the process. In the old system they were not available until months after data collection was completed and they were shipped to Washington, D.C.

Case Access

In the new "electronic" environment, NHTSA users will have several ways to use the system. They can access it from their desktop computers (when set-up for this connection) and query the system using either SAS, Oracle SQL queries, Crystal Reports, or the Data Archival and Retrieval System (DARS). The DARS system is still under development, but will ultimately permit access to cases and viewing of their contents.

OVERALL BENEFITS OF SYSTEM

The system has been designed to deal with several separate issues, therefore benefits fall into several categories.

No Paper

This reduces the need for mailing, envelopes, handling, shipping, storage and retrieval of cases. This reduces cost through the elimination of printing, duplication, postage, and handling of cases for purposes of their storage and retrieval (for requests received). The introduction of direct field entry of the data eliminates double data entry and the inherent problems of incorrect entry of the field data from the forms.

No 35-mm Slide Photography

This eliminates film purchase, developing costs, slide sorting, and slide duplication when a copy of a case is requested. With the use of digital photography, a photo can be duplicated anytime. However, the quality of the image is not as good as that of a 35-mm slide transparency. This will improve as we acquire higher resolution cameras in the future.

Cases will be available for NHTSA researchers directly from their desktop computers

This will eliminate the process of having to visit the case storage facility to view cases. Eventually this type of access may be available to the public via the Internet.

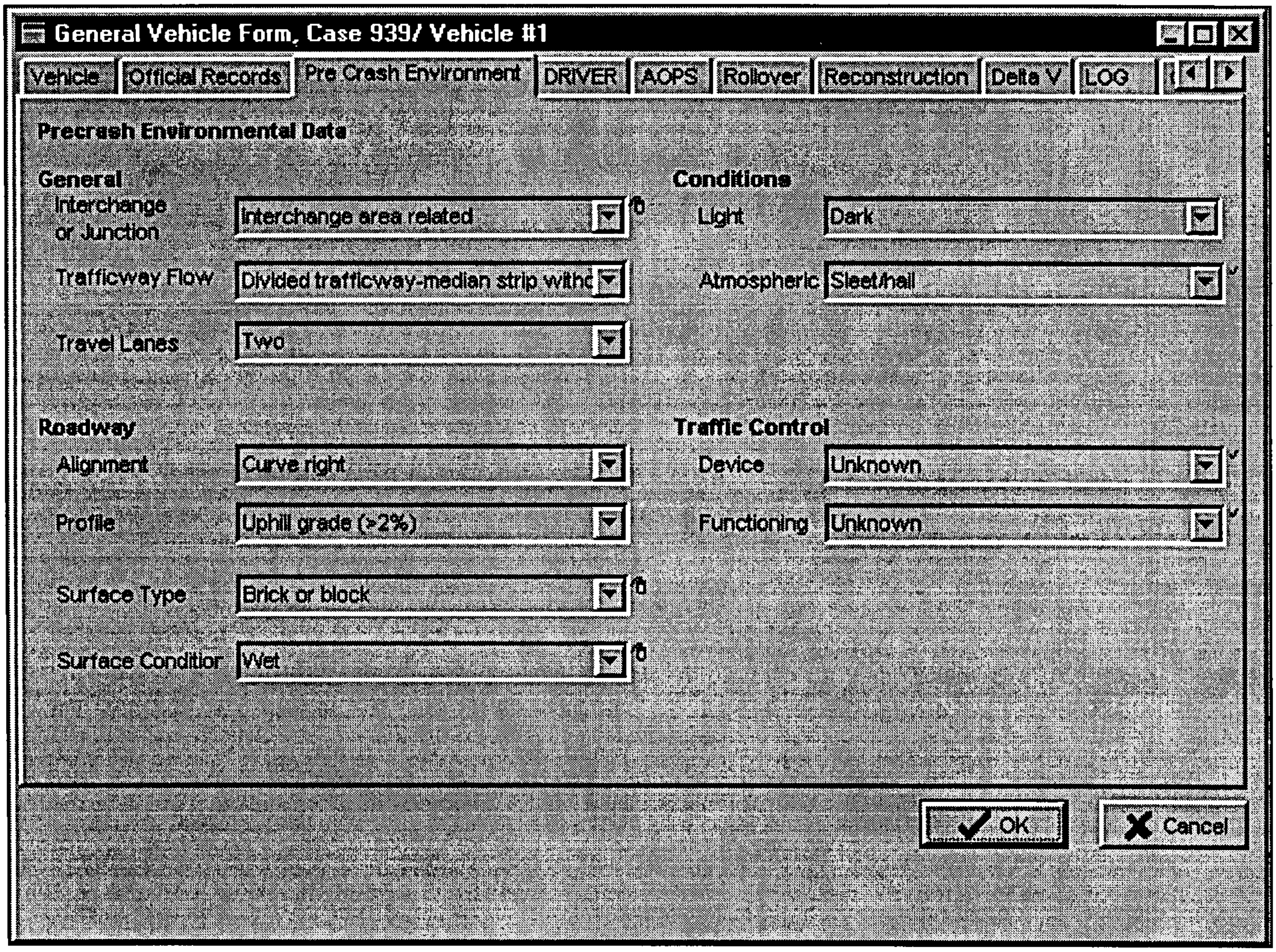

Figure 3. The pre-crash environmental data entry screen that researchers use for entering data.

THE SAFETY EFFECTIVENESS OF LIGHT-DUTY MOTOR VEHICLE OCCUPANT RESTRAINTS : NUMBERS OF OCCUPANT LIVES SAVED AND INJURIES PREVENTED BY SEAT BELTS IN ROAD TRAFFIC COLLISIONS IN CANADA, 1989 - 1995

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Paper Number 98-S6-P-20

ABSTRACT

The first Canadian 'National Symposium on Road Safety' was held in Montreal in 1988. The main purpose was to assess the prevailing levels of safety for the various road users of Canada's roads and highways and identify issues and related goals to pursue for realizing a safer national road transportation system. One of the main recommendations was a commitment to work towards increasing the usage rates of occupant protection restraint systems (e.g., seat belts, child restraints). The reaction to this major goal identified was swift and decisive. A proposal -- The National Occupant Restraint Program (NORP), was prepared by the Canadian Council of Motor Transport Administrators (CCMTA) and presented to the federal and provincial ministers responsible for road safety in September of 1989. The Council of Ministers endorsed the program's target objective of attaining a "95 percent restraint usage rate by occupants of light-duty motor vehicles* by 1995".

Retrospective trend analyses of changes in seat belt usage rates during the six years of NORP demonstrate that the goal was quite realistic. Through National Seat Belt Use Surveys conducted annually by Transport Canada (1996) it was possible to monitor and assess improvements in occupant restraint usage. Two of the most significant and encouraging results revealed that national seat belt usage rates for drivers of passenger vehicles increased from 73.9 % in 1989 to 91.6 % in 1994 -- a percentage increase of about 24 % and very close to the 6-year target objective established by NORP, and the usage rate for occupants of light-duty vehicles increased from 68 % to 87 % during the same period resulting in a 28 % percentage increase.

The major issue that required addressing, however, was to evaluate any safety impacts that can be attributed to the NORP program. In particular, there is a need to know whether the observed increases in seat belt usage rates over the program period yielded significant benefits (i.e., reductions in fatalities and injuries for collision-involved motor vehicle occupants), and if so, to measure the extent and value of these benefits towards the ultimate goal -- improving road safety. These general objectives formed the basis for the research study reported on in this paper.

* light-duty motor vehicles includes light-trucks, vans and passenger cars

INTRODUCTION

Before the extent and value of any road safety benefits attributable to increases in seat belt usage rates can be measured there a number of preliminary tasks to be carried out. To this end five main objectives were identified as the primary focal points for the successful conduction and completion of this research project including: developing a 'reliable' estimate of the safety effectiveness of seat belt restraint systems in preventing death and injury to all occupants of light-duty vehicles involved in road traffic collisions; designing and developing appropriate statistical analysis methodologies for estimating reductions in occupant fatalities and injuries that can be attributed to the increases in seat belt usage rates observed in light-duty vehicles during the NORP program time-frame; implementing these methods to estimate the number of light-duty vehicle occupant lives saved and injuries prevented due to the prevailing seat belt usage rates observed in each of the years between 1989 and 1995; estimating the incremental number of occupant lives saved and injuries prevented (if any) in light-duty vehicle collisions that can be attributed to the observed increases in seat belt usage rates over the NORP period 1989-1995; and developing estimates of the value/magnitude of any measurable benefits that can be accrued to the increased usage of available restraint protection systems by occupants of light-duty vehicles over the 1989-1995 study period. Lastly, from the findings of this research evaluation study, conclusions and recommendations discussing the impacts that can be attributed to the NORP program in improving road travel safety for occupants of light-duty motor vehicles involved in collisions are provided.

ANALYTICAL METHODS AND PROCEDURES

In order to develop methodology for estimating any reductions in fatalities and injuries that can be attributed to increases in seat belt usage by occupants of light-duty vehicles it is first necessary that estimates of the 'effectiveness' of seat belts in saving lives and preventing injuries are available. That is, a reliable (accurate) estimate of the expected number of unbelted occupant deaths and injuries that occurred and that could have been prevented if they had been wearing a seat belt must be 'known'.

Development Of 'Reliable' Estimates Of Seat Belt Effectiveness In Preventing Death And Injury To Occupants Of Light-Duty Vehicles

Three options for deriving sufficiently accurate estimates of seat belt effectiveness in preventing death and injury to occupants of collision-involved light-duty motor vehicles were identified:

➊ Utilize Canadian police-reported collision information and develop methods and techniques to correct for known limitations and biases inherent to these data bases, or

➋ Identify other available Canadian collision data bases that contain the relevant information required and that do not have the limitations and biases inherent to the police-reported collision data bases in ➊ above, or

➌ Search outside of Canada for research conducted and completed on seat belt effectiveness evaluation(s) that meets the requirements of our study.

Option ➊ was dismissed due to the inability to account for the serious limitations and significant biases contained in the Canadian police-reported data. The pursuit of Option ➋ revealed the existence of some estimates of seat belt effectiveness developed from detailed national accident investigation data bases -- known as 'Level II accident investigation case studies'. Level II accident investigations are conducted by specially trained accident investigators/reconstructionists and the breadth, detail and accuracy of the information collected on the factors and characteristics present in the collision are significantly greater than that collected in police investigated and reported (Level I) data bases. Specifically, the Level II Accident Investigation Passenger Car Study (PCS),1984 - 1992 [Stewart, 1996] is an in-depth investigation of motor vehicle collisions in which at least one passenger car is involved and at least one occupant of the vehicles involved was either killed (fatal collision investigations) or injured (injury-producing collision investigations). These data bases were analyzed by Stewart (1992) for the years 1984 to 1989 inclusive using Bayesian statistical probability methods in order to develop estimates of seat belt effectiveness. Unfortunately it was only possible to develop reliable estimates of effectiveness for front seat occupants of passenger vehicles because of the limited number of case studies investigated coupled with that fact that the target population for the study was restricted -- only accidents in which at least one passenger vehicle was involved were eligible for selection and investigation. Since a major objective of this present study required the development of seat belt effectiveness estimates that are reflective of all occupant seating positions and all light-duty vehicles, i.e., the entire fleet of light trucks and vans in addition to passenger cars, it was decided to pursue Option 3 -- search outside Canada for more accurate estimates. This lead to attention being turned to the estimates of seat belt effectiveness developed by the Office of Regulatory Analysis, Plans and Policy, U.S. Department of Transport, National Highway Traffic Safety Administration (NHTSA) (1994) and Leonard Evans (1987) for the following reasons.

Large collision data bases are required for deriving an 'optimum' estimate for the effectiveness of seat belts in preventing fatalities and injuries -- these types of data bases do not exist in Canada but are available in the United States. This is simply due to the large differential existing in the population bases, amounts of 'exposure (to risk)' and therefore consequences of exposure (to risk), i.e., collisions, between the two countries. There are approximately ten times more motor vehicle collisions in the United States than in Canada. These large U.S. data bases provide the capacity to select the collision configurations based on cross-classifications of occupant characteristics required, e.g., numbers of occupants, seating positions, ages of occupants, vehicle type and whether the seat belt was used or not by a particular vehicle occupant at the time of the collision. Subsequently, appropriate groupings, matching and comparisons of these collision case data characteristics (where at least one person is either killed or injured -- the injury severity level analyzed depends upon the effectiveness estimate being derived) provides the capacity to: control for extraneous factors; avoid the problems, limitations and biases inherent to Canadian collision data bases; and design and implement an optimum effectiveness estimation methodology that depends upon the availability of large collision data bases. Therefore, the estimates of seat belt effectiveness developed by NHTSA and Evans were utilized due to the benefits (discussed above) afforded by U.S. collision data bases.

The overall effectiveness of seat belts in saving lives among all occupants of passenger cars involved in collisions has been estimated by NHTSA to be 45 %. The term 'effectiveness' is defined as the fraction of fatally injured occupants who were not using a seat belt in motor vehicle collisions and who would not have been killed had they been wearing a seat belt, given all other factors being equal. The effectiveness of seat belts in preventing death and reducing injury severity levels, however, is variable depending upon the vehicle type and seating position of the occupant. Estimates of seat belt effectiveness by vehicle type , occupant seating position and injury severity level (Table 1.) were developed by NHTSA (1994).

Combining occupant injury distributions cross-classified by vehicle seating positions (obtained from Transport Canada's Traffic Accident Information Database -- TRAID [Evaluation and Data Systems Division, Road Safety Programs Directorate, Transport Canada, 1993]) with injury severity level distributions (obtained from Transport Canada's Level II Accident Investigation Passenger Car Study -- PCS, 1984-1992) and the respective seat belt effectiveness estimates in Table 1., an average seat belt effectiveness estimate for each of the three occupant injury severity levels can be derived. After carrying out these computations an average seat belt effectiveness estimate in saving the lives of light-duty vehicle occupants involved in collisions is 47 percent, in preventing moderate to critical injuries (MAIS 2-5) is 52.3 %, and in preventing minor injuries (MAIS 1) is 9.5 %. This overall average fatality reduction estimate of 47 % is quite plausible -- our Canadian estimate for front out-board occupants from the limited national sample of a restricted vehicle collision target group (only collisions in which at least one passenger car was involved) was 39 % [Stewart, 1992].

Finally, analysis of Transport Canada's PCS database for the years 1984 to 1987 inclusive yielded the proportional distributions of MAIS 1 and MAIS 2-5 occupant injury severity levels given by 0.8066 and 0.1934 respectively. Further analyses applying these proportional fractions as weights to the MAIS 2-5 and MAIS 1 injury reduction effectiveness estimates above permits a combined weighted average estimate of seat belt effectiveness in preventing injuries (over all MAIS 1-5 injury severity levels) to occupants of light-duty vehicles involved in collisions to be derived -- resulting in a value of 17.8 percent.

Data Sources For Estimating Occupant Seat Belt Usage Rates In Canada

Two basic sources of data exist for estimating safety belt usage rates among light-duty vehicle occupants. The first source involves the Transport Canada annual observational surveys of the driver or occupant population traveling in light-duty vehicles on the roads and highways. These surveys are considered to be quite accurate since they are based on direct observation of the

Table 1.
Estimates of Seat Belt Effectiveness (%) by Vehicle Type, Occupant Seating Position and Injury Severity Level

	OCCUPANT INJURY SEVERITY LEVEL		
	Fatalities	MAIS 2-5* Injuries	MAIS 1* Injuries
	SEAT BELT EFFECTIVENESS ESTIMATE (%)		
PASSENGER CARS			
Front Seat	45.0	50.0	10.0
Rear Seat	41.0	50.0	5.5
LIGHT TRUCKS AND VANS			
Front Seat	60.0	65.0	10.0
Rear Seat	41.0	50.0	5.5

* **MAIS** : Economic cost data is stratified according to the level of occupant injury severity. Severity is classified using the Abbreviated Injury Scale (AIS). Under this scale all non-fatal injury severity is defined as follows:

AIS 1 = minor injury
AIS 2 = moderate injury
AIS 3 = serious injury
AIS 4 = severe injury
AIS 5 = critical injury

Frequently, injured occupants sustain more than one injury. Therefore, each injured survivor is classified according to his or her highest (most severe) injury level. This is known as their maximum injury severity level and is abbreviated as MAIS.

traffic. They are limited, however, in that they are only conducted during day-time hours of 7 a.m. to 5 p.m. and therefore not necessarily representative of the seat belt usage rates for all light-duty vehicle collisions.

The other source of motor vehicle occupant restraint information comes from police-reported collision data records collected in all ten provinces and the two territories of Canada. These data are stored and maintained in Transport Canada's national TRAID database system and, when available, provide indicators of seat belt usage by all occupants of motor vehicles involved in collisions. The major criteria for establishing whether a restraint system was used or not relies upon the documentation of 'hard' evidence such as seat belt bruise marks on the occupants body or direct observation by the police investigating the accident. Quite frequently, unfortunately, the restraint status of a particular occupant is not determinable by the above direct methods and the only available evidence is statements made to the police by witnesses or persons involved in the collision. Due to their very nature these 'indirect' methods for establishing restraint status are considered to be biased and tend to yield inflated restraint usage rates. This is quite easily demonstrated by the fact that the recorded seat belt use rates for occupants involved in collisions during the years 1992 and 1993 were 92.3 % and 92.9% respectively, compared to 81.4 % and 83.4 % found in the observational day-time surveys conducted during the same two years. Inflated estimates are more of a problem for property damage and minor to moderate injury (MAIS 1-2) cases than for occupants who were killed in collisions. This is explained by the fact that a large proportion of occupants involved in high severity level collisions are killed on impact, and the attending police can make a direct observation of seat belt use status. Even in these cases it is surprising that the seat belt use status of a fatally injured motor vehicle occupant is still 'unknown' for approximately 10 percent of the cases.

Therefore, due to the high reporting bias inherent to the TRAID database, reliable estimates of seat belt usage are not generally available from police-reported collision investigations. With respect to the fatally injured occupant population, however, TRAID usage rates (although not precise) do provide the necessary data inputs to develop evaluation methodology for estimating the number of occupant lives saved in light-duty vehicle collisions. Overall, however, the observational surveys of the traffic on the roads and highways, although not directed at the collision-involved population, are believed to be the best available indicators of seat belt usage rates to use in the development of the evaluation methodology.

Three different evaluation methods, therefore, were developed to derive estimators of the number of light-duty vehicle occupant lives saved by seat belts. Method 1 utilizes seat belt usage information contained in Transport Canada's TRAID database, specifically national seat belt usage rates obtained from police collision reports for all occupants of light-duty vehicles involved in accidents. The other two methods (Methods 2a and 2b) utilize the occupant seat belt usage data obtained from 'direct' observational surveys of the traffic -- Transport Canada's annual national occupant restraint surveys. The difference, as will be seen, between Methods 2a and 2b involves a phenomenon referred to as 'selective recruitment" (of seat belt users) [Evans, 1987]-- a process which is not accounted for in Method 2a but is taken into account in Method 2b.

Method 1. An Estimator Of The Additional Number Of Occupant Lives Saved In Light-Duty Motor Vehicles Involved In Collisions In Each Of The Years 1990 - 1995 That Are Attributable To Increases In Seat Belt Usage Rates Over The 1989 'Base Year' Level Of 68 % : ***A Method Based On Seat Belt Usage Rates Among The Collision-Involved Light-Duty Vehicle Occupant Population***

Occupant restraint system devices will not save the life of every motor vehicle occupant who is involved in a potentially fatal collision. This is because the **effectiveness, e,** of seat belts in preventing death in motor vehicle collisions is not 100 % -- it is 47 % in light-duty motor vehicle collisions (as established earlier). This means that for every 100 unbelted occupants who died in a given year, 47 of them would have been saved if all 100 had been belted, and 53 would have died anyway because seat belts are not capable of preventing death to all occupants of motor vehicles involved in collisions. In reality, some motor vehicle collisions are non-survivable by all occupants even if they are wearing a seat belt.

In order to estimate the number of lives that were saved by seat belts in year i at year i seat belt usage rates, $S(R)_i$, we need to know the total number of restrained occupant deaths that occurred in year i , $D(R)_i$. This information permits us to conclude that (1 - e) % of all fatally injured occupants that were not saved by seat belts in year i is equal to $D(R)_i$. With this relationship established it is then possible to estimate the (unknown) number of lives that were saved by seat belts in year i at year i seat belt usage rates, $S(R)_i$. The mathematical formula for computing $S(R)_i$ is given as follows:

$$S(R)_i = D(R)_i * [e / (1 - e)] \qquad (1.)$$

Now: assuming that the ratio of belted to total occupants killed in light-duty vehicle collisions in the 1989 'base year', given by $R(R \mid T)_{1989} = 0.456$, remained constant over the years 1990 - 1995 inclusive; and given that the total number of light-duty vehicle occupant fatalities for a given year i, D_i, is known; and lastly that the effectiveness of seat belt systems, e, in preventing death to occupants of light-duty motor vehicles involved in potentially fatal collisions is known; it is then possible to estimate the expected number of occupant lives that would have been saved by seat belts in light-duty vehicle collisions in the years 1990 - 1995 at 1989 'base year' seat belt usage rates, $S(R,1989)_i$, by the following equation,

$$S(R,1989)_i = D_i * R(R \mid T)_{1989} * [e / (1 - e)] \quad (2.)$$

and the 'expected belted fatal cases (at 1989 seat belt use rate)' is computed using equation (3.).

$$D(R,1989)_i = D_i * R(R \mid T)_{1989} \quad (3.)$$

Subtraction of equation (2.) from equation (1.), i.e., $[\, S(R)_i - S(R,1989)_i \,]$, yields an estimator of the extra number of occupant lives saved (if any) by seat belts in year i that can be attributed to the increased seat belt usage rate in year i relative to the 1989 'base year' seat belt usage rate -- denoted as $ES(R)_{i\,:\,1989}$. The results of all computations of the equations involved for the implementation of Method 1 (as described above) are provided in Table 2.. The last column of the table gives the desired estimators -- the estimated number of additional lives saved by light-duty vehicle occupant seat belts in year i that would not have been saved had the seat belt usage rate remained at the 1989 'base year' level of 68 percent.

Table 2.
Estimates Of The Number Of Extra Occupant Lives Saved In Light-Duty Vehicle Collisions In Each Of The Years 1990 - 1995 (Attributable To Increases In Safety Belt Usage Rates) That Would Have Died If Seat Belt Usage Rates Had Remained At The 1989 'Base Year' Level Of 68 %

YEAR	S-B USE RATE [1]	TOTAL FATAL CASES [2]	BELTED FATAL CASES [3]	RATIO *(BELTED TO TOTAL FATAL CASES)* [4]	OCCUP. *LIVES SAVED* BY S-B *(DUE TO YEAR$_i$ S-B USE RATE)* [5]	EXPECTED BELTED FATAL CASES *(AT 1989 S-B USE RATE)* [6]	EXPECTED OCCUP. *LIVES SAVED* BY S-B *(AT 1989 S-B USE RATE)* [7]	EXTRA OCCUP. *LIVES SAVED* BY S-B *(DUE TO YEAR$_i$ S-B USE RATE)* [8]
Y_i	$\hat{UR}_i$ (%)	D_i	$D(R)_i$	$R(R \mid T)_i$	$\hat{S}(R)_i$	$\hat{D}(R,1989)_i$	$\hat{S}(R,1989)_i$	$\hat{ES}(R)_{i\,:\,1989}$
1989	**68.0**	**3,129**	**1,428**	**0.456**	**1,266**			
1990	76.0	2,804	1,439	0.513	1,276	1,279	1,134	142
1991	80.0	2,632	1,416	0.538	1,255	1,200	1,064	191
1992	81.4	2,583	1,453	0.562	1,289	1,178	1,045	244
1993	83.4	2,620	1,506	0.575	1,336	1,195	1,060	276
1994	86.8	2,360	1,399	0.593	1,241	1,076	954	287
1995	86.8	2,476	1,494	0.604	1,325	1,129	1,001	324

1 National seat belt usage rate for occupants of light-duty vehicles in road traffic.
2 Total occupants killed in light-duty vehicle collisions.
3 Total restrained occupants killed in light-duty vehicle collisions.
4 Ratio of restrained to total occupants killed in light-duty vehicle collisions.
5 Total number of occupant lives saved in light-duty vehicle collisions attributable to seat belt usage rate, UR_i.
6 Expected number of restrained occupants that would have been killed in light-duty vehicle collisions if seat belt usage rate had been at the 1989 level of 68 %.
7 Expected number of occupant lives that would have been saved by restraint systems if seat belt usage rate had been at the 1989 level of 68 %.
8 Extra number of occupant lives that were saved by restraint systems due to the increase in seat belt usage rate in year i over the 1989 'base year' level of 68 %.
^ Indicates the value has been estimated.

Interpretation Of Method 1 Results – The national seat belt survey usage rates for occupants of light-duty motor vehicles for each of the years 1989 to 1995 are given in column 2 of Table 2. -- denoted as UR_i. Comparing these usage rates with the 'extra occupant lives saved by seat belts (due to increased seat belt usage rates in year i over 'base year'1989)' -- last column of the table denoted by $ES(R)_{i:1989}$ -- reveals the additional number of occupant lives being saved in light-duty motor vehicle collisions in each of the years 1990 to 1995 that are attributable to the increases in seat belt usage rates over the 1989 'base year' usage rate of 68 %. Graphical representations of all major results are provided in Figures 1 and 2.

Examination of the results provided in Table 2. and Figures 1. and 2. reveals the following noteworthy findings. There were 7,722 light-duty vehicle occupant lives saved by seat belts in collisions during the six year NORP program period 1990 - 1995. An increase of 8 % in occupant seat belt usage by the light-duty vehicle motorists (i.e., 76 % in 1990 compared to 68 % in 1989) resulted in an 'additional' 142 lives being saved by seat belts in 1990 that would have been lost had the seat belt usage rate in 1990 remained at the 1989 seat belt usage rate level of 68 %. Further analyses of these results shows that each percentage point increase in seat belt usage in 1990 over the 1989 usage rate translates into an 'additional' 18 occupant lives being saved in collision-involved light-duty vehicles in 1990 who would have been killed had the seat belt usage rate in 1990 remained at the 1989 level of 68 %. These same types of analyses and interpretations comparing the years 1991 to 1995 with the 1989 'base year' reveal that: 191, 244, 276, 287 and 324 'additional' occupant lives were saved by seat belts in light-duty motor vehicles involved in collisions in the corresponding years 1991, 1992, 1993, 1994 and 1995 due to increases in seat belt usage rates (over the 1989 'base year' level of 68 %) of 12.0 %, 13.4 %, 15.4 %, 18.8 % and 18.8 % respectively. These results translate into approximately 16, 18, 18, 15 and 17 'additional' occupant lives being saved in collision-involved light-duty vehicles for each percentage point increase in seat belt usage over the 1989 'base year' level of 68 % in the years 1991, 1992, 1993, 1994 and 1995 respectively. An analysis of the collective benefits over the six year NORP program period (1990 - 1995) reveals that 1,464 'additional' light-duty motor vehicle occupant lives have been saved in collisions that are directly due to the increases in seat belt usage rates that have occurred since the comparison 'base year' 1989. In other words, 1,464 more occupant fatalities would have occurred during the NORP program period (1990 - 1995) if the seat belt usage rates among the occupants of light-duty motor vehicles had remained at the 1989 level of 68 %.

Method 2a. An Estimator Of The Additional Number Of Occupant Lives Saved In Light-Duty Motor Vehicles Involved In Collisions In Each Of The Years 1990 - 1995 That Are Attributable To Increases In Seat Belt Usage Rates Over The 1989 'Base Year' Level of 68 % : ***A Method Based On Observed Occupant Seat Belt Usage Rates In Light-Duty Vehicles Traveling On The Roads And Highways -- 'Without Selective Recruitment'***

This second method for deriving estimators of any 'additional' light-duty vehicle occupant lives that have been saved in collisions that are attributable to increases in seat belt usage is based on seat belt usage rate results obtained from observational surveys of the general traffic on the roads and highways. These day-time surveys have been conducted by Transport Canada annually between 1979 and 1990 and biannually after 1990. They are designed using a complex multistage stratified probability sampling plan resulting in a national sample of 240 roadside observational sites selected by province, road type and community size. The surveys are conducted during a one-week time period (either in the fall -- October, or in the spring -- June) between the hours of 7 a.m. and 5 p.m.. Seat belt use information was only collected for vehicle drivers in the 1989 - 1991 surveys while the surveys after 1991 have collected the belt use information for all occupants of the vehicles observed. The results of the 1989 to 1996 Transport Canada surveys providing seat belt usage rates for drivers of passenger vehicles, drivers of light-duty vehicles and all occupants of light-duty vehicles by year and month are given in Table 3..

Using these seat belt usage rates (Table 3.) estimators of any decreases in the numbers of casualties (fatalities or injuries) to collision-involved light-duty vehicle occupants that are attributable to increases in seat belt usage rates between two periods of time can be derived. Specifically, the reductions in light-duty vehicle occupant casualties (fatalities or injuries) realized in year i compared to an earlier time period say 'base year' b, denoted as $CR^{2a}(O,LV)_{i:b}$, can be estimated when four quantities are known -- the seat belt effectiveness estimate, the current year i seat belt usage rate, the comparison or 'base year' b seat belt usage rate, and the number of casualties (fatalities or injuries) that occurred in the comparison or 'base year' b. Inputting these quantities into the following mathematical formula (4.) and performing the computations yields the desired estimators of casualty (fatality or injury) reductions between the two evaluation time periods i and b:

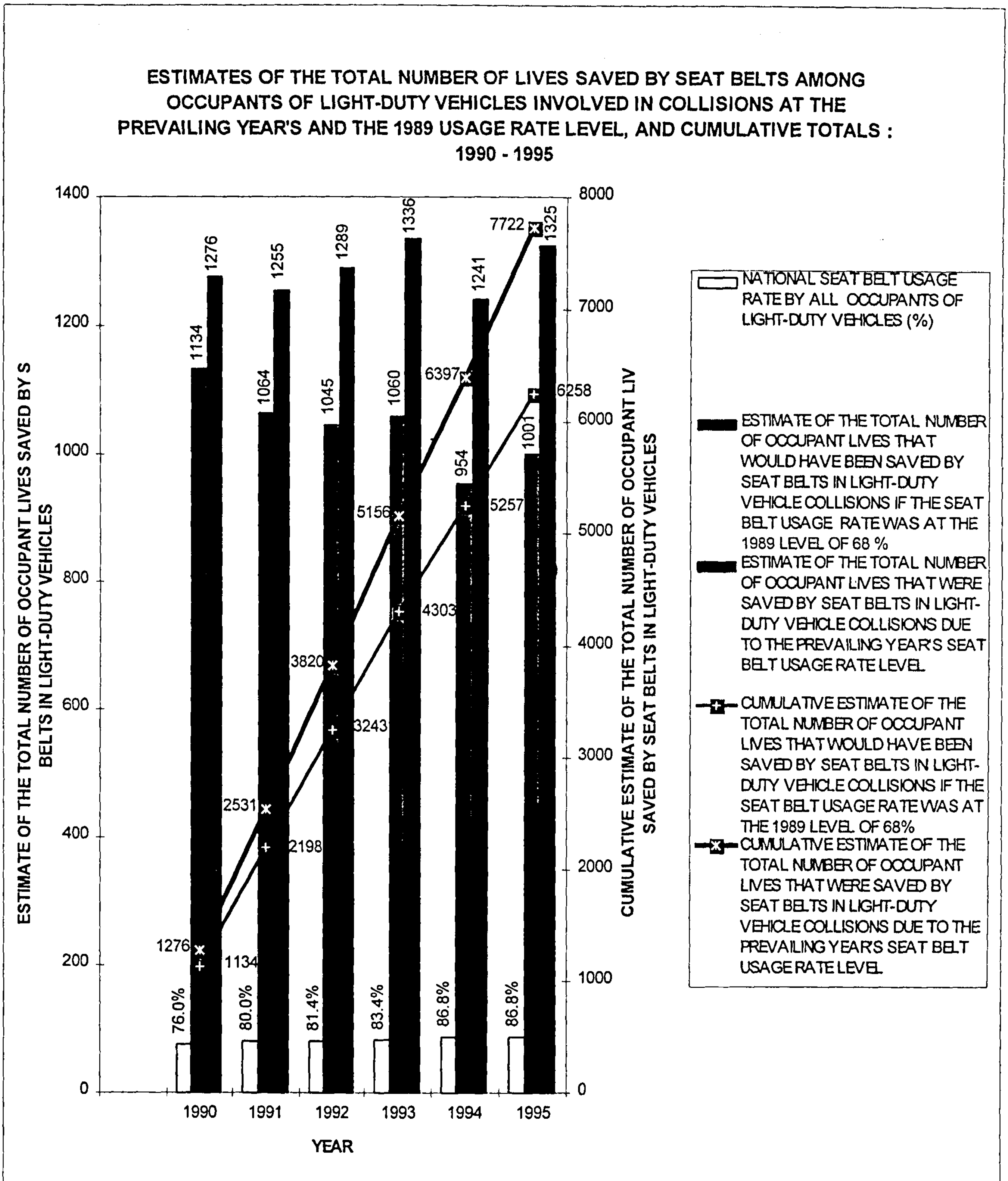

Figure 1. Estimators of : the total number of occupant lives that would have been saved by seat belts in collision-involved light-duty vehicles in each of the years 1990 to 1995 and cumulative totals over the years if the seat belt usage rate had remained at the 1989 'base year' level of 68 %, and the total number of occupant lives that were saved by seat belts in collision-involved light-duty vehicles in each of the years 1990 to 1995 and cumulative totals over the years that are attributable to the prevailing year's seatbelt usage rate level.

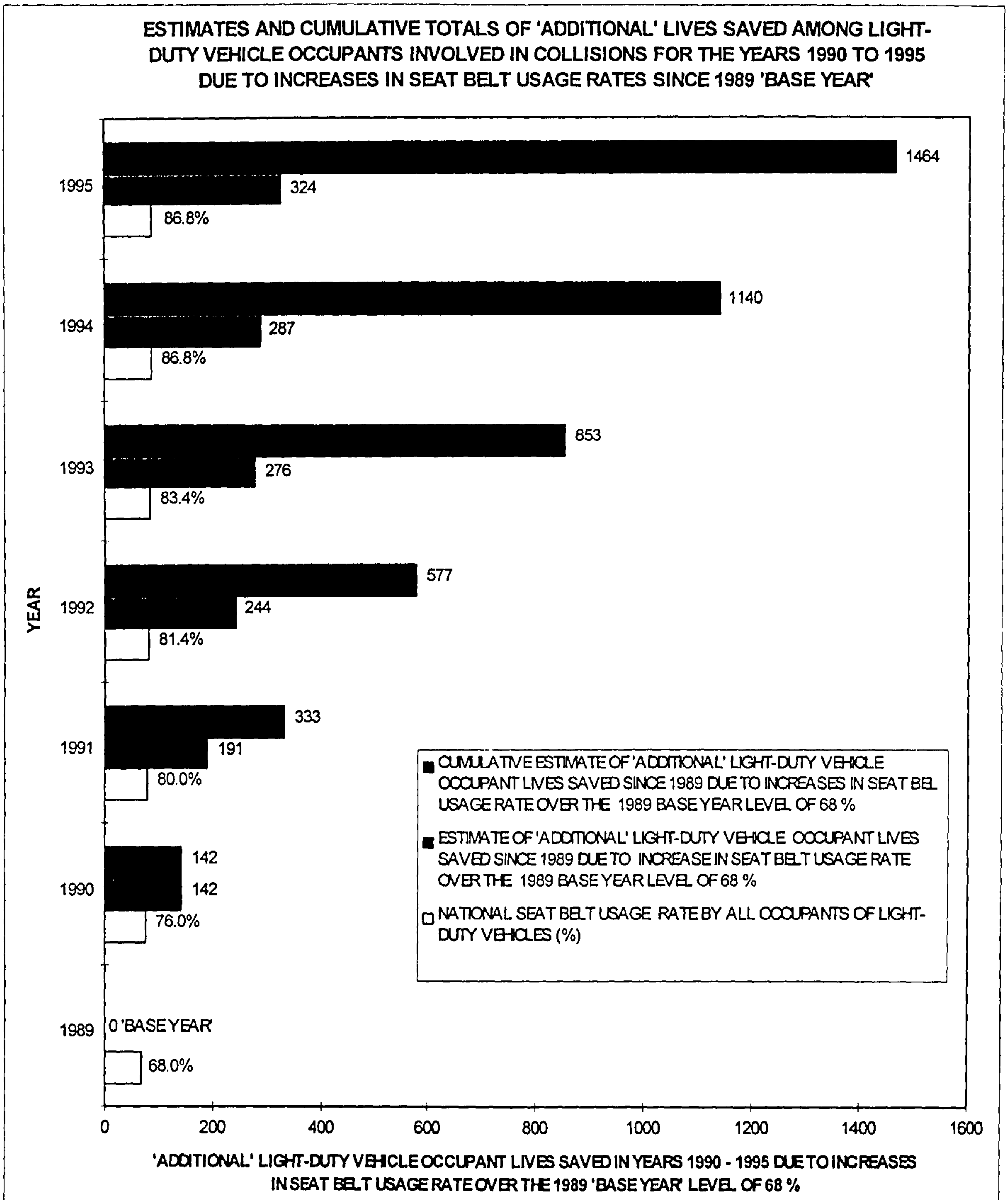

Figure 2. Estimators of : the 'additional' number of occupant lives that were saved by seat belts in light-duty vehicles involved in collisions in each of the years 1990 to 1995 that are attributable to increases in the seat belt usage rate level that took place in the prevailing year (i.e., 1990,...,1995) over the 1989 'base year' level of 68 %.

Table 3.
Estimators Of Seat Belt Usage Rates For Drivers Of Passenger Vehicles, Drivers Of Light-Duty Vehicles, And All Occupants of Light-Duty Vehicles : 1989-1996

Survey Year and Month	Seat Belt Use Rate: Drivers, Passenger Vehicles (%)	Seat Belt Use Rate: Drivers, Lt.-Duty Vehicles (%)	Seat Belt Use Rate: Occupants, Lt.-Duty Vehicles (%)
$Y_{i,m}$	UR(D,PV)	UR(D,LV)	UR(O,LV)
1989, Oct.	73.9	70.6	68.0*
1990, Oct.	81.9	80.0	76.0*
1991, June	85.1	83.0	80.0*
1991, Oct.	86.0	83.8	
1992, June	85.9	84.4	81.4
1992, Oct.	87.1	85.7	
1993, June	87.8	86.2	83.4
1993, Oct.	87.8	87.0	
1994, June	90.1	88.7	86.8
1994, Oct.	91.6	90.6	
1995			86.8**
1996, June	91.9		88.7

* These seat belt usage rates are estimated from the observed seat belt usage rates for drivers of light-duty vehicles for the respective year (column 3)

** A national seat belt survey was not conducted in 1995, therefore the previous year's estimate is used

$$CR^{2a}(O,LV)_{i:b} = \frac{[UR(O,LV)_i - UR(O,LV)_b] * e_c * C_b}{1 - [\, e_c * UR(O,LV)_b \,]} \qquad (4.)$$

where,

$CR^{2a}(O,LV)_{i:b}$ is the estimated reductions in casualties (injuries or fatalities -- depending upon injury severity level being evaluated) to occupants of light-duty motor vehicles involved in collisions in estimation year i compared to comparison 'base year' b,
e_c is the overall effectiveness estimate of seat belt systems in preventing casualties (death or injury) to occupants of light-duty motor vehicles involved in collisions (e_c has two different values as established earlier -- one for death reduction and another for injury reduction), $UR(O,LV)_i$ is the seat belt usage rate for occupants of light-duty motor vehicles traveling on the roads and highways in estimation year i,
$UR(O,LV)_b$ is the seat belt usage rate for occupants of light-duty motor vehicles traveling on the roads and highways in comparison 'base year' b,
C_b is the number of casualties (fatalities or injuries, depending upon the injury severity level reduction being estimated) that took place in comparison 'base year' b.

METHOD 2b. AN ESTIMATOR OF THE ADDITIONAL NUMBER OF OCCUPANT LIVES SAVED IN LIGHT-DUTY MOTOR VEHICLES INVOLVED IN COLLISIONS IN EACH OF THE YEARS 1990 - 1995 THAT ARE ATTRIBUTABLE TO INCREASES IN SEAT BELT USAGE RATES OVER THE 1989 'BASE YEAR' LEVEL OF 68 % :
A METHOD BASED ON OBSERVED OCCUPANT SEAT BELT USAGE RATES IN LIGHT-DUTY VEHICLES TRAVELING ON THE ROADS AND HIGHWAYS -- 'WITH SELECTIVE RECRUITMENT'

This method, unlike Method 2a, takes into account a phenomenon known as 'selective recruitment' -- a process in which the group of drivers who change from being non seat belt users to seat belt users have lower accident involvement rates than the remaining group of non users. Analytical methods to account for this have been developed by Evans (1987) and are therefore implemented in this study for the purposes of assessing the estimates developed by Methods 1 and 2a. The mathematical formula for implementing Method 2b to compute estimates of 'additional' light-duty vehicle occupant lives saved and injuries prevented in collisions that are attributable to increases in seat belt usage rates between two time periods i and b is given by:

$$CR^{2b}(O,LV)_{i:b} = \left[\frac{e_c\{\Delta u + 0.47[UR(O,LV)_i^3 - UR(O,LV)_b^3]\}}{1 + 0.47 - e_c\{UR(O,LV)_b + 0.47[UR(O,LV)_b^3]\}} \right] * C_b \qquad (5.)$$

where,

$CR^{2b}(O,LV)_{i:b}$ is the estimated fractional reduction in casualties (injuries or fatalities, depending upon the level of severity being evaluated) to occupants of light-duty motor vehicles involved in collisions in estimation year i compared to comparison 'base year' b,
e_c, $UR(O,LV)_i$, and C_b are as defined in the previous section under Method 2a,
Δu is the fractional difference between $UR(O,LV)_i$ and $UR(O,LV)_b$.

Interpretation Of Results For Methods 2a And 2b -- The estimators of the 'additional' light-duty vehicle occupant lives saved in collisions for the years 1990 to 1995 that are due to increases in seat belt usage rates that have occurred since the inception of the NORP program in 1990 are depicted in Figure 3. The results for the 'additional' light-duty vehicle occupant injuries prevented in collisions over the same time period (1990 - 1995) that are also attributable to the increases in seat belt usage rates since the NORP program implementation can be seen in Figure 4.

Examining the 'additional' light-duty vehicle occupant lives saved (Figure 3.) reveals that the increase in seat belt usage by the light-duty vehicle motorists from 68 % in 1989 to 76 % in 1990 (an 8 % increase) resulted in anywhere between 173 (Method 2a) and 188 (Method 2b) 'additional' light-duty vehicle occupant lives being saved by seat belts in 1990 -- that would not have been saved if the 1990 seat belt usage rate level had remained at the 1989 level of 68 %. This translates into about 23 'additional' light-duty vehicle occupant lives being saved in collisions for each percentage point increase in seat belt usage that occurred in 1990 over that of the 1989 'base year' level of 68 %. Comparison of the other years (1991 to 1995) to the 1989 'base year' reveal the following results: between 259 and 290, between 290 and 326, between 333 and 379, between 406 and 473, and between 406 and 473 'additional' light-duty vehicle occupant lives were saved by seat belts in collisions in the years corresponding to 1991, 1992, 1993, 1994 and 1995 that are directly attributable to increases in seat belt usage rates (over the 1989 'base year' level of 68 %) of 12.0 %, 13.4 %, 15.4 %, 18.8 % and 18.8 % respectively. Overall, this means that approximately 23 'additional' occupant lives were saved in collision-involved light-duty vehicles for each percentage point increase in restraint usage over the 1989 'base year' level of 68 % in each of the years 1991 though 1995. Further analyses of Figure 3 reveals that between 1,867 (according to Method 2a) and 2,129 (according to Method 2b) 'additional' light-duty motor vehicle occupant lives were saved in collisions over the entire NORP program period 1990 - 1995 due to increases in seat belt usage rates that have taken place since the 1989 'base year'. This implies that about 2,000 (the average of Methods 2a and 2b results) 'additional' light-duty vehicle occupant fatalities would have occurred in collisions during the six year NORP program period (1990 - 1995) if the seat belt usage rate levels among those occupants had remained at the 1989 'base year' level of 68 %.

Figure 4 illustrates the comparable results for the 'additional' light-duty vehicle occupant injuries that have been prevented in collisions for the six year NORP program period that are directly attributable to increases in seat belt usage rates that have occurred since the program's inception in 1990. It can be readily inferred that the increase of 8 % in seat belt usage by the light-duty vehicle motorists (from 68 % in 1989 to 76 % in 1995) translates into a minimum of 3,740 (according to Method 2a) and as many as 4,303 (according to Method 2b) 'additional' light-duty vehicle occupant injuries that were prevented by seat belts in 1990 over that of the 1989 'base year'. This is interpreted as: "between 3,740 and 4,303 light-duty vehicle occupant injuries were prevented in collisions in 1990 that would not have prevented if the 1990 seat belt usage rate level (of 76 %) had remained at the 1989 level of 68 %. Further interpretations of the results in Figure 4. reveal that each percentage point increase in seat belt usage in 1990 over that of the 1989 usage rate level of 68 % among light-duty vehicle motorists resulted in between 468 (according to Method 2a) and 538 (according to Method 2b) injuries prevented in 1990 that would not have been prevented had the seat belt usage rate in 1990 remained at the 1989 'base year' usage rate level of 68 %. Similar analyses and interpretations were carried out comparing the years 1991 through 1995 to the 1989 'base year' revealing the following: between 5,609 and 6,611, between 6,264 and 7,445, between 7,199 and 8,661, between 8,788 and 10,795, and between 8,788 and 10,795 'additional' light-duty vehicle occupant injuries were prevented by seat belts in collisions in the years corresponding to 1991, 1992, 1993, 1994 and 1995 that are directly attributable to increases in seat belt usage rates (over the 1989 'base year' level of 68 %) of 12.0 %, 13.4 %, 15.4 %, 18.8 % and 18.8% respectively. Taking an average of the estimates produced by Methods 2a and 2b for each of the five years translates into about 509, 512, 515, 521 and 521 'additional' occupant injuries being prevented in collision-involved light-duty vehicles for every percentage point increase in seat belt usage over the 1989 'base year' level of 68 %. Collectively, over the entire six year NORP program period (1990 - 1995) there were between 40,388 (according to Method 2a) and 48,610 (according to Method 2b) 'additional' light-duty motor vehicle occupant injuries prevented in collisions due to the increases in seat belt usage rates that have occurred since the 1989 'base year'. In total, therefore, approximately 44,500 (the average of the results obtained from Methods 2a and 2b) 'additional' injuries would have occurred during the NORP program period if the seat belt usage rates among occupants of light-duty motor vehicle travel had remained at the 1989 'base year' level of 68 %.

CONCLUSIONS

Road Safety Benefits

All three methods developed and implemented in this study for estimating the lives that have been saved and

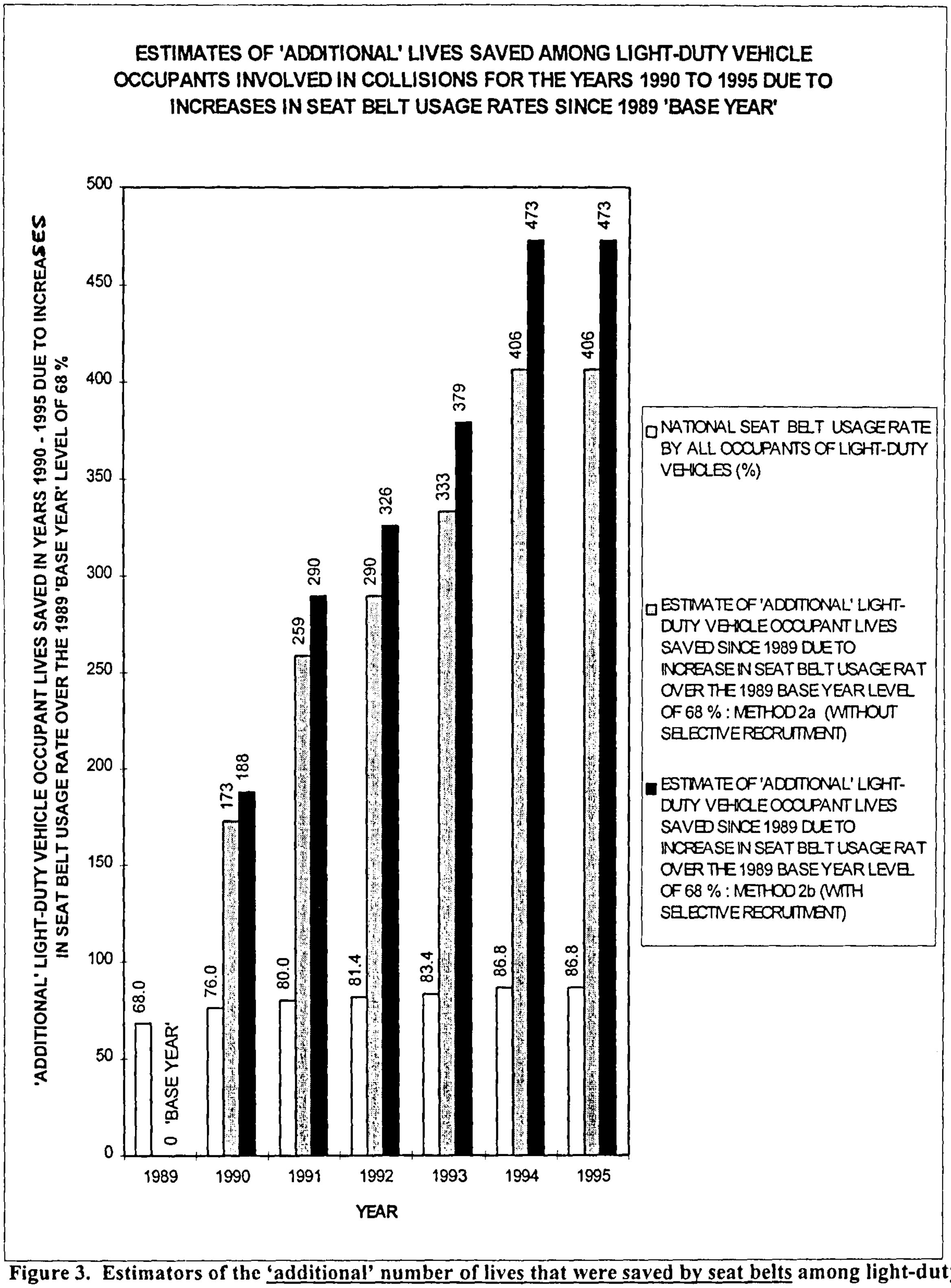

Figure 3. Estimators of the 'additional' number of lives that were saved by seat belts among light-duty vehicle occupants involved in collisions in each of the years 1990 to 1995 that are attributable to increases in the seat belt usage rate level that took place in the prevailing year (i.e., 1990,...,1995) over the 1989 'base year' level of 68 % for Methods 2a and 2b.

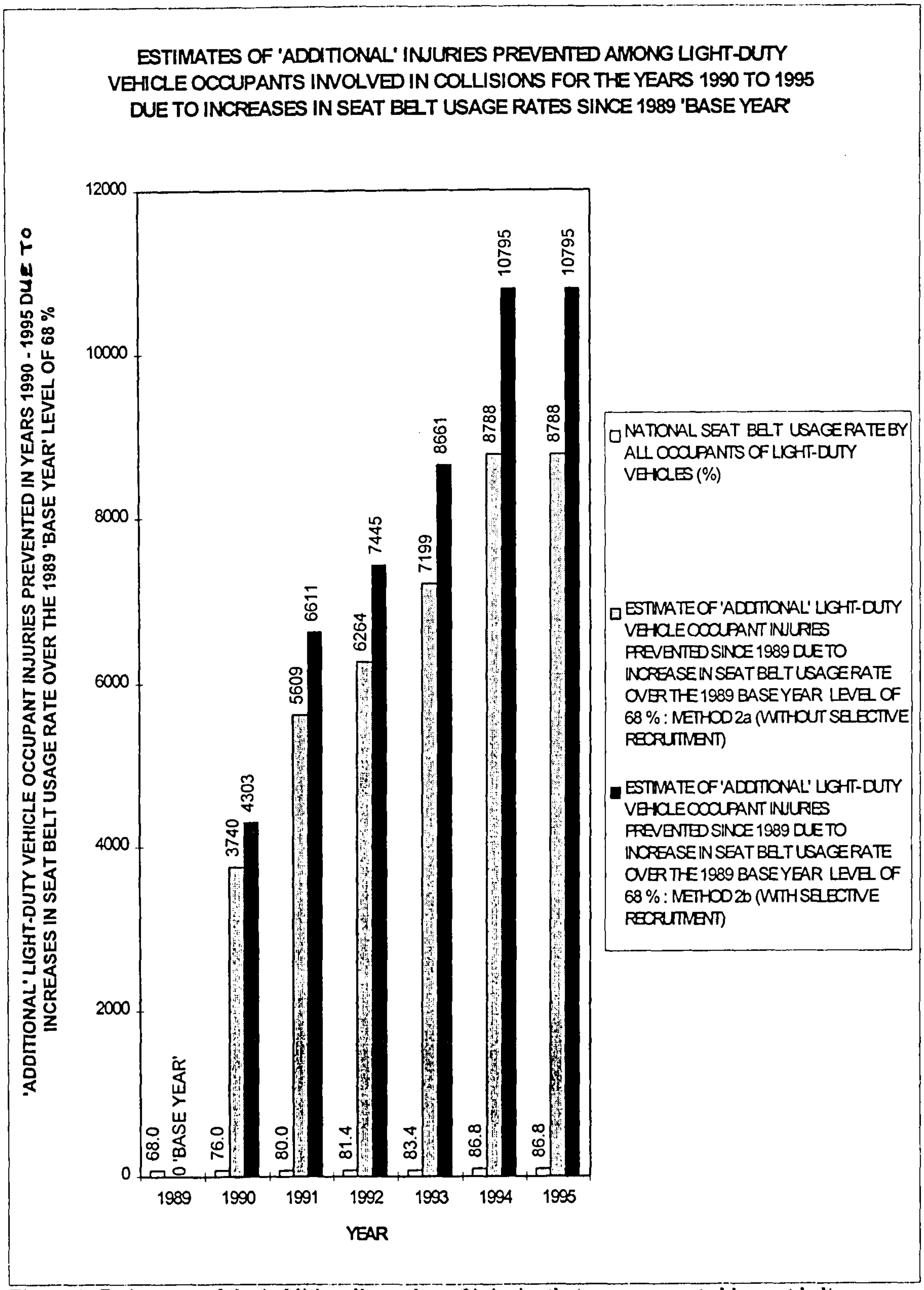

Figure 4. **Estimators of the 'additional' number of injuries that were prevented by seat belts among light-duty vehicle occupants involved in collisions in each of the years 1990 to 1995 that are attributable to increases in the seat belt usage rate level that took place in the prevailing year (i.e., 1990,...,1995) over the 1989 'base year' level of 68 % for Methods 2a and 2b.**

injuries that have been prevented among light-duty vehicle occupants that are directly attributable to increases in seat belt usage rates over the years are valid. The differentials in their strengths and weaknesses are owing to the accuracy of the input data required for each method as well as their respective capacities to develop estimates of 'total' and 'incremental' savings in lives and injuries due to the increased seat belt usage rates.

The appealing strength of Method 1 resides in its ability to estimate both the 'total lives saved' as well as the 'additional lives saved' that are directly attributable to the various levels of seat belt usage rate increases that took place over the specified evaluation time period -- in this case over the six year NORP program period. This is possible through the Method 1 estimation procedure because estimates of the expected number of total occupant lives saved by light-duty motor vehicle seat belt systems are derivable for any seat belt usage rate, and the difference between any two estimates computed for different seat belt usage rate levels provides the 'additional' or 'incremental' lives that were saved (if any) that are directly attributable to the differential in seat belt usage between the two evaluation time periods. One of the main weaknesses of Method 1 is that the estimators could, however, be 'under-estimates' due to the 'unknown' restraint use status for a significant proportion (10 % in this study) of the occupants who were fatally injured. The other weakness, or limitation, comes from the fact that the methodology does not permit the capability of estimating the 'numbers of injuries prevented' that are due to seat belt usage rate increases because sufficiently accurate data on the seat belt use status of injured occupants is not available.

The big advantage of Methods 2a and 2b come from their capacity to estimate both the 'additional' or 'incremental' lives saved as well as the injuries prevented that are directly attributable to increases in seat belt usage rates between two specified evaluation time periods. The major limitation, however, to both of these methods is their inability to estimate the 'total lives saved' or 'total injuries prevented' due to increases in seat belt usage rates. This is owing to the fact that the mathematical formulae only provide the capacity to derive estimates of the expected 'fractional reductions in casualties' for a specified period of time relative to a previous period in time that can be attributed to the differential in seat belt usage rate that existed between the two periods. Another limitation affecting these two methods is that they depend upon seat belt usage rates that are only representative of day-time travel (between 7 a.m. and 5 p.m. -- the time period during which the national seat belt surveys are conducted) which could result in 'over-estimates'.

Notwithstanding the above limitations, it is our opinion that the 'total lives saved' estimated by Method 1 and the average of the estimated 'fractional reductions in casualties (fatalities or injuries, depending upon the injury severity level estimated) ' in Methods 2a and 2b are considered to be quite reasonable (accurate) for quantifying the 'additional' lives saved and injuries prevented that can be attributed to increases in seat belt usage that took place between the 1989 'base year' and the end of the six year NORP program in 1995. Therefore the total number of lives that have been saved by seat belts among occupants of collision-involved light-duty vehicles during the period 1990 - 1995 is estimated to be in excess of 7,700. Two thousand of these 7,700 lives would have been lost if the light-duty vehicle seat belt usage rates had not increased from the 1989 'base year' level of 68 % to the higher levels observed over the six year period 1990 - 1995. In other words, increases in seat belt usage rates of 8.0 %, 12.0 %, 13.4 %, 15.4 %, 18.8 % and 18.8 % over the 1989 'base year' level of 68 % in each of the years 1990, 1991, 1992, 1993, 1994 and 1995 respectively has resulted in an 'additional' 2,000 light-duty vehicle occupant lives saved. With respect to injuries, it is estimated that approximately 44,500 have been prevented among light-duty vehicle occupants that are directly attributable to the seat belt increases that took place during the 1990- 1995 period.

Economic Benefits

From an economic perspective, it is estimated that the value of a 'lost life' and an 'injured life' (i.e., societal costs) are (on average) equivalent to a financial loss of $1.5 million and $ 11,800 respectively. The benefits, therefore, that can be accrued to the increased usage of available seat belt systems by occupants of light-duty motor vehicles over the six year NORP program period (1990 - 1995) are in excess of $ 3.5 billion.

SUMMARY AND RECOMMENDATIONS

The six year NORP program (1990 - 1995) had a significant impact on improving road travel safety. The increases in seat belt usage by light-duty vehicle occupants yielded large safety benefits with respect to lives saved and injuries prevented in motor vehicle collisions, which translated into sizable economic benefits (i.e., societal cost savings) of approximately three and one half billion dollars. The results of this research provide some incite and guidance on the expected 'potential' gains to be realized from the present (second) NORP program (1996 - 2001) that has been designed and implemented to affect further increases in the seat belt usage rates among the light-duty vehicle motorists.

Conservatively, the estimators derived from Method 1 indicate that about 17 'additional' occupant lives were saved in collisions in each of the years 1990 to 1995 for each percentage point increase in seat belt usage over the 1989 'base year' level of 68 %, and the equivalent figure, averaged from Methods 2a and 2b, was 23 'additional' occupant lives saved. On the injury side, it was estimated that approximately 516 light-duty vehicle occupant injuries were prevented in collisions for each percentage point increase in the seat belt usage rate. Now, according to the 1995 national seat belt survey, the seat belt usage rate among light-duty vehicle occupants was 86.8 %. If this usage rate could be raised to 95 % by the year of 2001 through efforts under the present NORP program this would translate into an 8.2 % increase. Combining this seat belt increase with the above estimators of the expected number of lives that would be saved and injuries prevented yields the final road safety benefits and associated economic benefits that can be attributed to the NORP 1996 - 2001. After carrying out the computations, it turns out that: between 139 and 189 light-duty vehicle occupants lives would be saved, and about 4,230 light-duty vehicle occupant injuries would be prevented in the year 2001. From an economic perspective, this translates into a minimum savings of about $ 258 million and the savings could be as high as $ 333 million -- and these benefits are all realized in the year of 2001. Similar road safety and economic benefits will also be realized in each of the years 1996, 1997, 1998, 1999 and 2000 -- with their relative amounts being directly proportional to the magnitude of the seat belt usage rate increase (over that of the 1995 'base year' level of 86.8 %) in each of the years. Although the total benefits to be realized from NORP 1996 - 2001 cannot be determined until the program is completed, it is possible to estimate the 'expected' benefits if the seat belt usage rate is increased to 95 % by the end of the year 2001 and if the overall 8.2 % seat belt usage increase (from 86.8 in 1995 to 95 % in 2001) increases uniformly (i.e., about 1.2 % per year) over the six year period 1996 - 2001. Under this plausible scenario the total number of 'additional' light-duty vehicle occupant lives expected to be saved in collisions that are directly attributable to the increases in seat belt usage rates would be at least 496 and could be as many as 672, and the corresponding figure for the number of injuries prevented would amount to 15,067. These road safety benefits translate into significant economic benefits -- with the total societal cost savings amounting to a minimum of $ 922 million dollars and possibly as much as $ 1.2 billion over the NORP 1996 - 2001 program period.

In light of the substantial savings that can be realized due to the 1996 - 2001 NORP, from both a human (lives saved and injuries prevented) and economic (societal cost savings) perspective, it is recommended that programs aimed at increasing and maintaining seat belt usage rates among the light-duty vehicle motorists be given a 'high' priority. Large investments in the order of 'tens of millions of dollars' in both human and financial resources are far out-weighed by the benefits that can realized from mounting intensive and effective programs, e.g., public education, enforcement, etc., for realizing a 95 % seat belt usage rate level among light-duty vehicle occupants traveling on Canada's roads and highways.

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THE CIREN EXPERIENCE

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ABSTRACT

The Crash Injury Research and Engineering Network, or CIREN links seven trauma centers from around the country together with engineers to study the cause, kinematics, and results of real world crashes. Each trauma center has a multidisciplinary team of physicians, medical researchers, safety engineers, crash reconstructionist, public safety professions, and others who review the crash and the patients. The network includes trauma centers in San Diego, Seattle, Newark, Baltimore, Miami, Washington and Ann Arbor. General Motors funds three of these centers. A high-speed computer network will soon link the seven centers. This state of the art teleconferencing system will allow on-line multidisciplinary analyses of crashes to be performed by personnel from the trauma centers, manufacturers and government agencies.

The first national conference was held last October in Ann Arbor. This research will hopefully aid the auto industry to continuously design safer cars. It is already helping the medical community, doctors and Emergency Medical Services personnel, to develop new diagnostic and treatment tools.

INTRODUCTION

The National Highway Traffic Safety Administration's (NHTSA) Crash Injury Research and Engineering Network is designed to help save lives and prevent harm from automobile crashes. The Network is known by its CIREN acronym, pronounced "siren". This effort focuses on improvements in prevention, treatment and rehabilitation to reduce deaths, disabilities and human and economic costs through medical and engineering research.

APPROACH TO RESEARCH

This multicenter research program involves the collaboration of clinicians and engineers in academia, industry and government. CIREN presently links seven trauma centers from around the country with engineers to study the cause, kinematics and effects of real world crashes. Each trauma center has a multidisciplinary team of physicians, medical researchers, safety engineers, crash reconstructionists, public safety professionals and others who perform in-depth studies of car crashes, injuries and treatments to improve processes and results. Trauma centers in San Diego, Seattle, Newark, Baltimore, Miami, Washington and Ann Arbor comprise CIREN. A high-speed computer network will shortly link the seven centers. This state of the art electronic rounds system will allow on-line multidisciplinary analyses of crashes to be performed by personnel from participating locations.

This research will hopefully aid the auto industry to continuously design safer cars. It is already helping the medical community, doctors and Emergency Medical Services personnel, to develop new diagnostic and treatment tools. A recent case from Miami demonstrates the potential for improving the survival from crashes.

THE IMPORTANCE OF CIREN

A few months ago, the head nurse in the Ryder Trauma Center Resuscitation Unit received a call from a police officer stating he was working a crash and was concerned that the driver, a nurse, might have a liver injury. The officer stated that the nurse said she was unharmed and wanted to have a taxi take her to her place of work. (She did not meet any of Florida's objective trauma criteria such as systolic blood pressure below 90 mm Hg, which mandate transport to a trauma center). The policeman was requesting that the Fire Rescue team on scene in coordination with air rescue transport her to the trauma center based on the subjective criterion of high index of suspicion of injury. He pointed out that although she was not obviously injured, the crash pattern, particularly the fact that she was only wearing her automatic shoulder belt, was identical to crashes that cause severe liver injuries and the victims initially appear fine. Additionally, he stated he had learned of this injury pattern in lectures provided to the Miami-Dade Police Department by the William Lehman Injury Research Center. A Miami-Dade Rescue and Fire Team attended to the victim at the scene and she was airlifted to the Ryder Trauma Center.

The police officer was right. Within minutes of arrival the patient was in the operating room. She had a very severe liver injury. It was the worst case scenario of the shoulder belt-liver injuries that the Lehman Center had described in the literature. The back of her liver and the veins that connect the liver to the vena cava, the largest vein in the body, were ripped from the vena cava. Traditional surgical techniques did not offer a solution for this catastrophic problem. The chief of Liver Transplant Surgery came to the Trauma Center operating room. Largely due to the innovative application of transplant techniques to a trauma situation, a definitive repair was achieved. The patient did quite well and was discharged home a few days later. The police officer at the crash scene applied newly learned knowledge about injury patterns to a real life situation. He saved the life of this crash victim. Had she not been rapidly transported to a trauma center with its wealth of clinical expertise, she would not have survived.

THE CIREN PROGRAM

The CIREN program is coordinated with the NHTSA, National Automotive Sampling System (NASS) in many ways, yet CIREN provides some details of injury causation not found in the larger program's data. NASS investigators use handheld pen-computers to collect data. The NASS information about the crash and the injuries that it produced is entered into a nationwide information network. Some 24 sectors included in the system are expected to collect data on approximately 5,000 crashes annually. The NASS cases are typically investigated some time, days or weeks, after the crash. Reviewing medical records, which are at times incomplete, makes injury determination quite difficult. It is not uncommon for caregivers to describe only the severe injuries in the record. Bumps and bruises, which may be highly informative for locating body positions during the crash, are often not described in the medical record.

CIREN will compliment NASS by zeroing in on approximately 350 nationwide crashes to produce highly detailed injury and damage profiles. The CIREN centers can provide very high quality data on the crash and the injuries because experts in clinical care and injury research can very precisely describe and photographically document all injuries while caring for the patient. Each of the centers is developing techniques that build high quality data collection into the already demanding task of providing often life-saving care. Some of the centers have developed computerized documentation systems that facilitate the description/documentation process. Additionally, the CIREN researchers can be on the scene and evaluate the cars typically within hours of the crash while the data are fresh. Most centers have developed arrangements with local police agencies that inform and often enable CIREN investigators to be on the crash scene with the police investigators. The CIREN program will study key traffic safety issues, such as air bags and new side-impact standards.

The CIREN centers will utilize an information system that is derived from the presently operational NASS system. The CIREN information system will link the seven trauma centers to each other, as well as other participating locations. The information system will make two important contributions to automobile crash research. First, it will facilitate teleconferencing among the participants in the trauma centers and experts in industry and government. This multimedia information system will allow conference participants to each review pertinent data including photographs, video and x-rays. The most qualified experts will be able to provide their input to analyses at the earliest stage. The highest quality interpretations of crashes should emanate from the CIREN program.

Second, the data and analyses will be available to qualified researchers in the shortest time through the online database; similar to what NASS provides.

FUNDING

General Motors (GM) has provided funding for the CIREN effort under a settlement agreement between GM and the US DOT. With these funds GM is supporting the University of Washington, University of Michigan and San Diego County; each for four years. (The other centers are funded by NHTSA). Each of the seven centers has a long history of excellence in a specific research area.

- Children's National Medical Center, Washington, DC – Pediatric injuries.
- R. Adams Cowley Shock Trauma Center, National Study Center for Trauma and EMS, Baltimore, Maryland – Orthopedic injuries, specifically lower extremity.
- New Jersey Medical School, New Jersey – Brain injury, Roll of direction of crash and compartment intrusion on organ injury.
- William Lehman Injury Research Center, University of Miami School of Medicine,– Mechanism and patterns of injury.
- University of Michigan Medical Center, Ann Arbor, Michigan – Long history of crash research through the University of Michigan Transportation Research Institute and burn injury.
- County of San Diego, Department of Health Services, San Diego, California – Unique advantage of most advanced EMS system in the country for trauma.
- Harborview Injury Prevention and Research Center, Seattle, Washington – Neck and pediatric injury, long term focus on injury control.

Additionally, General Motors has funded the initial one-year CIREN information network implementation effort. All seven centers are served through the information system funding.

CIREN builds on the work done by NHTSA funded trauma centers more than a decade ago. This program does not just increase the number of cases that can be studied in depth. It brings a new dimension of multidisciplinary expertise to the very complex problem of crash and injury causation analysis. Automobile designers and government regulators will benefit by augmenting their understanding of crash performance from not only dummy responses, but also through real world crashes involving people. The medical and emergency responder communities will benefit from ongoing injury research and the discovery of injury patterns. The CIREN program will be a driving force for education of care providers in a rapidly changing world of automobile safety technology. Continued improvement of diagnostic and therapeutic approaches to automobile injury will save lives and reduce morbidity from what has been called America's neglected disease, injury.

SERIOUS LOWER EXTREMITY INJURIES IN MOTOR VEHICLE CRASHES WISCONSIN, 1991 – 1994

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ABSTRACT

Using linked motor vehicle crash and hospital discharge records from Wisconsin under the auspices of NHTSA's CODES project (Crash Outcome Data Evaluation Systems), the incidence and risk factors for serious lower extremity injuries include fractures, dislocations and crushing injuries of the bones and joints of the lower extremity. Incidence rates of these injuries were 200/ 100,000 crash occupants. Of those who were hospitalized following motor vehicle crash injuries, 16% were diagnosed with a serious lower extremity injury. Using logistic regression models, risk factors for both front seat passengers and drivers include crashes with frontal components, higher posted speed limits, smaller cars and vans. Age, gender and belt-use could only be included in model for drivers, showing increased risk to female drivers, especially those over 60, and a small protective effect from seatbelts. Estimates of risks for specific injuries—including foot and ankle fractures are also included.

INTRODUCTION

Serious lower extremity injuries from motor vehicle crashes can result in expensive care, lengthy rehabilitation and life-long disability.[1] Previous studies indicate that fewer than half of those hospitalized with a serious lower extremity injury had returned to work six months following the crash.[2] Risk factors for serious lower extremity injuries have been identified in cases from trauma centers and include frontal collisions and occupant compartment intrusion.[3,4] Females were shown to be at higher risk, perhaps due to their smaller stature.[5] Literature from one case study also concluded that seatbelts and airbags were not effective in reducing risk, and from another, describes very different outcomes for unrestrained drivers compared to passengers.[4,6]

But trauma center studies do not include the experience of occupants in crashes who were not injured, and so are not as powerful at establishing risk factors. The advent of linked medical outcome and crash data provide a new tool for establishing the magnitude of risk factors for all occupants in crashes by comparing characteristics of crashes and occupants who are injured with those who are not.

We used linked hospital and motor vehicle crash data from Wisconsin over a four-year period to describe the nature and extent of serious lower extremity injuries from passenger vehicle crashes and the magnitude of risk factors for them. These linked data are from the Wisconsin CODES project, funded by the National Highway Traffic Administration.

METHODS

Data Sources

Wisconsin's motor vehicle crash database is housed at the Wisconsin Department of Transportation (WiDOT) During the study period, all crashes that involved either injury or property damage greater than $500 were reported by law enforcement agents. For 1994, WiDOT revised the crash reporting form somewhat, and data from this year have been reformatted to fit previous year's variables.

The Office of Health Care Information has housed the state's hospital discharge database since its inception in 1989. No personal identifiers are collected. Data include all items in the Uniform Hospital Discharge Data Set for inpatient admissions and total hospital charges. E Codes have been mandatory since April 1994.

There are no computerized emergency department or emergency medical services data which cover the state population.

Linkage Techniques

This study was conducted by the Wisconsin CODES project staff. In the CODES project, data are linked using a probabilistic linkage software program, Automatch. The theory and methods underlying the software have been described in the transportation safety literature.[7,8] Linkage variables in Wisconsin from the crash report include date and location of the crash, date of birth of the driver or injured occupant, sex and zip code of residence of the occupant, and whether the occupant was injured or transported by an emergency vehicle.[9-11] From the hospital data, linkage variables include the date of hospital admission (plus seven days to account for delayed admissions) county of hospitalization, date of patient's birth, sex and zip code or residence for the patient.

Study Population

We used public access linked data files for the years 1990 through 1994 for this analysis.
Some variables were not available for the year 1990, and therefore some analyses were confined to the years 1991 – 1994. Wisconsin has a population of about 5 million with one large metropolitan area, and a substantial rural population elsewhere.

We defined passenger vehicles as those recorded either as automobiles, light trucks or sport utility vehicles on the police crash report. Drivers and passengers were defined by their seating location on the crash report.

Definition of Serious Lower Extremity Injury

Serious lower extremity injuries were defined by the hospital discharge diagnoses. There were five diagnoses available in the database, and any serious lower extremity injury in any of these fields were included. Fractures, dislocations, crushing injuries and traumatic amputations of any part of the lower extremity were considered serious. Strains, sprains, contusions, abrasions, burns and fractures of the pelvic girdle and hip were not included in the definition or the analysis.

Crash configuration.

Data on the crash report that indicated the point of impact and the nature of the collision were used to categorize crashes by the amount of energy likely to be concentrated at the front of the vehicle. Categories include: multiple vehicle head on collisions, single vehicle fixed object collision, single vehicle crashes off road, and side collisions, with frontal damage. For the multiple logistic regression analysis, the comparison group was all other collisions which included multiple vehicle collisions when point of impact was the rear or side of the vehicle, single vehicle overturns, and single vehicle collisions into a movable object.

VIN

The Vehicle Identification Number is included in the Wisconsin crash reports, and was decoded using software from the Insurance Institute for Highway Safety modified for a VAX computing environment. These data were the source of information on vehicle size.

Estimated Seatbelt Use.

Information on seatbelt use is recorded by law enforcement agents at the crash site based either on information provided by the occupant or from the agents' observations. In all, 85% of occupants in Wisconsin crashes are reported as wearing belts, while WiDOT seatbelt observation data suggest that the rate of belt use was closer to 55% during the time period of the study. To correct for overreporting of belt use, our research team developed a method to estimate a probability of belt use for each crash occupant based on factors from the state observational studies. Variables used to estimate the probability of belt use included sex, age, make and model of vehicle, location in the state, and type of roadway. Because these data were not always available for uninjured passengers in the crash reports, estimates of probability are only reported for drivers. This procedure is explained in a previous NHTSA report [9]

Analytic methods

In addition to describing the nature and incidence of serious lower extremity injuries, risk factors were estimated from logistic regression models with various outcomes as dependent variables. This method controls simultaneously for multiple factors, and offers a direct estimate of the odds ratios for the association of the independent variables and the outcome of interest. Outcomes used as dependent variables in our models included the presence of any serious lower extremity injury, multiple serious lower extremity injuries, and specific injury diagnoses.

FINDINGS

Incidence of Serious Lower Extremity Injuries

During the five-year period, 1990 to 1994, there were more than 1.6 million occupants in passenger vehicle crashes reported to the Wisconsin Department of Transportation. Of these, 19,514 were hospitalized, and 3,138 (16%) were diagnosed with a serious lower extremity injury. Over the five-year period, the rate per 100,000 crash occupants ranged from 173 to 205 per 100,000 with no discernable temporal trend.

During 1994 and 1995 when external cause of event was reported in Wisconsin's hospital discharge data, 16% of all cases admitted with serious lower extremity injuries were from motor vehicle crashes. This was second to the large number of injuries from falls. During these years, hospital charges average $18,000 per patient with a primary diagnosis of a serious lower extremity injury. These charges do not include either the physician's fee or any follow-up care.

Table 1.
Incidence of serious lower extremity injuries in motor vehicle crashes,Wisconsin, 1990 – 1994

Year	Number of Cases	Rate /100,000 passenger vehicle crash occupants
1990	693	205
1991	566	173
1992	663	201
1993	618	180
1994	598	175

Specific Injury Diagnoses

The annual number of cases with specific diagnoses is reported as five-year averages (1990 – 1995). These diagnoses are not necessarily mutually exclusive:

Ankle fractures	183
Femur fractures	176
Tibia/fibula fractures	173
Fractures of the bones of the foot	112
Patellar fractures	69

Multiple serious lower extremity injuries were common – about 22% of cases sustained more than one serious lower extremity injury.

Seatbelt Use

For drivers, we estimated the probability that seat belts were being used based on a logistic regression model of seatbelt use independently observed by the Wisconsin Department of Transportation. Because seatbelt use as reported on crash forms is higher than rates observed of drivers, we assume that the reported use overestimates the actual. This overestimate has the effect of inflating the actual protective effect of seatbelts because uninjured occupants who are not wearing belts are reported to be wearing them. Our estimates of the effectiveness of seatbelts in providing protection against lower extremity injuries are lower than the estimates using reported belt use but may be a better estimate of their effectiveness. The measures of risk based on observed data suggest that belt use more effectively protects injuries proximal to the torso, with less protection for the foot. In general, the measures of risk based on reported use are substantially higher but are likely to be inflated.

Table 2.
Estimates of risk vary according to the method used to determine seatbelt use

Injury Diagnosis	Estimate of Risk for unbelted drivers when belt use is determined by police reports	Estimates of Risk for unbelted drivers when belt use probability is estimated from observational data
Any serious lower extremity injury	6.3	1.8
Fracture of the foot	4.6	1.3
Tibia/fibula fracture	10.0	1.9
Femur fracture	6.6	3.1

Risk Factors for Serious Lower Extremity Injuries

Drivers

From logistic regression models we find that the risks of sustaining serious lower extremity injuries were very high for crashes with a frontal component compared to other risk factors.(Table 3, attached) This association was more pronounced than for brain injuries or hospitalization with any injury, with odds ratios of 28 compared to 7.2 for brain injury and 9.7 for any hospitalization. The odds ratio for serious lower extremity injury increase with posted speed limit of the crash site, as is the case for brain injury and any hospitalization. Unlike brain injury, however, odds ratio for serious lower extremity injury are higher for women than men, and especially high for women over 60. Vehicle size also affects the odds ratio of serious lower extremity injury, as it does with brain injury and hospitalization, with the odds ratio decreasing as car and van sizes increases.

These odds ratios vary somewhat with the nature of the lower extremity injury (Table 4 attached). The odds ratio of sustaining a fracture of the foot in a head on collision were 53 times greater than a crash that did not involve impact with the front of the vehicle. Serious lower extremity injuries of each diagnosis had elevated odds ratios for crashes with a frontal component, and with higher posted speed limits, although the magnitude of the odds ratios varied by diagnosis. Odds ratios were high for crashes with a higher likelihood of increased impact forces. Therefore, in each case, head on collisions resulted in higher odds ratio estimates than did single vehicle fixed object collisions, with the comparison being crashes without a frontal component.

Our models also suggest older females were at higher risk for ankle and foot fractures but the odds ratio for fractured tibia or fibula were not significantly higher for women of any age.

Passengers

Logistic regression models that include passengers do not include information on age and gender because these data are not available for uninjured passengers. This also limits our ability to estimate seat belt use based on observed data. Both drivers and front seat passengers have higher odds ratios of any serious lower extremity injury, and of multiple serious lower extremity injuries than do back seat passengers (Table 5 attached). Odds ratio estimates were especially high for fractures of the foot (21 for drivers, and 13 for front seat passengers) compared to back seat passengers. Odds ratios were lower for fractures of the femur for drivers in this model, and were not significant for front seat passengers.

DISCUSSION

Limitations

These data provide a conservative estimate of the extent of problem of serious lower extremity injuries. Some people who are injured in Wisconsin crashes are hospitalized in Minnesota, and are not included in the Wisconsin hospital data system nor in the linked data set. Some cases may be included in the Wisconsin hospital data system, but are not linked to crashes because of errors in data recording in either the crash data system or by the hospitals themselves. Others may be missed because the crash was never reported to the police. In previous reports, we estimated that these situations result in an underestimate of about 20% of all motor vehicle related hospitalizations.[11] We can think of no reason that this would be different for serious lower extremity injuries.

While the study underestimates the extent of the problem, it is unlikely that the situations described above bias the risks estimated from the logistic regression analysis. For the results to be due to bias, a substantial number of cases with serious lower extremity injury in non-frontal crashes, for example, would have to be systematically referred to out-of-state hospitals. Given trauma referral patterns in Wisconsin, this is not probable.

Linked data p invaluable information on the medical outcomes of non-fatal crashes, but data from the hospital discharge system are limited. Because the data are limited to the initial hospitalization, we do not have actual information on the long-term outcomes of injuries. In addition, bilateral injuries cannot be discerned from hospital discharge data despite their enormous impact on the time it takes to become ambulatory after injury.

Because Wisconsin crash data do not include information on the age or gender of uninjured passengers, models of the effect of age and gender on injury are limited to drivers. In addition, belt use is estimated from observational data based in part on age and gender of passengers, so models on passengers have limited information on the role of seat belts as protective devices.

Despite these limitations, linked data make an important contribution to our knowledge of injury risk in crashes. Unlike trauma center studies and other case series, linked data include information on the characteristics of occupants and crashes in which injuries did not occur. Comparing the crashes that lead to injury with those that do not is a powerful method to measure risk.

CONCLUSIONS

Serious lower extremity injuries in crashes are common and costly. Our study shows that one of six people who are hospitalized following a motor vehicle crash has a serious lower extremity injury. One in every 500 passenger vehicle crashes reported to police involves an occupant who is hospitalized with a serious lower extremity injury.

To decrease the incidence of serious lower extremity injury to occupants in crashes, data from this study suggest that we need to improve passenger vehicle crashworthiness. We base this conclusion on the following evidence:

- Risks for all serious lower extremity injuries are highest in crashes with energy concentration in the forward part of the occupant compartment, and risks increase with crash configurations that are associated with large impact forces. The odds ratio for drivers' serious lower extremity injury in head-on collisions is 28 compared to 5.7 for single vehicle fixed object crashes. Both of these are odds of sustaining serious lower extremity injury when compared to crashes without a frontal component. We need to consider how to design cars that can manage the impact forces of frontal collisions in such a way as to protect the lower extremities. Lower extremities are closer to the point of impact in frontal collisions.

- The risks of serious lower extremity injuries are increased with smaller car sizes, suggesting that impact forces can be managed more appropriately. The protective effect of large cars and vans shows that it is possible to provide some occupant protection through changes in vehicle design.

- Risks for sustaining fractures of the foot are higher than for other injury diagnoses for all crash configurations with a frontal component – they are extraordinarily high for head on collisions – with odds ratios for drivers of 53 compared to crashes with no frontal component. The foot in a crash is likely to be closer to the impact than other parts of the leg, and is protected by less crush space. Front seat passengers also have high odds ratios for foot fracture when drivers and front seat passengers are compared to other passengers. The higher odds for driver foot fracture (21 compared to 13) suggests that driver side foot well or driver controls could be associated with increased risk.

- To the extent that we can determine, seatbelts do provide some protective effect for serious lower extremity injury to drivers. Seatbelts, are however, primarily designed to protect against head injury, and injury to

- the internal organs of the chest. The protective effect of seatbelts increases to the lower extremity injuries that are proximal (closer to the trunk) such as femur injuries. They had less protective effect for distal injuries, such as foot and ankle fracture. This suggests that occupants may be more appropriately protected through improved crashworthiness of the vehicle, rather than through occupant protection devices such as seatbelts. Airbags were not common enough during the years of our study to include in our analysis.

Finally, when occupant protection through vehicle design is being discussed, it is important to remember than for serious lower extremity injuries, women over the age of 60 have increased risks. This has been attributed to their smaller stature, and lower injury threshold. These populations deserve consideration in the design and standards for vehicle crashworthiness.

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Table 3. Odds Ratios and 95% Confidence Intervals for Three Injury Outcomes
Wisconsin 1991-1994
Passenger Vehicles, Drivers Only

Passenger Vehicles Only Drivers Only 1991-1994 Data Independent Variables	Any Lower Extremity Injuries		Brain Injury		Any Hospitalization	
Estimated Seat Belt Probability (10% change in probability)	0.76 ***	(.75, .78)	0.68 ***	(.67, .70)	0.75	*** (.74, .75)
Air Bag	1.17	(.80, 1.72)	1.06	(.70, 1.61)	0.90	(.73, 1.10)
2 Vehicle, Head On	28.00 ***	(23.9,32.81)	7.22 ***	(5.94, 8.77)	9.68	*** (8.94,10.49)
1 Vehicle, Fixed Object	5.66 ***	(4.85, 6.60)	3.60 ***	(3.13, 4.15)	3.93	*** (3.70, 4.16)
1 Vehicle, Off Road	3.28 ***	(2.39, 4.49)	2.15 ***	(1.59, 2.90)	3.12	*** (2.78, 3.50)
Side, Front End Damage	3.15 ***	(2.68, 3.70)	1.66 ***	(1.40, 1.96)	1.88	*** (1.76, 2.00)
Speed Limit 35-50	2.63 ***	(2.25, 3.07)	1.93 ***	(1.63, 2.29)	1.99	*** (1.87, 2.12)
Speed Limit 55+	3.88 ***	(3.36, 4.48)	3.49 ***	(3.02, 4.03)	3.10	*** (2.93, 3.29)
Age 16-29	0.60 ***	(.51, .71)	0.82 *	(.70, .96)	0.59	*** (.55, .63)
Age 60+	1.22	(.95, 1.57)	1.85 ***	(1.48, 2.32)	2.09	*** (1.91, 2.27)
Female	1.51 ***	(1.28, 1.79)	1.13	(.93, 1.38)	1.30	*** (1.21, 1.40)
Age 16-29, Female	0.96	(.76, 1.22)	0.89	(.69, 1.15)	0.95	(.86, 1.05)
Age 60+, Female	2.86 ***	(2.08, 3.94)	1.34	(.94, 1.92)	1.57	*** (1.38, 1.78)
Car, Compact	1.02	(.81, 1.28)	0.86	(.67, 1.09)	0.95	(.86, 1.05)
Car, Small	0.788 *	(.63, .98)	0.69 **	(.55, .87)	0.79 ***	(.72, .87)
Car, Medium	0.679 ***	(.54, .85)	0.76 *	(.60, .96)	0.75 ***	(.67, .84)
Car, Large	0.465 ***	(.35, .62)	0.46 ***	(.34, .62)	0.50 ***	(.44, .57)
Car, Luxury	0.396 ***	(.29, .52)	0.48 ***	(.36, .64)	0.47 ***	(.38, .59)
Van/Truck, Small	0.825	(.50, 1.37)	0.9	(.55, 1.48)	0.79 *	(.71, .87)
Van/Truck, Medium	0.509 ***	(.40, .64)	0.49 ***	(.39, .63)	0.49 ***	(.43, .56)
Van/Truck, Large	0.343 ***	(.64, 1.27)	0.52 ***	(.39, .71)	0.43 ***	(.31, .57)
Number of Injury Cases	1364		1242		7940	
Total Cases in Model	656895		(Models only include cases for which all variables have no missing data)			

* indicates sig. at .05 level ** indicates sig. at .01 level *** indicates sig. at .001 level

Table 4. Odds Ratios for Selected Lower Extremity Injury Outcomes Wisconsin 1991-1994
Passenger Vehicles, Drivers Only

Passenger Vehicles Only Drivers Only 1991-1994 Data Independent Variables	Fractured Ankle	Fractured Foot	Fractured Tibia/ Fibula	Fractured Femur	Other Lower Extremity Injury	Multiple Fractures	Any Lower Extremity Injury	
MODEL 2								
Estimated Seat Belt Probability (10% change in probability)	0.794 ***	0.83 ***	0.71 ***	0.76 ***	0.76 ***	0.78 ***	0.76 ***	(.75, .78)
Air Bag	1.513	0.99	1.46	0.54	2.03	1.42	1.17	(.80, 1.72)
2 Vehicle, Head On	27.965 ***	52.99 ***	27.19 ***	23.91 ***	18.98 ***	45.88 ***	28.00 ***	(23.9,32.81)
1 Vehicle, Fixed Object	6.32 ***	7.19 ***	6.35 ***	4.76 ***	2.90 ***	5.44 ***	5.66 ***	(.485, 6.60)
1 Vehicle, Off Road	2.345 *	4.03 ***	3.88 ***	2.32 *	4.22 ***	3.16 **	3.28 ***	(2.39, 4.49)
Side, Front End Damage	3.033 ***	3.19 ***	2.08 ***	3.27 ***	3.79 ***	2.28 ***	3.15 ***	(2.68, 3.70)
Speed Limit 35-50	2.244 ***	2.97 ***	2.95 ***	2.45 ***	2.67 ***	2.41 ***	2.63 ***	(2.25, 3.07)
Speed Limit 55+	2.994 ***	4.86 ***	4.24 ***	4.48 ***	3.68 ***	4.38 ***	3.88 ***	(3.36, 4.48)
Age 16-29	0.509 ***	0.39 ***	1.15	0.45 ***	0.63 *	0.50 ***	0.60 ***	(.51, .71)
Age 60+	1.012	0.44 *	1.86 *	2.14 ***	0.52	1.40	1.22	(.95, 1.57)
Female	1.96 ***	1.76 ***	1.43	1.12	0.94	1.49	1.51 ***	(1.28, 1.79)
Age 16-29, Female	0.96	1.31	0.62	1.46	1.02	1.00	0.96	(.76, 1.22)
Age 60+, Female	3.749 ***	4.54 ***	1.33	1.76 *	9.74 ***	1.88	2.86 ***	(2.08, 3.94)
Car, Compact	0.884	1.141	1.005	1.958 *	0.755	1.657	1.02	(.81, 1.28)
Car, Small	0.932	0.954	0.751	1.141	0.454 **	1.161	0.788 *	(.63, .98)
Car, Medium	0.615 *	0.845	0.663	1.051	0.581	0.92	0.679 ***	(.54, .85)
Car, Large	0.396 ***	0.416 **	0.253 ***	0.796	0.567	0.302 *	0.465 ***	(.35, .62)
Car, Luxury	0.314 ***	0.367 **	0.432 **	0.614	0.289 **	0.236 **	0.396 ***	(.29, .52)
Van/Truck, Small	1.074	0.429	1.13	1.417	0.559	1.506	0.825	(.50, 1.37)
Van/Truck, Medium	0.504 **	0.518 *	0.493 **	0.813	0.354 ***	0.641	0.509 ***	(.40, .64)
Van/Truck, Large	0.356 **	0.262 **	0.308 ***	0.602	0.328 **	0.468	0.343 ***	(.64, 1.27)
Number of Injury Cases	432	293	336	350	179	204	1364	
Total Cases in Model	656,895	(Models only include cases for which all variables have no missing data)						

* indicates sig. at .05 level ** indicates sig. at .01 level *** indicates sig. at .001 level

Table 5. Odds Ratios for Select Lower Extremity Injury Outcomes, Wisconsin, 1991 – 1994.
Passenger Vehicles, Drivers and Passengers

Passenger Vehicles Only
Passengers & Drivers
1991-1994 Data

Independent Variables	Fractured Ankle	Fractured Foot	Fractured Femur	Fractured Tib/Fib	Other Injuries	Multiple Injuries	Any Lower Extremity Injuries	95% C.I.
Reported Seat Belt Use	0.25 ***	0.31 ***	0.13 ***	0.18 ***	0.22 ***	0.22 ***	0.20 ***	(.18, .22)
Air Bag	1.68	1.28	1.42	0.61	2.27	1.55	1.30	(.89, 1.90)
Driver	5.77 ***	20.99 ***	1.43 *	2.56 ***	8.45 ***	5.85 ***	2.97	(2.44, 3.61)
Front Seat Passenger	3.79 ***	13.32 ***	1.29	1.74 **	3.51 **	3.69 ***	2.03 ***	(1.64, 2.52)
2 Vehicle, Head On	24.21 ***	46.02 ***	24.57 ***	19.48 ***	17.15 ***	42.11 ***	23.87 ***	(20.82, 27.37)
1 Vehicle, Fixed Object	5.39 ***	5.91 ***	5.72 ***	3.94 ***	2.99 ***	5.02 ***	4.90 ***	(4.30, 5.58)
1 Vehicle, Off Road	2.88 ***	3.28 ***	3.39 ***	2.31 ***	4.19 ***	3.28 ***	3.09 ***	(2.38, 4.00)
Side, Front End Damage	3.01 ***	3.18 ***	2.12 ***	3.19 ***	4.02 ***	2.55 ***	3.07 ***	(2.68, 3.53)
Speed Limit 35-50	2.04 ***	2.84 ***	2.38 ***	2.34 ***	2.36 ***	2.15 ***	2.37 ***	(2.07, 2.72)
Speed Limit 55+	3.00 ***	4.84 ***	4.22 ***	4.61 ***	3.56 ***	4.40 ***	3.91 ***	(3.46, 4.41)
			0.757					
Car, Compact	0.88	1.32	1.02	1.75 *	0.80	1.75	1.03	(.84, 1.26)
Car, Small	1.02	1.13	0.76 *	1.29	0.65	1.27	0.90 *	(.74, 1.10)
Car, Medium	0.81	1.11	0.68 *	1.39	0.80	1.17	0.86 *	(.70, 1.04)
Car, Large	0.80	0.71	0.56 *	1.30	0.92	0.60	0.82 *	(.65, 1.04)
Car, Luxury	0.57 *	0.67	0.71 *	1.01	0.43 *	0.60	0.68 ***	(.53, .86)
Van/Truck, Small	0.95	0.83	1.24 *	1.06	0.85	1.31	0.95	(.62, 1.45)
Van/Truck, Medium	0.60 **	0.74	0.66 ***	1.08	0.58	0.98	0.67 ***	(.55, .82)
Van/Truck, Large	0.46 **	0.52	0.50 **	0.83	0.44 *	0.64	0.52 ***	(.39, .69)
Number of Injury Cases	567	366	518	477	212	262	1838	
Total Cases in Model	1,001,801			(Models only include cases with no missing data)				

* indicates sig. at .05 level ** indicates sig. at .01 level *** indicates sig. at .001 level

A HALF CENTURY OF ATTEMPTS TO RE-SOLVE VEHICLE OCCUPANT SAFETY: UNDERSTANDING SEATBELT AND AIRBAG TECHNOLOGY

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ABSTRACT

In road safety, a common perception exists that technology and/or regulation can solve problems, and does so in a sequential and progressive manner. This is not always the case. Technology is no panacea and government interventions can do as much harm as good. Using historical methodologies, this paper explores the multiple attempts and failures of manufacturers, governments, and other groups to solve the rather simple safety concept of crash harm reduction through properly restrained vehicle occupants. This historical-methodology approach is suggested as an effective evaluation tool to measure other road safety interventions.

INTRODUCTION

Seatbelts save lives. No responsible road safety professional today would dispute this fact. They have been in use for approximately forty years and evidence of their effectiveness is abundant. Yet usage rates in the United States today remain shockingly low (around 60 percent), especially when contrasted with Canada, Australia, and Western Europe with rates approaching or exceeding 90 percent.[1] Comparing the experience in the US with that of other countries offers insights into the nature of seatbelt use and how road safety interventions work (or do not).

The availability of the technologies of seatbelts and passive restraints have failed to solve the problem of injuries and deaths in the United States caused by the occupants colliding with the interior of the vehicle or being ejected, after the vehicle has hit another object. Yet, the technology of seatbelts has allowed other countries to solve this problem to a large extent. The US problem then, is not with insufficient technology, but with the failure of drivers and passengers to use it. A reason for this behavior rests in the history of the relationship between US society and seatbelts, including the politics involved.

This paper explores the successive cycles of government intervention in the United States, each one an attempt to solve the problem of the human collision.[2] Using a comparative-world methodology, we contrast the case of the United States with that of Canada (especially British Columbia) and to a lesser extent with Australia and Europe. This approach illuminates the extent to which seatbelt usage has been cultural and political and demonstrates the need to consider social and human factors when evaluating or designing road safety initiatives. The political history of seatbelts in the US and society's interaction with both the belts and the politics, contributed to widespread apathy and even antipathy toward them, which has been a factor in the continued problem of deaths and injuries to unbelted Americans.

The First Attempt (to solve the problem): Government Regulated Seatbelts, 1966-1970

Initially, in the late 1950s automobile manufacturers introduced seatbelts to solve the problem of keeping the driver in his or her seat following a minor collision such that control of the vehicle could be maintained. They became an option on new vehicles—albeit not a popular one. In the mid 1960s legislators and activists (Ralph Nader being the most memorable of them) re-defined the problem to which seatbelts were the solution—they argued that seatbelts could prevent thousands of accident-related injuries and deaths by reducing the severity of the "second collision" between the occupant and the interior of the vehicle or from the occupant being ejected during an accident (the first collision being between the automobile

[1]For Canadian statistics see Transport Canada Road Safety, Leaflet CL 9709 (E).

[2]That is, preventing injury to people after the vehicle has hit something. We acknowledge that road safety involves much more than seatbelt usage, but this paper is only about the problem of occupant protection.

and another object).[3] Reducing second collision injuries and fatalities has remained a problem in the US for the rest of the century. Despite claims by individuals such as Ralph Nader that having seatbelts in every vehicle would solve the problem of preventing the so-called secondary collision, this failed to happen because people did not wear them.

From the early 1960s seatbelts were available as options on most American-made cars. In 1963 only 9 percent of cars had belts, yet usage rates ranged in those vehicles from 47 percent always using them on local trips to 74 percent on longer trips.[4] Approximately 30 percent of vehicles on the road in 1966 had them, although a National Safety Council survey found that full-time usage rates among people who chose option seatbelts was 44 percent (67 percent said they used them on longer journeys exceeding 25 miles).[5] Given a choice, automobile makers and consumers did not often opt for seatbelts (but, it's worth noting that those whose chose them as an option—who were actively involved in obtaining them—tended to use them).

For the those concerned with national public safety--such as health officials, certain governors, senators, and congressmen, and consumer advocates including Ralph Nader— something had to be done about the thousands being killed each year (43,400 in 1963[6] and approximately 50,000 by 1966[7]). Their solution was to legislate seatbelt installation along with a range of safety guidelines to make the interior of the vehicle less dangerous.[8] In 1966 the US government created a separate Department of Transportation with a mandate to set standards and to put in place mechanisms to monitor them (soon the National Highway Traffic Safety Administration [NHTSA] would be created for this purpose).[9]

The first motor vehicle safety standards went into effect in 1968. These safety standards and the creation of NHTSA were large steps forward in making motor vehicle travel safer. But the introduction of seatbelts as standard equipment on vehicles failed to make Americans buckle up and injury rates remained high. (Usage and accident rates at this time were similar in Canada where the majority of vehicles were produced by US manufacturers.)

The automobile manufactures (Chrysler, American Motors, General Motors, and Ford) predicted as much. Prior to the Motor Vehicle Safety Standards they argued that the public would not wear seatbelts, and that making them mandatory would ruin the styling of their vehicles and reduce sales.[10] Auto makers further argued that Americans were not ready for seatbelts and would resent having something they did not want, and the costs for it, imposed upon them.[11] The manufacturers claimed to have an interest in safety, but insisted that it could be better achieved through improved highways and driver education—not federally imposed standards.[12] While it is indisputable that the auto manufacturers' main motivation in making these arguments was their complete hostility to any government regulation of their industry, hindsight shows they had some valid points.[13]

Over thirty years later, it is worth examining their

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[3]Ralph Nader, Unsafe at Any Speed: The Designed in Dangers of the American Automobile (New York: Grossman Publishers, 1965, 1972), especially chapter three.

[4]New York Times (hereafter NYT), 12 April 1967, section XIV, p. 31.

[5]NYT, 10 April 1966, section XII, p. 9. Another survey, this one carried out by the Auto Industries Highway Safety Committee, found that 38 percent of drivers with seatbelts "sometimes" used them on shorter trips and 25 percent sometimes used them on longer trips.

[6]NYT, 7 April 1964, p. 34.

[7]Business Week, 11 June 1966, p. 179.

[8]Removing or re-designing dangerous protruding objects such as the metal "cookie cutter" ring on the steering wheel, were among the changes to design mandated by this legislation.

[9]This was several years after the United States government mandated that any vehicle purchased for government use through the General Services Administration be equipped with seatbelts and other safety-related equipment. The opposition to this government stance on the part of the automobile companies is written up in NYT, 31 August 1964, p. 27. The state of New York had also already ordered lap belts on all vehicles sold in the state. NYT, 18 September 1964, p. 34

[10]NYT, 19 February 1965, p. 37.

[11]NYT, 18 September 1964, p. 34; 24 February 1965, p. 81.

[12]Despite claims to be concerned about safety, General Motors under tight questioning from Senator Robert F. Kennedy during government hearings on this issue admitted to making $1.7 BILLION in profits during the previous year, and spending only $1.2 million on safety research and initiatives. Other manufacturers showed similar records. Newsweek, 26 July 1965, pp. 67-68.

[13]It should be noted that government involvement in the industry has always been huge—through constructing highways the US government has given an enormous subsidy to the industry.

arguments. Legislating seatbelt installation did not solve occupant restraint problems, but it also did not cause a reduction in sales nor make people fear automobile use. To their pleasant surprise, auto makers did not experience a decline in sales as a result of this legislation. If anything, the increased attention to safety on the newer cars became selling features as a result of a new public interest in the issue. Regardless of whether people wanted to wear a seatbelt all the time, many wanted them there along with the other new safety features of collapsible steering wheel, dual braking systems, a padded dash board, and safety door latches.[14] People seem to believe Nader who had said that people may cause accidents, but cars causes injuries.[15] Arguably, since this time a culture of conspicuous consumption of safety features from airbags to anti-lock brakes and four-wheel drive has emerged, making them emblems of wealth or class status as much as safety devices.

As the auto makers predicted, people did not like or wear seat belts. A historical perspective suggests, however, that the automobile manufacturers in the United States themselves played a large role in making their own prophesy come true. The evidence presented below indicates that through making seatbelts especially ugly and uncomfortable, publicly raising concerns about price increases, and desperately arguing the (minute) potential dangers of belts, they made the arrival of the seatbelt era in America more cumbersome, controversial, and difficult than it needed to be.

For example, take the engineering and styling of the belts. By the early 1960s, seatbelts in Europe had already evolved into an early version of the self-adjusting, three-point, fully-retractable harnesses that are in common use today.[16] The European models were readily available as examples on the thousands of imported automobiles solid in the US each year. US manufacturers chose instead to install manual-adjusting, especially large, belts that restricted movement, and installed shoulder belts separate from lap belts, making it necessary for the user to do up two separate buckles.[17] Moreover because these shoulder belts were not self adjusting, drivers wearing them often could not reach components on or near the dash board. Ralph Nader became especially critical of the manufacturer's tactic, suggesting that the deliberately engineering belts for "human irritation."[18]

The manufacturers complained loudly to the public and in the press about these belts. Executives publicly bemoaned the ugliness of the belts and how they detracted from the car's appearance. One likened them to "spaghetti" while another to the "vines" in "Tarzan's cave."[19] While Volkswagon and Volvo promoted the safety features (including belts) on their vehicles in their advertising and public relations, the US auto makers complained that seatbelts ruined the car's aesthetic appeal and raised prices.[20] A Chrysler executive commented that "We can't think of a better way of doing it." Yet, the European example was right in front of them. This executive further commented that the inconvenience of the belt design does not increase the chance that riders will wear them, thereby publicly encouraging people not to do so.[21]

The motivation for the auto makers' tactic was their resentment of government regulation. The dialog, as reported in the newspapers, between them and the US government (and Ralph Nader) suggests a war for public support on the question of regulating the automobile industry. The manufacturers chose to make seatbelts the focus of their objections to the new regulations—even though these rules also included many other safety features. In the press manufacturers told Americans that no conclusive evidence existed on the benefits of safety belts and that adding them and other design modifications to automobiles would raise prices significantly.

Manufacturers also called attention to the minor injuries that seatbelts cause (neglecting to mention that this was while saving one's life), and asserted that insufficient data existed to warrant their widespread use. They especially attacked shoulder harnesses for the abrasions they left on the necks of people in accidents (again ignoring the lifesaving that went on in the process). If people wanted an excuse for not taking the trouble to buckle their seatbelts, the manufacturers gave it to them. A 1967 New York Times reporter even commented that the controversy raised over shoulder harnesses probably degraded the strap

[14]NYT, 19 August 1965, p. 13, discusses Dodge stressing 12 new safety features on it's higher priced vehicles.

[15]Nader views discussed in Business Week, 11 June 1966, p. 179.

[16]Business Week, 11 June 1966, p. 192 discussed this safety belt and an article on 23 April 1966, pp. 52-54, discussed seatbelts and safety features on Volvo and SAAB vehicles, imported into the United States. The existence of European superiority on safety belts was also discussed in NYT, 18 September, 1964, p. 34.

[17]NYT, 2 April 1967, section XIV, p. 28.

[18]Ralph Nader writing in NYT, 21 March 1968, p. 12A.

[19]NYT, 2 April 1967, section XIV, p. 28.

[20]NYT, 22 August 1967, p. 41.

[21]NYT, 31 March 1968, p. 12A.

so much that Americans would not ever use it even if the belt were improved or subsequent research negated the significance of the abrasions (both of which did occur).[22] The combination of manufacturers negative attitudes toward seatbelts and unsubstantiated concerns about their safety could not have made seatbelts appealing to the average American.

Ralph Nader along with several senators fought back hard, especially on the subject of costs. To General Motors executives who complained of the costs, they countered that it was the world's most profitable corporation and therefore could absorb a few dollars for safety.[23] Subsequently Senators Warren G. Magnuson (Democrat from Washington) and Walter Mondale (Democrat from Minnesota) found evidence that the manufacturers had grossly inflated the costs of seatbelts in their propaganda. The senators' own research suggested that the costs of the new seatbelt was approximately $3, while the manufacturers stated the costs to range from $23 to $34.[24] It appears the automobile companies hoped to convince people to write their political representatives and ask for the repudiation of the motor vehicle safety standards through which, in their view, the government forced people to buy things, like seatbelts, that the did not want.[25] But the auto companies failed to understand the situation: not even the most right-wing Republicans on the government's safety committees took up the position of the automobile manufacturers. Supporting safety standards was politically popular as most Americans supported the idea generally.[26] It took the auto manufacturers a few years to recognize the new reality.

The end result of these seatbelt-focused exchanges was not public opinion against the regulations; people believed that making cars safer was a good idea. Instead this dialog contributed to negative opinions towards seatbelts specifically and helped instill the view that they were something being imposed on Americans by a "big brother" government that was growing. Nearly fifteen years later, in letters to the editor the public continued to echo these same sentiments.[27] The result of people not wearing belts was thousands needlessly dying, which in turn brought more government intervention in the industry and in Americans' lives—not less.

The Second Attempt: Additional Seatbelt Paraphernalia, 1971-1976

Because the imposition of safety standards failed to solve the problem of carnage caused by the second collision by the early 1970s, advocates for public safety decided they needed to undertake greater measures. The secretary of transportation believed that he had five choices (retain the present rules, conduct a five-year field test of air bags, require air bags as an option on all new cars, make seatbelt use mandatory, or mandate passive restraints on all cars starting with the 1980 model year).[28] The choice in the US, where the government now had some control over the automobiles on the market (a luxury that Canadian or Australian governments did not have) was to turn to new technology (while Canada and Australia turned to mandatory [seatbelt] usage laws [MULs]).

In the early 1970s the United States had recently been to the moon, proving its technological capacity to be unmatched in the world. A faith in technology permeated US culture. It became the prescription for the country's ill of motor vehicle accident casualties.

The US government regulators took three steps in the early 1970s aimed at increasing the amount of technology on vehicles. The first was to convince manufacturers to experiment with the relatively new airbag technology with a goal of introducing it within a few years.[29] The second move was to attempt to increase belt usage through reminder systems that buzzed when the seatbelt was not fastened. All cars manufactured for the 1971 model year (and subsequent years) had this feature. But, usage rates remained low, bringing yet another cycle of legislation—insisting that all new vehicles for the 1974 model year would have an interlock system installed which would prevent the vehicle from being started unless the seatbelt were fastened. Opposition to interlock technology was

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[22]NYT, 27 August 1967, section IV, p. 13. Dr. Haddon, director of the National Highway Safety Bureau, undertook investigation and reported his findings in January 1968, noting that in Sweden a study of 28,000 crashes that involved lap and shoulder seatbelts saw no one killed at speeds under 60 miles per hour. NYT, January 1, 1968.

[23]NYT, 7 January 1968, p. 54.

[24]NYT, 8 January 1968, p. 47.

[25]NYT, 15 September 1968, p. 46.

[26]Elizabeth Brenner Drew, "The Politics of Auto Safety," Atlantic Monthly (October 1966): 95-102.

[27]NYT, 6 November 1981, p. 30; and 31 December 1984, p. A26.

[28]NYT, 2 August 1976, p. 24.

[29]Popular Mechanics (February 1971), pp. 64-65. Experiments with airbags began in the late 1960s with Ford forming a partnership with Eaton Yale & Towne, Inc. to develop the airbag. They were tested by the Air Force using baboons. Newsweek, 1 January 1968.

widespread and probably created as much resentment toward seatbelts and government demands that people wear them as it did converts to the wearing of them. It should be noted that the Canadian government did not demand the interlock system and most manufacturers either left it off of vehicles being shipped to Canada or gave Canadians a bypass switch.[30]

The Third Attempt: Airbags and other Passive Restraints, 1976-1983

With interlock devices not working, US legislators and certain lobbyists proceeded to their third choice of airbags or other passive restraints (such as the automatic seatbelt developed first by Volkswagon).[31] The public widely seems to have embraced the idea of airbags as it gave an excuse for not becoming accustomed to seatbelt wearing and it fit with the western (and especially American) cultural tendency to see technology as a panacea thereby absolving individuals and society of taking responsibility for their own behavior.[32] Industry at first balked at the idea of airbags. They cited their excessive costs and the stressed the dangers that they believed inherent in airbags—especially to children.[33] The industry had "cried wolf" when it protested seatbelts on the basis of their safety, which made their calls of dangers with airbags much less credible at the time (nevertheless, the history of their use in the 1990s has born out these concerns to be real issues with airbags).

In 1976 airbags seemed like the only technology that might save Americans from themselves and NHTSA sought to make them mandatory. Manufacturers protested adamantly. The auto makers received a slight compromise from the transportation secretary William T. Coleman in 1976, who seems to have listened to the safety concerns. The auto companies agreed to make 250,000 vehicles with airbags each year, that would be sold to consumers and monitored by NHTSA to gather information about them.[34] Soon, in 1977, a new transportation secretary (Brock Adams) ordered that airbags or automatic lap and shoulder restrains be installed in all standard and luxury automobiles by 1982, and in all smaller cars by the 1984 model year.[35] General Motors protested this in 1979, still arguing that airbags might injure small children.[36]

In the 1980s the Reagan administration reversed pending legislation that would mandate passive restraints (airbags or automatic belts) in all vehicles. This move belonged to a general policy of deregulating American industries. The President called for improved driver training as the solution, rather than vehicle regulation.[37]

Consumer advocate groups and automobile insurance companies took the government to court over the reversal of this bill, and won.[38] Reagan's Transportation Secretary Elizabeth Dole was told that the problem of occupant restraint had to be solved to save lives, and she was given a year to draft new, replacement legislation or the old bill passed in 1977 would be re-instated. In 1983 she introduced a compromise that included phasing in airbags (on 25 percent of new vehicles after September 1 1987, 40 percent after September 1, 1988, and 100 percent by September 1, 1989. But, she also legislated that this requirement would be removed if enough individual states passed mandatory usage laws (MULs) that taken together covered at least 2/3 of the American population.[39] Automobile companies suddenly became huge proponents of seatbelts and MULs.[40]

The Fourth Attempt: Mandatory Usage Laws, 1984-1990s

More than a decade after parts of Australia made seatbelt usage mandatory, eight years after Canada began doing so, and after thirty-two other countries had adopted MULs, the US states began to look at the issue.[41] On

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[30]Vancouver Province, 17 July 1973, p. 5. It should be noted that most vehicles in Canada were US made, or made for the US market. 1973 probably marked the first year that the standards would be different.

[31]Popular Science (March 1974), p. 93.

[32]Business Week, 4 July 1977, p. 20. Discusses this as a problem with promoting airbags to a large extent.

[33]NYT, 3 July 1977, section IV p. 6.

[34]NYT, 12 December 1976, p. 6.

[35]NYT, 1 July 1977, p. 1.

[36]NYT, 2 October 1979, p. A17.

[37]Motor Trend (April 1981), p. 32. NYT, 24 October 1981, p. 1.

[38]NYT, 25 June 1983, section one, pp. 1,8; This decision to insist that the government return to the passive restraint technology approach could be interpreted as a legal statement supporting the notion of technology as a panacea for a major social or behavioral problem—that of people refusing to buckle a seatbelt.

[39]NYT, 12 July 1984, p. A18.

[40]On auto company involvement see NYT, 6 December 1983, p. 31. 25 April 1984, p. 22. 12 July 1984, p. A19.

[41]NYT, 6 June 1984, p. D25. 32 countries, 7 Canadian

January 1, 1985 the law went into effect in New York state and over the next few years other states passed similar legislation. Unlike in Canada or Australia, where the passage of such laws have contributed to long-term substantial decreases in the number and severity of injuries caused by the second collision, their effect in the United States has been more limited. This indicates that neither seatbelts, nor the law, alone or combined, contain the entire solution to the problem (if it did, US rates would resemble more closely those of other countries).[42]

Several likely reasons exist for the failure of seatbelts and MULs to save Americans, which will be explored here. One possible explanation for the law's failure to raise US usage rates to the levels seen elsewhere is that the law has often had limited enforceability. In some states (although not New York) it was a secondary enforcement law; police officers could not pull a vehicle over solely for the infraction of not wearing a seatbelt—there had to be another reason and the seatbelt would become an additional, discretionary ticket. This weakened regulation decreased the seriousness of the issue in people's minds. Although New York kept it a primary offense, it did not experience the same long-term levels of compliance as Canada, likely because the police themselves did not take enforcement of the MUL as seriously.[43]

Perhaps a bigger explanation for why MULs in the US have been less effective than elsewhere has been the lack of accompanying awareness of the need for seatbelts on the part of the US public. Compare the arguments for and against MULs in the US (especially NY state) and Canada (taking British Columbia [BC], which enacted an MUL in 1977, as the main source of data). In BC, newspaper editorials, letters to the editor and newspaper reports stressed the importance to the BC economy of passing such a law. With government-run medical insurance and motor vehicle insurance, the costs of unbelted drivers to the provincial economy became clear to most voters. For example, the BC Medical Association (Physicians) in 1976 argued that injuries cost on average $4000 a piece, and deaths $150,000 and that 115 of the 717 people who died in automobile crashes in the province the previous year would have survived had they been wearing seatbelts (thus a needless cost of $17.25 million dollars).[44] Because medical insurance came from tax revenue and vehicle insurance was run by the government (and thus considered like a tax) people could understand that taxes would go up if claims from injuries and deaths did not go down.

In the United States the costs to society were less clear for the average person than they were in BC. With hundreds of auto insurance companies and medical coverage companies to chose from in the US, and with a large population, the effect on society of the unbelted driver was less evident to the average person—although known to federal government agencies such as NHTSA and the insurance companies.

Arguments for and against the MULs given in the newspapers, by interests groups, and everyday citizens, differed between New York and BC. The argument against an MUL made frequently in the US—that the unbelted driver only endangers him- or herself—was quickly negated in the British Columbia campaign. Not only did an unbelted driver cost society, according to reporters and letters to the editor, but the unbelted driver could also lose control of the vehicle following a first collision and would be unable to avoid hitting another vehicle or pedestrian. British Columbians stressed the need to protect society in general ahead of any arguments about individual rights. Whereas in New York and the US, citizens stressed that individual rights should come before measures to protect society at large--even if society paid for the medical and vehicle losses through higher insurance rates. Fears of an Orwellian "Big Brother" government were often repeated by politicians and citizens in New York as the reason to oppose MULs.[45] Meanwhile, the state of Virginia refused to go along with the federal push for MULs on the principle that the state had a proud history of opposing the federal government—safety, monetary losses, and lives lost were subordinated to a political and cultural principle.[46]

Along with automobile companies, insurance companies became prominent proponents of MULs in the US.[47] While in general this is similar to BC where the one automobile insurance company, ICBC (the Insurance Corporation of British Columbia)[48] actively supported the

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provinces and the US territory of Puerto Rico had passed such legislation. The countries that had done so included Japan, Britain, France and the Soviet Union.

[42]While one could argue that this is because Australians or Canadians are more law abiding generally than the average American, no solid evidence exists to support this.

[43]NYT, 28 February 1985, p. B5; A police Chief named Margeson is quoted as saying only a few tickets in his jurisdiction had been issued, that "It's not a priority."

[44]Vancouver Province, 9 April 1976, p. 33.

[45]NYT, 12 October 1984, p. C1. That this debate happened in 1984 contributed to Orwellian interpretations.

[46]NYT, 28 February 1985, p. B5.

[47]NYT, 25 June 1983, p. 8.

[48]All motorists in the province must insure their vehicles

concept of an MUL, there is also a substantial qualitative difference. Whatever else British Columbians felt about ICBC, they could recognize it as an exclusively BC entity, designed to serve residents of the province. American insurance companies generally transcend state and regional boundaries, and Americans may not have seen them as having local and community interests foremost in their minds (ahead of their own financial statements). Thus, many citizens may have written off MULs as the imposition of a powerful insurance lobby in Washington DC and the state capitals, and not something as emerging from society.

In British Columbia the MUL did not result from federal government initiative, but from Provincial concerns and studies, and citizen interest. In 1975 ICBC sponsored a safety conference that examined the impressive results in the Australian state of Victoria (20 percent decline in fatalities and a 50 percent decline in hospital admissions from car accident injuries[49]) and the need for reducing government pay outs to injured individuals through government-run medical insurance and car insurance.[50] Citizens came to support the idea of an MUL and even push politicians who acquired cold feet, concerned about public reaction to a perception of an imposition on civil liberties.[51] Politicians debated the MUL for two years before finally passing the legislation.

This political waffling ironically may have made the laws more popular as people were able to fault the government for inaction on a proposal that would save lives and money.[52] Of course some people opposed the concept of legislating seatbelt use, but the majority seemed to accept its necessity as everyone paid for the costs of injuries and fatalities.[53] Education also played a large role in fomenting public support in British Columbia. In BC the MUL was combined with an intense education campaign—before and after the passage of the law—in the schools, at fairs, and in the media stressing why one should wear a belt.[54]

When the BC MUL finally passed in 1977 (with only one legislator opposing the bill[55]), approximately 65 percent of citizens supported it. It went into effect on October 1, 1977 and statistics (73 percent usage in the Vancouver and Victoria areas in March 1978) suggest that the majority of those who opposed it, wore their belts anyway. Prior to the MUL, only 28 percent in these areas used safety belts.[56] (By contrast in the United States in 1978 metropolitan-area usage was 14 percent).[57]

To contrast these facts with those from New York reveals striking differences. Governor Cuomo of New York approximated that during the time the state legislature debated the MUL, correspondence received from state residents was about "18,000-to-1 against."[58] Moreover, politicians in New York and other states were far from unanimous in their votes for the law. Most laws that did

through ICBC, a government-owned and regulated company, created in 1972.

[49]Vancouver Province, 26 March 1975, p 8.

[50]Vancouver Sun, 24 January 1976, p. 5 and 12 March 1976, p. 5. Vancouver Province, 26 March 1975, p 8.

[51]Vancouver Province, 29 October 1975, p. 4 an editorial notes that the highways minister said that any government with guts should pass a seat belt law, and that he supported one, but that the public should expect him or his government to initiate such a law. New Democratic Party (a semi-socialist party) Premier Dave Barrett echoed these remarks in the Vancouver Sun, 19 November 1975, p. 53.

[52]Vancouver Sun, 12 April 1975, p. 43 and 24 January 1976, p. 5.; Vancouver Province 21 June 1975, p. 5;

[53]Examples of opposition in letters to the editor in the Vancouver Sun , such as 20 September 1975, p. 5. Article stating that the majority polled favored the law in Vancouver Sun, 21 October 1975, p. 15.

[54]Advertisements promoting the MUL included instructions on how to wear a seatbelt and why one should wear one. For example, see Vancouver Sun, 24 September 1977, p. 27. ICBC also toured the Seat Belt Convincer, a seat mounted on a ramp that people could sit in, belted in. An attendant would pull a trigger sending the seat sliding down a 12 foot incline, coming to an abrupt stop at 9.6 km/h, producing a jolt sufficient to demonstrate the utility of the seatbelt; The Colonist (Victoria BC), 19 November 1977, p. 11.

[55]Vancouver Sun 26 March 1977, p. 16. By contrast when the state of Washington passed seat-belt legislation nearly a decade later, the vote was 33 to 15. Vancouver Sun, 8 March 1986.

[56]Vancouver Sun, 9 January 1978, p. A12. Vancouver Sun, 13 May 1978, p. A8. Within a year, these numbers dropped significantly , to only approximately 55 percent of drivers buckling up by December 1980. The Colonist (Victoria BC), 19 December 1980, p. 6. Subsequent studies following the implementation of MULs elsewhere in Canada reveal a pattern of high initial compliance, followed by a lessening of usage rates.

[57]NYT, 17 December 1978, p. 34.

[58]NYT, 1 February 1985, p. B2.

pass, did so with a bare majority.[59] The one similarity between New York and BC was that, at least initially after the MUL went into effect, the majority of people (over 70 percent) buckled up regardless of their opinion of the law.[60] Subsequently, in both places rates dropped (to 40 percent in NY after just three months, and in BC it gradually fell to a low of 55 percent over the next few years).[61] But since that time BC's rate has steadily increased reaching near 90 percent while that of NY has grown much more slowly.

This BC increase happened because of direct interventions on the part of ICBC. Following the decline to 55 percent, ICBC established its Traffic Safety Division with a mandate to promote seatbelt usage and other safer driving behaviors. ICBC created a three pronged approach to safety initiatives that has proven successful on many campaigns to this day. The first prong is police involvement through road checks and other enforcement programs (known as STEP—Selective Traffic Enforcement Program). The second aspect is a corresponding education campaign on radio and in newspapers (and more recently, television) that promotes the reason for the initiative and informs people that the police are actively looking for violators. The third prong involves making use of local traffic safety committees (usually comprised of representatives from town government, educational institutions, related businesses, and citizens groups) to promote the initiative locally through such means as fairs, contests, or banners in key locations; this last aspect gave communities partial "ownership" of the problem and the solution process. This approach was first used successfully to reduce drinking and driving (and the program remains in place today, providing consistent and sustained pressure).

In 1983 ICBC applied the approach to achieve compliance with the seatbelt MUL, and by maintaining the program through the years has helped bring the steady increase in seatbelt usage rates. In British Columbia these campaigns have included a particular focus on children and youth, with remarkable success.[62] At a time in their lives when they are supposed to be risk-takers, BC's youth has a high rate of seatbelt usage (and also thanks to these education programs, the lowest rate of drinking-and-driving incidents).[63] Given the contrast with the US, BC's long-term commitment to road-safety education has likely played a significant role in reaching a 90th percentile usage rate.

In the US some efforts at education occurred at the federal and state levels, but the quality and commitment appears to have been much lower.[64] In New York, legislators intended that the law itself would be the educator (and not an intimidator). But without accompanying education, people viewed the law as a nuisance, and not a real reason to buckle up.[65] Indeed, through the 1980s a large percentage of Americans continued to believe that it is better to be thrown free of the vehicle in an accident.[66] All of this suggests a need for increased educational efforts.

Overall, the contrast in US and Canadian MUL experience demonstrates the necessity of public involvement in creating the legislation whether directly through lobbying or indirectly through interacting with education programs or media reports that convince people of the need for a new regulation or a certain behavior. Having a comprehensive, multi-faceted education program in place before, during, and after the discussion of the MUL, contributed to favorable public interest in seatbelts

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[59]In New York in the lower house it was 82-60, only 6 votes more than the needed number for passage NYT, 22 June 1984, p. B3. In the NY senate the vote was 37 to 22 (NYT, 26 June 1984).

[60]NYT, 1 February 1985, p. B2.

[61]NYT, 9 May 1985, p. A13.

[62]All regions have seen a gradual increase in seatbelt usage as the population has aged. Moreover, younger generations have generally had higher usage rates than older ones. This suggests that those most opposed and most unaccustomed to wearing belts are gradually dying off (mostly of old age, but also in car accidents) or leaving the driving population, thereby increasing the percentage of people wearing seatbelts through natural aging of the population. Furthermore, psychologists have identified that people become more cautious as they enter their 30s and 40s, or have children. The US baby boomer population themselves, by moving into this more conservative age group helped to raise usage rates. These generational factors alone do not, however, account for the increased rate of usage into the 90 percentile range in Australia and Canada.

[63]Canadian Medical Association Journal 157, no. 12, 15 December 1997, pp. 1661-1662.

[64]Whether this is due to the nature of the education campaigns or the amount of money spent on them is not known but is a question worthy of study.

[65]NYT, 28 February 1985, p. B5, shows examples of these opinions.

[66]NYT 26 September 1984, p. C1. This report on education declared it a failure as fewer than 15 percent of Americans wear seat belts. This article also reported the persistence of a myth that it is better to be thrown free of a vehicle during an accident.

usage. Yet BC has some preconditions that New York does not. In Canada there has generally been a culture of accepting government regulation and direction and being angry when the government is not perceived as protecting its citizens. Moreover, with government-run medical and vehicle insurance, it was much easier for British Columbians to understand the cost to them personally of a society that does not buckle up.[67]

The Fifth Attempt: Airbags Revisited, 1990s

With US MULs still failing to reduce second collision casualties sufficiently, the US government returned to airbags and passive restraints in the 1990s. All passenger cars produced today for the US market must have airbags (in addition to seatbelts and buzzers, and MULs in most states). Yet, airbags are not as neat and simple a solution as seatbelts when the latter are used. Airbags only inflate once, are useless the occupants during any subsequent collisions or roll-overs, and cannot help them in incidents that do not involve a front-end collision. Used in conjunction with seatbelts, airbags provide approximately 5 percent more protection in frontal crashes. Yet they also have inherent dangers.

Until 1998 airbags exploded at such a high velocity as to be potentially dangerous. The airbag was designed to prevent serious injury to an unbelted 50th percentile male crashing at 50 kilometers and hour; but the power required to do this has proved deadly to smaller occupants (especially women and children). Making them mandatory on all vehicles meant that those people willing to wear belts faced unnecessary dangers. Because the majority of Americans did not buckle up, law makers and engineers began opting for a technology that was not necessarily more effective than a properly buckled three-point harness in a frontal collision.

This illustrates an industrial, one-size-fits-all mentality. No discussion has emerged until this past year of offering different types of technologies to suit individual needs (and still meet a federal occupant protection criteria). Recent Canadian regulators have demanded that airbags on vehicles destined for Canada be depowered (because the majority of Canadians wear their belts and do not require such a powerful bang for adequate supplementary restraint)—a first step toward a more flexible view of safety technology.[68] Law makers and manufacturers in the US seem unwilling to acknowledge that safety might require a more flexible approach than the industrial paradigm. Solving the problem of occupant restraint may require acknowledging this human factor--everyone is not created equal nor uses safety technology in the same way. (As GM safety engineer Paul Skeels said in 1966, designing an automobile interior for safety would be different for a belted versus an unbelted occupant.[69])

CONCLUSIONS

The Problem Persists

Although US efforts to protect people from the second collision have been less successful than those in other places, there have been some gains. US Injury and fatality rates did begin to fall in the 1980s, for the first time in history.[70] Recent surveys undertaken by NHTSA as part of President Clinton's new seatbelt usage drive suggest that over half of Americans favor a primary enforcement MUL. Although this same survey suggests that, at best, 66 percent of Americans buckle up every time they enter a vehicle, it also indicates that more people are starting to recognize the importance of seatbelt use.[71]

The history of the interaction of seatbelt technology with the US public suggests that there are large obstacles for society and safety advocates to overcome in order to see widespread usage and a resolution to the problem of preventing second collision injuries so long desired. Efforts at improving safety have often created greater resentment toward seatbelts and government safety measures among large sectors of US society. Negative memories of seatbelts and government intervention can be passed to the next generation, and continued low usage rates suggests

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[67]Canadian settlers followed the Mounted Police and the Hudson's Bay Company—the government--, while in the US the procedure was the reverse.

[68]Financial Post Daily, 14 November 1997, p. 30 and Canadian Press Newswire, 1 November 1996.

[69]Business Week, 11 June 1966, p. 184.

[70]NYT, 5 February 1984, p. 22. In 1983 43,028 people were killed on US highways, the lowest level in 20 years according to Transportation Secretary Elizabeth Dole, or 2.6 deaths per 100 million vehicle miles—the lowest level ever recorded. She attributed the drop to seatbelt use and anti-drinking-and-driving campaigns. In 1980 the death rate had reached 51,091.

[71]From the NHTSA website (http://www.nhtsa.dot.gov/people/injury/buckleplan/presbelt2/). This is inferred from the fact that 76 percent of drivers said they wear a seatbelt "all the time" when driving but over 10 percent of this group also stated that at least once in the previous week they had not worn the belt. That they lied suggests they know that they should be wearing it.

that they have been. Seatbelt education at the elementary school level might be necessary to counter parental influence. Ultimately to improve US usage, road safety promoters need to understand the failures and design programs with these in mind. The solution will likely be one that brings everyday citizens into the process and that allows them to understand the need for belts. Sustained, region-based education and enforcement programs, perhaps based on the BC model (but adapted to local, US conditions) is one possible way to take control of the situation, rather than waiting for a technological solution.

This exploration of seatbelts and airbags demonstrates that technology alone can not solve problems. Further experiments with technology are not the answers to the US problem of excessive injuries and deaths caused by second collision injuries. Through this comparative-regional methodology this paper illustrates the problem in fact rests with the political, cultural, and historical context of that technology. This paper also shows that the failure to address the cultural and political context of seatbelt technology in the US has resulted in five unsuccessful and different attempts to decrease the severity of second collisions through government legislation and additional technology (but without much public or community involvement).[72] Each attempt has been complicated by, and has further exacerbated, the culture and politics of seatbelt usage.

Comments on the methodologies

Road safety concerns have been with society since the onset of the automotive era. The issue of traffic safety generally, like that of occupant protection specifically, has a complex history and one that has not developed in isolation from the people that use it.

One way to understand what has helped to prevent deaths and injuries on the road (and why) or what did not help significantly (and why not) requires analyzing the situation in such a way as to establish variables and constants. Because history cannot be repeated in a lab, "virtual" variables and constants can be established through comparisons and contrasts with other regions that had the same problems, but achieved different outcomes from interventions. That is what we have done here. One of our constants is the MUL, while the multiple variables include: the BC combination of community involvement, police action, and sustained education on the issue of seatbelt wearing; the US style of federally-led usage initiatives; and the contrast in the initial conditions in each place such as cultural attitudes toward government regulation and the economic context of socialized medical and vehicle insurance.[73] With so many variables, determining the crucial ones is not an exact science, but it is one of the best means available to understand the social mechanisms involved.

Another way to understand the reasons for success and failure is to compare one historical era with another (put another way, through historical reflection). We compared attitudes toward technology in the 1960s and 1970s with more present day perspectives, and noticed the extent to which politicians, manufacturers, and the public considered technology as a panacea—and the more, the better.

ACKNOWLEDGMENTS

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[72]By contrast BC went from the first attempt (seatbelts in all vehicles) to the forth (MULs), without the steps in between.

[73]A good analysis of comparative methodology can be found in Theda Skocpol and Margaret Somers, "The Uses of Comparative History in Macrosocial Inquiry," Comparative Studies in Society and History 22 (1980): 174-195.

SEAT-BELT INJURIES IN MEDICAL AND STATISTICAL PERSPECTIVES

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I. ABSTRACT

This paper reviews many findings from the medical literature regarding injuries to belt restrained adult occupants of motor vehicles. The review is limited to a subset of that literature in which restraint system contact forces were associated with the injury. Thus, injuries caused solely by internal loadings or by contacts with objects other than the lap or lap/shoulder restraint systems were generally excluded. Head and extremity injuries are therefore not discussed for either lap-only or lap-shoulder belt systems, nor are thoracic injuries considered for lap belt only systems. The injury rates seen in a recent decade of FARS (Fatality Analysis Reporting System) data for front outboard occupants of fatal frontal crashes are noted for comparison.

II. INTRODUCTION - HISTORICAL REVIEW OF OCCUPANT PROTECTION SYSTEMS

Motor vehicle accidents have grown to be a major cause of death and injury since the first known crash-related occupant fatality occurred in 1895. Fortunately, statistics indicate that the death rate in terms of fatalities per 100 million vehicle miles traveled has declined from a peak of 24.1 in 1921 to the present 1.7 (NHTSA, NCSA, 1997). The recent steady reduction in the fatality rate has been the result of a combination of a variety of factors including vehicle crash safety, engineering developments, and improved roadway design among others. Unquestionably, the most important motor vehicle crash safety innovation which contributed to that reduction has been the installation and proper use of seat belts.

The aircraft type lap belt was first incorporated into passenger car design by the Nash-Kelvinator Corporation in September 1949 with the introduction of the reclining front seat, but these belts were not widely used (Johannessen, 1984). The safety benefit afforded to users of these aircraft-type seat belts was confirmed by the Cornell Aeronautical Laboratories report issued in 1953 (Automotive Engineering, 1996). The American Medical Association was so convinced of the injury/death reduction potentials that in 1954 the Association voted to support the installation of lap belts in all automobiles (Consumer Reports, 1998). Ford Motor Company introduced the lifeguard safety package with its 1956 models which offered front and rear lap belts (Automotive Engineering, 1996). Chrysler Corporation also included lap belts as an option on some models in 1955 (Automotive Engineering, 1996; Chrysler Corporation, 1955). Chevrolet introduced the first lap/shoulder safety belts in 1957 (Automotive Engineering, 1996). Most U.S. automobile manufacturers provided lap belts as standard equipment at the front outboard seating positions in 1964 (Johannessen, 1984), and at the rear outboard seating positions for the 1968 model year (FHWA, 1967).

By 1/1/68, Federal Motor Vehicle Safety Standard 208 required lap and shoulder belts on all U. S. passenger cars. In 1974, a lap/shoulder seat belt (with non-detachable shoulder strap) in its basic form was required in all front outboard seating positions. Unfortunately, usage of belt systems remained quite low in the U. S. until the mid-1980's (NHTSA, 1998; Warner, 1997).

Passenger car restraint systems continued to evolve, with the phase-in of automatic occupant protection for front seat occupants in the form of either: (1) automatic seat belts, or (2) the combination of airbags and manual lap/shoulder belts beginning with the 1987 model year, and the installation of lap/shoulder belts for outboard rear seat occupants in cars manufactured on or after December 11, 1989 (NHTSA, 1984; 1989).

III. THE PERSPECTIVE ON THE MEDICAL LITERATURE OF BELT RELATED INJURIES.

Although few papers provide any reliable estimates of crash severity, many of the belt related injuries described in the medical literature surely have occurred in very severe crashes. They cannot be rationally related to any quantification of accident severity; neither can the information provided be used for inferences for overall injury rate or for estimates of belt effectiveness.

A useful source of information on belt effectiveness and injury rate in severe crashes in the United States is present in FARS, a census of almost every fatal crash in the United States since 1975, drawn from state police and death records. Although no quantitative severity information is presented, the FARS census is certainly representative of crashes within the upper levels of crash severity. The FARS census of front outboard occupants in severe fatal frontal crashes (initial force direction 11, 12 and 1 o'clock) was examined for the decade beginning in 1986, when U. S. mandatory belt use laws began to take effect and usage rates began to increase sharply in the U. S. (Warner, 1997).

During those ten years of FARS, over 270,000 occupants of fatal crashes were coded to have been unrestrained, lap-only or lap/shoulder belted, and restrained but type of "restraint unknown". The "restraint unknown", "child restraint" cases, and "unknown if restrained" cases are omitted from Table 1, which classifies the remaining cases as to fatal injury rates.

	Occupants	"K" Injury	"K" Injury Rate, %
"Unrestrained"	129,327	70,553	54.6%
"Lap/Only"	4,617	1,117	24.2%
"Lap/Shoulder"	81,461	20,561	25.2%
Total	215,405	92,231	42.8%

Table 1. Injury Rates vs. Coded Restraint Type FARS 1986-1995 Front Outboard Seat Occupants in Severe Frontal Crashes

Belt usage estimates for all occupants in the U. S. averaged about 40% over that decade. Fatal injury rates to belt users averaged about 25% in these severe crashes, regardless of the belt system used. The data leads to two important findings relating to these very severe frontal crashes. First, restraint usage is definitely helpful in prevention of fatalities and many severe injuries, even at the higher end of crash severity. Secondly, at these high severity levels lap-only and lap/shoulder belts appear to offer about the same level of injury reduction to front outboard occupants; distinctions in fatal injury rates between lap-only and lap/shoulder belts are not apparent at the severity levels represented by the FARS census data.

This finding of about the same injury rate to lap only and lap-shoulder belted outboard occupants of FARS frontal crashes has also been seen to be true for rear outboard seating positions (Warner, 1997; Padmanaban, 1998). This result is surprising when viewed against the background of conventional wisdom and many studies which have provided estimates of restraint system effectiveness. It should be kept in mind that like many of the severe injuries described in the following sections, the FARS data generally represent the higher end of the crash severity spectrum. The performance advantages of lap and lap-shoulder belts when used properly are unquestionable for low and moderate crash severities, and in many examples of severe crashes. Clearly, extreme impact distributions and structural intrusions are involved in many fatal frontal crashes, rendering any restraint system less effective.

The protective benefit afforded to users of all types of occupant restraint systems is well known and has been extensively documented. Several general injury reduction principles can be identified with restraint system design. Belt systems are expected to: (1) limit or mitigate to the extent practicable occupant interior contacts, (2) prevent occupant ejection, (3) extend the deceleration force distance of a collision by coupling the occupant with the crush characteristics of the vehicle (4) apply crash forces to the anatomically strongest portions of the human anatomy, and (5) be convenient and comfortable for the user.

Restraint system performance is often criticized by a perceived "failure" to prevent injuries under all accident circumstances and severities. As with any other form of technology, advancements or improvements are all too often prospectively lauded at the expense of earlier designs which were of value but were replaced by systems which held promise of greater benefit. Nowhere has this become more obvious than in the area of restraint system design. A recent example is demonstrative. In 1977, it was claimed that the implementation of driver airbag systems alone would save 96,000 lives per decade using a nominal projection (NHTSA, 1977). That estimate was incorrect by a large factor. In actuality, only approximately 1,700 lives have been saved in the decade 1986-1996 (NHTSA, 1997).

As belt system usage increased, terms like "seat-belt injuries" have come into wide circulation in the medical literature. This review examines many case reports which compare the types of injuries reduced by use of belt systems versus those injuries "caused" by the various belt systems used. The reader should be aware that, in general, the injuries in such studies arise from accidents in the higher severity range, and in some cases from improper seat belt use. The instances of no or minor injury consequences sustained by occupants using identical restraints systems in similar crashes are usually not reported. Further, the patients which comprise the majority of these "seat belt injury" reports in all probability, would have suffered serious or perhaps fatal injury if they had not been wearing seat belts. It is often forgotten that seat belts per se are not hazardous. Further, the issue of "causation" of certain types of injuries is the consequence of a variety of additional factors that can not be related to a specific type of restraint system to the exclusion of all others.

A proper engineering approach to injury analysis includes many physical and biomechanical factors influencing restraint system/occupant injury performance. It is difficult to assess the importance of these factors in the absence of an in-depth investigation of many crash factors not available to most medical authors. Among these are vehicle factors relating to crash severity and engineering factors such as seat design (geometry, structure, seat and interior trim). Other aspects of restraint performance include restraint design features such as anchorage geometry, webbing areas, webbing material elongation, force limiting energy absorbing devices, retractor behavior, and pretensioners. Also important are factors of occupant anatomy and crash tolerance such as stature, weight, age, gender, obesity and pre-existing health conditions. Further, usage variables can be pivotal to successful belt performance: anatomical positioning, pre-impact position, and belt slack being very important.

In contrast to a multi-disciplinary approach which could possibly discern many of these factors, most medical articles in this area simply contain assessments of the medical condition of patients seen in hospital emergency rooms with little or no information regarding the crash severity, the vehicle, and its restraint. While these reports are potentially of great value to a physician who may attempt to treat a similar injury in other cases, they offer little useful information to one who is interested in restraint effectiveness evaluation or design.

Seat belts (or any of many other injury reduction devices taken singly or together) do not constitute a panacea for all crash injuries. Used properly, they are a highly valuable and essential contribution to injury reduction. However, the fact that certain injuries are associated with each kind of restraint system in severe crashes must be kept in the context of the multiple injuries they help us to avoid.

IV. "INJURY TYPES" AND RESTRAINT SYSTEM DESIGNS

Since the first use of the term "seat belt syndrome" (Garrett, 1962), it has been employed extensively to describe those injuries associated with the restraining effect of both lap and lap/shoulder restraint systems (Asbun, 1990; Bibliography No. 62). Generally, those injuries are claimed to be the result of decelerative forces being directed through the restraint system webbing to the underlying anatomical structures (Pansky, 1984). The reviewed medical bibliography does not purport to be all-inclusive, comprising each and every publication on these injury types. Rather, it is meant, rather to provide a starting point from which more exhaustive research can commence for those interested in these injuries.

Injuries of various types are frequently associated with a particular type of restraint system. Lap belts have been variously reported as being the "cause" of lumbar spine fractures and various abdominal injuries. As will be seen, many of the cases reported as "lap belt injuries" come from medical case histories from the 1960's and 1970's.

Careful review of the papers indicates that similar injuries to these body regions have been documented in occupants using lap and occupants using lap/shoulder belt systems, again without controlling for accident severity. The literature reviewed is readily divided regarding injured skeletal and soft tissue systems as shown in figures 1 and 2 (Pansky, 1984; Pike, 1990):

- cervical spine/neck
- thoracic spine
- lumbar spine
- thorax and contents
- abdomen contents

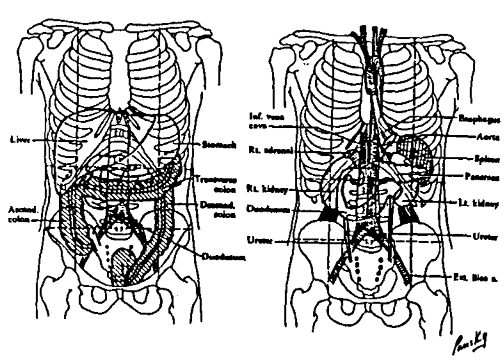

Figure 1. Topography of Abdomen and Thorax

(Pansky, 1984)

Table 2 identifies the specific citations for each region. Figure 3 (adapted from NHTSA, 1992) demonstrates the frequency distribution by region of numbers of citations reviewed. Table 3 gives a summary of reviewed citations regarding the 5 areas.

The authors were surprised to note that there were a greater number of citations relating to lap/shoulder belts than to lap belts in every anatomical region but one. Early citations were understandably linked predominantly to lap-belt-related injuries. These have been mistakenly cited out of context in some litigation situations as proof that addition of a shoulder belt would have prevented a specific injury. As is seen, this is not generally the case.

Some of the occupant injuries are reported as consequential injuries, resulting from contacts with the interior of the vehicle or other objects (Bibliography Nos. 18, 24, 33, 46, 52, 60,120, 128,129 refer to lap belt related cervical spine injuries among others). These are beyond the scope of this study.

V. DISCUSSION:

Perusal of the literature cited above provides a perspective on belt-related injuries in severe frontal crashes. The lumbar spinal and abdominal injuries often identified with lap belt forces applied above the bony pelvis are severe and often catastrophic. However, they are neither unique to the lap belt nor more severe than cervical spinal and carotid artery injuries which may result from lap/shoulder belt forces in other severe exposures.

It is clear that injuries will continue to occur in severe crashes, and that some of them will result from loadings which occur during contact with restraint systems which have been designed and proven to save lives and prevent injuries over the broad spectrum of crash severities.

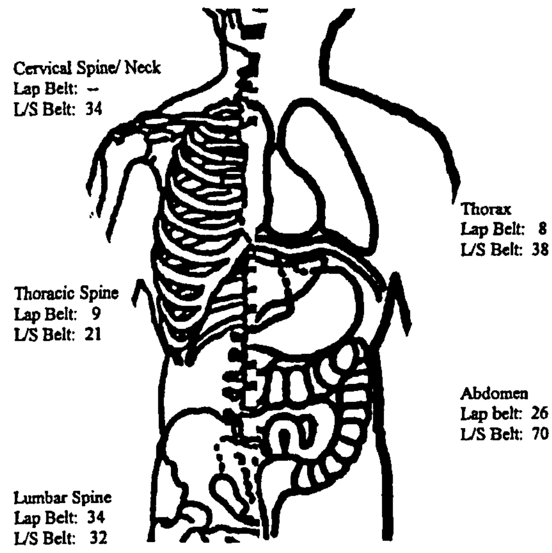

Figure 3 (NHTSA,1992). Frequency of Injury Citations by Type of Restraint

	Lap Belt	Lap/ Shoulder Belt	Not Specified or Other Belt
C-Spine/Neck	...	34	7
T-Spine	9	21	0
L-Spine	34	32	3
Thorax	8	38	4
Abdomen	26	70	17

Table 3. Summary of Injury Citations by Type of Restraint and Body Region

One is well advised to remember the overwhelming benefits of belt restraints in injury avoidance and mitigation while researching those relatively few cases in which injuries relating to restraint loadings, which result from the high forces generated in high-severity crashes.

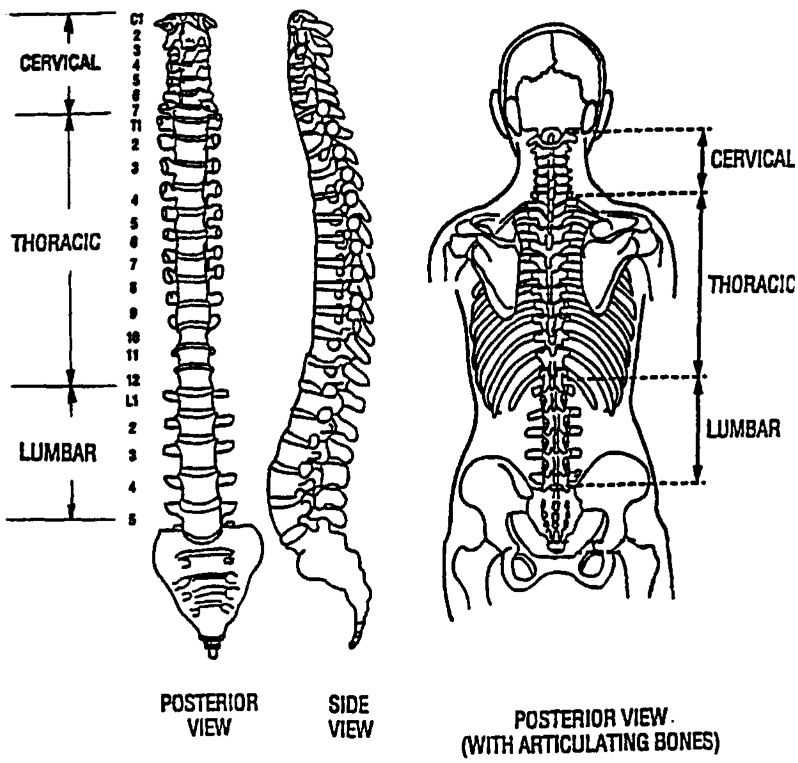

Figure 2. The Spine (Pike, 1990)

Body Region	Lap Belt Only	Lap/Shoulder Belt	Not Specified or Other Belt
C-Spine & Neck	0	12, 13, 18, 19, 24, 30, 32, 34, 35, 37, 39, 40, 41, 45, 46, 48, 52, 53, 60, 71, 86, 87, 89, 96, 116, 117, 118, 121-23, 126, 128, 129	34, 35, 46, 61, 85, 88, 127
T-Spine	18, 20, 24, 33, 38, 52, 120, 128, 129	6, 13, 18, 22, 24, 30, 39, 40, 48, 52, 63, 109, 116, 117, 118, 121-23, 126, 128, 129,	0
L-Spine	1, 3, 14, 18, 20, 22, 24, 29, 33, 38, 51, 52, 55, 69, 94, 96, 100, 101, 102, 103, 104, 105, 106, 107, 108, 110, 113, 114, 115, 119, 120, 124, 128, 129	1, 6, 14, 16, 17, 18, 20, 22, 24, 27, 29, 33, 38, 39, 40, 51, 52, 57, 63, 65, 69, 109, 116, 117, 118, 119, 121-23, 126, 128, 129	33, 125, 127
Thorax	24, 33, 52, 60, 100, 120, 128, 129	8, 11, 23, 24, 31, 32, 33, 39, 40, 44, 52, 54, 56, 57, 58, 60, 65, 69, 70, 71, 74, 78, 84, 90, 91, 96, 99, 111, 112, 116, 117, 118, 121-23, 126, 127, 132	9, 10, 33, 44
Abdomen	1, 3, 7, 14, 18, 20, 22, 24, 26, 29, 38, 47, 52, 55, 60, 69, 75, 97, 98, 114, 119, 120, 124, 128, 129	1, 2, 3, 4, 7, 8, 14, 15, 16, 17, 18, 20, 21, 22, 24, 25, 26, 27, 28, 29, 31, 33, 36, 37, 38, 39, 40, 42, 43, 44, 47, 48, 49, 50, 52, 55, 56, 57, 58, 59, 60, 62, 64-70, 72, 73, 75, 76, 81, 82, 91, 92, 111, 116, 117, 118, 119, 121-23, 127, 128, 129, 131	5, 9, 10, 33, 43, 44, 62, 73, 75, 77, 79, 80, 83, 92, 95, 125, 127

Table 2. Injury Citations by Type of Restraint and Body Region

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A VIRTUALLY EXACT CALCULATION OF SAFETY BELT EFFECTIVENESS

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ABSTRACT

A number of analysts have attempted to determine the effectiveness of passenger vehicle safety belts over the past 25 years. One of the more widely used is the double pair comparison (DPC) method. This note looks at the larger picture of motor vehicle crash data to show the limitations of DPC and to present a more general method. The author organizes crash data according to whether occupants were restrained or not, whether their crashes were potentially survivable only with belt use, and whether the occupants were actually killed. Based on this model, the author develops a virtually exact means of calculating restraint use and effectiveness in preventing fatalities. Calculations using data from the Fatal Accident Reporting System (FARS) show that safety belts may be more effective in preventing fatalities than previously thought. However, part of the reason for the higher calculated effectiveness is that belt use appears to be over reported in FARS. Finally, the author discusses the origin of uncertainties and errors in the results, and shows how the data can be adjusted to give more reasonable results.

INTRODUCTION

A number of analysts have attempted to determine the effectiveness of passenger car occupant restraints such as safety belts. One of the more widely used is the double pair comparison (DPC) method. It was developed and used primarily by Evans (1986) although he gives credit to Park (1984) for its original conception.

This paper takes a new look at accident data to illustrate how we can learn more from it. To do so, we develop a more sophisticated formalism and provide results for passenger car and light truck occupants. The technique permits exploring the effect of correcting data to account for misreporting belt use. This technique may have applicability to other epidemiologic problems.

The Universe of Crashes

Let us imagine that we have perfect knowledge of all crashes involving light motor vehicles that occur in the U.S. each year. Our unit is a passenger car, light truck, or van involved in a crash.

Figure 1 (see next page) shows a classification of those vehicles according whether a driver, a right front passenger, or both were killed, whether one or both would have survived only if they had been restrained, and whether either or both were actually wearing a seat belt. Columns in this figure, which define driver characteristics, are identified by capital letters and rows – passenger characteristics – by Roman numerals. Specific cells contain the number of vehicles in which there were an actual or potential driver or passenger fatality, or both (as indicated by the headings). Cells are identified by a capital letter indicating the column with a subscript identifying the row: E_{IV}, for example.

We have only limited knowledge of the potential consequences of accidents. We can uniquely identify the cases in only four of the cells of the resulting matrix: those in which both restrained occupants were killed (F_{VI}), those where a restrained driver was killed and there was no right front passenger (F_{VII}), and those in which a restrained occupant was killed and an unrestrained occupant survived (A_{VI} and F_I).

Effectiveness of Occupant Restraints

The traditional definition of effectiveness is:

$$E = \left(1 - \frac{R_t}{R_u}\right) \times 100\% \qquad (1)$$

Where: R_t = rate of loss or injury for the treated population, and

R_u = rate of loss or injury for the untreated population.

This applies to a situation where we measure a characteristic (driver crash fatality rates, for example) in two randomly parts of a population, one of which is treated and one is not. In an ideal experiment, the population would be randomly selected, all other factors would be equivalent, and there would be no confounding issues.

			all drivers who survived			all drivers who were killed			
			survivable		survivable if restrained		not survivable		
			unrestraind	restrained		unrestrained		restrained	i =
right front passengers who survived	survivable	unrestrained	no driver or right front seat passenger fatalities			D_I	E_I	F_I	I
		restrained				D_{II}	E_{II}	F_{II}	II
	survivable if restrained	restrained				D_{III}	E_{III}	F_{III}	III
right front passengers who were killed		unrestrained	A_{IV}	B_{IV}	C_{IV}	D_{IV}	E_{IV}	F_{IV}	IV
	not survivable	unrestrained	A_V	B_V	C_V	D_V	E_V	F_V	V
		restrained	A_{VI}	B_{VI}	C_{VI}	D_{VI}	E_{VI}	F_{VI}	VI
no right front passenger			no driver fatalities			D_{VII}	E_{VII}	F_{VII}	VII
			A	B	C	D	E	F	

Figure 1. A taxonomy of passenger car crashes.

With vehicle crashes, we cannot conduct an experiment in this fashion. We are only passive and imperfect observers of what happens on the road. We don't have two randomly selected groups with only one wearing restraints. Rather, the treated population is the group that chooses to wear restraints while the untreated do not. Thus, we must have a more pragmatic definition of effectiveness.

Within the universe of crashes that occur, considering what happens to drivers only, crashes can be classified according to severity and restraint performance in the following classes:

1. Crashes in which restraint use has no effect because an occupant would survive in any case (i.e. a fender-bender that an unrestrained person would survive as would a restrained person). These are not included in the rates, R_r and R_u, used in determining effectiveness because a restraint system could have no actual or potential effect on the outcome of any of these crashes. In Figure 1, these crashes are in column A for unrestrained drivers and in column B for restrained drivers.

2. Crashes in which restraint use makes the difference between death and survival (i.e. a serious crash that an occupant would survive *only* if restrained). These are important because they are the cases where this particular restraint system actually makes a difference. These crashes are in column C for restrained drivers (who survive as a consequence of using restraints) and column D (unrestrained drivers who are killed).

3. Crashes that are so severe that a driver would not survive even using this restraint. Some restraint system might have been effective here, but this one (safety belts) was not. If we had a 100 percent effective restraint system, there would be no crashes in this class. Here, column E in Figure 1 contains the unrestrained drivers (who are killed), and F those who are restrained (and are also killed despite the restraint).

Looking at crashes this way also points up the fact that restraint effectiveness and use determines how crashes are distributed in Figure 1. That is, if a restraint system is more effective, the result will be that some of the crashes that would have been in column E or F move to column D or C, respectively, in this figure. The spectrum of crashes, by severity, appears to be different for belted drivers than for unbelted drivers. This suggests that belted drivers may be involved in fewer severe crashes. (If the way in which crashes are distributed and characterized in this paper is still mysterious, see Appendix A for a more detailed discussion.)

Using the nomenclature of Figure 1 in equation 1 (that is, A is the sum of all cases in which an unrestrained driver survived), we define the effectiveness of this restraint system as:

$$E = \left(1 - \frac{\frac{E+F}{A+B+C+D+E+F}}{\frac{C+D+E+F}{A+B+C+D+E+F}} \right) \times 100\%$$

$$= \left(1 - \frac{E+F}{C+D+E+F} \right) \times 100\% \qquad (2)$$

$$= \left(\frac{C+D}{C+D+E+F} \right) \times 100\%$$

In other words, if all drivers had been restrained (treated), only those in columns C and D would have survived, while if none had been restrained, all drivers in columns C, D, E, and F would have died. See Appendix B for a discussion of this equation.

Let us define the ratio of restrained to unrestrained occupants within the two most serious classes of crashes: $\alpha = F/E$, and $\beta = C/D$. We can now write equation 2:

$$E = \left(1 - \frac{(1+\alpha)E}{(1+\beta)D + (1+\alpha)E} \right) \times 100\% \qquad (3)$$

If $\alpha = \beta$ we get:

$$E = \left(1 - \frac{K_B \times \frac{D_U}{D_B}}{(K_U)} \right) \times 100\% \qquad (4)$$

where K is killed drivers, D is total drivers, and the subscripts indicate belt use: B = belted, U = unbelted.

This equation is essentially the double pair comparison (DPC) method. The DPC restraint use ratio is taken from restraint use in a subset of crashes that killed the right front passenger all of whom had the same restraint status. Within that stratum, this ratio is the sum of A, D, and E divided by the sum of B, C, and F as defined above. This is approximate both because it depends on the equality of α and β, and because it does not use all of the available data included in equation 2 (see Appendix C).

Limitations of Input Data and Other Problems

The data generally used for estimating fatality-prevention effectiveness of safety belts comes from the Fatal Accident Reporting System (FARS). FARS provides a file of all fatal motor vehicle crashes on U.S. public roads. It is based primarily on police accident reports. Within Figure 1, solid lines enclose groups of crashes that can be differentiated using information in FARS. Figure 2 (below) which is in the same format at Figure 1, shows the data as it is available in FARS. Note that in this figure, the data in column K is equivalent to the data in column A of Figure 1, the data in column L is equivalent to the sum of the data in columns B and C in Figure 1, M is the sum of the data in columns D and E, and N is equivalent to column F. Similarly, the data in row 1 is equivalent to the data in row I in Figure 1, row 2 is the sum of II and III, row 3 is the sum of IV and V, and 6 is equivalent to row VI in Figure 1.

		all drivers who survived		all drivers who were killed		
		unbelted	belted	unbelted	belted	i =
right front passengers who survived	unbelted	Not in FARS		*j*	*a*	1
	belted					2
right front passengers who were killed	unbelted	*k*	*b*	*l*	*c*	3
	belted					4
no right front passenger		Not in FARS				5
		K	L	M	N	

Figure 2. Passenger car crashes in the Fatal Accident Reporting System (FARS).

The validity of FARS data can be no better than the validity of its source data. Many data elements in FARS -- whether a person lived or died, the descriptions of vehicles, age and sex of people involved, and type of roadway, for example -- are both reasonably complete and accurate. Belt use information in FARS is less so.

Police officers are almost never at the scene of a crash when it happens. Therefore, they must determine belt use for occupants from their investigation of physical evidence, claims by vehicle occupants, and information from emergency medical personnel or others who were first at the scene. Belt use information is obviously better for occupants who are killed in the crash or who are still in the car when police or emergency personnel arrive. That introduces a further bias in the data. Some police officers lack adequate training for judging belt use on the basis of secondary evidence.

For states that have belt use laws, or where belt use may be a factor in insurance payments, occupants may claim they were using a belt even when they were not. Specific evidence of bias in belt use reporting came from states that passed belt use laws. After belt use laws took effect, there was a greater increase in belt use reported in FARS than was observed in roadside surveys in such states. This suggests that errors in belt use are not random: there is probably a bias toward reporting higher belt than was actually the case, particularly in data from more recent years. Such reporting would affect any calculation of effectiveness from FARS.

The determination of safety belt effectiveness may also strongly depend on the size or type of vehicle, the age and sex of the occupant, and other factors. If this were so, the way in which the data is selected from FARS, or differing use rates among the range of people by age and sex in various types of cars would bias the determination of effectiveness.

Despite these limitations, FARS is one of the few data bases that can be used for evaluating safety belt effectiveness in preventing fatalities in serious crashes. Therefore, it is worth the effort to develop analytic methods that minimize or deal with the problems with FARS data.

A NEW SOLUTION TO THE EFFECTIVENESS PROBLEM

There is a highly accurate formulation of the problem that overcomes the limitations of the DPC. Consider again Figure 1 and the definition of effectiveness in equation 2. Writing out the full summations this is:

$$E = \left(\frac{\sum_{i=I}^{VII} (C_i + D_i)}{\sum_{i=I}^{VII} (C_i + D_i + E_i + F_i)} \right) \times 100\% \qquad (5)$$

This equation can be used by limiting the summations i = I through VI to get the effectiveness for drivers who are in crashes while traveling with right front passengers, or to i = VII for the effectiveness for drivers who are traveling without a right front passenger. The effectiveness is likely to be different in the two cases because the types or severities of the crashes may depend upon whether a passenger is in the vehicle.

To satisfy this equation, one needs the values for each individual cell in Figure 1. Unfortunately, we cannot readily separate the crashes in column D from those in column E, nor those in column C from those in column B. That is, we do not have good information on which individual crashes are potentially survivable only if an occupant is restrained.

We have particularly limited knowledge of those crashes in which there was no fatality, but in which there would have been one had an occupant been unrestrained. Whether an otherwise fatal crash would have been survivable if restraints had been worn implies a knowledge of the restraint's effectiveness. However, as will be seen, the FARS data set itself contains sufficient information to get around this apparent circularity.

Let us partition the data in a way that makes use of information about restraint use. First, we link restraint use within groups of cells of Figure 1. Figure 3 (see below), for example, shows the relationship between driver and passenger restraint use for the four cells at the lower center portion of Figure 1, C_V, C_{VI}, D_V, and D_{VI}. All of these crashes that are counted in these cells posed the same threat to the lives of the drivers involved: they would have been killed unless they were restrained. In all of these crashes, the right front passengers were killed regardless of restraint use.

C_V Driver Restrained, Passenger Unrestrained *u(1-w)*	D_V Neither Driver Nor Passenger Restrained *(1-u)(1-v)*	V
C_{VI} Driver and Passenger Restrained *uw*	D_{VI} Driver Unrestrained, Passenger Restrained *(1-u)v*	VI
C	D	

Figure 3. Relationships between driver and passenger restraint use for four cells in Figure 1. Formulae within each box give the proportion of vehicles with drivers and passengers restrained as indicated.

The cells on the left side of Figure 3 contain counts of the number of restrained drivers and the cells on the right count unrestrained drivers. The proportion of all drivers in the four cells who were restrained is u (the sum of the numbers in the two left cells divided by the sum of the number in all four cells). The lower two cells count restrained passengers. The proportion of passengers who were restrained is w when they are riding with restrained drivers (the count in the lower left cell divided by the counts in both left cells in Figure 3) and v when riding with unrestrained drivers (the cells on the right side of Figure 3). This representation can be made of any set of four adjacent cells for which the risk to all drivers is the same and the risk to all passengers is the same but not necessarily the same as to the drivers. Note that because u, v, and w are proportions, the sum of the proportions in each cell: $u(1-w) + uw + (1-u)(1-v) + (1-u)v = 1$.

If the values of u, v, and w were known, they could be used to determine the partition of data between crashes that have the same restraint use characteristics but that differ in the severity of the crash, such as D_{IV}, D_V, E_{IV}, and E_V. We could, for example, partition $D_{VI}+E_{VI}$ by noting that $E_{VI}/F_{VI} = (1-u)v/(uw)$.

From this point on, we shall use the nomenclature of Figure 2 -- K_1, L_2, and so on -- to indicate known values from FARS. Since the sum $(D_{VI}+E_{VI})$ is a known quantity (M_4 from Figure 2), we can express $D_{VI} = M_4 - E_{VI}$. The same type of relationship can be used for $F_V = N_4\, u(1-w)/uw$ and $F_{IV} = N_3 - F_V$. Similarly, D_V, E_V, and E_{IV} can be expressed using the values of M_4, N_4, and N_3, respectively by using the appropriate ratios of the numbers of people using and not using restraints. Then, D_{IV} is the difference between the total of the four cells $(D_{IV}+D_V+E_{IV}+E_V) = M_3$ and the values of the three of these cells that have been determined. In this way, values for all nine cells in the lower right section of Figure 1 can be expressed as a function of known FARS data and values of restraint use u, v, and w.

This bootstrapping technique can be used beginning at $A_{VI} = K_4$ to develop expressions for the values in the nine cells at the lower left of Figure 1 and from $F_I = N_I$ to obtain expressions for the nine cells at the upper right. Next, A_{III}, B_{III}, C_I, and C_{II} can be expressed in terms of their neighbors, A_{IV}, B_{IV}, D_I, and D_{II}, respectively, and u, v, and w. C_{III} can be expressed in terms of either C_{IV} or D_{III}. In this way, we can express values for all of the individual cells in Figure 1 except A_I, A_{II}, B_I, and B_{II}, which are not fatal to even unbelted front seat occupants.

Thus far, we have assumed that u, v, and w are the same for all sections of four cells in Figure 1 that have the same outcome severity. There is evidence that safety belt use is lower for crashes of increasing severity. In particular, we assume the following:

Since the behavior of the driver has a substantial effect on the severity of a crash, driver restraint use may take on different values depending on the severity of the crash as it affects the driver: u_o if the driver survives regardless of restraint use (columns A and B), u_i if the driver survives only if restrained (columns C and D), and u if the driver is killed regardless of restraint use (columns E and F). Let us further assume that the value u_i is the harmonic average[1] of the restraint use value u_o, and the value u.

[1] We use the harmonic average: $2/u_i = 1/u_o + 1/u$, because it has computational advantages (see below). The difference between the average and the harmonic average is very small as long as u_o and u are reasonably close in value. The results are not sensitive to this difference.

- The values of v and w are assumed to be the same throughout the Figure. Note that since passenger restraint use is dependent on driver restraint use, so that restraint use by passengers will actually vary proportionally to driver use by crash severity.

These assumptions give five unknowns requiring five equations for solution. These five equations come from the intersections between quadrants of Figure 1 and the relationship for driver restraint use. Specifically, four of the cell groups, $(C_{IV}+C_V)/(D_{IV}+D_V)$, C_{VI}/D_{VI}, $D_{III}+E_{III})/(D_{IV}+E_{IV})$, F_{III}/F_{IV} can be compared using values of restraint use independently from their derivation. The five equations are:

$$\frac{C_{IV}+C_V}{D_{IV}+D_V} = \frac{u_i(1-w)}{(1-u_i)(1-v)} \tag{6}$$

$$\frac{C_{VI}}{D_{VI}} = \frac{u_i w}{(1-u_i)v} \tag{7}$$

$$\frac{D_{III}+E_{III}}{D_{IV}+E_{IV}} = \frac{v}{1-v} \tag{8}$$

$$\frac{F_{III}}{F_{IV}} = \frac{uw}{u(1-w)} = \frac{w}{1-w} \tag{9}$$

$$u_i = \frac{2u_o u}{u_o+u} \tag{10}$$

For equation 8, $E_{III}/E_{IV} = (1-u)v/(1-u)(1-v) = v/(1-v)$, leading to the above result. The solution of these equations gives the three values of u and of v and w. The complete expressions come from substituting for $(C_{IV}+C_V)$, $(D_{IV}+D_V)$, C_{VI}, D_{VI}, $(D_{III}+E_{III})$, $(D_{IV}+E_{IV})$, F_{III} and F_{IV}. For example:

$$\begin{aligned} C_{IV}+C_V &= L_3 - \frac{u_o(1-w)}{(1-u_o)v}K_4 \\ &- \frac{u_o(1-w)}{(1-u_o)(1-v)}[K_3 - \frac{1-v}{v}K_4] \\ &= L_3 - \frac{u_o(1-w)}{(1-u_o)(1-v)}K_3 \end{aligned} \tag{11}$$

and:

$$C_{VI} = L_4 - \frac{u_o w}{(1-u_o)v}K_4 \tag{12}$$

Similar expressions can be developed for the values in the remaining cells to substitute into equations 6 through 10. The four equations that result are:

$$\begin{aligned} &\frac{1-u_i}{u_i}[L_3 - \frac{u_o}{1-u_o}\frac{1-w}{1-v}K_3] \\ &= \frac{1-w}{1-v}M_3 - \frac{1-u}{u}N_3 \end{aligned} \tag{13}$$

$$\begin{aligned} &\frac{1-u_i}{u_i}[L_4 - \frac{u_o}{1-u_o}\frac{w}{v}K_4] \\ &= \frac{w}{v}M_4 - \frac{1-u}{u}N_4 \end{aligned} \tag{14}$$

$$(1-v)M_2 - vM_1 = vM_3 - (1-v)M_4 \tag{15}$$

$$wN_1 - (1-w)N_2 = (1-w)N_4 - wN_3 \tag{16}$$

One can solve for v in equation 15 and for w in equation 16:

$$v = \frac{M_2+M_4}{M_1+M_2+M_3+M_4} \tag{17}$$

$$v = \frac{M_2 + M_4}{M_1 + M_2 + M_3 + M_4} \tag{17}$$

$$w = \frac{N_2 + N_4}{N_1 + N_2 + N_3 + N_4} \tag{18}$$

In equations 13 and 14, the variables representing driver restraint use, u_o, u_i, and u all appear in the form: $(1\text{-}u)/u$. Now define two new variables, $x = (1\text{-}u_o)/u_o$ and $y = (1\text{-}u)/u$, so that $(1\text{-}u_i)/u_i = (x+y)/2$. Equations 13 and 14 can then be restated by incorporating values for x and y giving two equations in two unknowns. Equation 14 can be solved for y in terms of x:

$$y = \frac{x^2 L_4 - \frac{w}{v} x (K_4 + 2M_4)}{\frac{w}{v} K_4 - x (L_4 + 2N_4)} \tag{19}$$

The result can be substituted into equation 13 giving a quadratic equation in x:

$$\begin{aligned} & x^2 (L_3N_4 - L_4N_3) \\ & - x \left[\frac{1-w}{1-v}(M_3(N_4+L_4)+N_4(M_3+K_3)) \right. \\ & \left. - \frac{w}{v}(M_4(N_3+L_3)+N_3(M_4+K_4))\right] \\ & - \frac{w}{v}\frac{1-w}{1-v}(K_3M_4 - K_4M_3) = 0 \end{aligned} \tag{20}$$

This equation is easily solved for x using FARS data. One of the roots is negative giving a meaningless value of restraint use. The remaining root gives unique values for driver restraint use. From the solution both driver and passenger restraint use can be determined. Using the relationships developed from Figure 3, the specific values in all cells of Figure 1 can be found, and equation 5 will give restraint effectiveness.

Somewhat the same procedure can be used for drivers who are traveling alone. The problem is that we have no equations similar to equations 6 through 10 above for this case. If restraint use is dependent on crash severity, we have two unknowns: u and u_i, using the nomenclature developed above. Note, however, that $E_{VII} = F_{VII}(1\text{-}u)/u$, $D_{VII} = M_7 - E_{VII}$, and $C_{VII} = D_{VII}u_i/(1\text{-}u_i)$. Making these substitutions in equation 5 and assuming that usage is the same for all drivers who are traveling alone when they are involved in fatal crashes gives:

$$E = 1 - \frac{(1-u_i)N_5}{uM_5 + (u-u_i)N_5} \approx 1 - \frac{(1-u)}{uM} \tag{21}$$

The second expression is exact if restraint use is independent of the severity of the crash (i.e. $u_i = u$). However, we must still obtain restraint use from other sources. This equation shows that the higher the observed use rate, the higher the derived effectiveness.

RESULTS

Table 1 (see following page), taken from FARS, shows the number of passenger cars in which a driver or right front occupant was killed in the U.S. from 1985 through 1992. It is in the same format as Figure 2. It includes all cases for which safety belt use is known. Within each cell, the numbers are listed with 1985 data at the top and 1992 data at the bottom. Note that for those cells where both a driver and a right front passenger were killed, M_3, M_4, N_3, and N_4, each count represents two fatalities. Table 2 (see second following page) provides the same data for 1985 through 1992 for cases involving light trucks in which belt use is known. Belt use is unknown for about 15% of all cases. Ignoring the unknown cases is equivalent to assuming that belt use among cases in which it is unknown is the same as in the known cases. This may slightly overestimate belt use.

Table 1.
Numbers of fatally injured passenger car occupants according to the characteristics of the crash. Data in each cell is shown for 1985 (at the top) through 1992 (at the bottom).

			all drivers who survived		all drivers who were killed		
			survivable	survivable / survivable if belted	survivable if belted	not survivable	
			unbelted	belted	unbelted	belted	i =
right front passengers who survived	survivable	unbelted	Not in FARS	Not in FARS	1813 1843 1871 1864 1779 1683 1412 1273	50 58 95 102 82 89 98 100	1
right front passengers who survived	survivable / survivable if belted	belted	Not in FARS	Not in FARS	112 188 154 327 319 356 304 303	218 404 588 657 691 727 786 788	2
right front passengers who were killed	survivable if belted / not survivable	unbelted	1780 1849 1801 1834 1733 1581 1437 1320	164 254 319 384 341 378 388 388	805 884 818 844 812 801 706 648	31 45 37 70 62 64 59 87	3
right front passengers who were killed	not survivable	belted	44 63 89 107 96 78 90 97	286 505 663 804 884 913 946 960	29 37 44 69 71 56 60 69	98 169 215 327 304 303 351 359	4
no right front passenger			Not in FARS	Not in FARS	6400 6713 6985 7368 7212 6745 6059 5586	828 1450 1810 2155 2339 2501 2699 2861	5
			K	L	M	N	

Table 2.
Numbers of fatally injured light truck occupants according to the characteristics of the crash.
Data in each cell is shown for 1985 (at the top) through 1992 (at the bottom).

			all drivers who survived		all drivers who were killed		
			survivable	survivable if belted	survivable if belted	not survivable	
			unbelted	belted	unbelted	belted	i =
right front passengers who survived	survivable	unbelted	Not in FARS	Not in FARS	567 569 596 678 681 702 630 555	4 10 11 21 18 17 20 29	1
right front passengers who survived	survivable / survivable if belted	belted	Not in FARS	Not in FARS	28 36 54 87 100 101 104 107	28 43 68 78 94 113 108 109	2
right front passengers who were killed	survivable if belted / not survivable	unbelted	463 508 613 641 595 648 562 523	23 43 75 106 107 101 126 126	166 171 206 190 165 224 203 175	4 8 13 10 12 10 20 15	3
right front passengers who were killed	not survivable	belted	4 3 8 17 11 19 20 16	28 47 62 90 93 101 124 120	2 6 7 12 18 6 12 14	8 12 39 15 38 21 33 33	4
no right front passenger			Not in FARS	Not in FARS	1858 2071 2394 2626 2676 2661 2597 2509	102 198 287 355 412 441 475 519	5
			K	L	M	N	

Table 3 (see below) shows the data on all passenger car fatalities for the years 1985 through 1992 fully partitioned according to the procedure outlined above. The effectiveness calculated for drivers traveling with right front passengers, the sum of columns C and D divided by the sum of columns C through F, is 63 percent. For right front passengers, the effectiveness is the sum of rows III and IV divided by the sum of rows III through VI which is 57 percent. This calculation found that, when traveling together, reported belt use averaged 49 percent for drivers and right front passengers, was 86 percent for right front passengers riding with belted drivers, and was 12 percent for right front passengers riding with unbelted drivers. According to this calculation, for the eight year period, 14,000 drivers and 12,400 right front passengers were saved by wearing safety belts. However, an additional 14,100 drivers and 13,000 right front passengers could have been saved if they had been belted.

Table 4 (see following page) shows the same partition of data for light trucks. The effectiveness calculated for drivers is 76 percent and for right front passengers is 73 percent. Belt use, according to this calculation, averaged 37 percent for drivers and right front passengers, 80 percent for passengers with restrained drivers, and 10 percent for passengers with unrestrained drivers. We calculated that belts saved 3,300 light truck drivers and 2,800 right front passengers, and could have saved an additional 5,500 drivers and 5,000 passengers.

For drivers who were alone in passenger cars and in light trucks, we have no independent way to estimate belt use. According to the 19 Cities Study, the average passenger car driver belt use for 1985 through 1994 was about 40 percent. Using a more conservative figure of 35 percent would give an effectiveness of 42 percent for passenger cars according to equation 21. We have no equivalent observations for light truck drivers. Belt effectiveness may be as high as 69 percent for light truck drivers traveling alone if their belt use was only 30 percent for this period. Using a more conservative figures of 25 percent for belt use of drivers alone in light trucks, their belt effectiveness would be 60 percent.

Table 3.
Numbers of passenger car occupants in fatal crashes from 1985 through 1992 partitioned according to the severity of the crash and restraint use by occupants.

			all drivers who survived			all drivers who were killed			
			survivable		survivable if belted		not survivable		
			unbelted	belted		unbelted		belted	i =
right front passengers who survived	survivable	unbelted			1,448	9,174	4,364	674	I
		belted			8,960	1,200	571	4,170	II
	survivable if belted		1,081	8,068	2,156	295	96	689	III
right front passengers who were killed		unbelted	8,260	1,304	348	2,257	737	111	IV
	not survivable		5,075	801	162	1,051	2,173	344	V
		belted	664	4,957	1,004	138	297	2,126	VI
no right front passenger					11,932	22,160	30,908	16,643	VII
			A	B	C	D	E	F	

Table 4.
Numbers of light truck occupants in fatal crashes from 1985 through 1992 partitioned according to the severity of the crash and restraint use by occupants.

			all drivers who survived			all drivers who were killed			
			survivable		survivable if belted		not survivable		
			unbelted	belted		unbelted		belted	i =
right front passengers who survived	survivable	unbelted			537	4,038	940	130	I
		belted			2,161	433	101	523	II
	survivable if belted	belted	390	1,876	304	61	23	119	III
right front passengers who were killed	survivable if belted	unbelted	3,638	466	76	568	214	30	IV
	not survivable	unbelted	915	117	48	361	358	49	V
	not survivable	belted	98	472	193	39	38	199	VI
no right front passenger					3,342	10,025	8,376	2,789	VII
			A	B	C	D	E	F	

These belt use figures show that approximately 11,900 passenger car drivers traveling alone, and 3,300 solo light truck drivers were saved. An added 22,100 passenger car drivers and 10,000 light truck drivers traveling alone could have been saved had they been wearing belts.

The grand total indicates that more than 47,000 people were saved by wearing safety belts in the eight years from 1985 through 1992. It is unfortunate that more than 69,000 were killed who could have been saved by buckling up.

Two surprising results come from this procedure. The first is that we found driver belt use to be somewhat higher than was observed in the 19 cities observations. The second is that the effectiveness found for safety belts is significantly higher than has been found by previous methods: nearly 60 percent for passenger car occupants and over 70 percent for light truck occupants.

DISCUSSION

The various equations and relationships developed here are exact and are derived using only algebra with which a good high school student would be familiar. This is in no way a statistical calculation, and no statistical approximations are involved. The approximations and sources of error involved in solving the equations are as follows:

- The FARS data on restraint use is not necessarily accurate as discussed above. Some people who survive fatal crashes may be out of their vehicles by the time the police officer arrives. Those who are interviewed by the officer may claim that they were using belts when they were not. Injured victims may have been unbuckled or removed from the vehicle by rescue personnel before the officer had an opportunity to determine belt use.
- Cases with unknown belt use have been ignored. If belt use in these cases is significantly different from belt use that was observed, it might skew the results.
- To a more limited extent than in the DPC method, we assumed that safety belt use is similar in crashes of differing risk. For example, the values of v and of w (passenger belt use with belted and unbelted drivers, respectively) were assumed to be the same in all eight sets of four cells. The values of u (driver belt use) vary with the seriousness of the crash as indicated by the risk to the driver.
- When this methodology is applied to small data sets, such as one year of data on light trucks, it is likely to give spurious results because uncertainties and inaccuracies in the data become much more important for such sets. The

result may be that none of the roots of equation 22 are valid, that values for the individual cells in Figure 1 may be negative, or that the effectiveness values derived may be completely unrealistic. See Appendix D for a discussion of this uncertainty.

The higher safety belt use found in the calculations probably comes from over-reporting of safety belt use to police officers, particularly in an era of safety belt use laws in many states. The higher effectiveness value may be due to the fact that this is the first attempt to define safety belt use from first principles that include all available real world data.

It is possible that safety belt effectiveness has improved over time as a consequence of improved design of both vehicles and belt systems. However, when the effectiveness of safety belts was calculated for the individual years from 1985 through 1992, there were no trends toward improved effectiveness in later years, indicating that this is not the case.

This analysis was not carried out beyond 1992 both because cars with air bags and automatic belts were becoming a significant fraction of the fleet by that time.

Adjustments to FARS Data

A criticism of the preliminary results of this work was that the effectiveness values that were found were unrealistically high. Belt use reported in FARS, particularly by people who survive fatal crashes, is also thought to be unrealistically high. As a consequence, some analysts have adjusted the effectiveness calculated using the DPC method downward to compensate. The present method offers a more direct means of addressing this question.

To better understand the consequences of over-reporting of belt use, we arbitrarily reclassified some of the FARS cases to reflect more realistic values of belt use. First, 30 percent of the passenger car cases indicating that both driver and right front passenger were wearing belts and where one or the other was killed were reclassified: 25 percent became cases in which neither driver nor right front passenger were wearing belts, and the remainder were classified as either driver or right front passenger only wearing belts. Fifteen percent of the cases where both driver and right front passenger were belted and killed were reclassified with ten percent becoming both unbelted and the remainder becoming cases in which one or the other was belted.

Table 5 (see next page) shows the redistribution of cases from the new solution of equation 22. The result of this change was to decrease overall belt use to a more realistic 39 percent and to decrease the calculated effectiveness for drivers from 63 to 57 percent, and for right front passengers from 57 to 54 percent. For drivers traveling alone, belt use can still be assumed to be 35 percent regardless of this process of redistribution. At this use rate, the calculated belt effectiveness rises substantially from 42 percent to 56 percent (which is consistent with effectiveness when there is a driver and right front passenger) with the reclassification.

For light trucks, the same procedure reduces belt use to 29 percent and effectiveness to 73 percent for drivers and 71 percent for right front passengers. For light truck drivers traveling alone, at 25 percent belt use the effectiveness would be 60 percent.

There is no formal basis for this reclassification of cases. A general justification is that the belt use calculated from this methodology is higher than observed belt use. The reclassification resulted in much more realistic overall belt use (the 19 Cities Study gives average driver usage of somewhat over 40 percent for this period). It also resulted in a modest reduction in the calculated safety belt effectiveness of roughly 5 percentage points. This gives some confidence that the effectiveness of safety belts is at least 55 percent for passenger car occupants and 65 percent for light truck occupants.

The error from misclassification of belt use is probably less than 10 percent, indicating that misclassification was not primarily responsible for these present results being higher than previous estimates. There is no error due to approximations (there are no significant approximations) nor are there any statistical errors (FARS is a census). This gives strong evidence that previous methods of determining safety belt effectiveness, such as those used in the 1984 decision by the Department of Transportation on occupant crash protection, may have underestimated it.

Table 5.

A recalculation of the numbers of fatally injured passenger car occupants for 1985 through 1992, completely partitioned according to the characteristics of the crash and the state of restraint of driver and right front passenger. For this calculation, the numbers of unrestrained drivers and right front passengers were reduced by 30 percent where only one was killed, 15 percent where both were killed, and ten percent for drivers alone who were killed. These were reclassified as neither being restrained except that 5 percent were reclassified as only driver or right front passenger restrained.

			all drivers who survived			all drivers who were killed			
			survivable		survivable if belted		not survivable		
			unbelted	belted		unbelted		belted	i =
right front passengers who survived	survivable	unbelted			1,474	9,223	5,529	795	I
right front passengers who survived	survivable	belted			5,768	1,196	717	3,113	II
right front passengers who survived	survivable if belted	belted	1,109	5,349	1,300	299	73	288	III
right front passengers who were killed	survivable if belted	unbelted	8,553	1,367	332	2,309	562	74	IV
right front passengers who were killed	not survivable	unbelted	6,272	1,002	64	444	3,322	435	V
right front passengers who were killed	not survivable	belted	813	3,923	250	58	431	1,701	VI
no right front passenger					17,053	31,670	24,727	13,314	VII
			A	B	C	D	E	F	

Statistical Validity

Although this paper uses no statistical techniques and does not develop any statistical formalism, it raises a problem that must be addressed with statistical techniques. The problem is that although FARS is a census of crashes, there is clearly a smallest FARS data file that will provide reliable results. For example, if one were attempting to determine the effectiveness of safety belts in Rolls Royces, there would be at most only a handful of cases in FARS from which to make that determination. They would not permit a meaningful calculation of effectiveness using the technique developed above.

In performing these calculations, the author found data sets that were too small to provide meaningful results, such as one year of data on light trucks. Appendix D is a pragmatic attempt to define the smallest data sets that can be accurately analyzed using this formalism. It shows that FARS data sets must have at least 30,000 vehicles with both a driver and right front passenger in order to provide reasonably accurate results.

CONCLUSION

The primary purpose of the research reported here was to develop a more exact and useful formalism for the determination of effectiveness. The fact that effectiveness values calculated using this formalism were found to be reasonable and consistent gives confidence that the formalism is valid.

One of the major contributions of this methodology is that it give a detailed picture of how many crashes were in each cell defined in Figure 1. Thus, for example, we can see the number of cases in which a crash would have been survivable if driver and passenger had both worn belts, and how many people actually survived.

It is the author's hope that this methodology will be used more extensively and that this work will stimulate refinements and further development of the formalism, and a striving to obtain better input data in FARS, restraint use, and other data sets. This would result in more refined values for restraint effectiveness, which is particularly important as the variety of systems increases. This approach might also prove useful for estimating the effectiveness of restraints in reducing non-fatal injury and of other safety equipment such as automatic safety belts and air bags when sufficient data are available.

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APPENDIX A: A Further Explanation of the Mathematical Formalism used in this Paper

The mathematical formalism used in this paper does not go beyond highschool algebra. What may be confusing to the reader is the nomenclature in which various variables are used to describe similar elements of the problem. The author apologizes for this complexity, but attempts to find simpler expressions failed. Thus, in this appendix, we shall attempt to clearly state what all of the variables stand for and the relationship between them.

All of the variables refer to the data and characteristics of drivers and right front passengers shown in figure 1. This figure introduces the names A_I through F_7 to describe the driver (capital letter) and right front passenger (subscript). The six states of either a driver or passenger are:

- people who survived an actual crash which are listed in FARS only if someone else was killed in the crash (A, B and C for drivers and I, II and III for right front passengers)
- people who were killed in an actual crash, and therefore were listed in FARS (D, E and F for drivers and IV, V and VI for right front passengers)
- people who wore safety belt restraints when they were in a crash (B, C and F for drivers and II, III and VI for right front passengers)
- people who were unrestrained when they were in a crash (A, D and E for drivers and I, IV and V for right front passengers)
- people who were in crashes that could have been survived regardless of belt use (A and B for drivers and I and II for right front passengers)
- people who were in crashes that could only have been survived if the occupant was wearing a safety belt (C and D for drivers and III and IV for right front passengers)
- people who were in unsurvivable crashes regardless of restraint use (E and F for drivers and V and VI for right front passengers)

The number VII is used to indicate that there was no right front passenger in the vehicle at the time of a crash.

Since the FARS data does not indicate whether a crash was survivable or not, we cannot make the distinctions shown in the last three bullets above unless an unrestrained driver or right front passenger survived (A and I) or a restrained driver or right front passenger was killed (F and VI). FARS data can tell us whether an occupant was restrained or not, and whether he or she was killed or not. Thus, FARS tells us the sum of B and C (but not B or C individually), the sum of D and E, the sum of II and III, and the sum of VI and V. Therefore, we chose to rename the data elements as follows:

K = A	1 = I
L = B + C	2 = II + III
M = D + E	3 = IV + V
N = F	4 = VI
and	5 = VII

Next, the variables u, v, and w were introduced to provide further relationships that can be used to derive the data in the individual cells of the matrix shown in Figure 1. They take on values of 0 (if no one in a particular cell was wearing belts) to 1 (if everyone in a cell was wearing belts). In particular, u_o is used to designate the belt use rate of drivers in survivable crashes and u (without subscript) is used to designate the belt use rate of drivers in crashes that could not be survived regardless of belt use. For those drivers in crashes that are survivable only if the belts are used, we designated belt use as u_i and assumed that it is a harmonic average of u_o and u:

$$1/u_i = 2/u_o + 2/u \quad \text{or} \quad u_i = 2uu_o/(u_o + u)$$

The new variables v and w indicate the belt use rate of right front passengers when drivers are belted and unbelted, respectively. It is well known that passenger belt use tends to follow driver belt use, so that v is close to zero and w is close to unity.

The final transformation is made solely for mathematical purposes. We found that passenger belt use could be expressed in terms of known values from the FARS file, so no further specification was necessary for them. However, to transform the equations involving u_o and u into solvable equations, we defined new variables x and y so that:

$$x = (1 - u_o)/u_o \quad \text{and} \quad y = (1 - u)/u$$

That transformation put equations involving u_o, u, and the FARS data into quadratic form with the variables x and y that can be exactly solved. From values of x and y, we can derive values of u_o and u, and can determine values for all of the individual cells in Figure 1. This not only permits an exact calculation of safety belt effectiveness, it provides remarkably detailed information about what happened to the people involved in real world crashes. It is a far more powerful solution than the double pair comparison method which is only a special case of the present methodology.

More importantly, this method permits a kind of experimentation that can explore uncertainty in certain variables in the FARS file. FARS is virtually exact in showing whether occupants of a vehicle lived or died by seating position. It is less reliable in showing safety belt use, particularly for occupants who survived and were capable of getting out of the vehicle before emergency personnel arrive.

The experiments that can be performed are of the "what if" variety: what if safety belt use for surviving drivers is overestimated by 10 percent? We need only increase u by 10 percent and we can see the effect on the calculated effectiveness.

APPENDIX B. The Equation for Effectiveness

Equation 2 may seem inconsistent with equation 1 at first glance. One might be tempted to write equation 2 as:

$$E = \left(1 - \frac{\dfrac{B + C}{B + C + F}}{\dfrac{A}{A + D + E}} \right) \times 100\% \qquad (22)$$

The numerator represents the proportion of cases where drivers were wearing safety belts who survived. The denominator represents the proportion of cases where drivers who were not wearing belts survived.

The first problem with this expression is that we have no way of knowing how many people were in crashes where there were no fatalities and would not have been even if belts had been worn. The second problem with the expression is that it ignores the problem that belted drivers may have a substantially different spectrum of crashes by severity.

The expression of equation 2 is derived by assuming that we could determine how many drivers would have been killed if the entire population of vehicles involved in potentially fatal crashes even if all had been belted (columns E and F). This becomes the numerator in the expression. For the denominator, we assume that we could determine how many drivers would have been killed if none had been belted (columns C, D, E, and F). Thus, equation 2 is fully consistent with equation 1.

APPENDIX C: The Double Pair Comparison Method

Evans defines what he calls the "true effectiveness" of belts for drivers as the ratio of the number of unbelted drivers who would have been saved had they been wearing belts to the total number of unbelted drivers who were actually killed. For drivers, referring to Figure 1, this is column D divided by the sum of columns D plus E. This is a more limited definition than the one described above (which is equivalent to columns C plus D divided by columns C plus D plus E plus F), so that Evans' label "true" is a substantial overstatement.

More importantly, Evans recognized that there is no direct way to measure which unbelted drivers would have been saved had they been wearing belts (or, as Evans formulated the problem, how many unbelted drivers would have been killed even if they had been wearing belts).

Evans procedure was to use known quantities from FARS to estimate what he called the "true effectiveness." Specifically, for belt effectiveness in protecting drivers, using the nomenclature of Figure 2, he proposed the equation:

$$E = (1-R)\times 100\% = 1-\frac{(a+c)/(b+c)}{(j+l)/(k+l)}\times 100\% \qquad (23)$$

where:

a = number of crashes killing a belted driver but not an unbelted passenger,

b = number of crashes killing an unbelted passenger but not a belted driver,

c = number of crashes killing both a belted driver and an unbelted passenger,

j = number of crashes killing an unbelted driver but not an unbelted passenger,

k = number of crashes killing an unbelted passenger but not an unbelted driver, and

l = number of crashes killing both an unbelted driver and an unbelted passenger.

Figure 2 shows what parts of the crash spectrum are defined by these letters. Note that $a+c$ and $j+l$ are all crashes killing a belted or unbelted driver, respectively, who was with any unbelted passenger. Similarly, $b+c$ and $k+l$ are all crashes involving any unbelted or belted driver, respectively, who is with an unbelted passenger who was killed. This is the belt use ratio defined as α or β above. (For completeness, similar relations can be developed involving only belted passengers in order to use more of the data available in FARS. One can also make the parameters relating to the right front passengers the dependent variables in such equations.)

In using this formulation, Evans is substituting the number of belted drivers who are killed (cells $F_1+F_3+F_4$ in Figure 1) for unbelted drivers who would have been killed even if they were belted (the part of $j+l$ that would have been killed even if they were belted or cells $E_1+E_3+E_4$ in Figure 1) in his "true effectiveness" equation. Since the ratio of these numbers is equal to the ratio of belted to unbelted drivers involved in unsurvivable crashes, he multiplies the number of belted drivers who are killed by the ratio of the total number of unbelted to belted drivers who are with passengers who are killed. To the extent that belt use is consistent in crashes that are sufficiently serious to kill either a driver or a right front passenger, this gives a reasonable approximation of Evans' "true effectiveness."

This substitution does not address the more fundamental limitation of Evans' definition of "true effectiveness," nor does it make complete use of the available data. The most general formulation of the DPC is as follows:

$$E = \left(1 - \frac{\sum_{i=1}^{6}(F_i)\dfrac{\sum_{i=4}^{6}(A_i+D_i+E_i)}{\sum_{i=4}^{6}(B_i+C_i+F_i)}}{\sum_{i=1}^{6}(D_i+E_i)} \right) \times 100 \qquad (24)$$

The elements of this equation are all known from FARS. While this is still an approximation, it can give a reasonable estimate of effectiveness.

APPENDIX D: Estimating The Minimum Data File Size for which this Method Provides Valid Results

The analysis developed in this paper does not use statistical methods in any way. However, the author recognizes that with small data files, uncertainties or variations in the input data -- the numbers of crashes in any one cell -- may introduce errors in the results of using this methodology. Because the numbers in the cells of Figure 1 are a complicated function of the numbers in the cells of Figure 2, the author has found no elegant method of analyzing how uncertainties in the numbers in each cell affect the answers provided by this methodology.

Fortunately, the computer provides a technique for experimentally exploring the effect of variation in the input data on the results of the analysis. First, let us assume that each of the numbers in each cell of Figure 2 is a Poisson distribution. That is, the injury consequences in each vehicle is effectively independent of all others. This is not strictly true because in a two vehicle collision, each vehicle may be in a different cell of Figure 2, and therefore the consequences for the occupants of one vehicle may be dependent on what happens in the other. Nevertheless, for our purposes, this is a reasonable assumption.

In a Poisson distribution, the standard deviation is defined as the square root of the mean. If we have 144 cases, the standard deviation of that number is 12. What this means is that we can assume that if we took a sample X times larger (where X is much larger than unity) and divided the number of cases in that larger sample by X, the result has a high probability of being between 132 and 156.

Let us now look at the figures in Tables 1 and 2. Note that the smallest numbers occur in the cells in which a driver was restrained and a passenger was not or vice versa: K_4, L_3, M_2, N_1, M_4, and N_3. In particular, if we look at the data in Tables 1 and 2, the smallest numbers are in just four cells, K_4, N_1, M_4, and N_3. Variations in any of the numbers in these four cells probably govern the validity of the results of the analysis.

We set up a spread sheet with data in the form of Figure 2 using the analysis of this paper to fill in results in Figure 1 and to provide driver and right front passenger restraint use (u, v, and w) and effectiveness. Next, we varied the values in the four cells with the smallest numbers to see the effect of such variation on the results.

Note that a standard deviation is larger for smaller numbers. For example, if the number of cases in a cell is 25, a standard deviation is 5 which is 20 percent of the value in the cell. If the number of cases is 100, the standard deviation is 10 which is 10 percent of the value.

The results were relatively insensitive to large variations in M_4 and N_3. Thus, variations in K_4 and N_1 govern the validity of the results. We found that a variation of 10 percent in these values substantially distorts the results, in some cases giving values of use that are either greater than one or less than zero which is clearly unrealistic, or values in cells of Figure 1 that are negative which is also unrealistic. We found that variations within 5 percent did not produce abnormal results, but that variations of 10 percent definitely did. From this, we conclude that the smallest numbers in cells K_4 and N_1 that produce reliable results are around 400 (standard deviation 20 which is 5 percent of the number of cases in the cell).

The files on which this analysis is based, this suggest that a minimum data file size of about 30,000 cases in which there is both a driver and right front passenger is necessary to provide accurate results.

LOWER BACK AND NECK STRAIN INJURIES: THE RELATIVE ROLES OF SEAT ADJUSTMENT AND VEHICLE/SEAT DESIGN

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ABSTRACT

The incidence of "whiplash" injuries is rising despite the almost universal introduction of head restraints in cars. The incidence of lower back strains is also significant. This paper describes a study of road accident victims suffering from lower back and neck strain injuries. Injury severity was assessed by a disability scoring system, and patients' progress was followed for 12 months. Vehicles were examined to assess impact speeds and seat characteristics. Where possible, measurements were carried out with victims sitting in their vehicles.

No differences in victims' symptoms were found between rear as opposed to frontal impacts. Women suffered significantly greater disability than men, despite ostensibly more favourable head restraint positioning. For long-term outcome, smaller horizontal distance from head to restraint was significantly associated with higher disability, contrary to expectations. Seat back inclination was important in lumbar strain cases. There was no clear dependence of injury severity on head restraint vertical positioning, impact direction or impact speed.

The possible implications of these results, and possible future strategies for reducing the incidence and severity of neck and lower back strain injuries are discussed.

INTRODUCTION

The increasing incidence of soft tissue cervical sprain injury - also referred to as "whiplash" injuries - and their concomitant clinical manifestations, termed Whiplash Associated Disorders (WADs) by Spitzer *et al* (1995) has been well-documented (Galasko *et al*, 1996, Morris and Thomas, 1996), and has occurred against a background of the increasingly prevalent fitment of head restraints in the front seats and, more recently, the rear seats of cars. These head restraints are fitted to prevent neck injury by limiting rearward hyperextension of the neck in a typical rear impact. While rearward hyperextension is undoubtedly a mechanism for crushing and breakage of the cervical vertebrae in very severe cases, it has also been assumed to be the mechanism for the less severe, AIS1, whiplash-type injuries, despite the fact that the precise clinical definition of these non-life-threatening, but highly debilitating, injuries is not known. Mertz and Patrick (1967) showed that eliminating head motion relative to the torso completely, by having a volunteer's head permanently in contact with a high, rigid seat back, allowed very severe rear impacts to be survived without ill effect. Thus, publicity campaigns have been mounted, urging people to adjust their restraints to be as close to the head as possible horizontally, and to be about level with the ears, or the back of the head, vertically. The current WAD "epidemic" is frequently blamed on the fact that very many people can be observed to ignore these recommendations.

But having one's head close to a softly padded head restraint is not the same as being permanently in contact with a rigid structure. Even where the restraint is rigidly attached to the seat and made of fairly stiff material, head movement, particularly for drivers, is essential in modern traffic conditions, and this is incompatible with keeping the head permanently in contact with the restraint.

Rearward hyperextension of the neck, however, if it is implicated at all in whiplash injury, cannot be the sole mechanism, since these injuries are also observed in victims of frontal and side impacts, where rearward hyperextension is presumed not to be a major factor (Maag *et al*, 1990, Foret-Bruno *et al*, 1991, Von Koch *et al*, 1995, Morris and Thomas, 1996). Some have sought to define whiplash as exclusively a rear impact phenomenon, linking the injury, by implication, to the rearward hyperextension mechanism. But since the injury is defined entirely by its symptoms (it is rare that any physical injury can be identified in these victims), and since it has been generally impossible to differentiate between impact directions in terms of symptoms, it seems rather unfair to define out of existence a large number of neck strain sufferers on the basis of an assumed mechanism for this undefined injury. Indeed, although Lövsund *et al* (1988) have shown that the risk of sustaining whiplash injuries is greater in rear impacts, Morris and Thomas (1996) have shown that frontal impacts actually produce greater absolute numbers of WAD sufferers, because the number of frontal impacts which occur is much greater.

The effectiveness of head restraints in preventing whiplash injuries has been investigated by a number of authors. Nygren *et al* (1984) obtained figures of 25% (fixed restraint) and 15% (adjustable), compared to no restraint (rear impacts only).

Other estimates of effectiveness have ranged from 63 % (Foret-Bruno *et al*, 1991) to no detectable effect (Morris and Thomas, 1996). Such wide variations in estimates seem to indicate that the causes of whiplash injury and the interaction between occupant, seat back and head restraint are but poorly understood.

One of the aims of setting up the Whiplash/Vehicle Study (WVS) was to try to obtain definitive evidence that head restraint adjustment does have an effect on neck strain injury outcome, in order to inform publicity campaigns urging people to use their head restraints properly.

METHODOLOGY

We did not address the incidence of neck strain injuries, but examined the injury severity of a sample of WAD sufferers. Any patient presenting at the Accident & Emergency department of a large hospital in the Manchester area with a whiplash injury as a result of a road traffic accident was considered for inclusion in the study. Other injuries at the level of cuts and bruises were allowed, but any injury with an AIS > 1, or which could have interfered with the assessment of the whiplash injury resulted in exclusion from the study. Casualty records at the hospital were examined on a daily basis to identify possible recruits, who were then invited to join the study.

A detailed personal interview was carried out by qualified medical personnel in the patient's home. The extent of impairment suffered by a patient in each of over 20 categories of activity and movement associated with everyday life was assessed, and these individual scores were converted into an "Overall Disability" rating, on a scale of 0-9 (see Murray *et al*, 1993, 1994 for details of the scoring system). Zero on this scale indicates no disability, and 9 represents a serious level of impairment, including being unable to return to work and/or difficulties maintaining an independent lifestyle. All patients had two follow-up interviews, at six months and twelve months after the accident.

The vehicles in which the patients had been travelling were examined by accident investigation specialists in sufficient detail to allow an estimate to be made of the impact speed. Some vehicles had no measurable damage, or suffered multiple impacts; impact speeds could not be estimated in these cases. Failure to examine a patient's vehicle for any reason resulted in that patient being dropped from the study. Patients were encouraged to be present at the examination so that details of seat and head restraint adjustment at the time of impact could be discussed. Photographs of the vehicle and, where possible, of the occupant in the vehicle were taken. Figure 1 shows the head to restraint distances which were measured.

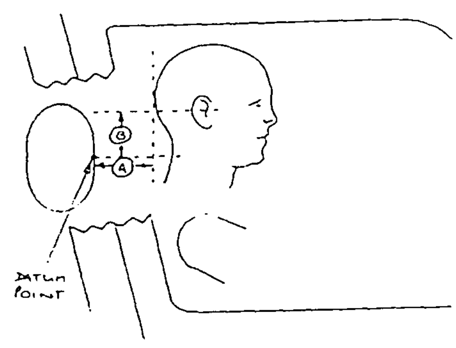

Figure 1. Head to Restraint Distances Measured

An unexpected finding which emerged during the recruitment phase of the project was the discovery of large numbers of patients with lower back strains. Many of these had not been diagnosed as such on the hospital casualty records, but the pain had developed by the time of the first assessment, a few days after the accident. By the time the potential size of this problem had become apparent, the study was well under way, so it was decided not to modify the recruitment criteria, but to record the presence and longevity of lumbar pain for each patient, so that this sub-group could be separated out in the analysis if necessary.

RESULTS

Of 227 initial recruits, 174 remained in the study for the full twelve months, and formed the final sample. These 174 had been occupants in 152 vehicles. The overall male:female ratio in the final dataset was 65:109, and this is similar to the male:female neck injury risk ratio found by Morris and Thomas (1996). Just over half the sample were involved in rear impacts, almost one quarter suffered frontal impacts, with side impacts accounting for the remainder.

Impact speeds could be estimated for 143 occupants. Due to lack of information regarding the second vehicle in the collision, the impact damage measured on each vehicle was converted to an "Equivalent Test Speed" (ETS), related to barrier impacts.

A number of patients were unable to attend the vehicle examination, and this reduced the sample available for analyses involving head restraint distance measurements to 103 occupants. A few of these had very large horizontal head to restraint distances, but very low disabilities. It was found that all those with a horizontal distance greater than 22cm (three in the final sample, more in the initial group) were actively leaning forward at the time of impact, either at junctions or actively bracing themselves for impact in a hunched-forward posture. Their disability scores were significantly lower than the rest of the sample, despite a (non-significantly) higher average impact speed. They have been excluded from the analysis, bringing the sample size down to 171, of which 100 had known restraint measurements and 140 had known ETS. Fourteen occupants had no head restraint.

Comparison with the General Population

Data on head restraint adjustment in the general population have been published elsewhere. Table 1 compares the average horizontal and vertical restraint distances for male and female front seat occupants in the Whiplash/Vehicle Study (WVS) with those reported by Parkin *et al* (1994) (drivers), and Cullen *et al* (1996) (front passengers). Parkin's figures have been adjusted to allow for the fact that they were measured from the centre of the body of the restraint, as opposed to the front face. No population figures are available for rear occupants.

Table 1.
Occupant Distribution and Average Horizontal and Vertical Head Restraint Measurements.
(Distance measurements are in centimetres)

Seat Position	Sex	Number (WVS)	Horizontal Dist. (WVS)	Population Ave (Hor)	Vertical Distance (WVS)	Population Ave (Vert)
Driver	M	41	10.3	10.1	6.9	10.0
	F	45	9.4	10.1	3.4	10.0
Front Passenger	M	4	10.5	6.6	7.0	8.0
	F	9	7.0	6.6	2.4	4.0

Comparing our sample with the reported population measurements, it is clear that there is a much smaller variation due to seating position, and a larger variation between the sexes. Drivers in our sample had horizontal head restraint distances similar to the population average. Vertical measurements, particularly for women drivers, were smaller than the population average. The smaller group of front seat passengers, on the other hand, were apparently in a more risky situation horizontally, but not vertically, compared to the general population. If horizontal and vertical restraint distances were really correlated with risk of sustaining whiplash injury, one would expect a whiplash sample to display greater average distances than the general population, not the similar or even smaller ones seen in Table 1 for most occupants.

Analysis of Whiplash/Vehicle Study Results

The statistical test used was an Analysis of Variance, using the F ratio. In the following, the threshold of statistical significance is taken to be 5% (95% confidence, $p=0.05$), and such cases appear in **bold** in the tables. In addition, p-values between 0.05 and 0.1, although not meeting this criterion for significance, are quoted in the text where applicable. Each factor was analysed separately because missing values in the dataset would have reduced the sample size dramatically if only cases with complete data had been considered.

Analysis by Average Disability scores: Gender. Average values of the overall disability scores at each of the three assessments were calculated and compared for a number of sample sub-groups. The most clearly unambiguous result to emerge from the analysis was the difference between average disabilities for males and females:

Table 2.
Average Disability vs Gender:

Gender	Number	Average Disability at Assessment...		
		1st	2nd	3rd
Male	64	**2.94**	**1.94**	**1.05**
Female	107	**3.54**	**2.57**	**1.58**

As would be expected, as time passes, people recover from their injuries; this is reflected in the decreasing values of the disability scores at the three assessments (initial, six month and twelve month). However, 57% of the sample still had some degree of disability a year after their accidents, and 10% scored four or more at this stage. Men consistently had lower average disabilities than women, and the differences were significant ($p=0.032$ maximum) for all three assessments. This is despite the observed gender differences as regards distances from head to restraint (Table 1), which should put men at a disadvantage compared to women. The possibility that this result may be due to differences in impact speed are explored in Table 3:

Table 3.
Average Disability vs Gender and Equivalent Test Speed:

Gender	Number	Ave Disability at Assessment...		ETS (km/h)
		1st	3rd	
Male	53	2.91	**0.98**	19.9
Female	87	3.46	**1.64**	19.7

The estimated speeds are almost identical, and the third assessment scores have remained significantly different ($p=0.014$), despite the reduction in numbers. The initial assessment scores now just fail to achieve significance ($p=0.078$). All further analysis was carried out on the male and female subgroups separately.

Analysis by Average Disability Scores: Other Factors. Tables 4, 5 and 6 show average disabilities against a number of other likely influencing factors for the two gender groups. Each category in these tables has also been tested for differences in estimated speeds. No significant differences were found.

Table 4.
Average Disability vs Awareness of Impending Impact and Sex:

Sex	Awareness	Number	Average Disability at Assessment...		
			1st	2nd	3rd
Male	Aware	34	2.76	1.94	1.06
	Unaware	24	3.33	1.96	0.96
	Not known	6	2.33	1.83	1.33
Female	Aware	38	3.42	2.45	1.45
	Unaware	48	3.52	2.50	1.50
	Not known	21	3.81	2.95	2.00

Awareness of impending impact, rather surprisingly, does not seem to be a factor in whiplash injury outcome, with no significant differences between the aware and unaware groups. The "female, awareness not known" group seems to be anomalous, with average scores markedly higher than the other groups, but again the differences were not significant ($p>0.1$).

Table 5.
Average Disability vs Impact Direction and Sex:

Sex	Category	Number	Average Disability at Assessment...		
			1st	2nd	3rd
Male	Rear Impact	33	3.00	1.61	**0.67**
	Not Rear	31	2.87	2.29	**1.45**
Female	Rear Impact	55	3.45	2.53	1.69
	Not Rear	52	3.63	2.62	1.46

Average disability in rear impacts was significantly below that for other impact directions for males at the third assessment ($p=0.02$). But the other trends were not consistent over the three assessments, nor between males and females. This indicates that, for males, the long-term prospects for recovery are worse if they received their injury in a frontal impact. However, if this effect is real, it is surprising that it is not confirmed by the larger sample of females.

Table 6.
Average Disability vs Head Restraint Type and Sex:

Sex	Restraint Type	Number	Average Disability at Assessment... 1st	2nd	3rd
Male	No restraint	2	5.00	1.00	0.00
	Fixed	11	3.45	1.55	0.55
	Adjustable	51	2.75	2.06	1.17
Female	No restraint	12	3.42	2.42	1.58
	Fixed	8	2.50	2.25	1.38
	Adjustable	87	3.66	2.62	1.60

Apart from males at the first assessment, fixed head restraints appear to be better than adjustable restraints, but none of the differences was significant. More surprisingly, the "no restraint" cases were not significantly different from the others, either. Since head restraints are more likely to be beneficial in rear impacts, Tables 7 and 8 show the Head Restraint Type data further subdivided by impact direction:

Table 7.
Average Disability by Headrest Type and Impact Direction: <u>Males only</u>

Imp Dir	H/rest Type	Number	Average Disability at Assessment... 1st	2nd	3rd
Rear	No restraint	2	**5.00**	1.00	0.00
	Fixed	4	**4.75**	1.25	0.25
	Adjustable	27	**2.59**	1.70	0.78
Not Rear	No restraint	-	-	-	-
	Fixed	7	2.71	1.71	0.71
	Adjustable	24	2.92	2.46	1.67

Table 8.
Average Disability by Headrest Type and Impact Direction: <u>Females only</u>

Imp Dir	H/rest Type	Number	Average Disability at Assessment... 1st	2nd	3rd
Rear	No restraint	8	3.00	2.38	1.88
	Fixed	4	2.50	2.25	1.50
	Adjustable	43	3.63	2.58	1.67
Not Rear	No restraint	4	4.25	2.50	1.00
	Fixed	4	2.50	2.25	1.25
	Adjustable	44	3.68	2.66	1.52

In Table 7, adjustable restraints were significantly better than either fixed or no restraints ($p < 0.01$) for males at the first assessment after a rear impact. But every other category of assessment, impact direction and gender in Tables 7 and 8 shows fixed restraints to be better than adjustable, albeit the differences are non-significant. This is also the only category which shows a statistically significant disadvantage in not having a head restraint.

<u>Analysis by Banded Disability Scores.</u> The analysis so far has used average disability scores to test for differences between a number of dichotomous variables (sex, restraint type, impact direction etc). To test for the effect of continuous variables, such as impact speed, seat back height, occupant weight etc, the disability scores were grouped into "low" (score 0-3), "medium" (score 4-6) and "high" (score 7-9) bands, and the average values of the variables under investigation calculated and compared for each disability band. The analysis was carried out on the initial disability scores (first assessment) for the whole sample, then for males and females separately. The whole process was then repeated for the final disability scores (third assessment).

No correlations were found between disability and occupant-related factors, such as height, age, weight, seated height, seat back height or the ratio of seated height to seat back height. Tables 9 and 10 show the data for seat back inclination, equivalent test speed and head restraint horizontal and vertical measurements, for the complete sample at the first and third assessments:

Table 9.
Initial Disability vs Occupant/Vehicle Factors:

	Initial Disability (grouped)						Group Total	
	Low or none		Medium		High		Mean	Valid n
	Mean	Valid n	Mean	Valid n	Mean	Valid n		
S/back angle (degrees)	18.6	98	19.5	52	21.1	9	19.0	159
ETS (km/hr)	19.4	87	19.5	43	24.2	10	19.7	140
H/rest Horiz. Dist.(cm)	9.6	65	9.4	33	9.5	2	9.6	100
H/rest Vert. Dist. (cm)	5.3	65	4.2	33	3.0	2	4.9	100

For the initial disability scores, both seat back inclination and equivalent speed show a monotonic rise through the disability groups, implying that greater values of these parameters are associated with higher disability, though the differences are not significant. For horizontal distance between head and restraint, there is no monotonic trend, while for vertical distance, the trend indicates that lower disability is associated with the restraint being at a greater distance below the ears. This trend is, however, not significant. Splitting the sample into male and female subgroups did not clarify the situation.

Table 10.
Final Disability vs Occupant/Vehicle Factors:

	Final Disability (grouped)						Group Total	
	Low or none		Medium		High		Mean	Valid n
	Mean	Valid n	Mean	Valid n	Mean	Valid n		
S/back angle (degrees)	19.0	143	18.2	15	32.0	1	19.0	159
ETS (km/hr)	19.7	124	20.3	15	16.0	1	19.7	140
H/rest Horiz. Dist.(cm)	**9.9**	92	**5.9**	8	-	0	9.6	100
H/rest Vert. Dist. (cm)	5.0	92	4.1	8	-	0	4.9	100

For the final disability scores (Table 10), seat back angle and equivalent speed are no longer monotonic. Head restraint vertical distance shows a similar trend to that in Table 9, but again, it is not significant. For head restraint horizontal distance, the medium disability group had a significantly smaller mean distance than the low disability group ($p=0.038$). Splitting the sample by gender did not clarify the seat back angle, speed or vertical distance trends. For horizontal distance, the female low and medium disability groups, at 9.5 and 5.4cm respectively, just failed to achieve significance ($p=0.051$), due to the smaller sample size. The male subset showed a similar trend, but with only one case in the medium disability group, the difference was not significant. The direction of the trend for the horizontal distance result, coupled with the fact that these are third assessment scores and there were no significant differences at the first assessment, leads to the conclusion that a large horizontal distance between head and restraint is associated with better recovery from whiplash injury, in contradiction to the results of similar studies conducted elsewhere.

LUMBAR INJURY

Just under half the sample reported lumbar pain continuing for more than a week after the first assessment. The incidence among males was similar to that among females, though males tended to recover slightly more quickly. There was a very slight tendency for rear impacts to carry a higher risk of lumbar injury than non-rear impacts.

The presence of a large proportion of people with lower back strains in the WVS sample could represent a serious complication. The study was based on measuring the overall impairment, or disability, of each patient. In the absence of any clinically observable injuries, this is the only usefully graded variable available which gives a measure of the severity of injury. However, the underlying source of this disability in any individual patient was not known. At the outset, it was assumed that it would be almost entirely due to neck strain injuries, but a lower back injury could also contribute to the overall score, and it would be very difficult to estimate what proportion of disability was caused by each injury.

Factors Influencing the Incidence of Lumbar Injury

Initially, an attempt was made to identify factors which correlated with the incidence of lumbar injury in the WVS sample. The sample was split into those who reported lumbar pain continuing for more than a week after the accident and those who did not. The average values of the "standard set" of vehicle parameters were compared for these two groups, as shown in Table 11:

Table 11.
Incidence of Lumbar Injury:

	Early Lumbar Pain	Number	No Early Lumbar Pain	Number
S/back angle (degrees)	**20.1**	80	**18.0**	79
ETS (km/hr)	20.3	66	19.3	74
H/rest Hor. Dist. (cm)	**10.6**	52	**8.4**	48
H/rest Vert. Dist. (cm)	4.5	52	5.3	48

Seat back angle and horizontal distance to head restraint were found to have a significant effect on the incidence of lumbar injury in this sample ($p=0.032$ and 0.034 respectively), and the trends for these variables were such that the lumbar injury cases were associated with greater seat back inclination and greater horizontal distance from the head restraint compared to the non-lumbar groups. Having said this, it is difficult to see why the distance between head and restraint should have an effect on lower back injuries, when it has no clear effect on the initial severity of the neck strain injuries which the head restraint is supposed to mitigate. One would expect the distance from head to restraint to be correlated to seat back angle and, indeed, it was, although back angle only accounted for 10% of the variation in restraint distance. It may be that this linkage is what is being "discovered" here.

Separation of Lumbar Injury Cases

Because the vehicle factors influencing lumbar injury and whiplash may be different, the sample was separated into those with "pure" whiplash and those who also had lumbar injury. Disability scores were banded, as in Tables 9 and 10 above, and initial disability scores and initial lumbar status were used.

The analysis was carried out for the entire dataset (171 non-leaning forward cases), then repeated for front and rear impacts and for aware/unaware categories (a total of seven selected subsets). The sequence was then repeated for the male and for the female subsets. For conciseness, only those subsets which showed better than 10% significance in one group or the other are presented. These are indicated by italics, while cases showing better than 5% significance are in bold. Seat back angle is measured in degrees, equivalent speed in kilometres per hour and horizontal and vertical head restraint distances in centimetres. Trends in the data are regarded as "sensible" in the discussions if they agree with some reasonable hypotheses. These are that higher disability will be associated with greater seat back angle, higher impact speed, greater horizontal distance between head and restraint and, finally, greater vertical distance of the centre of the head above the centre of the restraint.

Influence of Seat Back Angle In Table 12, trends in the "whiplash only" group were mixed, and none were significant, indicating that seat back angle is not of major importance in pure WAD. In the lumbar groups, several significant results were found, and most of the trends were sensible, particularly for males. Reverse, or counterintuitive, trends were traced to females, and were associated with frontal impacts, and with being aware of impending impact - indeed, the reverse trend was significant for the "Female, Aware, All Impact Directions" group. All trends in the rear impact subset were sensible except for the "Female, Aware" group (non-significant). Seat back angle is thus seen to be important for lumbar injury cases, especially in rear impacts. Awareness of impending impact, which has not been found to influence overall disability outcome, nevertheless has a confounding effect on the seat back angle trends for females with combined lumbar and whiplash injury.

Table 12.
Seat Back Angle:

		Initial Disability Score							
		Whiplash With Lumbar Injury				Whiplash Injury Only			
		0 - 3	4 - 6	7 - 9	p-value	0 - 3	4 - 6	7 - 9	p-value
Full sample, Unaware, All Impact Directions	mean	*18.00*	*21.88*	*25.00*	0.068	17.78	17.00	-	-
	n	15	17	3		18	16	0	
Full sample, Rear Impact, All Awareness	mean	**16.85**	**21.69**	**30.00**	<0.01	18.61	18.65	20.00	-
	n	20	16	1		23	17	1	
Males, All Impact Directions, All Awareness	mean	*18.88*	*23.45*	*20.00*	0.074	17.27	18.33	20.00	-
	n	17	11	1		26	6	1	
Male, Rear Impact, All Awareness	mean	**19.33**	**25.29**	-	0.047	18.15	19.25	20.00	-
	n	6	7	0		13	4	1	
Female, All Impact Directions, Aware	mean	**25.62**	**16.25**	**16.67**	<0.01	19.75	21.86	-	-
	n	8	4	3		16	7	0	
Female, All Impact Directions, Unaware	mean	*17.09*	*19.50*	*27.50*	0.060	18.60	16.25	-	-
	n	11	10	2		10	12	0	
Female, Rear Impact, All Awareness	mean	**15.79**	**19.50**	**30.00**	0.033	19.20	18.46	-	-
	n	14	10	1		10	13	0	
Female, Rear Impact, Unaware	mean	**15.89**	**20.71**	**30.00**	0.047	20.14	15.63	-	-
	n	9	7	1		7	8	0	

Influence of Impact Speed In Table 13, although there were more significant results in the lumbar category, there was no indication that the trend directions were different from the pure whiplash category. Trends generally were mixed. Significant trends in the sensible direction were associated with being aware of the impending impact, particularly for rear impact. Reverse trends were associated with being unaware of the impending impact, again particularly for rear impact. If anything, one would have expected that sensible trends would have been more likely to be associated with being unaware of the impending impact.

Table 13.
Equivalent Test Speed:

		Initial Disability Score							
		Whiplash With Lumbar Injury				Whiplash Injury Only			
		0 - 3	4 - 6	7 - 9	p-value	0 - 3	4 - 6	7 - 9	p-value
Full sample, Aware, All Impact Directions	mean	**16.65**	**15.63**	**31.33**	<0.01	18.52	24.25	28.00	-
	n	17	8	3		25	8	1	
Full sample, Unaware, All Impact Directions	mean	*26.71*	*21.40*	*20.33*	0.093	20.59	17.33	-	-
	n	14	10	3		17	15	0	
Full sample, Unaware, Rear Impact	mean	**27.00**	**21.89**	**21.00**	0.024	20.33	18.82	-	-
	n	12	9	1		12	11	0	
Female, All Impact Directions, Aware	mean	**13.33**	**14.25**	**31.33**	0.036	17.50	23.17	-	-
	n	6	4	3		14	6	0	
Female, Rear Impact, Aware	mean	9.00	10.67	-	-	**11.00**	**24.67**	-	0.014
	n	1	3	0		2	3	0	

Influence of Horizontal Restraint Adjustment In Table 14, two significant (better than 5%) results with sensible trends were obtained, both in the pure whiplash subsets, and both relating to males. The first was in the "All Impact Directions" category, but when this was broken down into front and rear impacts, the frontal impact group remained significant and sensible, whereas the rear impact group showed a reverse trend, which just failed to achieve significance. Generally, in the pure whiplash subset, the horizontal distance trends were counterintuitive for all rear impact categories (male and female), and sensible for all male front impact categories. In the lumbar injury subset, trends were mixed in rear impacts, but males continued to show sensible trends in all frontal categories, with one of these nearly achieving significance. Since head restraints are expected to be most beneficial in rear impacts, these results are difficult to interpret.

Table 14.
Horizontal Distance to Head Restraint:

		Initial Disability Score							
		Whiplash With Lumbar Injury				Whiplash Injury Only			
		0 - 3	4 - 6	7 - 9	p-value	0 - 3	4 - 6	7 - 9	p-value
Full sample, All Awareness, Rear Impact	mean	10.64	12.00	-	-	*11.06*	*6.83*	-	0.063
	n	14	13	0		17	6	0	
Male, Aware, All Impact Directions	mean	9.67	9.33	-	-	**7.17**	**14.00**	-	0.025
	n	9	3	0		12	2	0	
Male, All Awareness, Front Impact	mean	*0.00*	*12.00*	-	0.057	**5.67**	**14.00**	-	0.019
	n	2	2	0		6	2	0	
Male, All Awareness, Rear Impact	mean	12.80	14.20	-	-	*13.10*	*4.00*	-	0.078
	n	5	5	0		10	1	0	

Influence of Vertical Restraint Adjustment In Table 15, no clear pattern emerged between lumbar and non-lumbar categories, and no results were significant at better than 5%. Trends were mostly in the reverse direction, except for the male, non-lumbar category, where two sensible trends approached significance, possibly associated with being aware of the impending impact. However, lumbar injury females generally showed reverse trends, one of which approached significance, associated with being unaware of an impending rear impact. Since head restraints should be most beneficial in rear impacts, it is strange that the only near-significant result relating to rear impact was for a reverse trend.

Table 15.
Vertical Distance to Head Restraint:

		Initial Disability Score							
		Whiplash With Lumbar Injury				Whiplash Injury Only			
		0 - 3	4 - 6	7 - 9	p-value	0 - 3	4 - 6	7 - 9	p-value
Male, All Awareness, All Impact Directions	mean	6.23	5.62	-	-	*7.10*	*11.33*	-	0.066
	n	13	8	0		21	3	0	
Male, Aware, All Impact Directions	mean	6.44	3.67	-	-	*6.75*	*12.00*	-	0.079
	n	9	3	0		12	2	0	
Female, Unaware, Rear Impact	mean	*8.75*	*2.83*	-	0.079	1.80	2.33	-	-
	n	4	6	0		5	3	0	

The Horizontal Distance to Head Restraint Problem:

The only previous study known to have examined in detail a whiplash-injured population from real-world accidents, including medical follow-up and anthropometric measurements of the actual victims sitting in the cars that they were injured in was conducted by Olsson *et al* (1990). However, a major difference between Olsson *et al*'s study and ours is that our study was not limited to one make of vehicle - we had 53 different makes and models of vehicles, with a vast range of masses, structural designs and stiffnesses. Olsson *et al*, concentrating on a single make of vehicle (Volvos) produced a statistically significant result from only 33 subjects indicating that a horizontal distance from head to restraint of greater than

10cm was associated with increased severity of whiplash injury (severity was equated with longevity of symptoms). Their results have been used as a criterion for whiplash injury risk, either explicitly or implicitly, in a large proportion of the literature which has been published since.

In addition to the analysis presented above, strenuous efforts have been made to try to confirm the results obtained by Olsson *et al* regarding this 10cm horizontal distance threshold. Differences between average disability scores at each of the three assessments for the "no restraint" group and for the groups with head to restraint distances less than 10cm and greater than 10cm were sought with the data sub-divided by lumbar status, and taking into account impact direction, awareness of impending impact and gender (22 different subsets), and each of the three assessment scores was tested for each subset. The results may be summarised as follows:

Of 66 comparisons of average disability figures, in only 24 cases was the average disability at small distance to the head restraint less than that at large distance, in agreement with Olsson *et al*. In only one case did the difference between the restraint distance figures even approach significance, and that indicated that small distance was associated with *greater* disability, in contradiction to Olsson *et al*. It is also interesting that absence of a head restraint was only found to have a significant effect in two out of 66 comparisons.

SUMMARY OF FINDINGS

1. The results of this study were characterised by very large scatter, making it very difficult to pick out trends. This was compounded by missing data, due to the fact that it was not always possible to calculate an impact speed for the vehicle, and to the failure to obtain head restraint measurements for some occupants. Nevertheless, the sample available was considerably larger than that in any previous comparable study.
2. No discernible medical differences could be found between those involved in rear impacts compared to other impact directions.
3. The majority of the sample were drivers, and their average vertical restraint distance measurements were at least 30% smaller than those reported from observational studies of the general population. This is surprising, in a sample selected for neck strain injuries.
4. No correlations could be found between disability and seat back height as a proportion of occupant seated height, occupant age, height or weight. The non lumbar-segregated sample also showed no correlation between disability and awareness of impending impact or impact speed.
5. Significant gender differences were found, with men having lower disability than women ($p<0.032$). This is despite the ostensibly more favourable situation of women as regards vertical restraint positioning relative to the head, due to their smaller average stature. Women were not found to be more prone to lumbar injury than men.
6. People who had been actively leaning forward at the time of impact had significantly lower disability scores than the rest ($p<0.01$), and had to be excluded.
7. Comparison of restraint types produced inconsistent results. Adjustable restraints were significantly better than fixed restraints or no restraint for males in rear impacts, at the first assessment ($p<0.01$). However, second and third assessment scores for men, and all scores for women, showed that fixed restraints were (non-significantly) better. In general, very few comparisons showed a significant disadvantage in not having a restraint.
8. Comparison of impact directions also produced inconsistent results. Long-term disability outcome for males was found to be better after a rear impact ($p=0.02$), in contradiction to findings elsewhere, but the larger sample of females did not support this.
9. Horizontal distance from head to restraint had no effect on initial disability scores; a significant, but counter-intuitive (ie greater disability at smaller distance) effect was found for the third assessment scores in the overall sample ($p=0.038$). No significant effect was found for vertical restraint adjustment, though non-significant trends indicated that high restraint position was detrimental.
10. Segregating the sample by lumbar injury status revealed that large seat back angle was significantly associated both with incidence of lumbar injury in this sample ($p=0.032$) and with higher disability for those who suffered lumbar injury, especially in rear impacts ($p<0.01$ for the combined male and female sample), although awareness of the impending impact tended to have a confounding effect for females (reverse trend, $p<0.01$). Seat back angle was not important for non-lumbar cases.
11. Impact speed in the lumbar segregated sample showed inconsistent trends, very few of which were significant. Significant sensible trends (ie higher speed giving higher disability) were associated with being aware of impending impact and with rear impact; significant reverse trends were associated with being unaware of impending rear impact.
12. For horizontal restraint adjustment, sensible trends (ie small distance giving low disability) were found for males in frontal impacts in both pure whiplash ($p=0.019$) and lumbar (non-significant) subsets. The pure whiplash subset consistently showed reverse trends for all rear impact categories, though none were significant. No clear picture emerged as regards vertical adjustment.
13. Despite an exhaustive search of the data, including segregation by gender and lumbar injury status, no evidence could be found to support findings elsewhere that a horizontal distance between head and restraint of 10cm marks the threshold of the onset of long-term disability as a result of neck strain injury. Indeed, most of the trends ran counter to this hypothesis.

Our study did not address the incidence of Whiplash Associated Disorders, only the severity of a whiplash injured population. However, measures found to reduce injury severity normally also have a beneficial effect on incidence. Conversely, if a measure fails to have an influence on severity, its efficacy in relation to incidence must be questioned. We have found it all but impossible to find any benefits in terms of injury severity in the current ideas on how people should be encouraged to use their seats and head restraints. Apart from a few isolated sub-groups, people who conformed to the current received wisdom as regards head restraint adjustment were, at best, not found to be significantly different from those who did not. Frequently, they were found to be worse off. Further, the beneficial effects of "good" head restraint adjustment, where they occurred, tended to be concentrated in frontal impacts, where occupant kinematics make it difficult to see why a head restraint should have any effect at all. Certainly, head restraints were never designed with frontal impacts in mind.

A possible source of error in the results is the head restraint distance measurements themselves. These relied on the memories and good faith of the occupants who demonstrated their seating positions. All demonstrations took place within a few days of the accident, so memory should not have deteriorated. As regards good faith, the victims were all assured that the study was not related to any police or insurance company investigation, so as to encourage them to be as truthful as possible in their responses. There remains the possibility that, due to their injuries, some people were unable to adopt their normal, pre-accident posture, despite valiant efforts. However, to account for our results, there would have to be a trend for injured people to demonstrate a position closer to the restraint than they had adopted pre-accident, and for this trend to be greater for more severe injury. In the final analysis, this study (as did that of Olsson *et al*) had to rely on the truthfulness of the participants.

A further possible criticism is that, when the sample is disaggregated by gender, impact direction etc, some of the more controversial results do depend on significant differences between very small groups. However, while agreeing that statistical significance does not necessarily imply causation, it should be pointed out that significance testing does take sample size into account. It should also be borne in mind that, to make the results of this study non-controversial would require the majority of the trends observed (non-significant as well as significant) to be reversed.

DISCUSSION

If rearward hyperextension is, in fact a mechanism for whiplash injury, then a well-adjusted head restraint should counteract this, and our study should very easily have picked this out. The fact that our results generally did not show any benefit in being close to the restraint (in rear impacts, where hyperextension is most likely) could, of course, be accidental - even statistical significance does not necessarily imply absolute truth. But, while we do not advocate the wholesale removal of head restraints from vehicles, we do believe that something is happening which is not easily explained, and that the situation, and its possible solutions, deserve to be approached with an open mind. Two possible sets of tentative conclusions can be drawn from our study:

i. Rearward hyperextension is not a major factor in the mechanism of whiplash injury
ii. Whatever the real mechanism is, head restraints are not counteracting it, and the whole approach to the problem needs to be reconsidered

Alternatively (bearing in mind the wide range of vehicles in our study):

i. Other factors, such as vehicle mass and structural design (which affect the crash pulse experienced by the occupant) and the design and resilience of the seat back are so important that they completely mask the effects of restraint adjustment
ii. If these other factors are so important, then this implies that the car you drive may be more important than how you adjust your head restraint. The possibility that, given an identical car in an identical accident, a "well-adjusted" head restraint will result in less severe injury than a badly adjusted restraint cannot be excluded on the basis of our results but, if such an effect is present, then it is completely swamped by these other factors. The WAD "epidemic" is thus unlikely to be stemmed until whiplash injuries are taken into account in the design and construction of the vehicle and the seat

These two sets of possibilities are, of course, not mutually exclusive.

The Mechanism of Whiplash Injury

Returning to the problem of the mechanism, this must take account of the fact that whiplash injury can occur in frontal impacts, that it has been found to be associated with seat-belt use (Otte and Rether, 1985, Galasko *et al*, 1993) and that its incidence has increased despite the widespread introduction of head restraints (whether "properly adjusted" or not).

The Frontal Impact Mechanism Von Koch *et al* (1995) proposed that the prime injurious event is the forward flexion of the neck caused, in frontal impacts, by the sudden deceleration of the torso by the seat belt. In rear impacts, modern strong, resilient seat backs can cause the torso to rebound violently, again to be suddenly decelerated by the seat belt. Krafft *et al* (1996) found evidence to support this view. We feel it is possible that the use of head restraints with different force/deflection characteristics from those of the seat back could exacerbate this rebound problem by giving the head a different rebound acceleration from the torso. This effect could be more pronounced if adjustable head restraints with very slim supports are extended to a high vertical position; the opposite effect could result from the use of very springy seat back cushioning combined with dense, energy-absorbent foam in the head restraint. The latter case was considered by Spitzer *et al* (1995).

Rear seat occupants have been found to be at significantly lower risk of sustaining whiplash injury than front seat occupants (Carlsson *et al*, 1985, Lövsund *et al*, 1988), despite the fact that the rear seat occupants in these studies did not have head restraints. There were insufficient rear seat occupants in our study for meaningful comparisons to be made, but we feel that it may be significant that one of the differences between front and rear seats is that rear seat backs are much more rigidly attached to the vehicle. The crash pulse experienced by a rear seat occupant in a rear impact therefore tends to be more severe than that experienced by a front seat occupant in a seat with a resilient back, and head rotation, without a head restraint, is likely to be much greater. The rebound from the rear seat, however, will be much less dramatic.

Frontal Mechanism: Implications for Seat Design Some method of preventing seat rebound therefore seems likely to be desirable. Foret-Bruno *et al* (1991) found that collapse of the seat back in a rear impact generally had a beneficial effect on neck injury outcome, and others have reported similar findings (Muser *et al*, 1994, Walz and Muser, 1995, Parkin *et al*, 1995, Morris and Thomas, 1996). Given that seat back breakage is undesirable in terms of preventing serious injuries in severe rear impacts, Von Koch *et al* (1995) suggest that seats should be designed to undergo controlled plastic deformation in rear impacts, though the presence of rear occupants must also be considered. Another possible solution which has not, as far as we are aware, been proposed in the literature, may be to fire the seat belt pretensioners in a rear impact. This should prevent occupant rebound, though an automatic slow release mechanism may be necessary to prevent the occupant being pinned between a tensioned belt and a tensioned seat back.

The Aldman Mechanism A second alternative mechanism for whiplash injury was proposed by Aldman (1986). In this scenario, the most harmful event occurs early in the motion sequence, when the occupant's head is moving backward relative to the shoulders, and in the very early stages of head rotation. This produces shear forces, especially in the uppermost vertebrae, as the neck distorts into an s-shape, and this can also happen in frontal impacts (Walz and Muser, 1995). The transition from the s-shape to the extension mode involves a sudden change in the volume of the spinal canal, and it has been proposed that the pressure gradients induced by the sudden and rapid flow of blood and spinal fluid along the canal and through the associated transverse vessels can result in damage to the spinal ganglia (Boström *et al*, 1996).

Aldman Mechanism: Implications for Seat Design Prevention of the injury, if this proposed mechanism is sound, would involve limiting head movement relative to the torso to an even greater extent than that required to prevent gross hyperextension. The above proposals for reducing seat rebound by allowing controlled movement of the seat back could be counterproductive here, in that there could be a temptation to design the seat back force/deflection curve to be steeper than that of a conventional resilient seat in the early stages, in order to reduce intrusion into the rear passenger space, or to prevent activation of the plastic elements during normal use. This could result in the force exerted on the torso by the seat back, and hence the acceleration of the torso relative to the head, being higher in the early stages of motion, compared to a resilient seat back. A possible solution would be for the seat back to allow the torso to move backwards relatively unimpeded into the cushioning, so that the head can maintain the same orientation relative to the torso, until the head is in contact with the head restraint. From this point on, the acceleration imparted by the head restraint to the head should be the same as that imparted by the seat back to the torso; soft cushioning on the head restraint would not be compatible with this requirement unless the head is allowed to sink through this before significant acceleration force is applied to the torso. The head restraint must also not flex relative to the seat under loading by the head. The acceleration force, applied uniformly to the head and torso, could probably be quite large, but the corresponding deformation of the seat back must occur plastically, not elastically, so as to prevent rebound at the end of the impact sequence.

Prevention of Lumbar Strain Injuries

The foregoing, it is believed, should provide good protection against whiplash-type neck injuries, but what of the rest of the spinal column, particularly the lumbar region which, like the neck, does not benefit from the bracing effects of the rib-cage structure? It is felt to be likely that, if the shape of the underlying seat back structure, in the sagittal plane, is different from the shape which the spine happens to be in at the moment when the torso meets this unyielding structure, then large forces will be exerted on localised regions of the spine, forcing the spine to flex rapidly until it adopts the shape of the underlying structure. Our finding that lumbar strain injury is correlated with seat back inclination may be explained by such a differential loading mechanism, since it is highly likely that, if the seat back is greatly inclined, then the gap between the shoulders and the seat back will be greater than that between the lumbar area and the seat back. In a rear impact, therefore, the lumbar area will experience localised acceleration forces before the upper back. However, another mechanism which could come into play here may be the stretching of the spine axially. This could come about due to the torso being inclined from the vertical and the likelihood that the pelvis will accelerate much more rapidly than the torso in the horizontal direction due to higher friction between the pelvis/thigh area and the seat.

In frontal impacts, lumbar spine injuries have been shown to be associated with use of lap belts, due to flexion of the torso, while the pelvis is held relatively static (Nahum *et al*, 1968). With a three-point belt, rebound from the belt will result in the occupant impacting the seat back in much the same way as he does in a rear impact and, if the seat back is inclined, he will experience the same localised loading of the lumbar region. This "secondary" contact with the seat back from a frontal impact will be much milder than would be the case in a rear impact of equivalent severity. However, in practice, frontal impacts generally tend to be more severe than rear impacts, so the risk of lumbar strain injury to an individual may be poorly correlated with impact direction. In addition, it is likely that an occupant wearing a three-point belt will acquire some rotational motion relative to the pelvis and thighs in the early stages of the impact, as the unrestrained shoulder moves further forward than its partner. As the occupant rebounds from the belt, this rotation will continue until it is damped out by contact with the seat back. An occupant with a highly inclined seat back is therefore likely to achieve a much greater angular displacement of the shoulders relative to the pelvis/thighs before the rotational motion is curtailed, and this, too, is likely to be bad for the lumbar spine. Thus, regardless of impact direction, a highly inclined seat back may be a predictor of lumbar injury risk, as we found in our study.

The first step in counteracting these lumbar strain injuries, therefore, is to discourage vehicle occupants from adopting excessively "laid back" seating postures. This message may be poorly received by some front seat passengers, but in terms of alertness and ability to control the vehicle a reasonably upright posture in drivers is probably desirable anyway. However, some very tall drivers have to incline their seats to keep their heads clear of the roof, and it is understood that very short drivers are being advised to increase the seat back inclination in order to increase their distance from the driver's airbag, because of the injury risk which these devices pose in low-speed impacts.

The second, and more difficult, step is to improve the anthropomorphic characteristics of the underlying seat back structure. It may be that the range of shapes adopted by real people's backs when seated will preclude the specification of a single preferred shape for the metal seat back frame structure, in which case the problem would have to be addressed by the use of foam structures of progressively increasing stiffness between the "comfort cushioning" and the supporting framework, so as to avoid a situation where localised sections of the spine are, at any one time, in contact with much harder structures than adjacent areas of the back.

CONCLUSIONS

1. We were unable to demonstrate any beneficial effect from being close to the head restraint. Three possible reasons for this have been considered:
   i. Some injury mechanisms are not being addressed by current head restraint designs.
   ii. Variations in vehicle mass and stiffness and seat design, particularly resilience, are so important that they totally mask the effects of restraint adjustment. This leaves open the possibility that, given an <u>identical</u> car in an <u>identical</u> accident, a "well-adjusted" head restraint will result in less severe injury than a badly adjusted restraint.
   iii. It is possible that the results have been influenced by the difficulties experienced by injured people in reliably demonstrating their seating positions.

2. Lumbar strain injuries seem to be associated with seat back inclination. Our thoughts on possible mechanisms and remedies have been presented.

3. There is an urgent need for clarification of the mechanism of these neck and back strain injuries, as well as for the development of good mathematical models of the spine and much more biofidelic dummy spines than are currently available.

4. TRL are currently following up the study here presented with a similar study, concentrating on lumbar strain injuries, and with work on mathematical modelling and dummy spine development.

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REVIEW OF VEHICLE MEASURES FOR REDUCING ACCIDENTS AND INJURIES

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ABSTRACT

This paper outlines possibilities for improvements to vehicle design that would reduce the occurrence of collision and the severity of injuries from accidents on the roads. It highlights vehicle safety measures which are believed to hold the greatest benefit at the current time. These proposals for the way forward relate to conditions in the United Kingdom and to a lesser extent in the European Union. The views given are those of the Parliamentary Advisory Council for Transport Safety (PACTS) rather than those of the individual members of its Vehicle Design Working Party who initiated and contributed to the study on which this paper is based. For the purposes of this paper, the various measures are only described in outline, but references to further information on specific issues are available separately on request from PACTS.

INTRODUCTION

PACTS (the Parliamentary Advisory Council for Transport Safety) is a British organisation which forms a link between those professionally employed in transport safety and Parliamentarians and government departments. Its Vehicle Design Working Party is reviewing the vehicle factors which contribute to the occurrence of road accidents and the resulting injuries. This review has two aims: firstly to check the extent to which current accident data and analyses are adequate for these tasks and secondly to review what the existing studies suggest for the next stage in improvements to vehicle design for safety. This paper is a summary of the findings for this second aim. For each category of road vehicle, accident avoidance and injury protection are discussed separately and this is followed by overall conclusions and recommendations for action. Full discussions for each safety issue are not included because of the need for brevity, but references on which the current review is based can be obtained from PACTS (St. Thomas' Hospital, Lambeth Palace Road, London SE1 7EH, UK).

CARS

Included with cars are recreational vehicles, people movers and two-axled four-wheel drive vehicles. Vans and light goods vehicles are intermediate between cars and heavy goods vehicles as far as appropriate safety features are concerned and it is usually obvious which type of safety feature is suitable.

Accident Avoidance

Braking - Although brakes work reliably for quite long periods of time, they may suddenly fail in some respect especially if they are not properly serviced. Wet or icy weather may lead to loss of grip between the tyres and the road. The car may then slide, drift or spin and may not stop in time to avoid an accident. One extreme case occurs when roads are flooded and one or more wheels aquaplane. Another extreme circumstance is gross overloading at the rear which may lead to unexpected front wheel lock on braking and consequential loss of steering control. Anti-locking brake systems (ABS) can prevent or alleviate most of these situations. An obvious requirement is for the fitting of ABS to become compulsory. However accident evidence suggests that ABS has not been very effective in reducing accident rates. Detailed work suggests that this is not just a risk homeostasis effect, but includes drivers who do not brake hard enough to activate ABS and also ABS-fitted cars struck in the rear by other cars not so fitted. Instructions and training must be developed to match up with any requirement to fit ABS more generally. Another possibility is that powerful old cars may be put to the test by enthusiastic young drivers but the ABS may no longer be working.

Handling - Most recently designed cars have good safe handling up to extreme handling conditions and even then most are satisfactory. However drivers do lose control of cars in accidents which have not involved using the brakes. Accident studies show that drivers may take quite inappropriate actions when faced with emergencies, most typically by steering to avoid an obstacle just ahead but not reversing the steering a moment later in time to remain on the road. More expensive cars may be fitted with a wide range of different electro-mechanical systems from traction control to systems which cut the response to excessive steering demands or control incipient rollover and keep the car fairly level. At present these devices are expensive but costs will soon reduce. However it would be sensible to train drivers to cope better in emergencies.

Drivers' View - Most drivers are aware of limitations in their field of view, often when other vehicles seem to appear suddenly close by. Drivers who are short in their height of body have the greatest problems and it is suggested that seats adjustable in height are fitted to all modes of car with a poor field of view for short people. Widths of the A posts should be reconsidered, particularly close to the lower edges of highly raked windscreens. An improved field of view should help drivers avoid cyclists and pedestrians in some critical situations. Dirty, misted and frosted side windows as well as windscreens have been noted as contributors to accidents. The blind spot of most offside mirrors, which is apparent when merging into motorway traffic lanes, can be eliminated by bending or distorting one of the vertical edges of the mirror. The basic field of view problems are likely to be more important than many other problems that currently receive great attention.

Conspicuity and Lights - No recent data seems to be available on the influence of colour on conspicuity and consequently on accident involvement. White and very light colours may be the best, but yellow shows up well and dark colours may score by their contrast. Grey and dull colours are inconspicuous in dull and misty conditions. Lights compensate for deficiencies in conspicuity and automatic switching on of them may be sensible. Daytime running lights appear to reduce accident rates and although the evidence is still in dispute there is probably a good case for them in, for example, the northern countries of Europe. Vulnerable road users would probably gain from their use on cars because pedestrians and cyclists sometimes do not notice cars which are approaching them.

Rear Lights - Reconsideration of light arrays includes the separation of rear position and brake lights. The main issue is to ensure following drivers can distinguish between types of rear light and therefore take appropriate action. Motorway driving conditions illustrate these two different functions of rear lights most clearly. The use of Centre High Mounted Stop Lights is increasing and may help in this regard. A new standard is needed which alerts drivers to the need to avoid slow moving, stopped and parked vehicles in a consistent manner.

Warning and Control Systems - Cars have increasing numbers of electro-mechanical devices with sensors providing the inputs and actuators providing the appropriate powered output. Strictly, telematic devices include a communications link between the remote sensors and the devices. Apart from engine and environmental control measures, there are handling control modification devices which have already been discussed. There are also many possible types of driver warning systems. Those that monitor driver fitness to drive (due to drowsiness, alcohol, drugs, etc.) are potentially the most important for safety once the sensors work satisfactorily. Systems which enhance vision may have some value but trials and experience will show their potential.

External speed control linked to in-vehicle systems may prove to be valuable for improving traffic flow as well as enhancing safety. The simplest type is the maximum speed limiter as used on coaches and other vehicles. The next stage is to transmit the local speed limit to the limiting device on the car. External beacons can readily do this, but tamper proof systems are essential. The safety value might be greatest for reducing pedestrian and cyclist collisions with cars. A sophisticated system of local speed limits which further reduces the maximum speed very locally according to potential dangers of traffic, weather and other hazards ahead might have the most beneficial effect on safety, but the system would need some development. This would include pilot trails to find how drivers adapt to such a system in the longer term. It might prove to be less unacceptable to drivers than just having stricter local speed limits.

Control of cars within a traffic flow is also being developed in several different forms. Possibly the most effective, but also the most difficult, would be intersection control. Finally there is the automatic control of vehicles into streams with minimal spacing and without the need for drivers. Early systems already exist and the best initial application may be the long distance transport of goods.

Maintenance, Repair and Inspection - As vehicles become more complicated, the maintenance of them in safe working order will demand more sophisticated techniques. One great challenge will be the supervision of vehicles when they become old and systems in them fail much more frequently. Experience gained with ABS in service may suggest the best approach. Legal blame for accidents may prove impossible to assess. Contributions may come from the driver, the basic braking and handling, the ABS and the system modifying the handling response. The output from black boxes to record operating conditions at the time of accidents may need expert interpretation.

Injury Protection

Frontal Impact - Design to meet the EuroNCAP offset frontal impact conditions is proceeding. The problem areas seem to be the collapse of footwells and neck injury. The belt improvements with pretensioners and webbing grabbers combined with airbags seem to work effectively. Permitting the car structure to compress below the passenger compartment, rather than into it, is another advance.

Side Impacts - Design development to meet the latest tests is continuing. Measures are needed to prevent those on the far side from the impact from being thrown sideways into the debris and consequently being injured. Releasing belt pretensioners in side impacts may prove to be effective, particularly if front seat designs can be modified to assist in retaining the occupants. The near side occupants must be able to slide towards the far side, but those on the far side must not come adrift from their belts. The avoidance of head impacts into side structures is another current problem.

Rear Impacts - Correct positioning and redesign of head restraints should reduce neck injuries. It may be possible to reduce the sliding of occupants under their seatbelts and this may also be assisted by releasing belt pretensioners early on in rear impacts. Rear seats need head restraints for adults.

Seatbelts - In the UK, current challenges include persuading rear occupants to wear the belts provided for them. In other countries wearing rates are also low in the front of cars. Design for greater convenience may still be possible, and widespread provision of three point belts in the centre rear position is required.

Seats - Development is needed as already indicated. The rears of front seat backs need padding to help rear occupants, and in particular to prevent knees being thrust into the backs of belted front occupants.

Padding of Internal Structures - The measures suggested above may reduce head impacts into the roof, headers and cant rails. However, improvements in roof design should provide what is effectively padding for head impacts which cannot be provided in other ways.

Steering wheels - Those cars without driver airbags must incorporate energy absorbing components in their steering wheels. Some padding is needed for those steering wheels incorporating airbags for head impacts at just below the minimum speed set for firing the airbags in crash impacts.

Child Restraints - ISOFIX locations for child restraints in rear and front passenger seat positions should be fitted as soon as standardisation discussions permit. Design groups may be able to show that upper tethers which provide a further point of attachment are not essential.

Airbags - Accident evidence on the performance of European airbags is needed before detailed improvements can be considered. There may be a case for modifying the bags to reduce injuries to small people, those positioned close by the bag and young children in rear facing child restraints. The performance of airbags is much reduced when the impact is sufficiently angled for the occupant to be flung along the edge of the bag.

Door Latches - Tighter requirements for door latches up to the standards reached by most, but not all, models of car may be needed.

Compatibility - Much research is in progress and so it may be timely to restate the basic ideas. Compatibility of structures of different vehicles at the point where they impact each other should be matched in terms of stiffness of crush. They should be arranged so that they crush each other and do not slide past (except where intended) and do not penetrate each other without absorbing the intended amounts of energy as they crush. The basic crush stiffness of compatible front structures should closely match the first 700mm or so of the fronts of small cars whether fitted to goods vehicles, coaches or cars of any size. The sides and rears of all large vehicles should match up with the proposed extended fronts, whether they be side guards, rear underrun bumpers or the panelled structures of public service vehicles. The basic intention of using compatible structures is that small cars should be given the benefit of the maximum possible depth of crush in a frontal impact so that there is a reduced level of intrusion and a softened deceleration pulse. In other words the larger vehicle provides part of the increased depth of crush that the small car can use.

It may be possible to design the compatible nose section so that when it impacts a car in the side of the passenger compartment it does so sufficiently low down for the side impact performance of the car to be greatly improved.

Pedestrian and cyclist protection - The three component tests for pedestrian protection being addressed within the EU and by EuroNCAP are designed to provide basic protection for pedestrians struck by cars at the front bumper, front structure and bonnet areas. The latest studies suggest that this protection can be provided for a typical new design of car at a total cost which is well below five times the monetary value of injury savings to pedestrians. These costs are an acceptable price to pay. Accident studies show that the heads of adult pedestrians are likely to strike the A posts, header rails and windscreens of cars. Design developments are now needed to provide some level of protection in this area of car fronts as well as lower down. Cyclists should also experience some protection from these advances in design.

Conclusions and Recommendations

Although ABS has considerable potential, it so far has not been shown to reduce accident rates. Improved driver behaviour and training in the use of ABS may be helpful. However, in view of its characteristics and cost it may be sensible not to require it for cars with low power to weight ratios. Similar considerations apply to the various aids to safe handling.

A review of driver fields of view to somewhat tighten requirements would be appropriate. In particular A posts should be reconsidered. Daytime running lights may have benefit particularly for the countries of northern Europe. Alternatively a simple system to switch on running and position lights automatically in conditions of poor visibility might be more acceptable. A rethink of how to meet all the different requirements for rear light arrays in a logical manner is overdue. A simple electronic system to switch on suitable rear lights when a vehicle is approaching from the rear on a potential collision course may be helpful.

Telematics and electro-mechanical systems which might most greatly benefit safety are those that monitor driver condition, warnings of hazards, speed limiters linked to roadside sensors, intersection crossing aids and systems to eliminate the need for drivers on segregated tracks or lanes. The safety contribution of all telematic devices for cars must be carefully checked by pilot scale trials and experience in service.

The review of injury protection measures suggests that detailed redesign of seats, head restraints and footwells is needed to address situations causing injury. This may include pretensioning seatbelts in side and rear impacts. ISOFIX mountings for child restraints and more convenient rear belts are both needed improvements.

Further research and development into compatible front bumper structures for all vehicles should continue, keeping the various different aims in mind.

The three component tests for pedestrian protection on car fronts must be made into EC Directives. Further research is needed to extend protection at A posts, headers and side rails to reduce head injuries to adult pedestrians and cyclists.

COACHES, BUSES AND MINIBUSES

Coaches and buses are noteworthy for their low rates of occupant casualties, especially fatal casualties. If it were not for their being public service vehicles, it might have been possible to rate safety improvements for them at a low level of priority compared with that needed for other vehicles. However certain improvements, suggested by accident investigations, do seem to be possible and hence to be appropriate. Most noteworthy is the need for protective features for pedestrians, and to some degree cyclists, who are struck by them mainly on urban roads.

Minibuses come between buses and coaches on the one hand and cars and people movers (cars with up to eight passengers) on the other. Minibuses have traditionally been derived from vans, but are now becoming more satisfactory from an injury protection point of view. Their standard of interior design and trim for safety is also improving towards that typical of cars and coaches.

Accident Avoidance

Braking - Coaches and minibuses can have large variations in fore and aft positions of centre of mass and so the maintenance of stability when braking is not certainly achieved without electronic control of their brakes and the contribution of ABS. This is less important for buses because they are effectively restricted to relatively low speeds, mostly on urban roads.

Stability and Handling - Stability and handling when not braking seem to be minor problems. This partly stems from the high standards of resistance to rollover resulting from the tilt test requirements in the UK. However rollovers do occur and cause fatal and serious injuries which could be readily prevented by the wearing of seatbelts.

View from Driving Seat - As for large trucks, some pedestrian and cyclist accidents occur when a bus or coach driver does not see these road users immediately ahead and moves off from rest. Good all round vision is needed for all sizes of driver.

Speed limiters - The limitation of maximum speeds has proved to be technically feasible in coaches, although accidents are so few that detailed evidence of the safety consequence is lacking. There may be a special case for limiting the maximum speed of minibuses if their handling and braking performance is inadequate at higher speeds. The universal limitation of bus speeds down to a suitable maximum speed for urban use may be worth consideration.

Conspicuity - All vehicles larger than cars might usefully have high level lights to supplement those already required.

Injury Protection

Pedestrian Protection - It is surprising that some degree of protection for pedestrians struck by the fronts of these vehicles has not been developed. This is an urgent task because buses and coaches on urban roads cause a significant number of pedestrian casualties and a half of the road users killed by these vehicles are pedestrians. Currently frontal designs are much too rigid where pedestrians are likely to be struck and the indications are that these fatalities often occur at low speeds. Minibuses and people mover cars may require similar protective features much more like those needed for buses and goods vehicles than for cars.

Compatibility - Frontal structural designs to match those of cars and all other vehicles that may be struck by coaches and buses are needed in the slightly longer term. Apart from helping to reduce car occupant casualties, the low front bumper structures would help to reduce intrusion into the driving position of coaches. Being relatively small, minibuses need the extra protection that compatible front structures would provide.

Seat and Interior Design - There is a good case for going somewhat beyond the three current EC Directives 96/36, 96/37 and 96/38, which will require that retractable lap belts be fitted in all new coaches from 1999. Seats should be designed to be more protective when struck by passengers and also they should withstand loadings from both their own belts as well as from unrestrained passengers thrown into them from behind. Minibus seating is not always of a satisfactory level of design for safety. It should incorporate lap and diagonal belts which are retractable and this will be required in new minibuses from 2001. Bus seats should have suitable shape, cant and coverings so that passengers should not slide off them during emergency braking. Bus interiors need all the other components to be less injurious for standing passengers who fall as well as for seated ones who come adrift during emergency braking. Bus interior layouts are now being designed to meet standards which reduce risks to passengers boarding and alighting as well as when they are moving around the bus.

Conclusions and Recommendations

The overall safety record of buses and coaches is relatively very good with the exception of accidents involving pedestrians. It is most important that detailed studies are put in hand to find out how to provide some protection for pedestrians struck by buses and to a lesser extent coaches. This should lead to the development of component test procedures to check the suitability of frontal designs. This work will also be applicable to the front faces of goods vehicles and flat fronted people mover types of car. The coming of low front bumper compatible structures on public service vehicles will mean that studies should include procedures to suit this modification of frontal designs.

Coaches should be fitted with electronic braking systems including ABS. The overall safety of minibuses is not known with any precision but improvements are needed to seats, detailed interior design and most of the features proposed for cars.

TRUCKS AND HEAVY GOODS VEHICLES

These comments apply to all goods vehicles which are larger than cars. Heavy goods vehicles usually cause many more casualties in other vehicles, and to pedestrians and cyclists, rather than to their own occupants when there are collisions between them. Consequently many of the injury protection items relate to those for other road users.

Accident Avoidance

Braking - The main current emphases are on the various electronic control systems such as ABS, electronic systems to balance the braking and the timing of the braking between the various axles and wheels, and related systems such as for traction control and for the maintenance of stability and control when control is being lost. For these categories of vehicles, ABS and brake balance systems are the most important and regulations to require them are appropriate once they are proved to be operationally satisfactory with suitable maintenance and diagnostic support.

View from the Driving Seat - A current study in the UK is reviewing the problem of drivers not seeing pedestrians immediately in front of them and cyclists not being seen when at the front nearside corners of large vehicles. These are largely urban traffic problems which arise when the vehicles are starting to move away after having stopped. Alarms are already in use to alert those positioned just behind large vehicles when they are ready to be reversed. The driver's view along the nearside may be poor although mirror systems are usually adequate and in any case the consequences are less serious now that adequate sideguards on larger vehicles are required in the UK.

Conspicuity - Although road layout improvements at junctions have decreased the incidence of large goods vehicles not being seen, especially when they are turning at junctions, there is still a case for better marker lights along the sides of vehicles. Of greater importance is the need to reduce impacts into the rears of large vehicles by faster moving cars. A higher standard of rear lighting is needed which includes a proper differentiation between the use of lights which indicate a vehicle is braking, stopping or stationary from those which indicate its position when it is moving and can safely be followed.

Driver Warning Systems - Further research and development are still needed for systems which warn drivers of their reduced state of alertness and indeed of sleepiness when on long monotonous journeys. Warnings of hazards ahead such as traffic which has slowed down just ahead are also needed. Sophisticated speed limiting systems which slow a vehicle when its speed is over the local limit or because of the hazards in front of it are the ultimate development.

Rollover - High mounted loads on goods vehicles, and especially those which hang and can swing laterally, do sometimes tip the balance and roll over goods vehicles. The effect is similar to the lateral surge of partially emptied tanker vehicles. Accident evidence shows that there is almost no margin between the speeds and lateral accelerations at which these vehicles roll from those at which they are normally driven around sharp bends. Good suspension design improves the situation, but warning systems will probably not be successful. These concerns are important for the carriage of dangerous fluids such as fuel.

Injury protection

Compatibility at impact - Currently this is the most important safety development needed for goods vehicles, and has different implications for design at the fronts, rears and along the sides. Because of the high mass, rigidity of structure where it strikes other vehicles and unsuitability of shape at these points, there is a great need for improvement in structural design and layout if many fatalities and other casualties are to be avoided. Rear underrun guards, side guards and front underrun guards have made great contributions where they have been introduced and when their specifications are adequate. More recently far reaching compatibility proposals have suggested that all four wheeled and multi-axled vehicles have matching structures at the points of impact. These structures would be designed to correspond to the frontal stiffnesses and depths of crush typical of the fronts of small cars. The implication for trucks is that a matching low frontal bumper structure would be provided low down at the front and project forwards by from say 700cm to a metre.

Rear underrun bumpers have been shown to be valuable in the UK but maximum protection is not provided when the full permitted ground clearance is used in the design. Many car front structures can underrun the rear bumper guard.

Side guards of the low panel type in the UK appear to provide adequate protection for pedal cyclists and some protection for motorcyclists and cars striking them. Some details of the requirements need revision.

Pedestrian and Cyclist Protection - Pedestrians and cyclists suffer fatal and other injuries when struck by trucks and large vehicles and until now little has been done to provide protection for them. Most pedestrians are struck by the flat fronts of these vehicles and most obviously head injuries result, mainly because the structures that the heads of adults and children strike are relatively rigid. These and other frontal features could readily be improved in design, especially if in the longer term the fronts of trucks are designed to be compatible with small car fronts.

Interaction with Roadside Crash Barriers - These barriers are designed to fend off cars and so it is not surprising that smaller trucks tend to roll over them and heavier ones to flatten them. The basic dynamics of these situations suggest that such outcomes are almost inevitable. Heavier and taller barriers are much more costly and protection for cars and their occupants inferior. Research might show that existing barriers might deflect heavy vehicles striking them almost parallel to their paths of travel if the bumper ahead of the front wheel of the truck could interact with the barrier and not leave the wheel to roll over it.

Driver protection - Ejection is the greatest hazard and seatbelts prevent this, but currently it is not compulsory to fit seatbelts in HGVs, and many drivers do not use them even when fitted. Passive seatbelts which fasten themselves around the driver may improve wearing rates. Structural intrusion is the other main problem for heavy goods vehicles and this results from striking trees, heavy vehicles and structures such as bridge piers, from falling into ditches and from miscellaneous penetrations by posts and other objects. Structural strengthening cannot readily take all these situations into account, but weak cab structures should be avoided and local strengthening around the driver might also help on some occasions.

Conclusions and Recommendations

Goods vehicles make stringent demands on brake systems because of the large differences between laden and unladen conditions. It is recommended that ABS systems be generally required, with electronic control of brake systems especially for multi-axle vehicles.

Driver view forwards and low down so that pedestrians and cyclists can always be seen when they are close by, is a much needed improvement. The provision of pedestrian and cyclist protection at the front of all these vehicles is also important, although some research and development is needed initially.

The current UK requirements for front underrun guards, rear bumpers and side guards should be reviewed to tighten the specifications in one or two respects mainly with regard to reducing maximum permitted ground clearance. In the longer term fully compatible structures should be required on the fronts of all trucks, heavy goods vehicles and indeed on all vehicles.

One of the greatest hazards while driving is the onset of sleepiness and priority is needed for the development and introduction of systems to combat this.

Driver protection could be greatly advanced by persuading drivers to use their seatbelts. This might be helped by providing passive self-fastening belts for goods vehicle drivers. Some strengthening of cabs locally around the drivers and the use of protruding front bumper systems as recommended for full compatibility may be the most practical improvements.

MOTORCYCLES

Accident Avoidance

Motorcyclist casualties have declined greatly in some countries. This may be linked to more arduous training and test requirements and because the cost of driving an old car may be less than riding a motorcycle.

Braking - The introduction of ABS has been a major improvement in motorcycle design. The next stage is to work towards requiring them to be fitted to all motorcycles, except the smallest, and mopeds.

Conspicuity - Motorcycles are not easily noticed in many traffic and lighting situations both by night and by day, though bright and reflective clothing and helmets contribute to making the motorcyclist more conspicuous especially in heavy traffic. In terms of collision reduction or prevention, daytime running lights appear to be the most effective, although the effect might diminish if all vehicles had to be fitted with such lights. Small motorcycles would need enhanced lighting systems so that their daytime running lights would be as effective as those on larger machines.

Injury Protection

Leg Protectors and Trajectory Control - It has been shown in several projects that leg protection can be built into motorcycle designs. The high rate of serious leg injury shows the need for it. There is the possibility that the trajectory of riders thrown forwards in collisions may be adversely affected by restraints at the knees. Further studies should show how any extra risk of head injury can be avoided. The tendency of the machine to pitch can be reduced if the height of impact can be raised a little. It may be possible to decelerate the upper body and head before the rider is thrown over the motorcycle. Studies are showing how airbags may contribute to this.

Helmets - Several investigations have shown the effectiveness of crash helmets, but further design improvements in materials and in the distribution of the padding within them may be possible.

Clothing - Studies of both motorcyclist and pedal cyclist injuries show the value of tough clothing which resists abrasion. Some padding over vulnerable areas may also be worthwhile.

Conclusions and Recommendations

The fitting of ABS braking systems on all but the smallest motorcycles is probably the first priority. The universal provision of leg protection remains a high priority, provided that it does not adversely affect the incidence of head injuries to a significant extent. Daytime running lights may be desirable for all motorcycles as long as the smaller machines have enhanced lighting systems to give the same light as on larger machines. Developments in clothing, both for protection and conspicuity, should match efforts for actively discouraging unsuitable clothing.

PEDAL CYCLES

Any restriction or reduction in the use of cars in the UK as a result of an integrated transport policy would be likely to increase the use of pedal cycles and this would almost certainly lead to an increase in road casualties, unless there are remedial measures taken to improve the design and layout of the road system and improved cyclist training. The following are some of the possible safety features for pedal cycles suggested by accident studies.

Accident Avoidance

Brakes - Wet braking has been improved during the last decade in the UK and the standard now reached might usefully be adopted more generally in the EU.

Stability - Many injuries result from falling off pedal cycles in incidents both on and off the road. Uneven and rough surfaces contribute to these cases. Road edges, much used by cyclists, are sometimes hazardous due to debris thrown there by vehicle tyres and because of projections and sunken gratings in the gutters. Large wheeled bicycles are usually more stable than those with small wheels. Slow cycling trials indicate the degree of stability and some improvements can probably be made.

Conspicuity of Cycle and Rider - Drivers failing to notice cyclists is the most frequently noted contributory factor in daylight as well as in darkness. Tests show that white and brightly coloured clothing improves the conspicuity of cyclists. Fluorescent and reflective stripes, patches, helmets and clothes are all valuable aids. Half metre spacer arms projecting to the offside lead to some increases in the gaps between cyclists and overtaking vehicles and these seem likely to reduce some impacts to near misses.

Reflectors and Lights - Forward and rearward facing reflectors, when correctly aligned, are valuable for conspicuity in conditions of poor daylight and during the hours of darkness. Pedal reflectors are most effective, but side facing reflectors have more limited value. A high standard of cycle lighting is very desirable so rechargeable and dynamo systems should be encouraged. Intermittent electronic cycle lights are a useful extra for conspicuity. Powerful cycle lights are also invaluable for helping riders avoid obstacles and for seeing bends on poorly lit roads. Finger tip control for the most powerful bulbs may be a way of conserving battery power.

Rider View to Sides and Rear - The ability to glance to the sides and rear is needed and the cycle should not wobble as a result. Rear view mirrors may be an additional help, but the mirror should not disturb the handlebars if it is struck by an overtaking vehicle.

Injury Protection

Although possibly a half of injuries occur when cyclists fall off their machines, the severity of injuries in these cases is usually low compared with those from impacts with road vehicles. Taking both circumstances together, severe injuries are mostly to the head with some to the neck and thorax. However upper limb injuries are very numerous and lower limb injuries only slightly fewer, but neither are fatal. This means that head protection is essential and either a padded hard helmet or the 'hairnet' type (fairly popular in Australia) is effective in preventing most of the more serious injuries. Study of helmets damaged in accidents shows that impacts to the front are by far the most numerous, with some impacts occurring at the sides. This suggests that preferential protection could be provided at the front. The design limitations include the need to maintain an all round field of view and also to provide adequate ventilation, especially for cycling in hot weather.

It seems unlikely that pedal cycles could be altered to provide protection for the upper limbs. However abrasions and infections through open wounds are common and there is a good case for cyclists wearing tough clothing on the arms and trousers which protect the knees.

Conclusions and Recommendations

Gross underreporting of accidents and injuries involving cyclists is still widespread, although statistics of fatalities may be almost complete in some countries. This factor must always be allowed for when using cyclist accident data for policy planning purposes.

The design standards for lights should be upgraded as indicated. Much greater attention should be paid to the use and condition of lights and reflectors in service. The condition of brakes in service is often not satisfactory.

Large gains in conspicuity and in protection could be made by advances in the design of clothing, which cyclists find acceptable.

Helmets can probably be further improved with regard to protection and comfort in use. The voluntary use of helmets should be strongly encouraged to raise wearing levels, with a view to compulsion in the longer term, especially for children.

VIDEO IMAGE PROCESSING AND DATABASE FOR TRAFFIC ACCIDENT RECORDING SYSTEM

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ABSTRACT

This paper discribes the outline of Video Image Processing and Database System(VIDS) developed as a support system of TAAMS* to analyze the image information and the image processing technology which is adopted to TAAMS. VIDS is composed of two main functions, one is a function to save a picture of the videocassette tape with huge information on the laser video disc** with a good cost performance and to search, other is an Analyse-Supporting-Function to construct the database which supported the analyses such as the speed of the vehicle, the collision sounds, and the view obstruction events for instance. In a word, VIDS enables to process the image data of a lot of accidents and the near miss cases, etc. collected by TAAMS with low-cost, in a short time and a large amount of it. Moreover, the constructed data base is used for the research of the occurrence mechanism of the traffic accident, the accident prevention measures or the driver education etc.. In addition, VIDS is evaluated as one tool which practicably uses a lot of video pictures to which it is forecast to be going to increase more and more in the future. In this paper, some of the middle result of the database and the subject in the future constructed with VIDS are considered.

INTRODUCTION

TAAMS records not only accident but also near miss cases by detecting the brake sound and the horn to avoid the danger. The horn is not necessarily used under the dangerous state which becomes tense. It is used as a method of transmitting communications when urging or warning the other party to behave in case of no particular state. Therefore, the state to use the horn suggests potential danger, and those pictures are necessary to research the mechanism of the occurring accident.

The medium, videocaseet tape usually used TAAMS, is good performance and has extremely large capacity. However, It is remarkably difficult to analyze and process actually, because of abundant amounts of information a voluntary comparison of the picture (similarity and difference). In addition, a video picture is sequential data, and has a definite difficulty in a random search. Moreover, video-tape has the problem of preservation for long time so that the picture quality deteriorates from passing year, and actually, most of valuable image data collected is not used effectively. To analyze the video image data of TAAMS, we developed VIDS as a support system to construct the database, which was able to search a video image at random and efficiently.

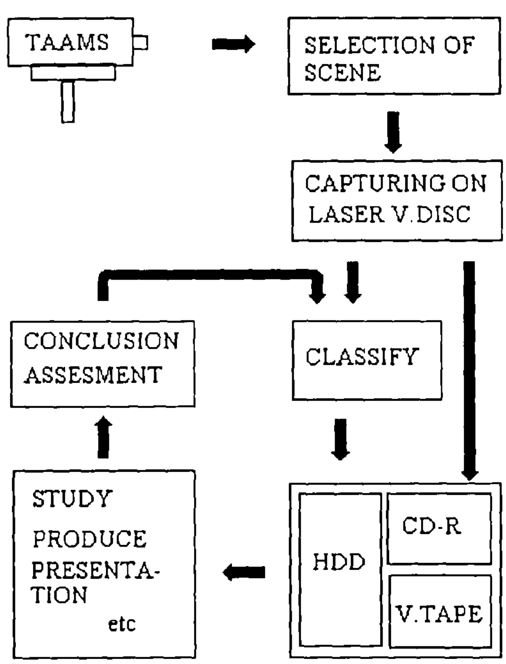
It is being proven that VIDS is not only a tool which give a time shortening (favor) for research the traffic accident mechanism from the picture of TAAMS, but also a support system offers us a profitable new hint. The later is more important aspect VIDS.

*Footnote is explained at the last page.

Video Image Processing and Database System

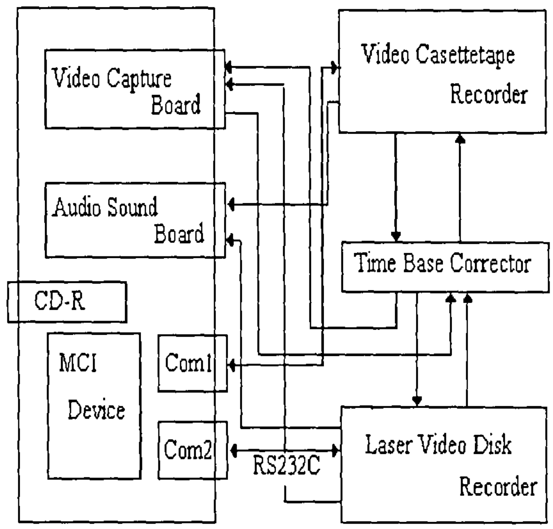
Outline-Figure 1 illustrates a basic flow chart of VIDS which constructs the image database by selecting, preserving, analyzing, and classifying the picture of TAAMS. The procedure of the VIDS is as follows; First of all, the pictures from the videocassette tape is displayed by VIDS in real time, and captured the picture elected to the laser video disc. The captured picture data is observed more in detail and classified. The in-depth analysis, for example, the speed of the vehicle, the collision sound, the brake sound and traffic, etc. are performed with other analytical application software linked with VIDS and these topic informations and analytical results are arranged by VIDS, and saved in the character database on the hard disk. Because the analyzing picture is displayed from the laser video disc directly by the function of VIDS, an observation and an analytical operation can be done, smoothly. This character data base links with the picture data on the laser disk, and both of them are composed the image database. If these results is suggested the proposal of a new classification, the classified items are added into the image database, and the data is updated to be available as basic data for the study.

Figure 1



The basic composition chart of VIDS is illustrated in Figure 2. It is composed of a personal computer (CP U:Pentium II, 266 MHz), a videocassette recorder (Mitu-bishi BV-2000R with RS232C Interface), a laser videodisc recorder(Sony LVR-3000AN with RS232 C Int-erface), and various devices in the personal com puter.The development language is Visual Basic 5.0.

Figure 2



Record Medium- we examined the hard disk and the laser disk where three conditions (passing year's deterioration, a large capacity, and the random access) were satisfied when the medium of the image database was selected. Table 1 shows the comparison of the performances of the both. The difference is hardly seen as a random access by the both. But, the laser disk is selected for the reasons why are a good cost performance and safety to protect for data trouble. However, the fault breaks out in the capture operation to the laser videodisk. This fault derives from the system it by which the picture frame controls on the laser disk device. Generally, it is necessary to stand by which the number of capturing frames of original picture is allocated in the blank area on the laser video disc so that the user may record the picture on the laser video disc.

Because of the allocation in the blank area procedure, the work that the user counts the number of frames beforehand is a very annoying and not a little in the case of wrong specification. Executing the procedure, the user will consume man-and-hours considerably.

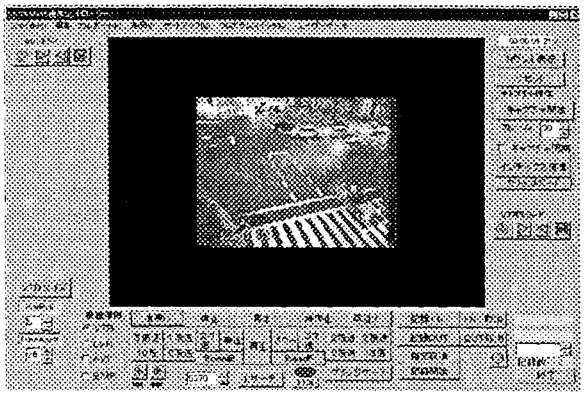
Table 1

Performance comparisons of record media		
	HDD	LVD
Access speed	Excellent	9600bps
Quality	Less excellent	Excellent
Capacity	13GB/48min.	1/48min.
Amount/year	65GB	5
Procedure	Easy	Difficult
Data Security	Danger	Safty

Automatic capture function- Because VIDS had added the automatic capture function to cancel the complexity when capturing on the laser video disk, the load of the user was extremely reduced. Figure 3 shows a main screen of VIDS. The user can do all work by clicking the mouse on this screen. The user reads the picture from the videocassette tape displayed on the screen, and specifies the IN and the OUT point of the capture which wants to be made surely. The following task automatically capture specified area as VIDS controls the videocassette recorder and the laser record -er, and records the captured address and other inform-ation in the user data area of the laser video disc simultaneously.

When capturing, the most important algorithm is method of the search for the IN point of the video cassette tape and a synchronization between the video cassette tape-recorder and the laser video disc recorder. A synchronous error are ±5 frames or less. The margin of 10 frames is set beforehand when capturing.

Figure 3



File Capture Function- VIDS can be captured to the file type of AVI and BMP . Because the synchronization between image devices is made even when capturing as AVI file, we can get a clear file without uselessness of the top and bottom in the file . The performance of capturing depends on the performance of the captureing driver used, and the routine uses the component which is called "OCX".

To analyze the speed of the car, the image resolution 640 × 480 pixels and 30 frames per second are required.

Troubleshooting-The following two points are described as a main troubleshooting. The first is the control trouble of the recorder device concerning the lack on the image signal of the videocassette tape, and the second is a trouble of the computer crash concerning the operating system.

The trouble of the recorder device control is as follows; VIDS regularly confirms the address on the tape by generating the timer event while searching for the IN point. The case where there is abnomal signal on the videocassette tape when confirming the address, is often happened. In this case, the videocassette tape-recorder might foll on the uncontroled state with disregarding the command, stopping or rewinding.

The reason for the cause which enters such a state is that the gap is occasionally caused in the commissure of the scene and the scene when the image that TAAMS is saved in DRAM is recorded on the videocassette tape.

Only if the image is displayed, it is not a trouble which becomes a problem. However, when the capture is done in each frame by the computer, it becomes aserious trouble. Then, VIDS provides the routine of an emergency procedure, and recovery from the uncontroled state automatically (or semi-automatically).

Next is about a computer crash which is occured to our regret daily. As the solution, IN and OUT point of capturing which the user specified, the state of capturing progress and user's areas are always checked, and written in the log file by VIDS. Therefore, only the user orders the processing of the remainder to VIDS by reset the computer even if the computer stops abnormally during capturing, the task is promoted automatically, and there is no damage by an abnormal stop. If we had selected the hard disk as a picture record medium, VIDS will have been a fatal system.

DISCUSSION

Relation picture data selection function of TAAMS and VIDS

TAAMS was developed as a device which selectively collected the accident and the near miss picture. However, it was clarified that extremely sharpening the detected function of TAAMS caused the obstacle to the collection of an important picture by the field test. Therefore, it is necessary to collect to some degree a lot of data, and select efficiently data needed from them. VIDS was developed as a support system for the efficiently selecting, and VIDS enabled to capture the data collected by TAAMS easily comparatively and to construct the image data base with the development.

On the other hand, from the different views, the VIDS suggested that is being included very important informations in the picture which related to the sounds collected by TAAMS (device selected according to the sound). For instance, the situation of a very light horn etc. is data which shows daily behavior of drivers as a scene of the conversation of the car and the car though it is not a state of the near miss.

Moreover, TAAMS dose not overlook a natural phenomenon that is the groan sound of the electric wire by the storm and the lump fall sound of the snow etc. also, it is natural, and record the work situation of the road construction. These picture data has the possibility to use widely as basic data which investigates the change in traffic under broken situation.

Paraphrasing the function of such TAAMS, it is a picture diary by which affecting suitable of a social and a natural phenomenon and traffic stuation is expressed (record),and a machine which measures citizens' traffic manners. When the traffic safety is educated, a real colliding scene by TAAMS will show a superior persuasive power to a lot of character information. Importance is to be able to classify and to analyze the huge image data collected in relation to the sound of these TAAMS systematically by developing VIDS.

Subject in the future

Efficiency of analysis-At first, we attempted the development of the data base including the technology which made the computer recognize the image and the voice, too. For examples, the object of recognition is the shape of the car, the direction, the type of collision, the brake and a collision sounds and a horn, etc.. Studying will have advanced remarkably if succeeding in the practical use of this technology. However, the theme of the shape of the image and the audio recognition have too a lot of obstacles, our development is not advanced.

Delivery of image-We recognized the complexity of the mechanism of the traffic accident occurrence again while investigating the accumulating image. The reason is to be gradually clarified about the doubt of a local rule of the driver not publicly admitted, or a fact to look for the correlation to the occurrence frequency and the traffic of the accident and the near miss, or a reality which measures of suggested anti-collision did not effect of expecting, by the process of studying. The more this kind of finding will increase though the advance by studying, but it is likely to become a result that only the theme is left behind.

About the future of the database of TAAMS, strongly, we feel the development of the data delivery system by an appropriate form to researchers in all fields, administrative organizations, and operation managers of vehicles,etc..

Three-Dimensional Image-The image of TAAMS is a fact, and a shocking collision scene gives people a strong impression. However, because the story is a short time at before and after the collision, and a camera position is located for an objective expression, the effect of production that people makes a hero of the collision scene is thinly, also has the fault to make the strength of the image forgotten at once. Therefore, we think that the development of the three-dimensional picture processing technology is necessary as an analytical technique which clarifies the fact obtained from the traffic circumstances which is behind a short scene or the driver's view-point. If the technique is used, the persuasive power to people will rise further, and keep the scene in the mind for a long time.

CONCLUSION

VIDS was developed as an analytical support system of the TAAMS image data. VIDS is composed of a function to capture the picture of the videocassette tape to the laser video disc easily and a function to construct the image data base at the same time.

It is evaluated as a useful tool for an efficient analysisand a classification while flexibly updating the image data with a large amount of information.

*TAAMS is a system which senses the sound, and records the image data saved in DRAM till then by CCD camera on the videocassette tape by the NTSC procedure. One scene is composed between 260 and 300 frames, and the scene is not recorded in case of the sound which does not reach at a constant level so that the sound entering from the sensor may pass various filters.

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** Laser video disc: A metallic powder of Sb, Se, Bi, and Te are spread on the polycarbonate base, and these metals melt by the heat of the irradiated laser beam and they become an alloy. When playing on the display, the difference of reflectivity in alloy part and non-alloy part is read by the own device. Non-contact laser picking up . Analog record method. 87,000 frames/both sides. User data area of 128KB. Diameter 12 inches , protected with the cartridge.

COMPARISON OF YOUNG AND ADULT DRIVER CRASHES IN ALASKA USING LINKED TRAFFIC CRASH AND HOSPITAL DATA

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ABSTRACT

This report describes the most serious young driver crashes in Alaska for the period 1991 through 1995. Rates, characteristics, and medical and financial outcomes of young driver crashes are compared with that of adult driver crashes. This research project demonstrates the usefulness of data linkage in crash research. Using the Mini Crash Outcome Data Evaluation System (MINICODES), trauma registry hospital discharge data were linked with traffic crash records. The data were analyzed to compare drivers aged 16-20 with drivers aged 21-50 who were involved in a crash resulting in the hospitalization or death of a crash victim. The CrashCost Program was used to estimate costs associated with young driver crashes for the five years.

Young drivers were 2.9 times more likely than adult drivers to be involved in crashes that resulted in the hospitalization of a crash victim, and 2.6 times more likely to be involved in a crash involving a fatality. Human factors were recorded as contributing factors for 68.2% of the young drivers, compared with 55.5% of the adult drivers (P<.0001). The highest hospital charge averages were those incurred by the victims of motorcycle crashes. Total costs associated with the young driver crashes were estimated to be over $300 million, which resulted in a cost per young licensed driver that was 3.4 times the cost per adult licensed driver.

INTRODUCTION

Motor vehicle crashes are the leading cause of death for young people in the United States aged 15 to 20 years. National statistics reveal that teen drivers are disproportionately involved in crashes. In 1995, young drivers aged 15 to 20 years comprised only 6.7% of the driving population, yet they accounted for 14% of the drivers involved in fatal crashes and 17% of the drivers in police-reported crashes. The losses these crashes represent in terms of human suffering are vast and difficult to quantify. The financial toll has been estimated at $31 billion annually (1).

There are a number of factors that impact the driving performances of teens including age, inexperience, supervised driving, and night driving. An examination of the effects of the different state laws on 15-17 year old driver fatality rates found that the minimum legal driving age and curfew laws had the greatest impact on driver fatality rates (2). Delayed full licensure age, night driving curfews, and supervised driving have all been shown to be effective in mitigating the high crash rate among 16 year olds. In upstate New York, however, where a combination of these strategies are employed, crash involvement rates remained low through age 24, compared with the other northeastern states studied (3).

The National Highway Traffic Safety Administration (NHTSA) recommends that states adopt a graduated licensing system that combines delayed full-privilege licensure, supervised driving, and night driving curfews. An evaluation of the effectiveness of New Zealand's graduated licensing system, in place since 1987, reveals a 23% reduction in crash injuries for the 15 to 19 year old population (4). Eleven states now have some form of graduated licensing. Evaluations of graduated licensing in California, Maryland, and Oregon demonstrated a 5-16% reduction in young driver crashes (5).

Motor vehicle crashes are the leading cause of death for Alaskans aged 16 through 20 and cause almost 50% of the unintentional injury deaths for this age group. Drivers in this age range were involved in 13.1% of police-reported crashes in Alaska during the period 1991 through 1995 while they accounted for only 6.3% of licensed drivers in the state. The crash rate of drivers aged 16 through 20 from 1991 through 1995 was 135.9 crashes per 1,000 drivers, which was 2.4 times the crash rate of drivers aged 21 through 50 (56.9 per 1,000 drivers).

Among 16 through 20 year old drivers, the crash rate in Alaska decreased each year to age 20. The crash rate of 17 year old drivers was 24% lower than that of 16 year old drivers; the 18 year old driver crash rate was 22% lower than that of 17 year old drivers; the 19 year old driver crash rate was 21% lower than that of 18 year old drivers; and, the 20 year old driver crash rate was 12% lower than that of 19 year old drivers.

The purpose of this study is to describe the most severe young driver crashes in Alaska, between 1991 and 1995, in terms of rates, characteristics, and medical and financial outcomes; to make comparisons between youth driver crashes and adult driver crashes; and, to demonstrate the usefulness of data linkage in crash research.

METHODS

Computerized crash records from the Highway Analysis System (HAS) for 1991 through 1995 were obtained from Alaska's Department of Transportation and Public Facilities. This system contains information on motor vehicle crashes on a trafficway, either recorded by police or self-reported. Alaska law requires that any motor vehicle crash which results in death, injury, or property damage of $500 or more must be reported to the Alaska Department of Public Safety. Data include passenger demographics, type of vehicle, type of crash, contributing factors, type of injury, and body region injured. There are up to two contributing factors listed per driver involved in a crash, recorded by the enforcement officer. They fall into four main categories: human error, roadway conditions, environmental elements, and vehicle defects.

Hospital discharge data were extracted from the Alaska Trauma Registry, also for 1991 through 1995. The trauma registry is a statewide information system housed in the Alaska Department of Health and Social Services, which includes detailed data on all injury hospitalizations in the state. Alaska's trauma registry is somewhat unique in that trauma data are collected from all Alaskan acute care hospitals, of which there are 24, and are collected on all patients admitted for 24 hours or more. Data include patient demographics, ambulance service transport and treatment, hospital treatment and length of stay, diagnosis, injury severity, discharge status, charges, and payer billed.

In order to associate circumstances of crashes with corresponding injury outcomes, crash records and trauma registry records were linked using the Mini Crash Outcome Data Evaluation System (MINICODES), developed by the National Association of Governor's Highway Safety Representatives (NAGHSR) with the support of NHTSA. This software relies on a probabilistic linkage methodology which is particularly useful with data that lack identifiers or may contain incomplete or erroneous information. The methodology has been extensively tested and has demonstrated high precision matching (6).

Trauma registry records were considered for linkage by virtue of an external cause of injury code (E Code) in the range 810.0-816.9 and 819.0-819.9, motor vehicle traffic collision injury. E Codes are a coding system within the International Classification of Diseases, 9th Revision, Clinical Modification (ICD-9-CM), which are routinely entered into the Trauma Registry for each trauma patient. The identifiers used for linkage of the two databases were sex, age, birthdate, geographic region, and probable hospital admission date and time. Additional variables were used to review questionable matches. They consisted of vehicle type, crash type, residence city, crash city, position of injured person in vehicle, anatomical location of injury, and the injury description.

Only the most serious crashes were considered for study, i.e. those involving the hospitalization or death of a crash participant. A **hospital crash** refers to any motor vehicle traffic crash resulting in at least one victim of the crash admitted to a hospital for 24 hours or more. A **fatal crash** refers to any motor vehicle traffic crash resulting in at least one fatality. A **fatality** is defined as a death that occurs as a direct result of a motor vehicle crash within 30 days of the injury or during an acute care hospital stay if the patient was originally hospitalized within 30 days of the injury.

Through linkage of traffic crash data with trauma registry data, two populations were identified for study: drivers in crashes and victims of crashes. Drivers were divided into two groups, those aged 16 through 20 who are referred to as **young drivers**, and those aged 21 through 50, referred to as **adult drivers**. These two age groups were used for comparison to avoid the introduction of older drivers who are involved in crash patterns unique to their group. The victims of the crashes were described in terms of outcome, hospital charge payment source, and costs. The victims were also divided into two groups, those who were victims of young driver crashes and those who were victims of adult driver crashes.

Safety equipment consists of safety belts, safety belts with harnesses, child safety seats, and helmets. **Alcohol involvement** is recorded as a contributing factor on the police record if alcohol use is confirmed by a test or suspected. **Disability** is defined as the expectation that the patient will never be able to return to his or her pre-injury level of function in the judgement of the trauma registrar collecting the information from the medical record file.

Average hospital charges per crash victim were calculated using available trauma registry data. Because not all of the hospitals release this information, hospital charges are missing on about 50% of the trauma registry patients. More inclusive cost estimates were derived using the CrashCost Program obtained from NHTSA. This software program estimates the economic costs of motor vehicle crashes, including direct medical expenses, direct "other" expenses and indirect costs. The CrashCost program also accounts for unreported crashes and adjusts for locality and current economics (7).

The CrashCost estimates were based on Alaska specific data on the number of crash fatalities and the number of patients identified with an Abbreviated Injury Scale (AIS) score of four (severe injury) or five (critical injury). Injuries of an AIS of three or less are not adequately tracked by the trauma registry since only patients admitted to the hospital for one or more days are entered into the database. Therefore, the national ratio based estimates from the CrashCost Program were used to estimate the number of these less severe injuries.

RESULTS

A total of 3,158 trauma registry records were considered for linkage with traffic records, resulting in 2,183 matches, or a 69.1% matching success rate. The linked trauma registry records were compared with the unlinked records to see if the linked records were representative of the unlinked records. There were no significant differences between the groups in sex and age, however, there were significant differences relating to geographic location of crash and type of crash. The crashes among the linked trauma registry records occurred more often in the urban areas (Anchorage, Fairbanks, the Kenai Peninsula, Matanuska-Susitna Borough, and Juneau) ($p < .0001$). There was a significantly smaller percentage of Alaska Natives in this group than in the unlinked data group ($p > .01$). The mean injury severity was greater among the linked records than among the unlinked records ($p < .05$). The linked data also included less pedestrian injuries ($p < .0001$) and more driver injuries ($p < .0001$) than the unlinked data.

Drivers

Linkage of traffic crash data with trauma registry data resulted in 2,508 drivers identified for their involvement in hospital and fatal crashes: 488 young drivers and 2,020 adult drivers. A comparison of crash involvement rates of young and adult drivers, annualized over the five-year period, is shown in Table 1. Young drivers were 2.9 times more likely to be involved in crashes that resulted in the hospitalization of a crash victim, and 2.6 times more likely to be involved in a crash involving a fatality.

Table 1.
Annualized Young and Adult Driver Involvement Rates in Hospital and Fatal Crashes, Alaska, 1991-1995

	Young Drivers (Age 16-20) N=488		Adult Drivers (Age 21-50) N=2,020		Rate Ratio
	N	Rate*	N	Rate*	
Hospital Crash Involvement	408	3.15	1,659	1.10	2.86
Fatal Crash Involvement	80	0.617	361	0.240	2.57

* Rate per 1,000 licensed drivers

The young and adult drivers in hospital and fatal crashes are compared in Table 2. The two groups of drivers were similarly distributed by sex and use of safety equipment. Hospital and fatal crashes occurred most often during the summer months (July and August) among both groups of drivers. The time of day of the crash was also similar between the two groups. Adult driver crashes that resulted in serious injury peaked in late afternoon and early evening (25.6%) and young drivers were most at risk between noon and 4 PM (23.4%).

Table 2.
Comparison of Young and Adult Drivers in Hospital and Fatal Crashes by Driver Age, Safety Equipment Use, and Crash Time, Alaska, 1991-1995

	Young Drivers (Age 16-20) N=488		Adult Drivers (Age 21-50) N=2,020	
	N	Percent	N	Percent
Sex				
Male	324	66.4%	1,444	71.5%
Female	164	33.6%	579	28.7%
Safety Equipment Use				
Recorded	462		1,871	
Used	252	54.5%	1,053	55.9%
Not Used	210	45.5%	818	44.1%
Unrecorded	26		149	
Crash time				
Midnight-4am	90	18.4%	304	15.0%
4am-8am	36	7.4%	187	9.3%
8am-noon	48	9.8%	232	11.5%
noon-4pm	114	23.4%	403	20.0%
4pm-8pm	111	22.7%	517	25.6%
8pm-midnight	89	18.2%	377	18.7%

There are up to two contributing factors recorded in the traffic crash database for each driver in a crash. As indicated in Table 3, the percentage of young drivers with a contributing factor due to human error, as recorded by the investigating officer, was significantly higher than that of the adult drivers (p<.0001). Conversely, there was a greater percentage of adult drivers with "no contributing factor" recorded to describe their involvement in the crash (p=.01).

Table 3.
Comparison of Young and Adult Drivers in Hospital and Fatal Crashes by Contributing Factor, Alaska, 1991-1995

	Percent of Young Drivers with the Contributing Factor N=488		Percent of Adult Drivers with the Contributing Factor N=2,020	
	N	Percent *	N	Percent *
Human	333	68.2%	1,122	55.5% **
Vehicle	22	4.5%	49	2.4%
Environ-mental	23	4.7%	75	3.7%
Roadway	41	8.4%	122	6.0%
None	78	16.0%	551	27.3%***
Unknown	7	1.4%	21	1.0%

* Up to two contributing factors per driver so that column does not equal 100%
** p < .0001
*** p = .01

The contributing factors attributed to the young and adult drivers are detailed in Table 4. "Unsafe speed," i.e. speed too fast for conditions, was recorded as a contributing factor of the crash for 29.1% of the young drivers. "Alcohol" was believed to be a factor in the crashes of almost 16%. Conversely, alcohol was a recorded factor for 24.9% of the adult drivers, with unsafe speed ranking second at 19.9%.

Table 4.
Comparison of Young and Adult Drivers in Hospital or Fatal Crashes by Contributing Factor, Alaska, 1991-1995

	Percent of Young Drivers with the Contributing Factor N=488		Percent of Adult Drivers with the Contributing Factor N=2,020	
	N	Percent*	N	Percent*
Unsafe Speed	142	29.1%	401	19.9%**
Alcohol	76	15.6%	502	24.9%***
Driver Inattention	59	12.1%	142	7.0%
Failure to Yield	45	9.2%	144	7.1%
Driver Inexperience	36	7.4%	28	1.4%
Pavement Slippery	32	6.6%	107	5.3%
Improper Lane Usage/Passing	27	5.5%	76	3.8%
Traffic Control Devise Disregard	24	4.9%	79	3.9%
Other Human Factor	19	3.9%	81	4.0%
Turning Improperly	10	2.0%	35	1.7%
Fell Asleep	9	1.8%	42	2.1%
View Obstructed	8	1.6%	36	1.8%

* Up to two contributing factors per driver so that column does not equal 100%
** p = .04
*** p = .04

Victims

Table 5 describes the outcomes of the two crash victim groups. There was no significant difference between the victims of the young driver crashes and those of the adult driver crashes in injury severity or length of hospital stay.

Table 5.
Outcomes of Young and Adult Driver Crashes, Alaska, 1991-1995

	Young Driver Crash Victims N=584		Adult Driver Crash Victims N=1,894	
	N		N	
Total Deaths	99		344	
Scene Deaths	67		228	
Hospital Deaths	32		116	
Hospitalizations	517		1,666	
	Mean		Mean	
Injury Severity Score *	10.8		11	
Length of Hospital Stay (days)	6.7		7.6	
	N	Percent	N	Percent
Head Injury	208	40.2%	628	37.7%
Chest Injury	116	22.4%	402	24.1%
Spinal Cord Injury	14	2.7%	43	2.6%
Discharged with Disability	70	13.5%	186	11.2%

* Injury Severity Score is on a scale from 1 to 75, with 75 the most severe. An ISS of 16 or greater defines major trauma.

Average hospital charges for both groups of victims are listed in Table 6. These figures are based on available cost data from the trauma registry. Included are charges by type of vehicle, contributing factor, and use of helmets and safety belts. There were no significant differences between the two groups at the 95% confidence level in any of the categories compared. The highest average charges were those associated with motorcycle crash patients. The average charge for hospitalization for non-helmeted victims of young driver crashes was twice that of the helmeted victims.

Table 6.
Hospital Charges of Young and Adult Driver Crashes by Vehicle Type, Contributing Factor and Safety Equipment Use, Alaska, 1991-1995

	Young Driver Crash Victims, N=517		Adult Driver Crash Victims, N=1,666	
	Mean	Standard Error	Mean	Standard Error
All	$16,269	$ 1,640	$18,174	$ 1,146
Vehicle Type				
Passenger Car	$15,250	$ 1,889	$17,397	$ 1,450
Motorcycle	$27,354	$ 8,344	$30,148	$ 6,279
Pick-Up Truck	$18,482	$ 5,653	$15,599	$ 1,748
Contributing Factor				
Unsafe Speed	$14,344	$ 2,575	$22,778	$ 2,511
Alcohol Use	$19,426	$ 5,614	$18,911	$ 2,184
Driver Inattention	$17,129	$ 4,452	$15,504	$ 2,848
Failure to Yield	$10,201	$ 2,294	$19,062	$ 2,797
Safety Equipment Use				
Safety Equipment Used	$15,543	$ 2,223	$15,943	$ 1,514
Safety Belt	$15,220	$ 2,547	$14,355	$ 1,176
Motorcycle Helmet	$17,309	$ 3,699	$28,323	$ 9,519
No Safety Equipment Used	$17,087	$ 2,512	$19,599	$ 1,774
No Safety Belt	$14,259	$ 2,420	$19,518	$ 2,505
No Helmet	$34,640	$19,672	$28,407	$ 7,029

The distribution of payers billed for hospital expenses associated with the 2,183 hospitalized victims are presented in Table 7. Of the patients involved in the young driver crashes, the largest percentage billed their hospital expenses to private health insurance (33.1%), followed by those who were uninsured (19.3%), and those covered by automotive insurance (14.7%).

Table 7.
Payers Billed for Hospitalization of Victims of Young Driver and Adult Driver Crashes, Alaska, 1991-1995

	Young Driver Crash Victims N=517		Adult Driver Crash Victims N=1,666	
	N	Percent	N	Percent
Private	171	33.1%	472	28.3%
Uninsured	100	19.3%	368	22.1%
Automotive	76	14.7%	225	13.5%
Indian Health Service	50	9.7%	174	10.4%
Medicaid	40	7.7%	110	6.6%
Military	24	4.6%	118	7.1%
Champus	12	2.3%	42	2.5%
Medicare	10	1.9%	48	2.9%
Other/Unknown	34	6.6%	109	6.6%

Table 8 gives estimates of the total costs associated with young and adult driver crashes in Alaska for the five years using the CrashCost Program. Cost per young licensed driver was 3.4 times the cost per adult licensed driver.

Table 8.
Cost Estimates for Young and Adult Driver Crashes, Alaska, 1991-1995 *

	Young Driver Crashes	Adult Driver Crashes
	N	N
Fatalities	99	344
Injuries **	7,648	26,569
Property Damage Only	34,333	119,248
	Cost	Cost
Direct Medical Costs	$ 36,750,837	$126,786,020
Direct Other Costs	$134,898,306	$468,099,927
Indirect Costs	$131,086,293	$454,729,271
Total	$302,735,436	$1,049,615,218
Cost per Licensed Driver	$2,336	$697

* Cost estimates based on NHTSA CrashCost Program
** Injuries include hospitalized and non-hospitalized

DISCUSSION

Alaska is similar to the rest of the nation in that young people are disproportionately involved in motor vehicle crashes, and crash injuries constitute a major health problem among this group. Alaska is, however, distinctive by having the lowest population density of any state, about one person per square mile. There are 13,485 miles of roads but only five of Alaska's urban centers are connected by road. The formidable terrain, isolation, and extreme weather conditions make access to medical care a challenge for residents and visitors alike who are involved in motor vehicle traffic crashes. Teen drivers demonstrated a greater propensity for involvement in the most severe crashes compared with adults, but the involvement rate did not increase significantly with injury severity.

The serious and fatal crashes involving young drivers were more likely attributed to human factors compared with crashes involving adult drivers. These data suggest that immaturity, inexperience and risk-taking behaviors contribute to young driver crashes.

The high percentage of safety belt and helmet nonuse among both of the study populations (44%-46%) is partially explained by the fact that these were the drivers in crashes resulting in the most serious injuries, including injuries to themselves. The Youth Risk Behavior Survey of 1995 reported that about 20% of Alaska high school students surveyed responded that they rarely or never use safety belts. Among those who ride motorcycles, about 40% rarely or never wear helmets (8). In response to the 1995 Alaska Behavioral Risk Factor Survey, 33.1% of adults reported that they did not always use safety belts (9). These percentages are all higher than comparable national percentages. Lap and shoulder belts are 40-50% effective in reducing deaths and 45-55% effective in preventing moderate-to-critical injuries to passenger vehicle occupants (10). NHTSA estimates that helmets are 29% effective in preventing fatal injuries to motorcyclists and in a recent study showed that motorcycle helmets are 67% effective in preventing brain injuries (11).

Alcohol was not the leading contributing factor in young driver crashes as it was for adult driver crashes. This has been reported by other researchers and can be attributed largely to an alcohol purchase age of 21 in all states and a zero tolerance law for drivers under the age of 21 in 30 states, including Alaska. Zero tolerance means that anyone with a BAC level above 0.02 g/dl is considered legally intoxicated (1, 12, 13).

Almost 50% of hospitalized victims of teen driver crashes relied on private or automotive insurance to pay their hospital expenses. One hundred victims, or 19.3%, were uninsured. The hospital charges of an additional 26.3% of the patients were billed to a government program. NHTSA estimates that nationally private insurance companies pay 55% of medical costs for hospitalized patients of motor vehicle crashes and the government pays only 23% (14). Alaska has a large Native American population and several military bases, which contribute to a significant role of the federal government in covering the cost of medical care in the state.

The highest average costs of hospitalization were incurred by motorcycle crash victims. Unhelmeted crash patients topped the list with an average cost of over $34,000, double that of the helmeted victims in the same group.

Using the CrashCost Program, the estimated costs for teen driver crashes in Alaska for five years was over $300 million. The financial burden quickly becomes an issue of public policy when such a large percentage of the cost is reimbursed with public funds.

There were several limitations to this study. Every driver in a crash was included in the crash involvement rates. Multiple car crashes involving more than one driver added multiple drivers to the statistics, often into both age groups simultaneously. In reality, driver responsibility for crashes is more complex than that, with participants assuming varying degrees of fault. For the purpose of this study, however, driver responsibility was given equal weight and was based on involvement.

Missing and incorrect data is undoubtedly partly responsible for the inability to link all trauma registry records with traffic crash records. The error rate in data linkage due to the linkage process itself has not been quantified. It is believed, however, that the 31% in non-linked data was largely due to unreported traffic crashes. A comparison of hospital discharge files and police road injury data in Australia resulted in a linkage rate of 64%. The researchers found increased linkage with injury severity and varying linkage rates with different types of crashes (29% for motorcyclists vs. 79% for motor vehicle drivers.) They also noted that the casualties outside the urban area linked less often to a police report than the urban casualties. Their conclusion was that the low linkage rate was largely due to the underreporting of crashes by police (15).

An under reporting of pedestrian injuries was reported by Agran, Castillo and Winn in 1987, in a comparison of police report information with hospital monitoring system information in Orange County, California. It was estimated that police underreported pedestrian injuries by 20%. The researchers also noted that nontraffic incidents were especially underreported, mainly because the police database criteria excludes cases occurring on private property (driveways, sidewalks and parking lots) where a large percentage of pedestrian injuries occur (16). Similarly, Alaska's traffic crash data reporting system excludes incidents on private property, as well as those involving vehicles not customarily used for transport on roads.

Other possible reasons for the under reporting of traffic crashes include lack of police officers in the rural areas, reluctance of crash participants to notify police, and failure of local enforcement personnel to submit investigation forms to the Department of Public Safety.

The mean age of the injured victims of young driver crashes was slightly lower than that of the entire population of injured victims studied (25 vs. 30). Since the CrashCost estimates were based on national averages, the present discounted value of lost productivity for victims of young driver crashes would differ slightly from the value of lost productivity for victims of all crashes. The difference, however, is likely to be minor.

RECOMMENDATIONS

The factors contributing to Alaska's young driver crashes -- youth, inexperience, and risk-taking behavior -- are analogous to those seen in other states and countries. Currently there is no graduated licensing system in Alaska; however, legislation has been introduced and is currently under consideration during the 1997-98 legislative session. Alaska is also one of few states that does not require any instructional permit prior to obtaining a full privilege license. Graduated licensing has been shown to successfully reduce young driver crashes. It is recommended that Alaska adopt a graduated licensing system that is appropriate for Alaskans, to include the requirement of supervised driving under an instructional permit, a probational driving period, and raising the minimum age for full licensure to 17. The expected result would be a reduction in injuries and deaths, mitigation of the impact of crashes on Alaska's stretched emergency medical services, and a significant cost savings.

Alaska has a primary safety belt enforcement law for children under age 16 and secondary enforcement for those aged 16 and over. There is a helmet law for motorcyclists under age 18 and all motorcycle passengers. At the least, the primary safety belt law and the helmet law should be expanded to include young drivers through age 20 to protect those drivers at greatest risk. Even more effective are universal laws, i.e. mandated usage for all persons, which have been shown to increase belt usage 10-15% and helmet usage to 100% (10,11).

In the past three years Alaska has enacted two zero tolerance laws for young people under 21 years of age. A minor caught in possession of or consuming alcohol, regardless of motor vehicle involvement, can have his or her driver's license revoked. A minor also can be sited for "driving while intoxicated," for any level of alcohol registered on a breathalyser test. These laws send an important message to young drivers about drinking and driving in a state that has a major problem with alcohol involvement relative to a great variety of injuries. Full commitment by state and local jurisdictions is needed to enforce these and all other traffic safety laws.

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PELVIC BEHAVIOR IN SIDE COLLISIONS: STATIC AND DYNAMIC TESTS ON ISOLATED PELVIC BONES

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ABSTRACT

Car manufacturers are more and more concerned with the protection of the occupants in lateral impacts. Field accident analysis dealing with automotive side collisions suggest that the pelvis is very vulnerable, but there is a lack of knowledge of the behavior of the pelvic bony structure and of its biomechanical tolerance. This knowledge however is essential in order to optimize protection devices and car structures with regard to the security of the occupants.

An experimental study of the pelvic bony structure subjected to static and dynamic loads was carried out in order to document its biomechanical behavior and its injury threshold. 22 pelves were tested under side loading conditions. Displacements, applied force, and local strains of the pubic rami were obtained.

From this study, the main conclusions drawn out were:

- A good agreement is observed between the real life observations and those coming from the in-vitro tests.
- Static fracture threshold is lower in this study than those reported for whole body tests, but is closed to Cesari static results.
- The dynamic fracture threshold is well bordered by the chosen energy level of impact, and consequently, a first corridor including the behavior of the pelvic bony structure up to the level of injury is proposed.

INTRODUCTION

Side collisions represent 15 to 20% of the automotive crashes in which at least one of the occupants was injured but are the cause of 25 to 30% of serious and fatal injuries encountered in all car accidents. The real world crash investigations dealing with lateral impact suggest that the pelvis is very vulnerable. The protection of the occupants in the case of lateral impact is becoming one of the main concerns of the car manufacturers. The optimization of protection devices and car structures still remains difficult to achieve taking into account the behavior of the human body. Since many papers were published dealing with the mechanical behavior of the pelvis, few data are currently available on the behavior of the pelvis, particularly for the isolated bone. The results of the present study thus aim at a better understanding of the pelvis mechanical behavior. This knowledge is of importance in order to design improved crash dummies or mathematical models of the car occupants.

An experimental protocol was thus set up in order to reproduce the injuries observed in real life. Ten isolated pelvic bones were first tested with a static machine, in order to study the overall behavior of the bone structure, and to determine the fracture threshold. Then, dynamic tests were also conducted on isolated pelves. 12 pelves were tested under side loading conditions, using a drop tower with an energy of 30 Joules, this energy level having been determined from the static fracture threshold. The pelves were thus impacted with a falling mass of 3.68 kg at a speed of 4 m/s. Displacement, accelerations, impact force and local strains on the pubic rami were obtained. The fractures observed during those tests were coherent with those observed in real life. Ramus fractures, pelvic ring disruption, or posterior injuries such as sacral fracture were observed. For two dynamic tests, no fractures were obtained, suggesting that the impact conditions were well chosen in order to assess the rupture threshold of the pelvis. Furthermore, other parameters were obtained, such as the geometrical and some histological characteristics of the tested pelves, in order to correlate them with the observed behavior of the specimens.

METHODOLOGY

Several authors described PMHS tests to study the tolerance and the behavior of the pelvic area in side impacts. They consisted essentially in the whole body subjected to lateral impacts. A high variety of means was used, as well as a wide range of mass and impact speed. Sled tests were first described by Melvin [17], Kallieris [12], and Marcus [16]. Recently, Cavanaugh [3] and Zhu [29] presented a series of 17 cadaver tests. Impactor tests were also realized by Cesari [4-6,22], Nuscholtz [19-21], Viano [28], and Chamouard [2]. Finally, Tarriere [27] carried out whole body tests using a drop tower.

On the other hand, tests on isolated pelvic bone were rarely described in the literature. Cesari presented four static tests on hemi pelves [5], and Scales provided data for a F.E. model presented by Plummer [22]. This knowledge is however more and more necessary to design, provide parameters, and validate mathematical models of the pelvis, without taking into account the soft tissues.

Before setting up an experimental protocol, an examination of real life injuries is needed, essentially to insure us that the test produced fractures are in good agreement with those sustained in real crashes.

In a previous study [10], a field accident analysis was carried out to determine precisely the panel of typical injuries observed at the level of the pelvic area in side collisions. A series of 219 occupants and 381 injuries AIS 2+ [1] from the LAB accident database was retained. The main advantage of this database is its ability to provide both medical description and accident circumstances. All the cases were studied, including those involving low mass cars, trucks and fixed obstacles. The pelvic area injuries sustained in side impacts were selected. Pelvic bone fractures, femoral fractures, and low abdomen injuries were included. Thus, a complete examination was realized for the area comprised between the mid abdomen and the mid thigh.

The pelvic fractures were most frequently found (184), followed by the femur fracture (56), and soft tissue injuries (106). By order of importance (Figure 1), pubic fractures were first found (above 50% of all injuries), then femur fractures (25%, from which 75% of diaphysis), acetabular fracture (12%) and posterior fractures, such as sacro-iliac joint and sacral fractures (11%). Pelvic content injuries consisted essentially in retroperitoneal hemorrhages (10%).

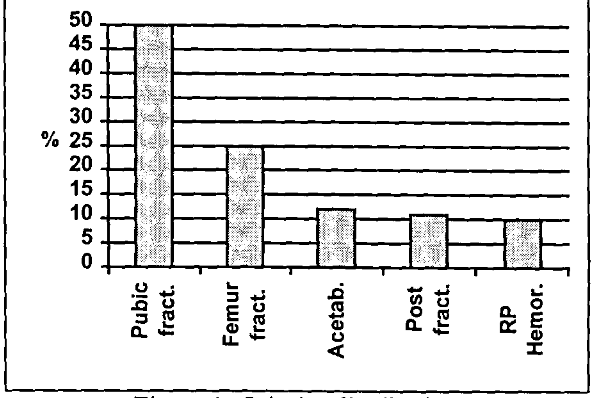

Figure 1 : Injuries distribution

This analysis, focused on injuries selected on the pelvic region, is consistent with other available data [7,8,11,13,15,18].

STATIC TESTS

The typical pelvic injuries were well identify through the previous accident analysis. The following step of this study consisted in a series of static tests, in order to access the overall behavior of the bony structure, the pelvic ring deflexion and the strains at sites of a high probability of fractures.

A reliable loading and a good stability are required for the immobilization of each pelvis. An easily reproduced position, based on standard anatomic landmarks, is also necessary. The positioning was chosen to insure stability and to get most of the bone structure free when subjected to the load. The line between the two anterior superior iliac spines was oriented vertically, corresponding to the Y-axis (Figure 2).

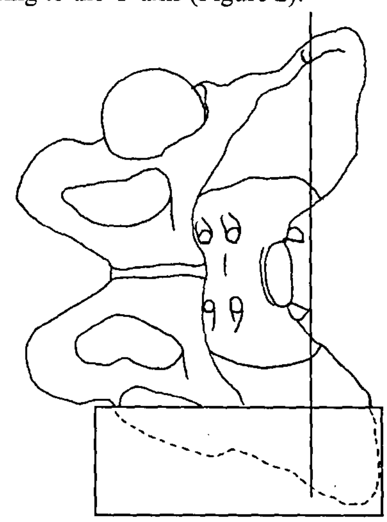
Figure 2 : Anterior view

Therefore, each pelvis was placed in a metallic box and cast with a low melting temperature alloy (< 60° C), the Cerrobend®, up to the external edge of the left ischial tuberosity. Thus, the pelvic ring and the pubic rami were totally free in this configuration. These boundary conditions were chosen because they could be easily reproduced in a finite element model.

The force applied to the pelvis was recorded from a load cell. Six transducers were used to measure the displacements of two points of the pelvic bone according to the reference system defined on Figure 3. The point "A" is situated at the right anterior inferior iliac spine, while point "B" is the superior edge of the pubic symphisis. Two plastic balls were screwed into the bone to materialize these two anatomical points.

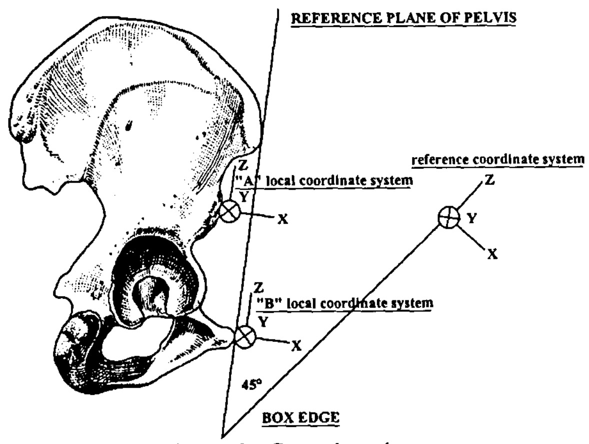

Figure 3 : Superior view

Eight strain gages were glued on each side of the four pubic rami. A ninth gage was placed on the internal side of the iliac wing, 1 cm above the sacro iliac joint. These points were determined by the usual location of fractures (Figure 4).

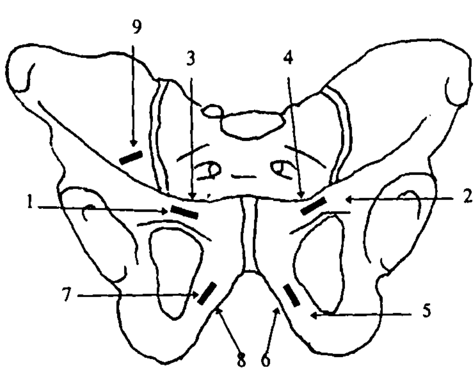

Figure 4 : location of strain gages and A & B points

10 pelvic bones were tested. They were provided from fresh cadavers through the department of anatomy of the "Faculté des Saints Pères" in Paris. Nine of them were male specimen. The age range from 47 to 86 (mean 67 years). Metastasis or a long period of bed rest did not damage the specimens chosen, except for one of them. One of them was frozen and no more data were available. Their principal characteristics are reported in Appendix 1.

Before testing, all the pelves were weighed, and their volumes determined by simple methods, so that their density can be calculated. Several measures were also taken, such as maximum width, diameter of the pelvic ring, and distance between iliac spines. In order to document as accurately as possible the geometry of the tested specimens, a geometrical acquisition was carried out on each tested pelvis using a 3D-measuring device. The measuring protocol was designed in order to provide a classification of the pelves in accordance with the work of Reynolds [26]. Thus, a library of 105 points was acquired.

Each pelvis sustained 3 kinds of tests, at a speed of 5 mm/mn, with an Inströn testing machine. A vertical load (Y direction) was first applied to the right iliac crest, increasing to a maximum of 500 N then returning to 0. Subsequently, the right acetabulum was loaded with a metallic sphere fitted to its diameter up to 500 N then down to 0. Finally, the last test involved increasing the load through the acetabulum until fracture occurred. X rays were taken to confirm and locate fractures. Three types of data are available: displacements, strains, and stiffness via a force displacement curve.

RESULTS

The iliac tests were characterized by effort-displacement curves with a high range in terms of Y displacement of the iliac wing. Responses varied from 1.6 mm to 11.8 mm for a loading of 500 N. The highest value was observed for the female specimen, for which the geometry was quite different (Figure 5). Perpendicular displacements were also measured, of the same order of magnitude as those in the loading direction.

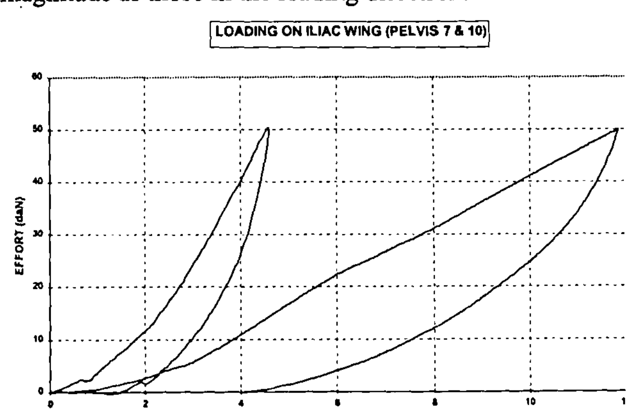

Figure 5 : Force Displacement curves of 7th & 10th Pelvis

Pubic symphisis exhibited lower displacements, from 0.1 to 2.7 mm for the Y direction (Figure 6). Perpendicular values did not exceed 1.2 mm for X & Z directions, except for the female pelvis (2.2 & 2.5 mm). Complete data are reported in Appendix 2.

Point	AIIS			PS		
Direction	dX	dY	dZ	dX	dY	dZ
Min (mm)	0.2	1.6	2.1	0.1	0.1	-0.2
Max (mm)	3.6	11.8	10.8	2.2	2.7	2.5
Mean (n=10)	1.5	4.4	4.2	0.5	0.7	0.6

Table 1 : Displacements on Anterior Inferior Iliac Spine (A) and Pubic Symphisis (B) for 500 N

Displacements observed from the acetabular tests are lower than those of the iliac loading, and range only from 1.2 to 2.5 mm. The 3D analysis of the displacements shows that the deformation pattern of the structure is complex. Coupled movements of the same order of magnitude as those in the loading direction (+Y) are also observed (Figure 7), in the posterior anterior (+X) and vertical (-Z) directions. Complete data are reported in Appendix 3.

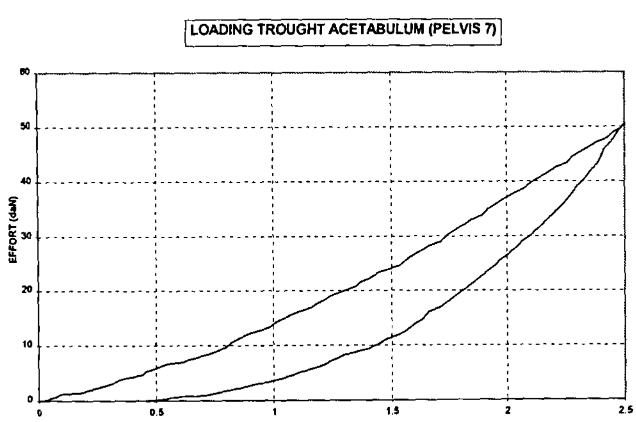

Figure 6 : Force Displacement curves of Pelvis 7

Point	AIIS			PS		
Direction	dX	dY	dZ	dX	dY	dZ
Min (mm)	0.3	1.2	-2.1	0.4	0.4	-1
Max (mm)	2.4	2.5	-0.4	1.6	1.8	0.3
Mean (n=10)	1	1.7	-1.1	0.9	0.9	-0.4

Table 2 : Displacements on Anterior Inferior Iliac Spine (A) and Pubic Symphisis (B) for 500 N

The pubic symphisis exhibits a displacement in the same direction as those of the acetabulum, but of half the magnitude (Figure 8). Finally, one can see that the highest displacement at the level of the pubic symphisis is often observed in the posterior anterior direction.

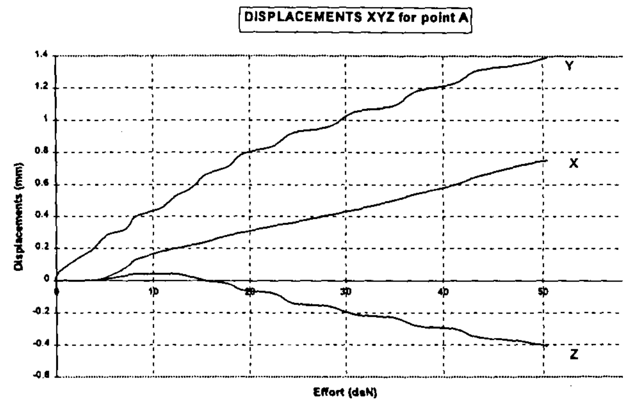

Figure 7 : Displacement curves for Ant Inf. Iliac Spine

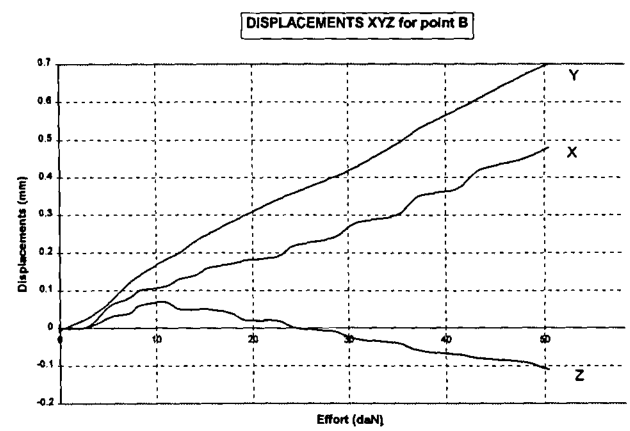

Figure 8 : Displacement curves for Pubic Symphisis

Strain gages

As far as the strains are concerned, it can be noted that all external pelvic strains measured negative values (compression) while all internal pelvic strains are positive (traction). This observation can be related to the postero-anterior displacement of the pubic symphisis. A symmetrical distribution of the stresses can be observed for the two ilio pubic rami, which was not found for the ischio pubic rami.

The following curves (Figure 9) from fracture tests show the behavior of the 10 pelves loaded through acetabulum. Fracture occurs for maximum forces ranging from 1100 to 3450 N (mean 1750 N), and for displacements ranging only from 3.5 to 7.5 mm (mean 5.2 mm). The highest displacement for the pubic symphisis was often observed for the posterior anterior direction, particularly before the fracture occurred.

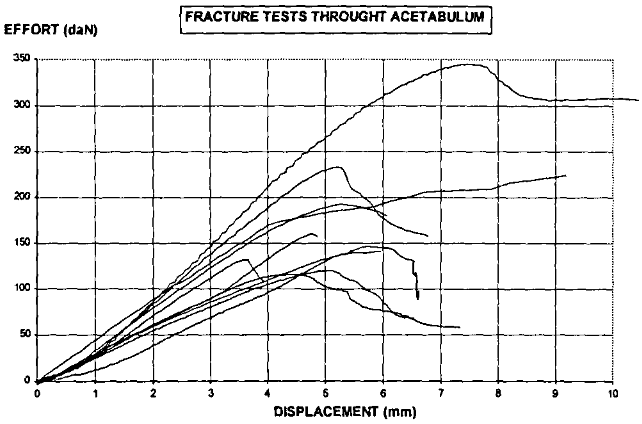

Figure 9 : Force-displacement curves from fracture tests

The load displacement curves enable the computation of a "pseudo-stiffness" of the structure, defined as the ratio between the load and the corresponding displacement (slope of the curve). The results of the tests show a significant difference between the stiffness computed for the load on the acetabulum (denoted Ka), and the pseudo stiffness for the load on the iliac wing (denoted Ki). The greatest ratio between Ka and Ki was found for the female specimen (pelvis 7), for which displacements of the iliac wing were the highest. The others pelves exhibited ratios from 1/2 to 1/3.

	S01	S02	S03	S04	S05	S06	S07	S08	S09	S10
Acetabulum	403	254	416	423	337	249	201	227	231	333
Iliac Wing	206	129	211	206	155	72	46	88	141	105

Table 3 : Stiffness Comparison (N/mm)

DYNAMIC TESTS

The first results, together with a few computer simulations, enabled us to estimate the loading energy necessary to obtain an injury. Nevertheless, the dynamic behavior of the pelvis is not well known when the pelvis is subjected to an impact. A new series of 12 pelves was carried out to access the biomechanical characteristics of the pelvic bone, without soft tissues or pelvic content. Thus, 12 isolated pelves were tested under side loading conditions, using a drop tower with an energy of 30 Joules. The positioning of each pelvis was previously described for static loads, and applied in a same manner for the dynamic procedure (Figure 2). The energy level was determined from static fracture thresholds. The pelves were thus impacted with a falling mass of 3.68 kg at a speed of 4 m/s.

A drop tower was used for these tests (Figure 10). It consisted of a falling mass guided between two rails which enables impact speed around 4 m/s.

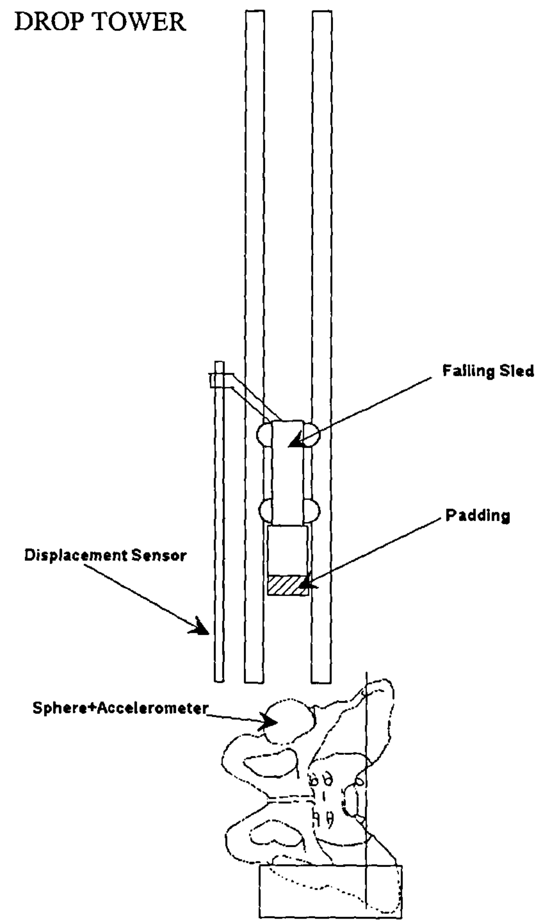

Figure 10 : Schematic view of the testing set-up.

The falling mass was fitted with two accelerometers, the first one to calculate acceleration, force and displacement during the impact. The second one was used to determine precisely the impact speed. A good correlation was found between these two sensor values at the moment of the impact.

A displacement sensor was also used to measure the pelvis deflection.

A metallic ball was fitted into the right acetabulum, to distribute the load on the whole joint surface. Its diameter was chosen by the preliminary geometric measurements. An accelerometer was included in this sphere to know its kinematics and calculate the force applied to the acetabulum. At the time of first impact, only the impacting mass and the impacted sphere were involved, and the high peak force, due to the contact, did not reflect the biomechanics of the pelvis. Thus the applied force was computed from both the falling mass accelerometer and the sphere accelerometer, as follows (Figure 11):

$$F_y = M_{mass} \times acc_{mass} + M_{sphere} \times acc_{sphere}$$

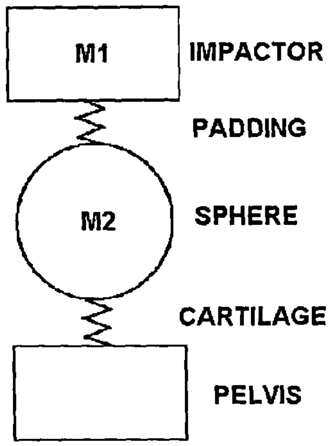

Figure 11 : simplified model of the experimental set-up

To avoid direct contact between two metallic surfaces, a 11-mm thick silicon padding was set at the inferior side of the falling mass. The deflection of this silicon padding was calculated and reached 82 % of its thickness. This padding played the role of a physical filter and thus the raw data were used for the accelerometers. So, direct measurement by displacement sensor cannot be used. But, another advantage of using this internal accelerometer is to calculate directly the deflection by integrating twice the signal. So this data can be used to establish behavior curves.

This experimental set-up was verified by several tests on a padding surface, which was calculated to simulate the behavior of a human pelvis, in terms of acceleration and displacement. The results obtained are illustrated by the following figure (Figure 12).

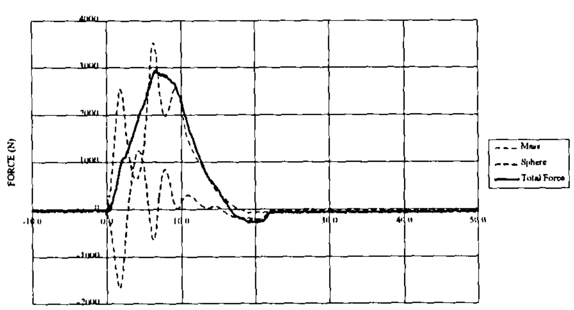

Figure 12 : Impact force with the experimental model

In addition, four strain gages were glued on the external side of each pubic ramus (Figure 13). The number of gages was reduced compared to those used for static tests, because information provided for internal and external sides of the same ramus was redundant. These strain gages were oriented along the main axis of the ramus. They were not used to measure stress precisely, but to compare the behavior of one ramus to the others. Nevertheless, they can be used to determine the moment of the fracture for each ramus.

All these tests were recorded at a 10 kHz sampling rate.

Only one impact was delivered on the acetabulum through the metallic sphere. The choice of a single impact on the acetabulum was deduced from static tests. The stiffness of the pelvic ring in side loading, at least twice than those of the iliac wing, represents the major stiffness of the pelvic ring. Previous cadavers tests presented elsewhere, for which a double pelvis impactor was used [10], confirmed this difference of stiffness.

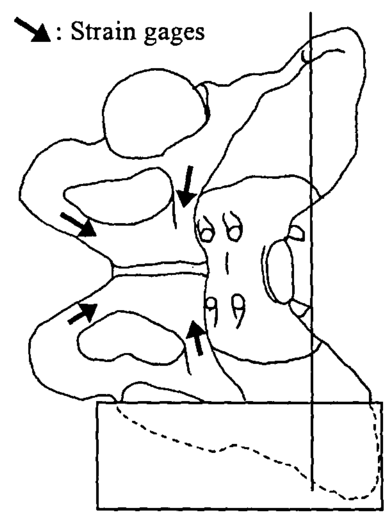

Figure 13 : positioning of the pelvis and location of the strain gauges.

Twelve pelvic bones were tested. They were provided from fresh cadavers through the department of anatomy of the "Faculté des Saints Pères" in Paris. Five of them were male specimens. The age ranged from 62 to 81 (mean 70 years). Metastasis or a long period of bed rest did not damage those cadaver bones. They were all stored at -18 °C before tests. A careful dissection kept undamaged the ligaments, especially posterior ligaments.

	Mass	Volume	Density
Mean	1240	1060	1.17
Min	870	750	1.1
Max	1480	1350	1.25

Table 4 : Main characteristics of the dynamic pelves.

A geometrical acquisition was also carried out on each tested pelvis using a 3D-measuring device, as described for static tests. X-rays for each pelvis were also taken to archive an image and to be sure that a previous fracture or metastasis did not damage the pelvis.

For the isolated pelvic bone, the impact energy was calculated to reach 30 Joules. This value was deduced from static tests, and represents the mean energy to obtain ramus fractures. The falling mass was adjusted to 3.68 kg, and the height calculated for an impact speed close to 4 m/s.

After each test, the pelvis was subjected to a careful observation in order to document the injuries. X-rays (antero-posterior, oblique and lateral) were taken and archived. They will be useful to compare the real life data with the experimental results.

RESULTS

Each pelvis was tested only once. 2 of them were intact after the impact. The 10 others exhibited a great variety of fractures from a single pubic ramus fracture to the complete pelvic crush. This first observation enabled us to confirm that the energy level was well chosen in order to approach the fracture threshold of the pelvis. These fractures, when occurring, were similar to those observed in the previous accidental study or in the literature. They are described in Appendix 6 and summarized in Table 5.

Fractures of one or two pubic ramus	4
Fractures of pubic ramus associated with posterior fracture (sacrum)	4
No fracture	2
Fractures of ilio pubic ramus extended to the acetabulum	1
Fractures of three or four pubic ramus	1

Table 5 : experimental results in terms of produced fractures.

Only pelves, which sustained posterior and anterior fractures, exhibited a high permanent displacement, always exceeding 10 mm (the maximum being over 70 mm). Pelves exhibiting only pubic fractures presented no or low permanent displacement after the test (less than 5 mm).

For the purpose of analysis, 3 groups were constituted: the first one without any fracture (2 pelves), the second one with only anterior fractures (6 pelves) and the last one with both anterior and posterior fractures (4 pelves).

One the other hand, the behavior curves were correlated to the three groups (Figure 14). Typical aspects were observed. The group without fracture is characterized by a high peak force and a displacement less than 5 mm, while the group of crushed pelves presented a high displacement with a low peak force.

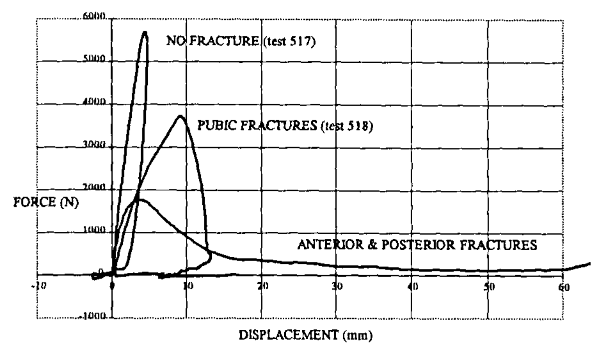

Figure 14 : behavior's patterns of the tested pelvic bones.

When a fracture was observed, the maximum force did not occur simultaneously with the maximum displacement. Actually, displacements at the instant of first fracture never exceeded 10 mm. Posterior injuries always occurred after anterior fractures. No significant correlation was found between force max and displacement at the moment of Force max. Complete data are reported in Appendix 6

Maximum force and maximum displacement for each test are summarized in the following graph (Figure 15). Three areas can be determined, and related to the anatomical damages, as defined before.

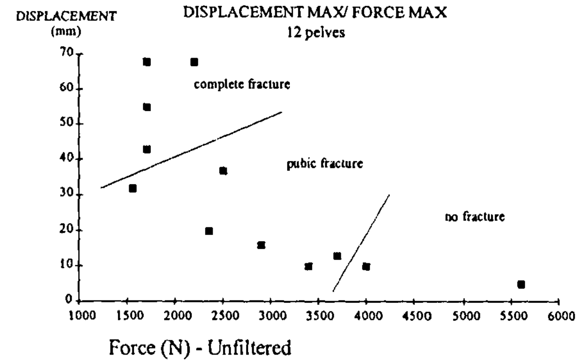

Figure 15 : classification of the pelves with regard to the ratio between the maximum displacement and the maximum force.

Data obtained from strain gages were also examined (Figure 16). The strain gages were oriented along the main axis of each ramus. A high range of responses was observed. Right and left ilio pubic rami exhibited symmetrical signal during the impact, from 0.2 % for tests without pubic fracture to 1.2 % for tests with pubic fracture. For the ischial gages, the lowest value reached 0.1 % and never exceeded 0.8 %. It was assumed that the maximum of the strain curve was contemporaneous with the beginning of the rupture of the bony structure. A more detailed analysis still remains to be done in order to classify, when multiple fractures occurred, the order of occurrence of the different injuries.

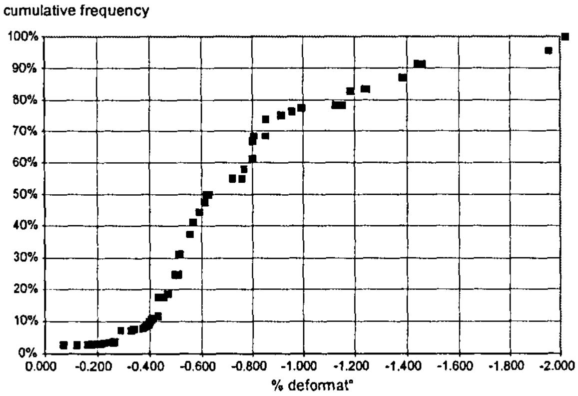

Figure 16 : Cumulative frequency of maximum strain for each pubic ramus

HISTOLOGICAL STUDY

Complementary studies were carried out in order to correlate the response of the pelvis with other parameters: geometry, bone mineral content and thickness of the cortical bone. A first approach was achieved for the static pelves, for which the bone mineral content was studied. The histological characterization of the specimens was obtained after inclusion in a polyester plaster. Each pelvis was sliced parallel to a reference plane (Figure 17) based on the foramen superior. Sixteen to 20 slices were obtained, according to the height of each pelvis. The thickness of the cortical bone was studied, and the mineral content of each slice determined by calcination. This method enabled us to access the overall mineral content as well as the mineral content of the sacrum, the iliac wing or the pubic rami. Furthermore, the mineralization of each ischio-pubic ramus by its length was calculated as an index (C/L) for the analysis.

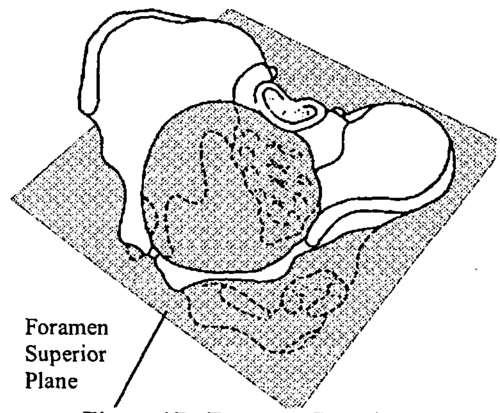

Figure 17 : Foramen Superior

A multiple regression analysis, including geometrical, mechanical and histological parameters, was performed with the results of the previous static tests.

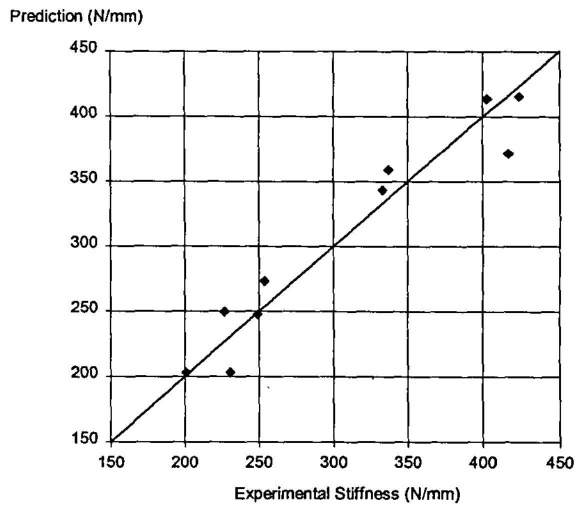

Figure 18 : Predictive fonction of the pelvic ring stiffness

A predictive fonction of the pelvic ring stiffness was first found, with only 3 parameters, with a R-squared, ajusted for degrees of freedom, up to 90 % (Figure 18):

SPR = 619.71 + 0.95*M - 0.29*V - 319.22*C/L

Where:

SPR = stiffness of the pelvic ring.

M = pelvic overall mineralization.

V = total volume.

C/L = index of ischio-pubic ramus mineralization.

Since the P-value is less than 0,01, there is a statistically significant relationship between these variables at the 99% confidence level. This relationship can be improved by adding the pelvis density as follows (Figure 19):

SPR = 115 + 416*D + 0.81*M - 0.24*V - 326.74*C/L

Where:

D = density of the pelvic bone.

The adjusted R-squared statistic for this enhanced fonction is 93,75 %.

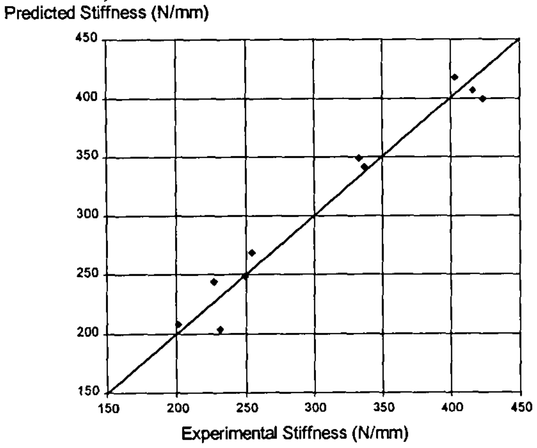

Figure 19: Enhanced predictive fonction of Stiffness

Another multiple regression analysis was performed, using the maximum force applied for a pelvic static fracture. First results, which are less significant than those from the stiffness, incited us to take into account 2 pelves (Figure 20). The first one is the female specimen, while the second is a 47-year-old specimen. Since variables as " age " and " gender " could be explained by others parameters such as thickness of the cortical bone, or geometry, for example, experiments on a wider sample are necessary to conclude.

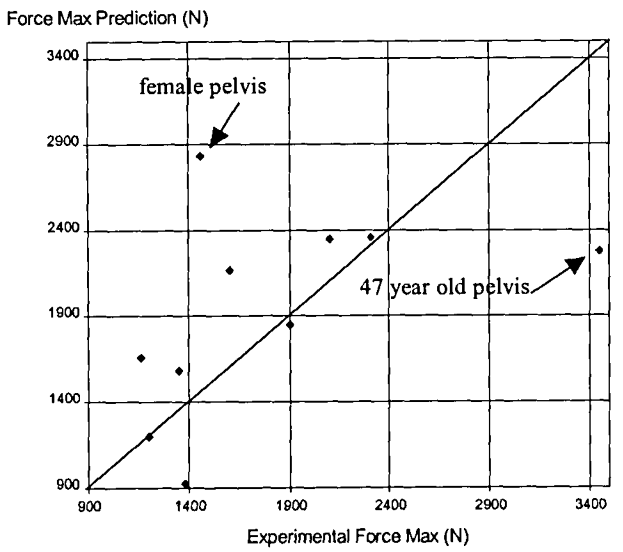

Figure 20: Maximum static force, measured & predicted

DISCUSSION

Several points can be noted for the static tests. The following comments can be made regarding the biomechanical aspect of the pelvic static behavior:

1 - Fracture threshold levels are lower in this study than those reported for whole body tests, but could be compared to Cesari static tests [5].

2 - Both displacement curves and strain gages show the specific behavior of the pubic symphisis, which can explain the mechanism of fracture.

As far as the anatomical aspect is concerned, it should be noted that:

1 - There is a lack of posterior injuries (i.e. sacro iliac disjunction), and opposite fractures.

2 - These experimental fractures were not well detected by X-rays.

The low thickness of the cortical bone of the pubic rami in this series, as well as the slow loading of the structure, and the removal of the load when the measured force began to decrease, can explain these observations.

Finally, the specific behavior of the female specimen should incite to study the influence of male and female geometry on mechanical responses.

On the other hand, varied fractures obtained from the dynamic tests are consistent with those observed in real life accidents. It was checked that the boundary conditions did not influence the results. Indeed, no fractures were observed near the interface between the pelvic bone and the low melting point alloy. Furthermore, a finite element study, using a published model [24], enables us to simulate different boundary conditions. Three different cases were examined, as follows:

- Loading with a metallic sphere in the acetabulum and the same immobilization as in the experimental tests.
- Loading with a metallic sphere and immobilization of a sphere fitted to the symmetrical acetabulum.
- symmetrical loading with two spheres in the acetabula.

No significant differences were found between the simulation results, thus confirming that the chosen boundary conditions were well adapted to this test.

A great range of responses was observed for those 12 pelves tested with a constant energy of 30 Joules. Displacement, applied force, local strains and fracture threshold were obtained. Applied force, from 1550 to 5600 N, was higher than those measured for static tests. Displacements at the moment of the fracture never exceeded 10 mm, which is close to those obtained for static tests. As those tests were performed with a constant energy, these results depend essentially on the geometrical characteristics and material properties.

Furthermore, more information was collected concerning both geometrical and histological data. It is expected that the most important parameters will be the thickness of the cortical bone and the bone mineral content, followed by the geometrical characteristics. A finite element simulation study is underway in order to assess the relative influence of these parameters and will be correlated with the results of the present study. These preliminary results, obtained from 12 pelvic bones tested on a drop tower, enable a first approach of an injury threshold on isolated pelvic bone (Figure 21). Displacement curves, force-time curves, as well as behavior curves from force and displacement, contributed to establish a tolerance level of the pelvic bone subjected to a side impact loading condition.

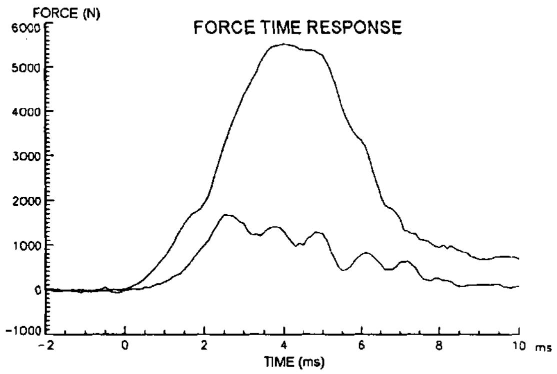

Figure 21 : experimental corridor.

CONCLUSION

This study enables us the assessment of the injuries sustained by a pelvis loaded in side impact conditions. The correlation between field accident studies and the experimentally reproduced injuries is a first step in the description of the injury mechanisms and of the tolerance of the pelvic bone. This knowledge is of particular interest for the optimization of protection devices and car structures as well as for the dimensioning of dummies or the definition of biofidel human models.

Complementary studies are yet underway in order to correlate the dynamic response of the pelvis with other parameters: geometry, bone mineral content and thickness of the cortical bone. In the course of this study, these parameters were planned to be documented. A wide geometrical database is now available and will be soon presented. The histological characterization of the dynamic specimens is also underway. Those pieces of information will thus be available for all the tested specimens, and further analysis will enable to draw out some correlation between geometrical, mechanical and histological data.

The assessment of the protection level must be provided for vehicle occupants in terms of pelvic resistance. All these studies will provide quantitative information suitable for the assessment of the efficiency of side impact protection devices.

ACKNOWLEDGMENTS

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APPENDIX

Number	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
Age(years)	63	?	57	61	70	72	63	86	86	47
Gender	M	M	M	M	M	M	F	M	M	M
Weight(kg)	66	?	72	?	77	55	90	60	90	130
Height(cm)	163	?	174	?	175	160	165	167	175	180
Storage	+4°C	-20°C	+4°C	+4°C	+4°C	+4°C	+4°C	+4°C	+4°C	+4°C

Appendix 1 : Characteristics of the 10 static pelves

	Loading on Iliac Wing up to 500 N					
	Anterior Inferior Iliac Spine			Pubic Symphisis		
displ. (mm)	dX	dY	dZ	dX	dY	dZ
Pelvis S1	1.7	2.0	2.8	0.2	0.7	0.4
Pelvis S2	3.1	2.6	3.7	0.1	0.2	-0.1
Pelvis S3	1.1	1.6	2.1	0.2	0.5	0.1
Pelvis S4	1.6	1.9	3.8	0.2	0.3	/
Pelvis S5	0.6	2.8	2.3	0.3	0.4	-0.2
Pelvis S6	1.8	7.5	5.8	0.8	0.8	1.2
Pelvis S7	3.6	11.8	10.8	2.2	2.7	2.5
Pelvis S8	1.1	5.9	4.7	0.6	0.8	/
Pelvis S9	0.2	3.4	2.9	0.1	0.1	/
Pelvis S10	0.5	4.6	3.3	0.1	0.6	0.6

Appendix 2 : Displacements for iliac tests up to 500 N

	Loading through Acetabulum up to 500 N					
	Anterior Inferior Iliac Spine			Pubic Symphisis		
displ. (mm)	dX	dY	dZ	dX	dY	dZ
Pelvis S1	0.5	1.2	-0.4	0.7	0.6	0.3
Pelvis S2	0.3	1.6	-0.8	0.4	0.4	-0.3
Pelvis S3	0.4	1.6	-2.1	0.8	0.9	-0.9
Pelvis S4	0.8	1.4	-1.0	0.8	0.6	/
Pelvis S5	2	1.7	-2	1.5	1.1	-1
Pelvis S6	1.3	2.1	-1.7	1.0	1.1	-0.6
Pelvis S7	2.4	2.5	-0.6	1.6	1.8	0.1
Pelvis S8	1.2	2.1	-1.3	1.0	1.0	/
Pelvis S9	0.5	1.8	-1.1	0.6	0.5	/
Pelvis S10	0.7	1.4	-0.4	0.5	0.7	-0.1

Appendix 3 : Displacements for acetabular tests up to 500 N

Pelvis number	**Injuries**
S1	Right Ilio & ischio-pubic rami + sacrum
S2	Right Ilio & ischio-pubic rami
S3	Right Ilio & ischio-pubic rami
S4	Right Ilio & ischio-pubic rami
S5	Right Ilio & ischio-pubic rami
S6	Right Ilio & ischio-pubic rami
S7	Right Ilio & ischio-pubic rami
S8	Right Ilio & ischio-pubic rami
S9	Right Ilio & ischio-pubic rami
S10	Right Ilio & ischio-pubic rami

Appendix 4 : Main results of the static tests

N°	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11	D12
Sexe	F	M	M	F	F	F	F	M	M	M	M	F
Age (years)	77	65	62	73	65	81	81	70	67	72	75	73
Pelv.Mass (g)	1100	1480	1320	870	1350	1090	1060	1460	1270	1160	1440	1270
Volume (cm3)	975	1350	1060	750	1100	960	850	1310	1130	1030	1190	1050

Appendix 5 : Main characteristics of the dynamic pelves

Pelvis number	F Max (N)	$d_{(F\ Max)}$ (mm)	D Max (mm)	Injuries
D1	2197	8	68	Ilio & ischio-pubic rami + sacrum
D2	2350	4	20	4 pubic rami
D3	5600	5	5	None
D4	1700	7	68	Ilio & ischio-pubic rami + sacrum
D5	3700	9	13	Ilio & ischio-pubic rami
D6	1700	7	43	Ilio & ischio-pubic rami + sacrum
D7	4000	8,5	10	None
D8	1550	9	32	Ilio pubic ramus
D9	2500	4	37	Ilio & ischio-pubic rami
D10	1700	4	55	Ilio & ischio-pubic rami + sacrum
D11	3400	5	10	Ilio (extented to acetabulum) & ischio-pubic rami
D12	2900	7	16	Ilio & ischio-pubic rami

Appendix 6 : Main results of the dynamic tests

CHANGES IN EXPOSURE AND ACCIDENT RISK FOR CAR DRIVERS IN FRANCE

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Paper Number 98-S6-W-38

ABSTRACT

This paper aims at analyzing changes in risk exposure as revealed by the last two travel surveys carried out in 1981-82 and 1993-94, and at assessing variations in accident risk by linkage with accident data for the corresponding periods. The findings show that car trips are on average longer and faster in 1994, but there is still a lot of very short journeys. The proportion of female and elderly people in the driver population is increasing. Trip purposes still differ according to driver sex. Linkage with accident data reveals a general decrease in the risk per kilometer traveled, tending to confirm the hypothesis of a general improvement in driving standards.

INTRODUCTION

The quantitative analysis of road safety issues is based on study of the distribution of accidents and victims. But in order to target prevention efforts more accurately in this field, one has to identify the high-risk groups. This means comparing accident data with reference populations, i.e. with risk exposure data. Risk exposure may be represented by different indicators, such as inhabitants, cars, driving licenses, kilometers traveled, journey times, etc. Reference indicators are generally selected with a specific objective in view, and the choice naturally affects the results of risk assessment, particularly the hierarchy of high-risk groups.

Data for injury accidents are taken from official statistics drawn up on the basis of Police reports. Exposure data are generally more difficult to obtain, hence the usefulness of transport surveys such as the French National Personal Transportation Survey. Through trip notebook attributed to each vehicle, it provides substantial information about vehicles and their drivers, distances traveled, time spent driving and trip purpose.

The aim of this paper is to present an analysis of these notebooks and to evaluate the changes in exposure characteristics and in accident involvement by comparing the data from the last two transport surveys carried out in 1881-82 and 1993-94 and police accident data for the same periods.

DATA AND METHODS

Data Source and Population Studied

The purpose of the French National Personal Transportation Survey is to produce a picture of the driving habits of households in France (Saglio et al, 1993). The results obtained may serve to measure structural changes insofar as this type of survey is conducted approximately once every decade (in 1959, 1966-67, 1973-74, 1981-82 and 1993-94).

The data collected from May 1993 to April 1994 concerned a sample population of 20 000 households. Each household was interviewed on two occasions, and between the two visits a car trip notebook was attributed at random to one vehicle in the household, to be completed by the driver(s) of the vehicle concerned over a 7-day period between the two visits. The driver had to note the characteristics of the trip at each stop, including the number of kilometers traveled and the time of day of the journey. All stops had to be mentioned, including those made to drop off or pick up passengers, but excluding stops at traffic lights, level crossings, etc.

The vehicles concerned by the notebook included private cars, small vehicles requiring no driving license, camping cars or light utility vehicles (vans). For the purposes of our analysis we concentrate on private cars only.

Allowing for households which were not main places of residence and consequently were not included in the survey, and for non-responses, 9 515 log books were properly completed and described 197 003 journeys (Armoogum and Madre 1995). 8 783 of these notebooks were for private cars and described 183 450 journeys. A comparison of the results produced by the car notebooks with other sources of information, including daily journey descriptions, shows that the weekly notebook method can be used to observe 83 % of annual mileage (Madre, 1996).

In the previous French National Personal Transportation Survey, conducted from March 1981 to February 1982, a sample of 2 677 exploitable car notebooks describing 55 334 journeys was available (Fontaine and Saint-Saens, 1988).

Accident data used for the risk evaluation were drawn from the Road Traffic Injury Accident Analysis Bulletins (BAAC) compiled by the French police for each injury accident. We took accident data from the BAACs corresponding to the two transport survey periods when cars where involved, i.e. 259 656 cars in 1981 and 167 854 cars in 1993-1994.

Method

Accident risk may be evaluated using various indicators which correspond to different objectives. The following are the most commonly used* .

- The number of accidents or victims per year represents the risk to the community.
- The number of accidents or victims related to the number of inhabitants is often used in international comparisons of road safety, since it is the most readily available criterion. It is also used to analyze the risk associated with different types of accident, such as domestic accidents, aggressions, suicides, disease, etc. It is mainly a public health criterion. But strictly in the road safety field, it does not reveal any differences in the mobility patterns of the different populations concerned.
- The number of accidents or victims related to the number of vehicles gives a clearer idea of the mobility pattern, and also allows for the degree of motorisation in international comparisons, but it does not allow for the different types of vehicle use. It is often used, nevertheless, in particular by insurance companies, to calculate their premiums.
- The number of accidents or victims related to fuel consumption takes mobility into account, but does not provide differential results.
- The number of accidents or victims related to distance traveled, or time spent driving are indicators currently used in road safety. The time factor introduces the notion of mean journey speed. The relative risk obtained using this indicator amplifies the gaps between groups who drive at very different speeds : "fast" drivers represent a greater relative risk per unit of time than per unit of distance.

Our aim was on the one hand to analyze the change in risk exposure as revealed by the vehicle note books from the last two transport surveys, and on the other to assess the change in the road accident risk by comparing these data with the accident data for the corresponding periods. We used an aggregated approach, comparing different driver groups defined according to their socio-demographic characteristics. The journeys were analyzed according to distance traveled, time taken and mean journey speed. The mean speed includes stops at red lights, road junctions, level crossings, etc. It corresponds to the mean speed for all the kilometers traveled by the group concerned. While less informative than spot speed, which is a particularly important criterion in accidentology, but difficult to measure in the event of a collision, mean journey speed does reflect the behavior of different groups of drivers. It must be remembered, however, that it is closely linked to the type of road network used. This geographical criterion was not revealed by the vehicle log books, since previous tests had demonstrated that the quality of this data collected over a one-week period was unsatisfactory.

The relationships with car characteristics are also examined but only for the last Transport survey insofar as these criteria were not registered in the previous survey.

* We don't mentioned here exposure indicators based on non at fault drivers (induced exposure method)

EXPOSURE CHARACTERISTICS AND CHANGES

General Results

The average number of car journeys in the course of a week increased little between the two surveys (20.7 journeys per week in 1981-82 vs. 20.9 in 1993-94), i.e. three journeys per day. The average journey distance rose from 10.1 km to 11.8 km. Mean journey time also rose, but to a lesser degree, from 16.5 minutes in 1981-82 to 17.7 minutes in 1993-94. The distances traveled were covered at a higher speed, mean journey speed increasing by almost 10%, from 36.7 km/h to 40.1 km/h. While the proportion of short journeys was smaller in 1993-94 (Figure 1.), it was still high, with 52% of all car journeys no longer than 5 km, compared with 58% in 1981-82.

Average journey speed increases with the distance traveled. The reason for this is that the longer the journey, the smaller the part spent on urban roads, where the speed limit is lower. Note that for the same distance, the average speed increased between the two surveys. The greater increase in speed over longer journeys may be due to the development of the motorway network, particularly in periurban areas around major conurbations. This stagnation in the number of journeys, accompanied by an increase in the distances traveled and in speed, is found in the analysis of all types of transport (Orfeuil, 1996).

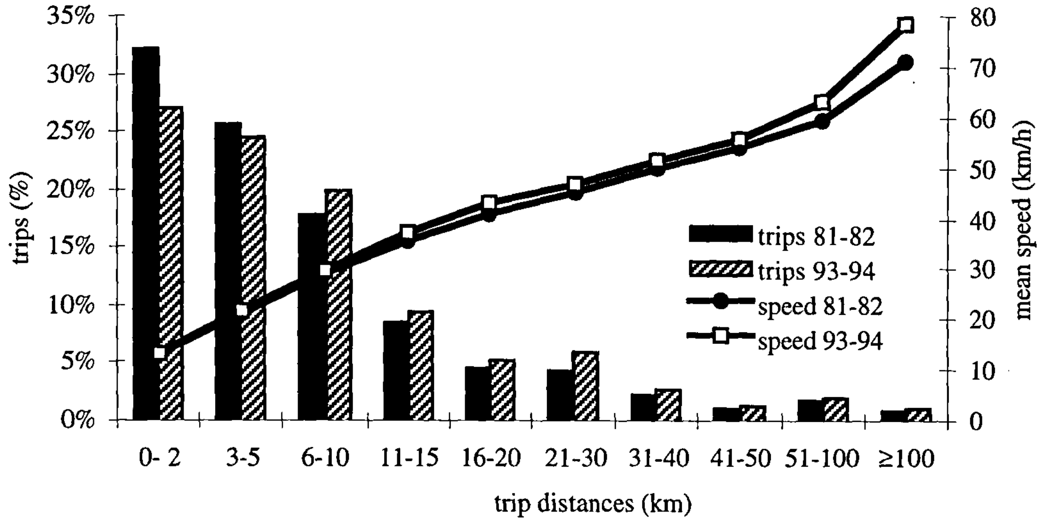

Figure 1. Car journeys and mean speed according to distance traveled.

Table 1.
Exposure Characteristics According to Sex and Age of Driver

	km traveled %		mean journey distance km		mean journey time mn		mean journey speed km/h	
Year	81-82	93-94	81-82	93-94	81-82	93-94	81-82	93-94
Sex								
men	74.2	66.4	11.6	13.8	18.0	19.5	38.6	42.5
women	25.8	33.6	7.3	9.0	13.6	15.2	32.4	35.8
Age								
< 20	1.9	1.4	10.9	12.1	16.8	19.2	39.1	37.7
20 à 24	11.4	8.6	10.3	12.5	16.4	17.7	37.5	42.3
25 à 34	31.5	25.8	9.5	11.3	15.5	16.7	36.7	40.6
35 à 49	33.0	37.9	10.1	11.5	16.5	17.2	36.7	40.1
50 à 64	18.1	18.8	10.9	12.7	17.9	19.2	36.5	39.6
≥65	4.0	7.6	10.9	11.6	18.2	18.9	36.2	36.8
Together	100	100	10.1	11.8	16.5	17.7	36.7	40.1

Exposure Characteristics According to Sex and Age of Driver

Female drivers accounted for 33.6% of the kilometers traveled in 1993-94 compared with 25.8% in 1981-82 (Table 1.). The share of journeys made by female drivers rose from 35% in 1981-82 to 44% in 1993-94. Women made up 43% of regular or occasional drivers in 1993-94, up from 38% in 1981-82. The distances they travel are shorter than those traveled by men (9 km on average, compared with 13.8 km for men in 1993-94), and the average speed slower (35.8 km/h for women and 42.5 km/h for men). This reflects the higher proportion of urban driving done by women. This is borne out by the SOFRES panel survey on car driving (Fontaine and Gourlet, 1996), which showed that in 1994, 37% of the distance driven by female drivers was on urban roads and 17% on motorways, compared with 30% and 22% respectively for men.

The aging of the population and the fact that the number of years during which people drive has increased, enabling them to participate more in social life (Chich, 1991), have contributed to the larger share of elderly people in the driving population. The share of kilometers driven by drivers age 65 or over increases from 4% in 1981-82 to 7.6% in 1993-94. Mean journey length varies little with driver age, but the highest mean speeds are observed in the under-20 age group in 1981-82 and in the 20-24 age group in 1993-94. The lowest speeds are observed in the 65-and-over age group in 1993-94. This is also the age group for whom the percentage of urban mileage is lowest, probably because at this age there are no daily journeys to and from work (which often involve more urban driving) and because elderly people more often live in rural area. The lower mean journey speeds may therefore indicate a more "careful" style of driving among senior citizens.

The analysis also reveals a decrease in the share of mileage traveled by young drivers and an increase in that of drivers in the 35-49 age group. This may correspond to the time of life when many households buy themselves a home and move out of the city into the suburbs and also to the demographic changes.

Trip Purposes

As in the previous survey, work-related travel (driving to work and back, and professional journeys) represents 30% of kilometers traveled (Fontaine and Saint-Saens, 1988). Distance traveled and mean journey speed are higher than average for leisure trips (18.4 km and 47.2 km/h in 1993-94). The smallest trips are for accompanying children (5.2 km in 1993-94).

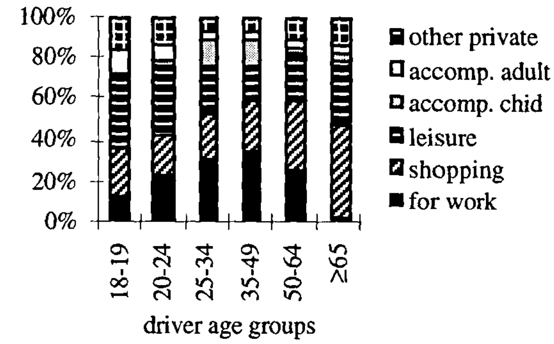

Figure 2. Breakdown of trips made in 1993-94 according to driver age.

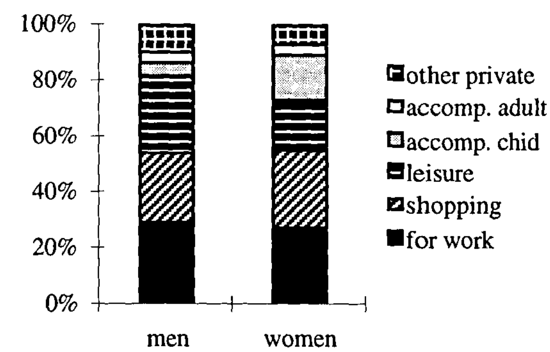

Figure 3. Breakdown of trips made in 1993-94 according to sex of driver.

Reasons for journeys made differ according to age and sex of driver. The breakdown of trip purpose according to driver age (Figure 2.) reflects the different stage of the life. Work related trips are less frequent for young drivers and also for those over 65. This corresponds to students and retired people. In the same way, leisure trips are more frequent for these age group.

Accompanying children is more frequent between 25 and 40 years old, when people have young children. Shopping represents nearly half of the trips made by the elderly age group.

We had already noticed in the 1981-82 survey that the type of vehicle use differed considerably with the sex of the driver : women generally used their vehicles for shopping or for driving people back and forth (Fontaine, 1988). This still applied in 1993-94 : 15% of the journeys made by women were made to take a child somewhere, compared with only 5% of journeys made by men for the same reason (Figure 3.).

The mean distance traveled by a woman accompanying a child is 4.8 km, compared with 6.4 km for a male driver accompanying a child. Work-related travel vary little in frequency between male and female drivers, but men drive longer distances on average than women (12.8 km and 9.2 km respectively to travel to a fixed place of work in 1993-94).

Taking all types of journey together, men are less frequently alone in their cars than women (61% of men and 64% of women make journeys alone in their cars). The difference is greater for shopping (58% of men alone vs. 64% of women alone) and for journeys for leisure (42% of men alone vs. 51% of women alone). This may be the consequence of a traditional attitude : when a couple go somewhere by car, it is usually the man who drives. The journeys most often made alone in the car are journeys to and from work (90% of women alone and 88% of men alone).

Table 2.
Exposure Characteristics According to Car Characteristics in 1993-94

	km traveled %	mean journey distance km	mean journey time mn	mean journey speed km/h
Age (years)				
<3	25	14.5	20.1	43.5
3-4	21	12.7	18.4	41.4
5-9	36	11.3	17.1	39.8
≥10	18	9.3	15.6	35.7
Mass (kg)				
< 800	22	9.3	15.6	35.6
800 - 1000	41	11.3	17.3	39.2
> 1000	37	14.5	19.4	44.7
Power (kw)				
< 40	20	9.2	15.7	35.3
40 - 49	31	11.8	17.5	40.3
50 - 69	36	12.6	18.2	41.4
≥70	13	14.5	19.2	45.2

Exposure According to Car Characteristics

The results concern only the period 1993-94 because the previous survey did not take into account car characteristics such as mass and power. Table 2. shows that mean trip distance increase with car mass and power and decrease with car age. New big vehicles make more kilometers than old small cars. In the same way, mean journey speed increase with car mass and power and decrease with car age, insofar as the longer the trip the longer the part spent outside urban area and motorways.

RISK EVALUATION AND CHANGES

We privileged the distance traveled as the exposure risk indicator since it is one of the most commonly used in road safety, but some results are also given for time spent driving as exposure.

General Results

Between the periods analyzed, mobility increased by 51%, with more cars on the road and drivers covering larger distances. At the same time, the number of injury accidents decreased. Consequently, the accident risk in terms of the number of accidents per kilometer traveled decreased. For the car driver population the risk decreased by 61%, from 1.5 injury accidents per million km traveled in 1981-82 to 0.6 injury accidents per million km traveled in 1993-94.

This decrease in risk, observed in numerous countries, confirms the classical hypothesis of a process of "collective learning" in motor vehicle driving (Brenac, 1989). Improvements to the inter-city motorway network may also have played a role in reducing the accident risk, insofar as motorways are among the safest roads, with a high traffic capacity. This could explain the increase in mobility in terms both of mean journey speed and of the number of vehicle-kilometers.

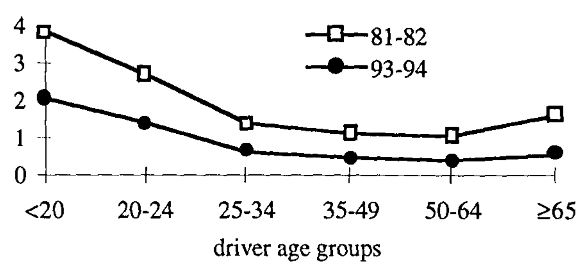

Figure 4. Injury accidents per million km according to driver age.

Risk by Age and Sex

The shape of the injury accident risk curve per km according to driver age groups is the same in 1981-82 and in 1993-94 (Figure 4.). The highest risk is observed among very young drivers, and is explained partly by their inexperience ; the risk then decreases to reach its lowest levels in the 35-64 age group, before increasing again for drivers age 65 and over, although this increase is more marked in 1981-82 than in 1993-94. The largest relative decrease in risk between the two surveys is observed in the elderly driver group (66% decrease in the accident rate of drivers age 65 and over), and the smallest relative decrease is that of young drivers (49% decrease between the two surveys).

Taking all age groups together, the injury accident risk related to distance traveled in 1993-94 was 1.2 times higher for men than for women. And the risk of a fatal accident was 1.9 times higher for men than for women. These ratios are comparable to those recorded in the earlier survey.

The analysis of the SOFRES survey on vehicle use (Fontaine and Gourlet, 1996) reveals that taking non-injury and injury accidents together, women have a higher accident rate per million kilometers (19.5) than men (14.8). This higher involvement in non-injury accidents (with material damage only) may be explained by the relatively greater share of urban driving. The APSAD (1994) also noted that although the frequency of (non-injury and injury) accidents was higher among female drivers, the average cost was lower.

When driver sex and age are taken into account, the traditional results appear again (Table 3.), but the differences are much less marked in the case of women. Young men are at much greater risk than young women. This excess risk exposure of young men is a finding commonly observed in road safety studies. Women age 65 and over, on the other hand, are at greater risk of injury accident involvement than men of the same age, probably because they are less accustomed to driving.

For some authors (Chipman et al, 1993) the accident risk related to journey time is more pertinent than the risk related to distance traveled, insofar as the time drivers take to cover a given distance is the reflection of their perception of risk. When comparing the two criteria, however, the environment criterion must be checked so as not to confuse congested urban traffic situations and difficult driving conditions on small country roads.

When time spent driving is considered as exposure measure (Table 4.), the highest risk groups are also drivers under 25 years old, particularly men. But whereas women age 65 and over are at greater risk over a given distance than men of their generation, when journey time is taken into account, women are at less risk than men for a given driving time whatever the age group. Similar results are found in Ontario (Chipman et al, 1993).This corresponds to their different journey speeds. The mean journey speed for women age 65 and over is 31.2 km/h, compared with 38.3 km/h for men in the same age group. This may be explained by the more urban nature of the journeys made by women, but also by the difference in their driving experience, elderly women often having started to drive later in life. This difference in the age at which men and women start to drive is tending to disappear (Fontaine and Hubert, 1997), so it is possible to assume that the excess accident risk per km driven to elderly women compared with elderly men will decrease further.

Table 3.
Injury Accidents per Million Kilometers in 1993-94

driver age	driver sex	
	men	women
<20	2.4	1.5
20-24	1.7	0.9
25-34	0.8	0.5
35-49	0.5	0.4
50-64	0.4	0.5
≥65	0.5	0.6

Table 4.
Injury Accidents per Million Driver Hours in 1993-94

driver age	driver sex	
	men	women
<20	90.9	54.0
20-24	74.1	35.7
25-34	33.3	18.8
35-49	21.8	15.3
50-64	17.7	16.7
≥65	20.8	18.6

The high-risk groups are the same in both cases : male drivers under 25 years of age. The behavior of young men at the wheel is often blamed for the excess risk. It is also suggested that they drive in more difficult conditions (Massie and Campbell, 1993). Young drivers, particularly young men, drive more frequently at night : 19% of their mileage is done between 8 p.m. and 5 a.m., whereas all drivers together travel 10% of their mileage during the same period of time (Fontaine and Hubert, 1997). For the same distance driven at night, they are more likely to be involved in accidents than any other driver category. Note that other factors, such as drinking, type of road and vehicle, number of vehicle occupants and type of journey, with peers or family, very certainly play a part.

Risk According to Car-Driver Characteristics in 1993-94

Among car characteristics, age is the most registered data : there is 3% of unknown data for this in the accident database and that of the Transportation Survey. The other criteria linked to power and mass are a lot less well known because the code which makes it possible to identify them is often wrongly coded especially in the accident database. It appears that the number of unknown classification numbers is higher for older vehicles so we firstly estimated the risk of involvement according to the age of vehicles and then we considered the other criteria, taking into account car age groups to limit biases.

Car Age - Table 5. gives the rates of injury accident involvement per million km traveled according to car age. The highest risk is observed for vehicles more than 10 years old. This has already been observed in previous study (Fontaine et Saint-Saens, 1988).

Table 5.
Risk of Accident per Million Kilometers

car age	accident per million km
less than 3 years	0.47
3 to 4 years	0.49
5 to 9 years	0.57
10 years and more	0.75
Together	0.56

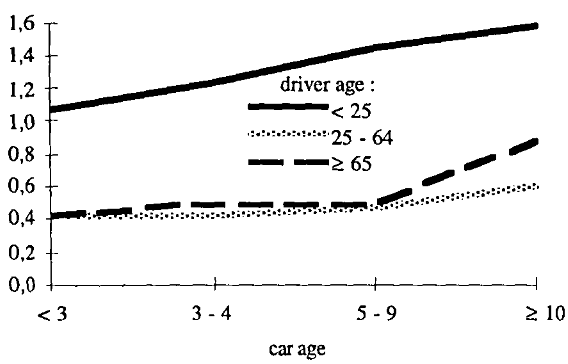

Figure 5. Accident involvement per million km traveled according to car and driver age.

Older vehicles are more frequently driven by young drivers. Thus, drivers under 25 do a quarter of their mileage in vehicles which are 10 years old or more whereas this only accounts for 17% of the mileage of drivers over 25 (Fontaine et al, 1997). It is therefore important to take the age of drivers into account as the under 25s show an over-risk compared to older drivers. Figure 5. shows that the age of drivers differentiates the risk more strongly than vehicle age. Thus the rate varies from 0.4 accident per million km for the 25 to 64 year group driving a vehicle less than 3 years old to 1.6 accident per million km for the under 25s at the wheel of a vehicle more than 10 years old. We can also observe a higher risk in the over 65 group driving a vehicle more than 10 years old. However, in terms of stakes, the latter group of users only accounts for 1.8% of accidents and 1.1% of kilometers driven.

Car Mass and Performance - We have seen that there is less available information about the criteria of car mass and performance in that the code is not known or is wrongly coded. Insofar as this missing data is more frequent for older vehicles, we estimated a risk of involvement in accidents according to mass and performance for vehicles less than 10 years old.

Firstly, the performance was estimated by the power of the vehicles which was crossed with the mass in order to identify the effect of small sports models (Fontaine and Gourlet, 1994) then we analyzed the ratio power/mass. Some groups, for whom we had little data, if any, were not selected.

Table 6.
Accident Involvement per Million Km for Vehicles Less Than 10 Years Old.

mass	power	driver age (years)		
kg	kw	< 25	25 - 64	≥ 65
<800	< 39	1.2	0.7	0.6
<800	40-49	0.8	0.4	0.5
<800	50-69	0.7	0.5	0.6
<800	≥70	3.4	0.3	-
800-1000	< 39	0.5	0.3	0.3
800-1000	40-49	0.7	0.3	0.3
800-1000	50-69	1.0	0.3	0.4
800-1000	≥70	2.0	0.7	0.4
> 1000	40-49	1.5	0.2	0.2
> 1000	50-69	0.7	0.2	0.2
> 1000	≥70	2.3	0.2	0.2

Table 6. shows that the effect of the driver age is still very important but it is amplified by the vehicle power, especially for lighter vehicles. Thus, although globally the risk for the under 25s is nearly 1 accident per million km, this rate goes up to 3.4 when a young person drives a light sports vehicle weighing less than 800 kg with a power of 70 kw. It is to be noted that this category of small, light, fast vehicles is relatively old in that the more recent sports vehicles are also heavier. The percentage of cars bought second-hand is

probably high in this group (Girard and Michel, 1991).

If we consider the ratio mass/power (Figure 6.), the effect of age once again appears as being very important and amplified by the type of vehicle driven as the relative risk is close to 4 when a young person drives a powerful vehicle, the risk being taken as equal to 1 for all vehicles. Young drivers are far more sensitive to the type of vehicle driven than older ones.

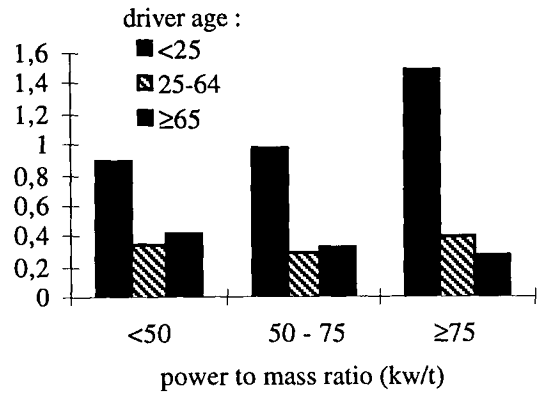

Figure 6. Accident involvement per million km for vehicles less than 10 years old.

CONCLUSION

This analysis of two transport surveys from the risk exposure standpoint show a larger proportion of women and elderly people in the driver population. Comparison with accident data reveals a general decrease in the risk per kilometer traveled, tending to confirm the hypothesis of a general improvement in driving standards. A high level of risk is always observed for young male drivers, while the excess risk previously observed among elderly drivers has decreased substantially. The category of young drivers driving light, powerful sports vehicles stands out as having a high accident involvement risk. The choice of a sports type vehicle often goes hand in hand with high risk taking, but the consequences are more serious for young drivers. The over 25 age group seem a lot less sensitive to the type of vehicle

The results show that male drivers under 25 years of age represent the highest risk group per distance driven and per time spent driving. But whereas women age 65 and over are at greater risk over a given distance than men of their generation, when time spent driving is taken into account, women are at less risk than men for a given driving time whatever the age group. This may be explained by the nature of the journeys made by women, but also by the difference in their driving experience, elderly women often having started to drive later in life. A comparison with the results of a previous travel survey carried out in 1981-82 shows that the difference in the age at which men and women start to drive is tending to disappear, as is the difference in distance traveled. Looking to the future, one can expect an increase in the proportion of elderly drivers on the roads, particularly women, accompanied by a decrease in the accident risk to these drivers. As a result, the relative risk to young drivers will appear higher.

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LINKING ONTARIO COLLISION, VEHICLE REGISTRATION AND TRAUMA DATA

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ABSTRACT

A feasibility study was conducted to link the police reported traffic collision reports with both trauma data and vehicle registration data. For the purposes of this study, the data was limited to that from the Province of Ontario. The study examines the benefits of being able to do such linking and the limitations of the data sources that affected the number of successful matches. The study also investigates some of the barriers of obtaining and linking the data on a regular basis such as ownership, security and confidentiality.

OVERVIEW

Certain research questions that arise sometimes cannot be answered using a single data source. In order to answer complex questions it is advantageous to link databases together. For example, there was interest in examining the fitment of seat belts in light duty vehicles by analyzing injuries that were sustained by the seat belt wearing occupants of vehicles involved in a collision. The requirement was to determine if there was significantly more injuries caused by seat belt wearing in similar type crashes across different makes and models of vehicles.

In order to draw useful conclusions from this type of analysis there was a requirement to obtain several pieces of information: the type of collision that occurred (e.g. side impact, rear-end etc.), the type of injury that was sustained to occupants of the involved vehicles, whether the occupant was restrained, and the type of vehicle (including make, model and model year) in which the person was an occupant. All of this information was not contained in a single database. However, the existence of separate databases which together could contain all the necessary elements, presented the opportunity to attempt to electronically link them.

This paper examines existing databases that could be used in such analysis, describes how they might be linked and reports on the attempt to link them. This study does not analyze specific safety related issues such as the question posed above. The scope was simply to look at the process of linking the selected databases and discuss the issues related to such a process.

SOURCES OF DATA

For the purposes of this study, data was limited to the province of Ontario for the years 1991 to 1994, inclusive. This limitation was required due to the availability of required data. The identified sources were: collision data (Ontario Motor Vehicle Accident Report System (OMVARS)), hospital discharge data (Ontario Trauma Registry Comprehensive Data Set (OTRCDS)) and vehicle registration data (Ontario's Vehicle Registration Database (OVRD)).

Collision Data

Transport Canada creates a national collision database each year based on electronic data supplied by each of the ten provinces and two territories called the Traffic Accident Information Database (TRAID). Although each of the jurisdictions may code and record their collision report information differently, a protocol had been designed to compile all the collision data into a similar format. The initial idea was to use the Ontario data as compiled in the TRAID database as the basis for the collision data required for this study. However it soon became clear that the use of the data contained within the Ontario Motor Vehicle Accident Reporting System (OMVARS) would be useful in its original format for the following reasons:

1) The system records the date of birth for all drivers, TRAID has age only. Date of birth is more specific than age of person and therefore, at least for drivers, would help enable more accurate matching as date of birth is contained with the selected hospital data (OTRCDS).
2) TRAID does not store the vehicle plate number or the Vehicle Identification Number (VIN). However, the OMVARS records the license plate number and jurisdiction (province, territory, state, country) of each involved vehicle. The plate number could potentially be used to link into a registration database to get specific vehicle information.
3) The OTRCDS is designed to collect and store collision related information. Much of that information is collected using codes similar to the OMVARS.

There is some ability to segment the persons involved in collisions by the severity of the injuries sustained (this is true in both TRAID and OMVARS). Although the variable 'injury severity' is separated into three broad injury related categories (minimal, minor, major), it does provide a reasonable method to segregate the injury data. It is expected that those coded with a 'major' injury should be a reasonable estimate of those persons who were admitted to hospital for at least one night as the OTRCDS is limited to such cases. The number of major injuries recorded by the OMVARS is listed in Table 1 below.

Table 1
Number of Major Injuries
As Reported in Ontario
(Motor Vehicle Accident Reporting System)

Year	Major Injuries
1991	7,005
1992	6,690
1993	6,644
1994	6,023
Total	26,362

Hospital Patient Discharge Data

For the purposes of this study, the Ontario Trauma Registry Comprehensive Data Set (OTRCDS) was used as the source for hospital based discharge data. This database is a compilation of patients who were admitted to one of twelve 'lead' trauma hospitals in the province of Ontario. Although this database contains only a portion of persons admitted to all Ontario hospitals, there are certain advantages that make it better than more typical hospital discharge data for linking. Some of these advantages are :

1) The database is designed to capture collision related information such as the vehicle type, location of vehicle impact, seating position and collision configuration. These type of data elements make it extremely useful when trying to link with standard collision data reporting systems.

2) Injury information is collected using the Abbreviated Injury Scale (AIS). This coding scheme is very familiar to the analysts at Transport Canada as it is used primarily in the road safety community for examining the extent of injuries that happen in motor vehicle collisions.

3) The date and time of injury is recorded rather than just time and date of admission to hospital. It is possible that the time of admission may lag several hours after the actual time of the injury whereas the time of injury should be close , if not identical to, the time of the collision reported in the OMVARS.

4) The data is recorded in such a way to make it possible to differentiate persons who were involved in a traffic related incidents to those who were not. The database uses the coding system for external causes of injury (E-Code) as defined by the World Health Organization's Internal Classification of Diseases. In this study, cases that had an ecode of 810 - 829 were selected.

Collection of data for the OTRCDS began in 1991. At the time of this study, the last complete year of data was 1994. It is evident that the quality of the data improved over those years, especially for collision specific variables such as collision configuration which has improved in reporting from 26% in 1991 to 60% in 1994. Similar improvements are evident across all collision specific variables.

Due to concerns over confidentiality there were certain variables not available to the author for this study that may have otherwise been useful in making successful linkages. Three in particular were the person's name, the collision report number and the geocode. All of these could be extremely useful in the linking process. It is encouraging that the latter two have been included in the design of the OTRCDS.

Table 2
Persons Admitted to Lead Trauma Centers
Injuries due to Motor Vehicle Collision

Year	Trauma Records
1991	816
1992	1,192
1993	1,357
1994	1,369
Total	4,734

Registration Data

Although the generic vehicle type (e.g. car, tractor trailer, school bus etc.) and model year are captured in the collision data, there is extremely limited specific vehicle information collected in motor vehicle accident reports. In the OMVARS, the vehicle make and model information is limited to a total of eight characters and there is no standard for how these eight characters are coded. Therefore a variety of codes and sometimes extremely cryptic combinations exist in the collision data. Combination of characters such as 'FORDESCRT', 'FORDESCOR', 'FRDESCRT', ESCRTFRD, 'ESCORT" and even 'FORD" are all coded for 'Ford - Escort'. In such a format there is no allowance for other information such as size, series etc. This limitation makes doing any sort of analysis on specific make and model extremely difficult, if not impossible.

The OMVARS does capture the vehicle license plate number and jurisdiction. Therefore, theoretically, it should be possible to extract this information and try to verify which vehicle is registered to a specific plate. The registration file is suppose to contain a Vehicle Identification Number (VIN). The VIN, when decoded, has the potential to give specific information such as vehicle make, model, series and other vehicle specific information.

There were two concerns about this process. First, in order for such a algorithm to work, the registration database must keep a history of the vehicles that have been registered to a certain plate. This is imperative as the linking to the registration file is done after the collision has occurred (in some cases several years). The vehicle registered to a license plate may have changed over time. This is possible as persons change vehicles either by desire (sell old vehicle, replace it with new) or by necessity (vehicle is involved in collision and is unrecoverable). Persons are permitted to register subsequent vehicles to the same plate. If no history is maintained then it is impossible to determine the VIN that was registered to the plate at the time of the collision. This could have a very profound influence on any analysis done as vehicle may have originally been a Chevrolet Caprice but now the plate is registered to a Ford F-10 pickup. The Ontario registration database is designed to maintain such a history.

The second concern is that the VIN that is registered to the plate is valid. Since the VIN is a 17 character code there was concern over the likelihood of invalid VIN's entered into the registration system. If the VIN is invalid it will be impossible to decode. Of the VIN's of light duty vehicles (automobiles, light trucks and vans) involved in fatal or non-fatal injury collisions during the years 1991-1994 inclusive that were entered into the decoding software 'VINDICATOR', about 85% were able to be decoded. Whether this is similar to the registration file as a whole was unable to be determined in time for this paper.

It is important to realize that there are some vehicles from other provinces and countries involved in collisions that occur in the province in Ontario. Fortunately, on average, between 1991 and 1994 about 95% of all vehicles involved in injury and fatality producing collisions in Ontario were registered in Ontario. The other 5% were ignored for the purposes of this study.

LINKING COLLISION DATA TO HOSPITAL DATA

Potential Linking Variables

All variables that are similar in both databases are perspective linking variables. As mentioned earlier, an advantage of using the OTRCDS is that it is designed to capture collision related variables such as collision configuration, person position, type of vehicle etc. that would not normally be captured as part of hospital discharge data. In order for such data to be useful there but be a reasonable level of recording of this data. In Table 3 is a list of the potential linking variables and the proportion of observations where the information was recorded.

An additional concern is that although similar data elements are collected in both the collision and hospital databases, different codes are sometimes used to capture the same information. Before the linking process can begin, this differing codes require modification if the process is going to be successful at all. Although for the most part the OTRCDS tried to be similar to the OMVARS it sometimes varied.

Table 3
Limitations of Potential Linking Variables

	Data Sources	
Data Element	**Trauma Registry**	**Collision Data (Ontario)**
Date of Collision	Coded as date of injury	100% Complete
Time of Collision	Hour & Minutes (9% Unknown)	Hour Only 0.5% Unknown
Person Gender	0.5% Unknown	0.5% Unknown
Person Age	0.1% Unknown	0.5% Unknown
Person Date of Birth	0.2% Unknown	Available for drivers only
Type of Collision	68% Unknown	0.1% Unknown
Type of Vehicle	60% unknown	In order to 'match' some 'translation' required.
Vehicle Damage Location	76% Unknown	2.5% Unknown
Person Position	43% Unknown	0.1% Unknown
Person Injury Severity	At least one night in a lead Trauma Hospital	Coded as 'Major Injury'
Person Ejected	44% Unknown	0% Unknown

Although not an explicit variable within the OTRCDS, the limitation is that it contains only persons who were admitted for at least one night. Therefore, to maximize the potential number of successful and accurate linkages, the records from the collision data were limited to major injuries. In addition, the number of cases contained in the OTRCDS are less than the total of all hospital admissions as there are only twelve lead trauma hospitals recording the data in this format. Therefore, total number of hospital records is a significantly small proportion of all persons sustaining major injuries as reported in the OMVARS (see Table 4 below).

Table 4
Compare Number of Hospital Discharge Records To 'Major Injury' Records

Year	Hospital Discharge Records	Major Injuries	Proportion of Major Injuries
1991	816	7,005	11.6%
1992	1,192	6,690	17.8%
1993	1,357	6,644	20.4%
1994	1,369	6,023	22.7%
Total	4,734	26,362	18.0%

Linking Process

A deterministic method was used for linking the databases. That is, the selected variables from each of the two databases (OTRCDS and OMVARS) had to have identical values in order to be linked. In addition, only a single record within each of the data sources could contain the same values as otherwise there was no constructive way to choose one of the records over the other. An extremely conservative approach would have been to use all the potential linking variables and simply select only cases that are matched in one iteration. However, in light of the number of observations contained within OTRCDS that had incomplete information recorded in the collision related variables, this was not practical.

The challenge was to minimize the possibility of incorrectly linking records, while at the same time maximizing results. The larger the number of variables used to match the records, the higher the probability of a correct link. The fewer variables used to match, the higher the probability of 'duplicates' and also the higher the probability of incorrectly linking cases.

For each iteration the process is the same (summarized in Table 5). First, the variables to be used for matching are selected. Each of the databases (hospital and collision) are separately sorted by the variables selected in step 1. After the sorting is complete, it is determined which of the records is unique within the database and which are duplicates. The result of this step is four distinct data sets, two for each of the hospital and collision databases (Hospital - duplicates of selected variables, Hospital - no duplicates, Collision - duplicates of selected variables, Collision - no duplicates). The cases that were determined as containing duplicate values are excluded from any possibility of matching during the current iteration as it is impossible to differentiate which of the records should be matched to any records with similar characteristics in the other database.

The fourth step was to merge together the two data sets containing no duplicates. Instances where the values of the selected variables match identically to a record in the other data set are linked. Records that are linked are output to the file containing all successful matches. The observations contained within the duplicate subset and non-matched subset are recombined for subsequent iterations.

With each iteration the variables selected for matching are changed. The challenge for such a process is to decide at which point the observations that have been linked are likely to be incorrect matched. That is, are there two few variables being used so that observations that are 'matched' do not really represent the same case.

Table 5
Basic Procedures in the Linking Process

Procedure	Explanation	Data Set(s) Created
Select Variables	Select variables from those listed in Table 3 to be used for matching.	
Sort Data	Sort hospital and collision that are not yet matched by the selected variables	1) Collision Data - sorted 2) Hospital Data - sorted
Separate Unique Records From Duplicate Records	If duplicates of variables to be used for matching exist then all similar records are excluded from current iteration for a potential match.	3) Collision Data - Duplicates 4) Collision Data - Non-duplicates 5) Hospital Data - Duplicates 6) Hospital Data - non-duplicates
Merge data sets by selected variables	Using only the proportion of the data with no duplicates, merge data sets 4) and 5) by the selected variables. Successful matches are added to linked records. Unsuccessful matches are retained for subsequent iterations	7) Linked Records 8) Collision Data - not linked 9) Hospital Data - not linked
Prepare records for subsequent iterations	Prepare remainder of records for subsequent iterations. Bring together subsets 3 and 8 and 5 and 9. Start next iteration.	

Results

The results of linking the collision and hospital databases are listed below in Table 6. On average there is about 65% of the records in the trauma data matched to the collision data. The fewest number of variables used during the process were the date, time, hour, gender and age of the person. Depending on the level of expertise with the data and comfort with linking, this may actually be too many or too few variables.

Table 6
Number of Trauma Records Linked to Collision Data

Year	Trauma Records	Collision Records	Number Matched	Proportion of Trauma Records Matched
1991	816	7,005	550	67.4%
1992	1,192	6,690	797	66.9%
1993	1,357	6,644	877	64.6%
1994	1,369	6,023	892	65.2%
Total	4,734	26,362	3,116	65.8%

LINKING COLLISION DATA TO REGISTRATION DATA

The end result desired by linking the collision data to the registration database is to be able to determine vehicle specific information about the vehicle involved in the collision. In order to do this there was a two step process. The first step was to determine the date and the license plate number of the vehicles involved in the selected collisions. Both had to be available for a possible match to take place. Therefore, if a plate for a vehicle was not present or invalid in the collision database then it would be impossible to link it to the registration file. The second step is to decode the VIN's that are registered to each of the plates. VIN's that cannot be decoded are considered invalid and also affect the final results. Only when there is a valid VIN that has been 'decoded' can the link be considered successful.

Results

On average, the proportion of the number of vehicles involved in fatal and injury producing collisions that had a license plate recorded in the OMVARS that has a license plate recorded was around 92% over the four years. The VIN was decoded for only light duty vehicles due to a limitation the software being use for this process. On average about 85% of the VIN's were being successfully decoded. Although the VIN was decoded, it was necessary to try to determine whether the VIN actually represented the vehicle that was in the collision. The only way to do this was to use the vehicle model year and the cryptic vehicle make information on the collision data. As it would have taken considerable time to verify all cases, about 50 per year were spot checked. There was close to 100% agreement.

FINAL RESULTS

Table 7
Number of Persons Linked To Make and Model (VIN's decoded only for Light Duty Vehicles)

Year	Vehicle Type	Number matched	Vehicle Make and Model Matched	Proportion of Vehicle Occupants Matched
1991	Light Duty Vehicle	393	323	82.2%
	Other Vehicle	74		
	Pedestrian	83		
	Total	550		
1992	Light Duty Vehicle	588	497	84.5%
	Other Vehicle	112		
	Pedestrian	97		
	Total			
1993	Light Duty Vehicle	649	536	82.5%
	Other Vehicle	115		
	Pedestrian	113		
	Total	877		
1994	Light Duty Vehicle	688	564	82.0%
	Other Vehicle	99		
	Pedestrian	105		
	Total	892		

In order to determine the overall success of this process it is important to examine the number of hospital records that were able to be linked to persons coded in the collision database and, where these persons were occupants of vehicles, what type of vehicle they were in at the time of the collision. As can be seen in Table 7 about 82% of all light duty vehicle occupant records that were linked to hospital information were also linked to detailed vehicle information.

DISCUSSION

The overall success of linking the particular databases used in this study depended greatly on the linking together of the hospital data and the collision data. The availability of the VIN's was fairly high and was really an insignificant factor in the final number of records matched. Only matching about 65% of hospital records to collision records may seem disappointing. However, the potential for a higher ratio of matches is excellent due to the existence of other very useful variables such as person name, collision report number and geographical area that were unavailable for this study.

Certainly the actual number of records that were linked with both the vehicle and hospital information were fairly low, especially considering the type of research question posed at the beginning of the paper. By the time an analyst starts to segment a few hundred records across dozens if not hundreds of vehicle models, the number of records for each specific vehicle make and model is going to be extremely small and any resulting analysis likely to be inconclusive.

The potential of such linking on a larger scale cannot be overlooked. In addition to the question that was posed at the beginning of this paper, many other types of road safety related questions could be answered by linking such databases. One of the main ones could be the overall cost of collisions. The availability of hospital data could help analysts better calculate the costs (at least in terms of hospital stay and procedures required to help rehabilitate the injured persons). In addition, the OTRCDS is designed to capture the emergency services that are used and the amount of time required for each of these services. In a much broader sense, such linking could also help decide policy direction by helping determine the type of collisions that are causing the most severe injuries and helping organizations prioritize resource allocation for specific research.

All that said, there are obstacles and challenges to doing database linking. The more important ones are probably ownership and confidentiality. In cases where there are different owners of each of the databases there may be some contention as to who should be allowed to do the linking, who should be responsible for storing and maintaining the data, and who should be able to use the data on an ongoing basis. These issues are many times not separate from confidentiality, as certain laws may give certain rights to some who collect data but not to others. Also, in this electronic age some jurisdictions are bringing in legislation to limit the amount of linking of separate databases to protect the rights of individual privacy.

This was the author's first attempt in linking databases. I think this study has proven that such linking is, at least, technically possible. It is obvious that the larger the quantity of similar variables and the higher the quality of the information contained on the candidate databases, the more successful the linking will be. However, for linking to be successful and useful on a much larger scale will require the cooperation and goodwill of database owners, database operators and also legislators.

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MOTOR VEHICLE DATA IN CANADA: PAST, PRESENT AND FUTURE

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ABSTRACT

Canada has set a goal to achieve the safest roads in the world by the year 2000. The success of this achievement can only be measured through relevant and accurate data. What data are available to support this initiative? Canada first started collecting motor vehicle related data in 1903. What has been done since?

This paper will trace the development of motor vehicle related data collection in Canada, from the first vehicle registration in 1903, to the formation of the Road Safety Directorate at Transport Canada, and its mandate to collect TRAID, to the current NCDB, and beyond.

The paper will also examine the development of other motor vehicle related databases in Canada, and the strategic plans to allow maximum utilization of these databases.

INTRODUCTION

The National Road Safety Symposium, held in February, 1994, Toronto, Canada, set a goal for Canada to possess the safest roads in the world by the year 2000. The road safety communities in Canada have been working vigorously and cooperatively towards the achievement of this goal. It is realized that the measure of our success is dependent upon accurate, accessible and comprehensive databases.

Since the early 1900's, Canadian motor vehicle related statistics have been produced and published in various ways. Despite this accomplishment, the National Road Safety Symposium in 1994 identified that the "lack of relevant, accurate, accessible, timely, standardized and integrated data hampers the development, delivery and evaluation of road safety countermeasures." (Safety Coordination Advisory Committee, 1994) The need to resolve this data problem was deemed a national priority.

Before we explore the extent of the "lacking", it is important that we first take stock and determine what relevant data are already available.

The Past

Vehicle Registrations - For the purpose of discussion, this paper will examine vehicle registrations of three main vehicle types: the passenger vehicles, the commercial vehicles and the motorcycles.

The earliest motor vehicle related data in Canada were passenger vehicle registrations collected in 1903 by the province of Ontario. (Urquhart and Buckley, 1983) That year, Ontario established the motor vehicle registration with 178 passenger vehicles registered. In 1905, New Brunswick joined the registry with 12 passenger vehicles recorded, and Ontario tripled its number of passenger vehicles to 553 that same year. Shortly after, the provinces of Quebec, Saskatchewan and Alberta (1906) followed suit, with British Columbia in 1907, Manitoba in 1908, Nova Scotia in 1909 and Prince Edward Island in 1913. By 1914, all 9 provinces and the two territories in the Dominion of Canada had established passenger vehicle registration systems, and the registry recorded over 74 thousand passenger vehicles in total. When the province of Newfoundland became the tenth province of Canada in 1949, it had already established full vehicle registries of passenger vehicles, commercial vehicles and motorcycles. By 1949, the total number of motor vehicles registered in Canada had reached over the 2 millions mark. Table 1 summarizes the first year that each province and the two Territories started its motor vehicle registrations, by vehicle type.

Total passenger vehicle registrations showed a continuous and rapid growth to 1931 when a slight decline was recorded. Growth in registrations resumed in 1934, continuing until 1941. A decline in registration from 1942 to 1945 coincided with the war years. Beginning in 1946, when passenger cars were again produced, registration have continued to increase each year. Figure 1 illustrates the registration trends of the passenger vehicles, commercial vehicles, motorcycles and the total from 1903 to 1996. (Urquhart and Buckley, 1983).

The collection of commercial vehicle registration data is less concordant than the passenger vehicle registration. The lack of uniformity in the definition of commercial vehicles is a primary problem. Generally, commercial vehicles include buses and trucks, both large and small. Many provinces' use of the term "commercial vehicles" to cover many of the small trucks, such as pickup trucks often used for personal transportation, is misleading. Prior to 1960, some station wagons were included with commercial vehicles in British Columbia. Often the distinction between passenger and commercial vehicles was based more on the vehicle type rather than the use of the vehicle. For

Table 1.

Year In Which Each Province/Territory Started Collection of Motor Vehicle Registration Data

	NF	NB	NS	PE	QU	ON	MB	SK	AB	BC	Terr.
Total	1949	1905	1909	1913	1906	1903	1908	1906	1906	1907	1914
Passenger Vehicles	1949	1918	1920	1918	1914	1903	1908	1923	1921	1923	1914
Commercial. Vehicles	1949	1918	1920	1918	1914	1916	1922	1923	1921	1923	1915
Motorcycles	1949	1922	1922	1918	1914	1912	1910	1922	1922	1922	1914

example, taxi cabs were included with passenger vehicles while small trucks used primarily for personal transportation were included under commercial vehicles. Furthermore, although attempts were made to eliminate duplicate registration, however, commercial vehicles are often registered in multiple provinces, and such duplications were not easily detected. The lack of uniformity in the definition of "commercial vehicles" and the duplicate registrations have caused the commercial vehicle registration data of earlier years to lose its integrity.

The earliest commercial vehicle registration appeared in 1914 when Quebec showed 384 commercial vehicles registered. The two Territories were next to collect commercial vehicle data when their registry collected 5 commercial vehicles in 1915. Ontario followed in 1916, with New Brunswick and Prince Edward Island in 1918, By 1923, all the 9 provinces and the two territories in the Dominion of Canada had established commercial vehicle registration systems, and the registry recorded over 54 thousand commercial vehicles in total

Motorcycle registrations were first collected by the province of Manitoba in 1910, with 55 motorcycles registered. Two years later, Ontario established its motorcycle registry with 1,754 motorcycles registered in that year. It should be noted that, in the early years, most provinces did not require off-road motorcycles to be registered. However, in the early 1960's, the advent of large importation of motorcycles from Japan brought motorcycle registration into necessity.

<u>Collision Statistics</u> - Data for motor vehicle collisions in Canada are based on collisions occurring on public roads and streets, including boulevards and paths adjacent to the travelled portions. The data are obtained from police reports following a police investigation of the collision. Police departments across Canada are required to attend collision scenes, and file reports on all fatal, and injury involved collisions, as well as property damage only collisions exceeding the damage level set by the provincial/territorial legislation.

The earliest motor vehicle collision statistics were recorded in 1921 when only fatal victims were recorded. In that year, there were 197 motor vehicle related fatal victims. The collection of fatal victims only remained until 1933 when some of the provinces expanded the categories, and began to collect injured victims in addition to the fatally injured victims. Furthermore, these data were broken down by road user class - drivers, passengers, pedestrians, bicyclists and motorcyclists. Figure 1 illustrates the trend of fatally injured victims in motor vehicle collisions from 1921 to 1996.

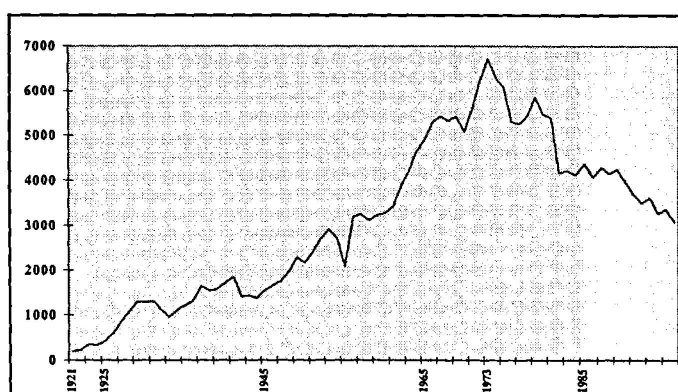

Figure 1. Fatality Trend of Motor Vehicle Collision Victims, 1921 - 1996.

Despite the improvement, the motor vehicle collision data still had many limitations. In 1940, the four western provinces - British Columbia, Alberta, Saskatchewan and Manitoba set up an inter-provincial committee to consider uniformity in inter-provincial matters related to motor vehicles. That committee was the start of the modern day Canadian Council of Motor Transport Administrators (CCMTA). In the early fifties, Ontario and Yukon joined the small committee, and by 1956, all ten provinces and the two territories were members of the committee. In 1977, Transport Canada participated as a full member.

At the Dominion-Provincial Conference in December, 1954, it was decided that detailed motor vehicle collision data should be published on an annual basis by the Dominion Bureau of Statistics (later became Statistics Canada). It was believed that these publications would provide significant collision data and overall trends in total collisions, fatalities and injuries resulted from motor vehicle collisions.

Many problems plagued the collection of motor vehicle collision data. The responsibility of collision reporting rested primarily with the provinces and the territories. Each province/territory had its own collision reporting forms, and these forms varied in terms of reporting standards and data elements. For example, the collision reporting threshold for property damage only collisions varied from one jurisdiction to another. In 1971, the reporting threshold varied from $50 - $200.

As the number of motor vehicles increased in Canada, road safety for its citizens became a primary concern for the federal government. The federal government's role and leadership in the field of road and motor vehicle traffic safety was assigned to the Ministry of Transport (later became Transport Canada) in 1967. On January 1, 1969, the Road and Motor Vehicle Traffic Safety Branch was created with the appointment of a Director. The Branch immediately began its work in drafting an appropriate legislation to enable the Ministry to fulfill its mandate. The Road and Motor Vehicle Traffic Safety Act received Royal Assent in March, 1970, and became effective on January 1, 1971. (Road Safety, 1973)

With the formation of the Road and Motor Vehicle Traffic Safety Branch at the federal Ministry of Transport, the responsibility for the collection of detailed collision statistics was transferred from the Dominion Bureau of Statistics to the Road and Motor Vehicle Traffic Safety Branch in 1974. Under a CCMTA agreement, each province/territory was to send its annual collision data file to the Road and Motor Vehicle Traffic Safety Branch who then undertook the responsibility to combine all the files into the national Traffic Accident Information Data system (TRAID).

The Present

Vehicle Registrations - Since 1989, motor vehicle registration data became much more precise, with registration of each type of vehicle based on the Gross Vehicle Weight (GVW) obtained from the Vehicle Identification Number (VIN).

Today, the 1996 Canadian Vehicles in Operation Census (CompuSearch and DesRosiers) shows over 15.8 million light vehicles (GVW Classes 1 & 2), and the 1996 Trucking Industry Profile (Polk) shows almost one million heavy vehicles registered in Canada. The term, "commercial vehicles" has been replaced with "heavy vehicles" which describes all vehicles over 4538 kilograms in weight (GVW Classes 3 to 8).

Figure 1 illustrates the growth of passenger vehicles, commercial vehicles, motorcycles, and the total vehicles in Canada from 1903 to the present. ((Urquhart and Buckley, 1983), (Road Safety, 1980-1997)

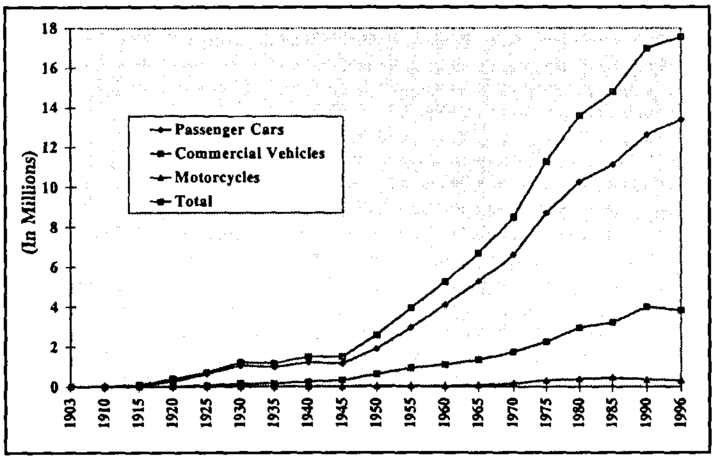

Figure 2. Motor Vehicle Registration Trend, 1903-1996.

Collision Statistics - Since 1974, the Road and Motor Vehicle Traffic Safety Branch at Transport Canada has been compiling annual incident based collision files from each of the province/territory. The files received from the jurisdictions came in various formats - electronic or hard copies. The Road and Motor Vehicle Traffic Safety Branch processed the files into one national format. The national file became known as Traffic Accident Information Data system (TRAID).

The incident based TRAID file was a major improvement over the summary collision statistics collected by the Dominion Bureau of Statistics. TRAID became the major source of information for the federal government to prepare its annual statistics related to motor vehicle collisions. The Canadian Motor Vehicle Traffic Accident Statistics, collected in cooperation with CCMTA, has been providing annual national collision statistics since 1979. TRAID also serves as a major database for research at Transport Canada for its work on the formulation of motor vehicle safety standards and regulations. In addition, the database also serves as a primary database for regulatory impact analyses.

Although the creation of TRAID provided the road safety community with wide variety and much improved use of collision data, it nevertheless had many shortcomings. Timeliness of the data was one major problem. The provincial files would arrive at Transport Canada in a variety of formats. While the bigger provinces sent their data in electronic format, the smaller provinces would send hard copies of the collision reports, and Transport Canada assumed the responsibility of key editing the data into electronic format. After all the data were converted to electronic format, Transport Canada then had to translate the provincial/territorial data values into the national TRAID values. Often, by the time the TRAID file became available, it would be 18 to 24 months after the collision year. In addition to the timeliness issue, the lack of standardization amongst the jurisdictions on the reporting threshold continued to be a problem for jurisdictional comparisons. This lack of standardization was identified in the early years, but the problem remained unresolved. While most of the provinces have now set $1,000 in property damage as its reporting threshold, the two biggest provinces in Canada - Ontario and Quebec, continued to be different.

At the 1990 CCMTA conference, the federal government, together with the 10 provinces and the two territories agreed to setup a new system to replace TRAID. The provinces/territories would submit to Transport Canada, its annual collision data file in the standardized National Collision Database (NCDB) format. Such a system would permit Transport Canada to provide the annual national collision file in a more timely fashion. Currently, the provinces/territories and Transport Canada are working vigorously together in developing the NCDB, and the expected launching date is in the near future.

In addition to the improvement on timeliness, NCDB will also provide much more up-to-date information on road safety research and policy development. It will provide information on the more current road safety issues such as daytime running light, airbag deployment, blood alcohol concentrations, and more detailed descriptions on the role of the road infrastructure. Furthermore, NCDB will provide the Vehicle Identification Number (VIN) which will allow researchers to learn about the exact features of the vehicles involved in the collisions.

The Future

In response to the goal set by the 1994 National Road Safety Symposium for Canada to achieve the safest roads in the world, CCMTA formed a 2001 Challenge Monitoring Committee and a Road Safety 2001 Work Plan (2001 Challenge Monitoring Committee, 1996). The Work Plan made the following recommendations in response to the Symposium's finding that the "lack of relevant, accurate, accessible, timely, standardized and integrated data hampers the development, delivery and evaluation of road safety countermeasures":

- establish data needs based on safety targets and program objectives for all road user groups.
- develop a universal integrated data management model with stakeholders input to satisfy municipal, provincial and national needs. The data management model should include management of data input, custodian of data, and applications.
- develop standards for data input from a variety of sources such as police, health care, coroner, insurance, vehicle registry, traffic survey, driver training etc.
- explore technological applications such as IVHS, GPS, GIS, automated data collectors (vehicle and infrastructure based), and electronic data input.
- assess needs of relevant training of personnel involved in collecting and reporting collision -relevant data.

With those recommendations, CCMTA, in 1996, established a Project Group on Road Safety Data and Research. The Project Group held a workshop and regular meetings with the provinces, territories, road safety researchers and stakeholders. Several recommendations resulted from the Project Group's report to the CCMTA. A Research Committee was established to determine the data needs of the road safety researchers, and a Data Management Steering Committee was formed to develop a universal integrated data management model. It is hoped that this model will provide standards for data input from a variety of sources, thus allowing accessible data linkage. An

Inventory of Road Safety Databases and Research Information in Canada (Road Safety, 1997) was published, and the publication contains a comprehensive listing of road safety related databases in Canada. This Inventory is presently being developed for accessibility via Internet. This easy accessibility will allow road safety researchers and stakeholders to view the availability of motor vehicle related data. In today's parsimonious financial environment, it is hoped that the Database Inventory would also eliminate duplicate efforts in data collection.

CONCLUSION

The ability to conduct road safety research, programming and policy decision-making is dependent upon accurate and comprehensive databases. Certainly Canada has made significant improvement with the collection of motor vehicle related data. With the cooperation and collaboration of all road safety stakeholders, we are confident that Canada will achieve the safest roads in the world by the year 2000.

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A STATISTICAL METHODOLOGICAL FRAMEWORK FOR ESTIMATING, ASSESSING, EVALUATING, MONITORING AND INTERPRETING ROAD TRAVEL RISK PERFORMANCE MEASURE INDICATORS : A 'RISK ANALYSIS AND EVALUATION SYSTEM MODEL' COMBINING TRAFFIC COLLISION AND 'EXPOSURE TO RISK' INFORMATION TO IDENTIFY 'HIGH RISK' ROAD TRAVEL PATTERNS AND CHARACTERISTICS

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ABSTRACT

One of the many important tasks facing traffic safety managers is deciding upon which, and of these the 'best/optimum' measures/countermeasures to implement for addressing their main goal -- improving road safety. The ability to make these decisions is largely dependent upon the availability of relevant, accessible, timely and standardized data on the incidence of travel and occurrence of vehicle collisions on the roads and highways. In essence, the Road Safety Directorate of the Canadian federal Department of Transport is continually striving to understand and augment its knowledge with respect to the process of motor vehicle collision causation in order to recognize opportunities for avoiding accidents and reducing casualties. An area crucial to traffic safety research is the development of evaluation methods for measuring and subsequently identifying *'high risk'* road user groups and their associated travel patterns and characteristics. This component of the countermeasure development process is difficult to pursue since the overall *road travel risk of accident occurrence* is directly affected by the joint interactive and ever-changing effects of numerous driver-passenger-vehicle-road-trip-environment-temporal travel pattern *risk levels* existing within the transportation system. Other factors including implemented countermeasure programs, economic conditions, vehicle/driver regulations, and social factors also influence the *prevailing risk levels*, at any given time, for road systems users.

It is useful to define the *risk levels* associated with all of the various factors contributing to accidents by comparing their appearance in accidents with some comparable measure of their appearance in traffic. This latter measure we refer to as the *'exposure to risk'* associated with the factors, i.e., the extent to which they are exposed to the possibility of accidents, by appearing in traffic. Although a variety of *exposure measures* have been advocated (e.g., trip frequencies, driver/vehicle frequencies, travel time, etc.) the most suitable for describing and comparing *road users' exposure* is driver and passenger kilometers of travel -- the *exposure measure* that is recommended and used in this study.

This paper presents the results for five main objectives identified in a recent *road travel risk* research study conducted by Transport Canada. The first objective involved the development and implementation of a statistical methodological framework that combines collision and *'exposure to risk'* data to measure and interpret *risk performance indicators*. Secondly, a *'risk analysis and evaluation system model'* for evaluating, comparing, and monitoring the *relative risks* of collision, injury and fatality encounter associated with the various driver-passenger-vehicle-road-trip-environment-temporal travel patterns and characteristics was developed. The third objective involved the development and implementation of statistical methods and procedures for measuring levels of errors associated with the various types of *road travel risk, relative risk, and relative risk odds-ratio performance indicator estimators* to identify significant differences in *travel risks* prevailing on the roads and highways. Fourthly, using Canadian collision and *'exposure to risk'* data bases, the modeling framework was applied to measure the *relative risks* of collision, injury and fatality encounter for selected road user groups and their travel patterns and characteristics. From these results *'high risk' road travel patterns and characteristics* were identified. Finally, conclusions and recommendations regarding the uses and applications of the *'risk analysis and evaluation system model'* for identifying road travel problem areas/issues and evaluating remedial measures/countermeasures for improving road safety are provided.

INTRODUCTION

The concepts of *'risk'*, *'relative risk'*, and *'relative risk odds-ratio'* estimation; *'risk analysis'* methods; and *'risk assessment/evaluation/management'* have long been recognized as necessary components and techniques for measuring, assessing, monitoring, evaluating and comparing the *level(s) of risk* (i.e., *level(s) of safety*) existing on our roads and highways. This has been well established and advocated for over sixty years by numerous professionals from varied disciplines within organizations with responsibilities in road transport safety [Vey, 1937; Cameron, 1969; Caroll, 1971, 1975; Foldvary, 1975; Accident Causation, 1980; Fernie, 1982; Hauer, 1982; Risk and Shaoul, 1982; Toomath and White, 1982; Wolfe, 1982; Stewart and Sanderson, 1984]. In spite of this 'urgent need' for the capability to assess and evaluate *road travel risks* (on a continuous basis) and the fact that the justification and benefits for doing so have been stated and echoed for decades, there has been no coordinated initiative taken to develop a 'standardized' modeling framework, associated estimation methodologies and analytical systems/procedures for establishing 'standardized' performance measure indicators to use in carrying out *'risk assessments'* [Stewart, 1989, 1996b, 1996c, 1997a, 1997b, 1998a, 1998b]. This begs the obvious question: ***Why?*** Why is this area of *risk analysis research* that has been identified as crucial for measuring, monitoring and comparing *risk level(s)* associated with various driver-passenger-vehicle-road/infrastructure-environment-trip-temporal travel patterns and characteristics, and subsequently identifying profiles of ***'high risk' travel patterns*** on our roads and highways not being actively pursued? A large part of the answer to this question would appear to be found in the following three statements --

① There is a 'lack of' relevant, accessible, timely, standardized *'exposure (to risk)'* (road travel) data;
② There is no standardized modeling framework for conducting *risk analyses* (i.e., there is a need for a standardized *'risk analysis and evaluation system model'* for conducting *road travel risk assessments/ evaluations*);
③ There is a 'lack of' standardized mathematical and statistical methodology, techniques and procedures for estimating and interpreting *'basic risk'*, *'relative risk'* and *'relative risk odds-ratio'* performance measure indicators and associated level(s) of accuracy.

THE DESIGN AND DEVELOPMENT OF A 'RISK ANALYSIS AND EVALUATION SYSTEM MODEL'

Owing to the serious deficiencies identified above, the Evaluation and Data Systems Division of Transport Canada has been conducting research into the design, development and implementation of a 'standardized' Risk Analysis and Evaluation System Model (RAESM) [Stewart, 1989, 1996c, 1997b, 1998a, 1998b].

Concepts, Methods & Procedures for Standardization

In order to stimulate work in the area of road safety *risk estimation and assessment* and hopefully generate a renewed thrust towards advancing our knowledge of the continuously changing *road travel risks* on Canada's roads and highways six major research initiatives were identified for completion in the first phase of this research, including:

❶ The development of a *standardized road travel 'risk analysis and evaluation system model'* for identifying the steps to be carried out in a *risk assessment/ evaluation* study.
❷ Defining the concepts of *road travel 'basic risk'*, *'relative risk'* and *'relative risk odds-ratio'* and deriving methods and procedures for their 'interpretations'.
❸ Proposing and deriving various statistical/mathematical methodologies, problem formulations and procedures for estimating and computing *road travel 'basic risk'*, *'relative risk'*, and *'relative risk odds-ratio'* performance measure indicators. The 'appropriate' methodology depends upon the characteristic(s) of the target entity group's *road travel risk(s)* being measured and compared, and the type of input data available, e.g., 'frequency count' or 'proportional' data from 'incident' (accident, injury, fatality) and *'exposure (to risk)'* databases.
❹ 'Accuracy assessment' (error analysis) methodologies for measuring the statistical level(s) of accuracy associated with the 'estimated' *road travel risk* performance measure indicators are derived.
❺ Procedures for interpreting the various *road travel risk* performance measure indicators are developed.
❻ Finally, examples for each of the various types of *road travel risk (basic risk, relative risk,* and *relative risk odds-ratio)* performance measure indicators and associated statistical/mathematical methodology for their respective estimations and accuracy assessment are provided.

This paper presents the major results and findings from the six tasks (identified above) completed in this research.

The Concept of *'Road Travel Risk'* : The Relationships Between *'Risk'* and *'Exposure (To Risk)'* -- We define the *road travel risk level(s)* associated with all of the various factors contributing to accidents by comparing their appearance in road incidents (i.e., accidents, injuries, or fatalities) with some comparable measure of their appearance in traffic [Stewart and Lawson, 1987b]. The latter measure we refer to as the *'exposure (to risk)'* associated with the factors, i.e., the extent to which they are '*exposed*' to the 'possibility' of incidents (accidents, injuries and/or fatalities), by appearance in traffic. One of the main problems thwarting efforts to pursue the design and development of *road travel risk analyses and evaluation system models* arises from an inability to agree upon a suitable *exposure (road travel) measure* - i.e., a measure that 'best' reflects the appearance of road users and their characteristics on the roads and highways or, in other words, a measure that 'best' reflects the *amounts of road travel risk* -- '*exposure (to risk)*' -- encountered by road users and their characteristics. Another very important consideration is that the *exposure measurement* should be capable of providing insight into both the *'(risk of) exposure'* and *'exposure (to risk)'* [Risk, A. and Shaoul, J.E., 1982; Stewart, D.E., and Sanderson, R.W., 1984; Stewart, 1997b, 1998a, 1998b]. Although they sound similar these two concepts are quite different [Stewart, 1998b].

Although different *measures of exposure* have been advocated including: *'kilometers of travel'*, *'numbers of trips'*, and *'duration of travel -- time spent traveling on the roads'*, Stewart (1998a, 1998b) presents arguments favoring the use of *'kilometers of travel'* as the *standardized exposure measure* for the purposes of estimating/assess-ing *risk level(s)* on the roads and highways.

'KILOMETERS OF TRAVEL', THEREFORE, IS THE RECOMMENDED *'EXPOSURE (TO RISK)'* STATISTICAL MEASURE TO USE IN THE DEVELOPMENT OF A '*RISK ANALYSIS AND EVALUATION SYSTEM MODEL*'.

It is also imperative that a CONSISTENT *MEASURE OF EXPOSURE* BE EMPLOYED AND IT REMAIN COMPATIBLE OVER TIME. What is extremely beneficial, once a *standardized risk analysis and evaluation system model* is implemented, is the capacity to compare the *relative level(s) of road travel risks* over time (i.e., temporal comparisons) for different entity groups and under differing travel conditions. This is one of the most useful benefits received from the system. The most critical factors, therefore, to ensuring that the *road travel risk comparisons* over time are accurate, comparable and unbiased is the consistency, compatibility and accuracy of the *exposure measure estimates* developed.

A Modeling Framework for designing and developing a RAESM requires that we have knowledge of the *exposure (to risk)* for the various human, vehicle, road/infrastructure, environment, trip and temporal factors and their respective characteristics. We would therefore like to estimate *the 'extent' of* driver and passenger *kilometers traveled* for these factors. In other words, our search for *good exposure (to risk) data* is essentially a search for databases containing *detailed descriptions of travel by road users.* This information constitutes one half of the data necessary for designing and developing a *'risk analysis and evaluation system model'* [Stewart, D.E. and Sanderson, R.W., 1984; Stewart, D.E., 1998a, 1998b]. The second half of the information needed involves the availability of incident (collision, injury and fatality) data cross-classified by the various human, vehicle, road/infrastructure, environment, trip and temporal factors and their respective characteristics that are DIRECTLY COMPATIBLE AND CONSISTENT WITH THOSE AVAILABLE IN THE *EXPOSURE (TO RISK)* DATABASES.

With the availability of both of the above two types of databases it is possible to envisage the conceptualization of a *'risk analysis and evaluation system model'* that is capable of measuring, monitoring, comparing, evaluating, and assessing the accuracy of *the level(s) of risk -- level(s) of safety* -- on Canada's roads and highways. Figures 1 and 2 depict the components and their respective relationships that provide a modeling framework for use in the development of a *risk analysis and evaluation system.*

The relationships among the various components that impact upon and measure the *safety level(s)* existing on the roads and highways at any point in time -- program measures/countermeasures, causal factors, *exposure (to risk)*; human-vehicle-environment-road/infrastructure-trip-temporal *risk level(s)* existing on the road and highway systems; and the resultant incidence of accidents, injuries and fatalities occurring on the roads and highways are illustrated in Figure 1. Through examination of Figure 1 it becomes apparent that ALL CAUSAL COMPONENTS IN THE MODEL ARE IMPLICITLY REPRESENTED IN THE *'EXPOSURE (TO RISK)'* COMPONENT. The three key components -- *'exposure : extent, nature and quality of travel'*, *'incidence of accidents, injuries and fatalities'* and *'road travel risk levels existing on road and highway systems'* are therefore dependent upon one another and, from a mathematical perspective, functionally related. In other words, TO DESCRIBE THE *PREVAILING LEVEL(S) OF ROAD SAFETY TRAVEL (LEVEL(S) OF ROAD TRAVEL RISK)* ASSOCIATED WITH ENTITIES TRAVELING ON THE ROADS AND HIGHWAYS, OR CHANGES THEREOF, NECESSARILY REQUIRES A MATHEMATICAL FORMULATION THAT AT A MINIMUM CONTAINS ALL THREE COMPONENTS. This model provides the foundation and rationale for the statistical and mathematical methodology that has been developed and implemented for estimating *'basic risk'*, *'relative risk'* and *'relative risk odds-ratio' performance measure indicators.*

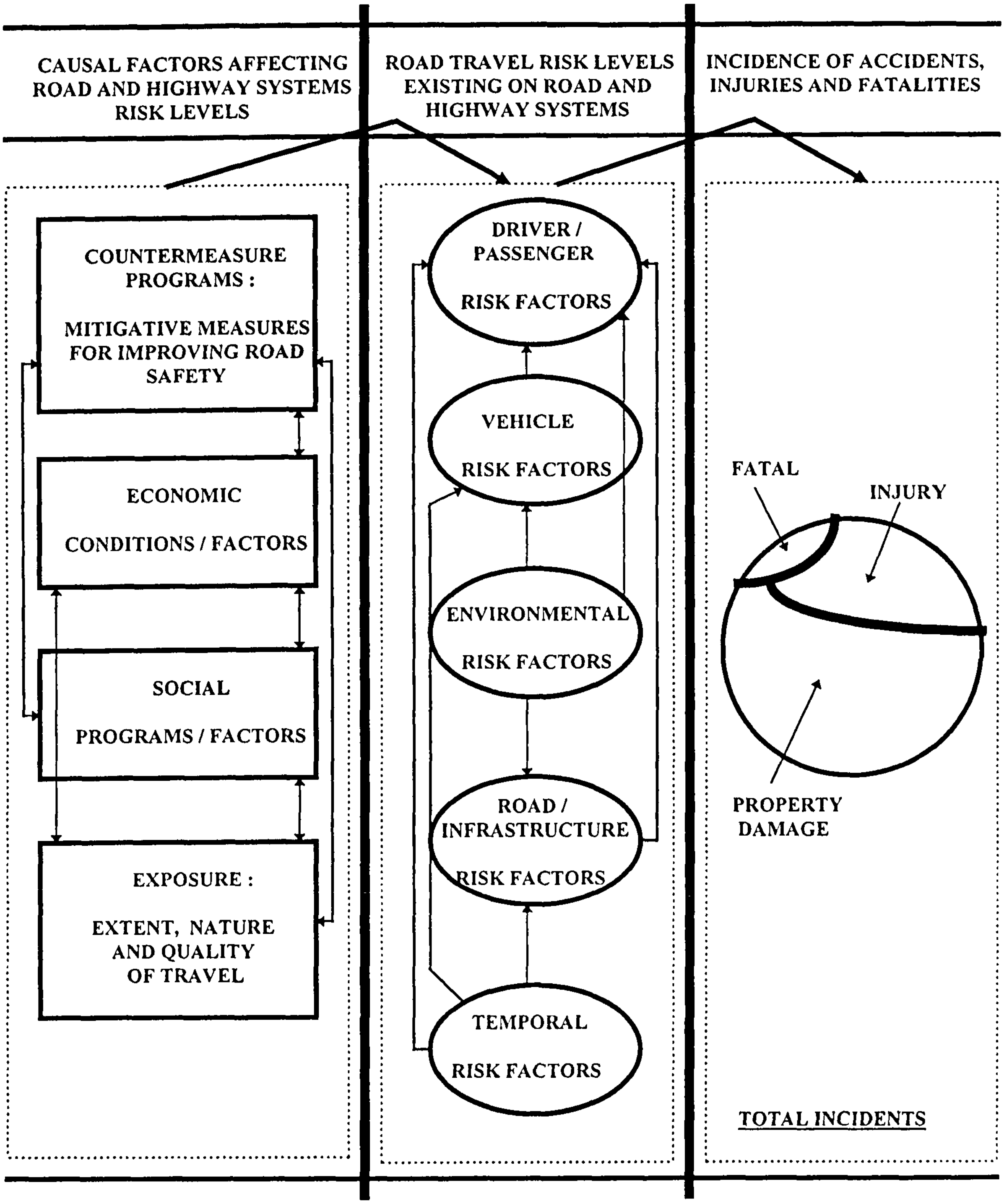

Figure 1. Relationship among causal factors, *risk levels* and incidence of accidents, injuries and fatalities.

Note: The arrows " ⟶ " indicate the road safety impact directions among the programs, causal factors, risk levels and incidence of accidents, injuries and fatalities.

Figure 2 provides a detailed description of the process for improving road safety through the use of a *RISK ANALYSIS AND EVALUATION SYSTEM MODEL -- 'RAESM'*. Existing countermeasure programs, economic conditions, social programs *and 'exposure (to risk)' / '(risk of) exposure'* -- extent, nature and quality of road travel -- all impact on the *prevailing level(s) of risk* for entities traveling on the roads and highways. By combining the 'exposure (to risk)' component (which contains the effects of the other three components, as discussed earlier) with the incidence of accidents/injuries/ fatalities in a mathematical formulation, ESTIMATES OF *'BASIC RISK'*, *'RELATIVE RISK'* AND *'RELATIVE RISK ODDS-RATIO'* PERFORMANCE MEASURE INDICATORS ARE DERIVED. By applying appropriate statistical methods for measuring the accuracy of these resultant *road travel risk* performance measure indicators, the *level(s) of risk* associated with the entities analyzed, as well as the *level(s) of risk differential existing between the entities evaluated*, are estimated. The results of the *risk analyses* are *interpreted* leading to *the identification of 'potential' road travel problem areas and issues* for remedial action considerations to improve road safety. Using the KNOWLEDGE OF the *basic risks, relative risks and relative risk odds-ratios* estimated for the various human-vehicle-road/infrastructure-environment-trip-temporal road travel factors and their characteristics, in conjunction with the magnitude of the problems (i.e., accident/injury/fatality incidence representation for the identical road travel factors and their characteristics), and other research information available, PRIORITIZATION OF THE IDENTIFIED PROBLEM AREAS/ISSUES CAN BE DONE. Next, it may be necessary to conduct directed research studies for the purpose of discerning the specific cause(s) of the *'high risk' road travel* associated with the group of entities identified. With the *'high risk' road travel* problem(s)/issue(s) well-identified (i.e., specific cause(s) found) the process of IDENTIFYING NEW COUNTER-MEASURES OR REMEDIAL MEASURES FOR REDUCING THE *'HIGH RISK' TRAVEL* BEING DONE BY THE IDENTIFIED GROUP OF ENTITIES BEGINS. The 'most suitable' countermeasure is then implemented. There are a number of criteria for evaluating and subsequently selecting the 'optimum' countermeasure, but the 'best' countermeasure would be the one that is generally most cost effective (i.e., the countermeasure with the potential for yielding the greatest improvement in road safety -- reduction(s) in *road travel risk level(s)* -- in relation to the costs for its implementation). This is determined by carrying out socio-economic impact analyses (SEIAs) and regulatory impact analyses (RIAs) including comprehensive cost-benefit analyses (CBAs) on the competing countermeasures and mitigative measure programs proposed and (usually) selecting the one that yielded the largest benefit-to-cost ratio. The qualifier 'usually' is to be noted since there are circumstances, once the evaluation is completed, that could result in a countermeasure or mitigative measure that does not have the largest benefit-to-cost ratio being selected for implementation. For example, the costs to implement countermeasure X could be significantly higher than that for countermeasure Y even though the potential road safety benefits compared to the costs (benefit-to-cost ratio) is larger for X. However, the maximum level of funds available for countermeasure development and implementation may be considerably lower than that required for option X, resulting in Y (the option with the lower benefit-to-cost ratio of the two) being implemented. Another type of circumstance could involve cases where the most cost-effective countermeasure may not, for various reasons, be deemed feasible or practical to implement, viz., 4-point seat belt harnesses in passenger vehicles; helmet use by all motor vehicle occupants of passenger vehicles; etc. In cases such as these it is necessary to assess tradeoffs and maximize the road safety improvement benefits by selecting the countermeasure(s) that are not only within the budget limitations available but are also 'practical' and 'implementable' -- i.e., the potential for educating and persuading the majority of the road users to adopt the mitigative measures is large. Having selected a countermeasure or mitigative measure program for addressing the problem area(s) and issues identified it is then implemented. In order to assess the benefit(s) of the countermeasure/mitigative measure programs with respect to their performance in making *improvements to the level(s) of safety (reductions in risk(s))* for road users, *'effectiveness evaluations'* and *'basic risk'*, *'relative risk'*, *'relative risk odds-ratio' performance measure indicator analyses* are conducted. These analyses and evaluations provide the 'knowledge' required for assessing the performance of the newly introduced countermeasures and/or mitigative measures. That is, for the target group(s) of road users affected: are *road safety benefits* being realized?; are the countermeasure or mitigative measure programs effective in *improving road safety*, and if so to what extent?; have the *road travel risk(s)* for the target group(s) been reduced? Finally, as can be seen in Figure 2, the process is iterative -- we return to *the basic risk*, *relative risk* and *relative risk odds-ratio estimation module* to *measure, compare, monitor and assess the level(s) of risk* at a later period in time. The full benefits of *a 'risk analysis and evaluation system model'* are only realized through a continuous iterative process whereby the *level(s) of road travel risk* are being measured regularly over time, i.e., on a fixed temporal schedule (e.g., annually, biannually) -- which is entirely dependent

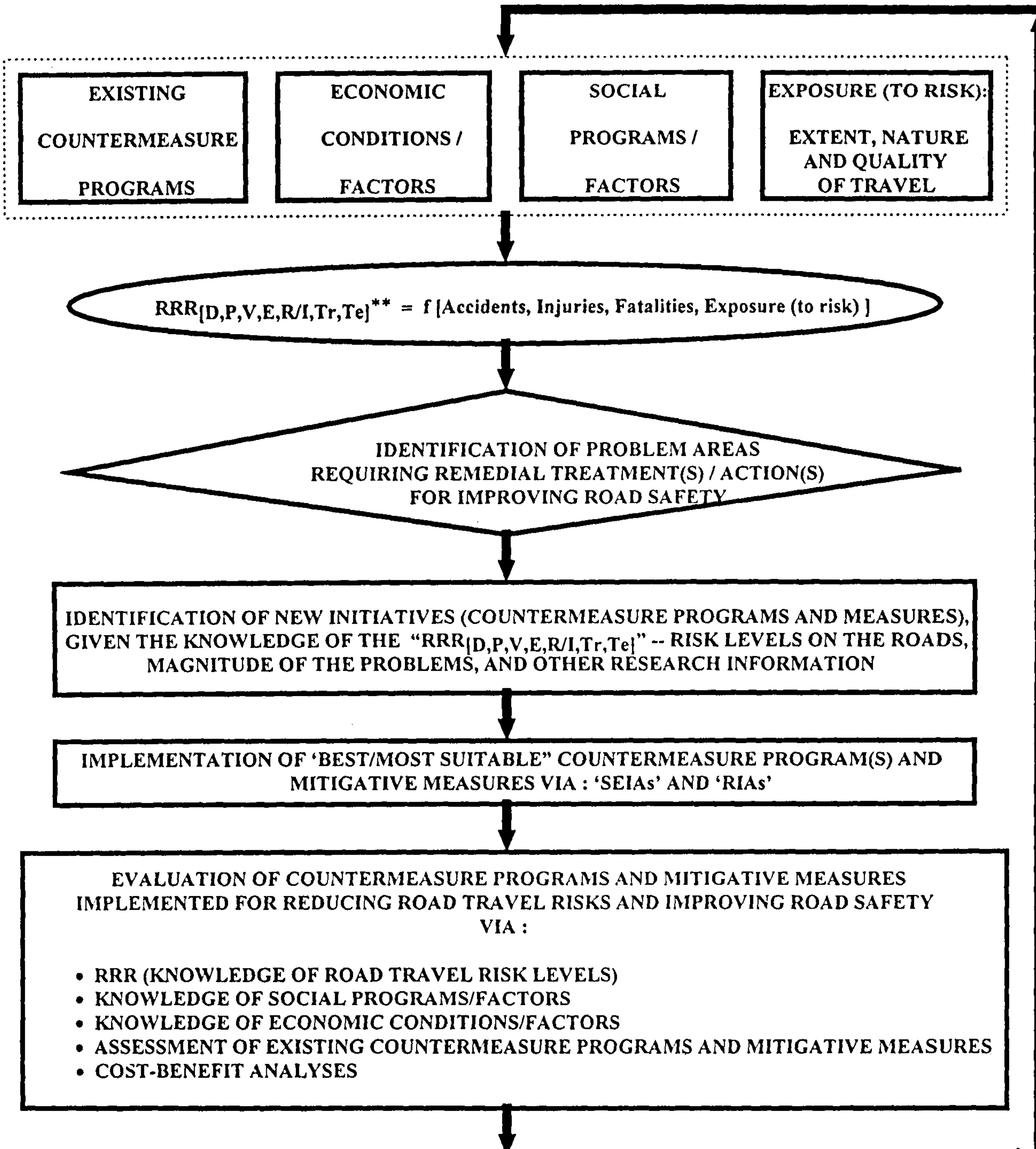

Figure 2. A *"Risk Analysis and Evaluation System Model -- RAESM"* process for measuring, monitoring, comparing and evaluating the *level(s) of road travel risk* on Canada's roads and highways.

** $RRR_{[D,P,V,E,R/I,Tr,Te]}$: *Relative Risk Ratio Road Travel Performance Measure Estimators* for various driver-passenger-vehicle-environment-road/infrastructure-trip-temporal travel pattern characteristics on the roads and highways. $RRR_{[D,P,V,E,R/I,Tr,Te]}$ are measured as a function of accidents, injuries, fatalities and *exposure (to risk).*

upon the priority level and resources made available for realizing, managing and operating such a system.

The previous sections have provided discussions of a modeling framework for standardizing the *road travel risk analysis, assessment and evaluation process,* including foundation principles and rationale for the implementation of *a 'risk analysis and evaluation system'*. The various phases involved in the process, i.e., from problem area(s) and issues identification to final assessment/evaluation of countermeasure/mitigative measure performance towards improving *the level(s) of safety -- reducing the level(s) of road travel risk(s)* -- on the roads and highways, have been described in detail. The remainder of this paper focuses on the *estimation, formulations, accuracy assessment and interpretations of the road travel 'basic risk', 'relative risk', and 'relative risk odds-ratio' performance measure indicators.* Specifically, the various statistical and mathematical methodologies for formulating and computing these various *'risk' performance measure indicators* including the data inputs required for each type of indicator are provided. Also, methods and procedures for measuring *the statistical level(s) of accuracy associated with the estimated risk performance measure indicators* are provided. Mathematical and statistical techniques and procedures for *interpreting the meaning/significance of the various 'estimated' basic risk, relative risk and relative risk odds-ratio performance measure indicators* are given. Lastly, *examples* are provided for *the various types of basic risk, relative risk and relative risk odds-ratio analysis methods along with associated accuracy assessment methods for each.*

THE *'PROPORTIONAL ROAD TRAVEL BASIC RISK'* PERFORMANCE MEASURE INDICATOR -- R^P : *AN ESTIMATOR BASED ON PROPORTIONAL DATA INPUTS*

The Estimator, R^P

The mathematical formulation for this relationship is given by:

$$R^P(I|TG_i,TC_j,T_z) = \frac{p(I|TG_i,TC_j,T_z)}{p(E|TG_i,TC_j,T_z)} \qquad (1.)$$

where,

$R^P(I|TG_i,TC_j,T_z)$ is the *'basic road travel risk'* performance measure indicator (computed from proportional data inputs on incidents and *exposure*) for a target group of entities i, TG_i, that measures their *road travel risk* of encountering a road incident of type I, while traveling under specified target travel conditions j, TC_j, during a specified time period z, T_z;

$p(I|TG_i,TC_j,T_z)$ is the proportional representation of the target entity group i, TG_i, involved in road incidents of type I, while traveling under specified target travel conditions j, TC_j, during a specified time period z, T_z;

$p(E|TG_i,TC_j,T_z)$ is the proportional representation of the target entity group i's, TG_i's, road travel (E) on the roads and highways, i.e., their *'exposure' to the road travel risk(s)*, while traveling under specified target travel conditions j, TC_j, during a specific time period z, T_z;

TC_j is a specified target travel pattern/condition determined by the presence of a combination of specified driver D_j, passenger P_j, vehicle V_j, road/infrastructure RI_j, environmental EN_j, trip TR_j, and temporal TE_j factors and their characteristics for which the *'proportional road travel basic risk'* of potential incident encounter, $R^P(I|TG_i,TC_j,T_z)$, for the target entity group i, TG_i, is being measured. That is, TC_j is a function of the various driver, passenger, vehicle, road/infrastructure, environment, trip and temporal factors present during target entity group i's, TG_i's, travel for a specified time period z, T_z, i.e., mathematically we have,

$$TC_j = f(D_j,P_j,V_j,RI_j,EN_j,TR_j,TE_j) \qquad (2.)$$

For example, the *road travel risks* for occupants 16-19 years old, while traveling in sports cars, on rural roads, when it is raining/roads are wet, for the trip purpose of returning home after a party, between 1:30 a.m. and 3:00 a.m. in the morning, can be measured. Although quite detailed, this particular example illustrates the voluminous amounts and types of *'road travel basic risk' estimation* that can be carried out in the initial processes of *identifying 'potentially high road travel risk' groups* of entities for subsequent consideration (i.e., research, evaluation, assessment) in the countermeasure/mitigative measure prioritization process. In essence, the level of disaggregation of the various human-vehicle-road/infrastructure-environment-trip-temporal factors and their characteristics that can be utilized for *measuring and evaluating road travel risks* is only limited by the amounts and level of detail of incident and *exposure (to risk)* data available for input into the *risk analysis and evaluation system model.* Therefore, estimates of the *road travel basic risk performance measure indicator* can always be computed -- it is their accuracy that is directly affected by the amounts and quality of incident and *exposure (to risk)* data available, in particular for very detailed levels of *road travel risk analyses,* as in the example above.

The Accuracy of R^P

The final mathematical equations for computing the resultant 95% confidence limits for $R^P(I|TG_i,TC_j,T_z)$ are given by:

$$R^P_{[L,95\%]} = e^{\{ln_e[R^P] - 1.96 * \sigma(ln_e[R^P])\}} \quad (3.)$$

for the lower 95% confidence limit ; and,

$$R^P_{[U,95\%]} = e^{\{ln_e[R^P] + 1.96 * \sigma(ln_e[R^P])\}} \quad (4.)$$

for the upper 95% confidence limit ;

where,

$$\sigma(ln_e[R^P]) = \sqrt{\left[\frac{[1 - p(I)]}{p(I) * n(I)}\right] + \left[\frac{\sigma^2(p(E))}{[p(E)]^2}\right]} \quad (5.)$$

and,

$ln_e[\,]$ is the natural logarithm (to the base e) of R^P ;

$\sigma(ln_e[R^P])$ is the statistical 'one standard error' estimate of variability for the natural logarithm (to the base e) of R^P;

$\sigma^2(p(E))$ is the statistical 'variance' estimate of variability for p(E) ;

$R^P = R^P(I|TG_i,TC_j,T_z)$; $p(I) = p(I|TG_i,TC_j,T_z)$; $p(E) = p(E|TG_i,TC_j,T_z)$; and,

n(I) is the total number of incidents of type I being evaluated that occurred on the roads and highways under target travel conditions, TC_j, during the specified time period z, T_z

The Interpretation of R^P

Assumptions and Limitations -- There are no assumptions that need to be made for justifying or interpreting the resultant values of the *proportional road travel basic risk estimator.*

There are no limitations or restrictions affecting the interpretation of the *proportional road travel basic risk estimators.* Since natural logarithms (to the base e) are used in computing the estimators and their associated 95% confidence limits (for measuring their accuracy), this ensures that a *proportional road travel basic risk estimator* can always be measured and has a logical upper bound, and the confidence limits measuring the *accuracy of the risk estimators* have a logical 'upper bound' and are 'near' symmetrical around R^P. This property is a necessary requirement in the conduction of *effectiveness evaluations* since the **effectiveness estimate** (of a particular countermeasure/mitigative measure) **is measured from the results of the *risk estimator*** as:

$$E = [100 * (1 - R)] \,\% \quad (6.)$$

where,

E is the ***effectiveness estimator*** (measured as a percentage), and
R is the ***'road travel basic risk' performance measure estimator*** (measured using 'proportional' data on *exposure (to risk)* and traffic incidents).

Therefore, the use of natural logarithms (to the base e) ensures that the *effectiveness estimate E* and the *errors measuring the accuracy of the effectiveness estimate* (e.g., 95% confidence limits) have a logical 'lower bound' of zero and that the error bounds around E are "near symmetrical".

Analytical properties -- The attractive properties associated with *the proportional road travel basic risk performance measure indicator, R^P*, and the proportional data inputs required for its estimation include:

$0 \le p(I|TG_i,TC_j,T_z) \le 1$ -- with 0(zero) resulting in the lower bound of zero for *the road travel risk estimator* ;

$0 < p(E|TG_i,TC_j,T_z) \le 1$ -- the *'exposure (to risk)'* is always greater than zero for meaningful *risk estimation*, i.e., if there is 'zero/no exposure' then there is 'no road travel' which results in *'NO RISK OF INCIDENT ENCOUNTER'* ;

$0 \le R^P(I|TG_i,TC_j,T_z) < \infty$ -- the *proportional road travel basic risk estimator* has a logical upper bound ;

$R^P(I|TG_i,TC_j,T_z)_{[L,95\%]}$ and **$R^P(I|TG_i,TC_j,T_z)_{[U,95\%]}$** are 'near' symmetrical around $R^P(I|TG_i,TC_j,T_z)$ and represent logical 'lower' and 'upper' 95% C.L. (statistical) bounds, respectively ;

$R^P(I|TG_i,TC_j,T_z)$ are UNIT-FREE (i.e., DIMENSION-LESS -- akin to engineering dimensional analysis) which is a 'desired analytical property' ensuring that all comparisons of the various types of *risk performance measure estimators* are always valid ;

$R^P(I|TG_i,TC_j,T_z)_{[EXPECTED]} = 1$. The 'expected value' of a *proportional road travel basic risk estimator* is '1', with the value of '1' meaning that the target entity group is not *'a high risk group'* for the target road travel conditions and time period being evaluated. This is a 'necessary property' for the *risk estimator* to possess *for differentiating among road travel risk level estimators for different entities (and their subgroups, as well)* on the roads and highways.

As will be seen in subsequent sections, the *'relative risk'* and *'relative risk odds-ratio' estimators* offer the same powers of interpretation -- the ability to *identify significant differences in road travel risks between and among entity groups*, and *significant differences in road travel risks between and among entity groups for specified road travel condition comparisons*, respectively.

Interpretation(s) – The following basic rules are used for interpreting the resultant *road travel proportional basic risk estimators*:

If $R^P(I|TG_i,TC_j,T_z) < 1$ $\Rightarrow$ Then the performance of the target entity or group of entities, TG_i, is potentially a *'low road travel risk' level* under target travel conditions j, TC_j, during a specified evaluation time period z, T_z ;

If $R^P(I|TG_i,TC_j,T_z) > 1$ $\Rightarrow$ Then the performance of the target entity or group of entities, TG_i, is potentially a *'high road travel risk' level* under target travel conditions j, TC_j, during a specified evaluation time period z, T_z ;

If $R^P(I|TG_i,TC_j,T_z) = 1$ $\Rightarrow$ Then the performance of the target entity or group of entities, TG_i, is potentially at the *'expected road travel risk' level* (given their *'exposure (to risk)'* representation on the roads and highways) under target travel conditions j, TC_j, during a specified evaluation time period z, T_z .

Although the above interpretations provide *the basic decision rules for assessing the resultant proportional road travel basic risk estimators*, the qualifiers -- "potentially" must be heeded. This is because the final interpretations must take into account the accuracy assessment measurements surrounding the final estimators. The examples provided in Figure 3 demonstrate the *caution that must be exercised when interpreting the final proportional road travel basic risk estimator results*.

Figure 3 gives hypothetical examples for five $R^P(I|TG_i,TC_j,T_z)$ results, indicated by [1], [2], [3], [4], and [5] in the graphical illustration. Result [1] demonstrates a *'high road travel risk' performance measure indicator* for target entity group TG_1. The error bounds for it (as well as for each of the other four indicator examples) are 'lower' and 'upper' 95% confidence limits (C.L.s), denoted as [L,95%] and [U,95%], respectively. Examination of the results shows that, even when the 95% C.L. error bounds of the *road travel risk indicator* for entity group TG_1 are taken into account, the group is still a *'high road travel risk' group*. Examining the results for target entity group TG_2 (result [2]) shows that, without taking the 95% C.L.s into account, they appear to be *a 'low risk road travel' group*. However, when the 95% confidence limits are taken into account, it can be seen that this group is not a *(statistically significant) 'low risk' group*. In other words, it cannot be claimed (at the 95% level of statistical confidence) that *the road travel risk levels* for this group TG_2 are necessarily *'low level'*. Therefore, more and better (more accurate) data and/or further research are needed to make a definitive decision regarding this group's status as a *'low road travel risk group'*. The entity group TG_3 is right on the *'Expected Risk Level'*, i.e., *road travel risk estimator* value of *1*. However, when the 95% error bounds on the risk estimator are accounted for, it cannot be claimed that this target entity group is *'a high risk'* or *'a low risk'*. As was the case for group TG_2, more and better data and/or research is needed to make a definitive decision as to the status of this group's *'road travel risk level'*. Result [4] for target entity group TG_4 demonstrates a definitive *'low risk road travel'* group. That is, with the 95% C.L.s taken into account, the TG_4 group is a *(statistically significant) 'low risk road travel' group*. Lastly, result [5] shows the target entity group TG_5 that appears to be a *'high risk road travel' group*, but once the error bounds on the *basic risk performance measure indicator* are taken into account, it cannot be determined whether this group *is 'a high risk'* or *'a low risk' road travel group*. Here again, further research and/or more and better quality data are required to draw any definitive conclusions about the *true 'road travel risk level'* of group TG_5.

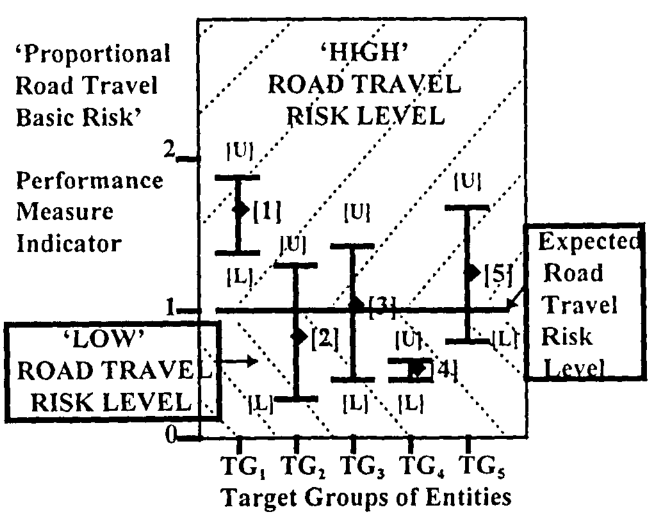

Figure 3. Interpretation of the '*Proportional Road Travel Basic Risk*' performance measure indicator.

It should be noted that a fixed '95% level of statistical confidence' has been used for measuring the error bounds on the *risk estimators* -- which forms the basis for drawing conclusions and arriving at decisions.

Another approach that could be used involves the estimation of the confidence levels, i.e., X% confidence limits, for which the UPPER X% CONFIDENCE LIMIT IS 'STRICTLY LESS THAN' THE *'EXPECTED' ROAD TRAVEL RISK LEVEL VALUE OF 1* (for an *estimated road travel risk indicator that is less than 1*) or, for which the LOWER X% CONFIDENCE LIMIT IS 'STRICTLY GREATER THAN' THE *'EXPECTED' ROAD TRAVEL RISK LEVEL VALUE OF 1* (for an *estimated road travel risk indicator that is greater than 1*). Although this approach will not provide constant 'fixed' confidence limits by which all interpretations, conclusions and decisions are made (for all of the *road travel risk estimators developed*) it does provide a definitive 'level of statistical confidence' for qualifying/supporting decisions made. That is, the results of all *road travel risk estimators* can be interpreted as:

"It can be concluded that, at the x% level of statisitcal confidence, target entity group TG_i is a 'high' (or 'low') (or 'expected level') road travel risk group"

THE *'FREQUENCY ROAD TRAVEL BASIC RISK'* PERFORMANCE MEASURE INDICATOR -- R^F : *AN ESTIMATOR BASED ON FREQUENCY COUNT DATA INPUTS*

There will be occasions where the proportional representations for the road incident (fatality, injury, or collision) involvement and/or *exposure (to risk)* -- kms. of road travel, for the target group of entities being evaluated are NOT KNOWN! Effectively, only the absolute frequencies of road incident encounter *and exposure (to risk)* are KNOWN! This happens when information is not collected or available for all categories or characteristics of a particular target entity group, target conditions and temporal period criterion involved in the evaluation. For example, all age groups (ages) of drivers required for a *risk analysis assessment/evaluation* may not be available in the incident database and/or the *exposure(to risk)* database. This can occur quite frequently in the case of directed studies where many characteristics of the entities being investigated/ studied are not all collected, such as 'only vehicles of certain types being included' in the sampling plan and data collection.

When only frequency count information/data is available the *road travel risk estimator(s)* are simply *'accident rate(s)'* which, from an interpretation perspective, provide no information regarding the *degree or level of risk* for the group(s) of entities and their travel pattern/circumstances being evaluated. That is, there is no capacity to assess whether the target entity group(s) are a *'high risk'*, *'low risk'* or *'at an expected level of risk'*. The only meaningful use of these *frequency road travel risk performance measurement indicators* is in *'relative risk' comparisons* between different group(s) of entities, or *in comparisons made with respect to the same group of entity(s) for two different temporal periods*. Even then, particularly in the latter case, extreme caution is in order owing to a phenomenon known as 'regression-to-the-mean' -- a process whereby entities with higher-than-average (or lower-than-average) accident frequency counts will regress (over time) towards the mean/average frequency count for the entity group(s) being analyzed. Hauer (1983) has demonstrated that the 'regression-to-the-mean' phenomenon is in fact a 'real phenomenon' that occurs with respect to accidents occurring on our roads and highways, and must be corrected for to meaningfully compare incident frequency counts (and rates as well) in a 'before' period to those in an 'after' period for two groups of entities. As can be realized by now, owing to the serious limitations and pitfalls inherent to the incident frequency count method for estimating, monitoring, comparing and evaluating *road travel risk(s)* for entities on the roads and highways, these types of *risk estimation* should be avoided. There would appear to be some merit in using the frequency count method for comparing the *level(s) of risk (i.e., 'relative risk estimators')* for two or more different groups of entities evaluated during the same temporal period.

For completeness, therefore, the mathematical and statistical methodology for computing the *'frequency road travel basic risk performance measure indicator'* and its related accuracy assessment are provided in this paper. For methodology on the other types of 'frequency' data input risk estimators see Stewart (1998). The mathematical formulation for this indicator is given by:

$$R^F(I|TG_i,TC_j,T_z) = \frac{(I|TG_i,TC_j,T_z)}{(E|TG_i,TC_j,T_z)} \qquad (7.)$$

where,

$R^F(I|TG_i,TC_j,T_z)$ is the ***frequency road travel basic risk performance measure indicator*** (computed from **frequency count data inputs on incidents** and *exposure (to risk)*) for **a target group** of entities **i**, TG_i, that measures their ***road travel risk*** of encountering a road **incident of type I,** while traveling under specified **target** travel **conditions j**, TC_j, during a specific **time period z**, T_z;

$(I|TG_i,TC_j,T_z)$ is the **frequency count representation** of the **target** entity **group i**, TG_i, involved **in road incidents** of **type I**, while traveling under specified **target** travel **conditions** j, TC_j, during a specific **time period z**, T_z;

$(E|TG_i,TC_j,T_z)$ is the **frequency count representation** (i.e., **kms of travel**) for the **target entity group i's**, TG_i's, **road travel (E)** on the roads and highways, i.e., their **'EXPOSURE' to the road travel risk(s)**, while traveling under specified **target** travel **conditions j**, TC_j, during a specific **time period z**, T_z; and,

TC_j is a **specified target travel pattern/condition** (as described earlier in Section 5).

The Accuracy of R^F

The details concerning the mathematical and statistical methodologies developed for deriving the formulae for measuring the accuracy of *the 'frequency road travel basic risk' performance measure indicator* are not provided in this paper. Only final results are given and the reader is invited to contact the author for the formulations and derivations.

The lower 95% confidence limit for $R^F(I|TG_i,TC_j,T_z)$ is given by equation (8.).

$$R^F_{[L,95\%]} = e^{\{\ln_e[R^F] - 1.96 * \sigma(\ln_e[R^F])\}} \quad (8.)$$

and,

the upper 95% confidence limit for $R^F(I|TG_i,TC_j,T_z)$ is given by equation (9.).

$$R^F_{[U,95\%]} = e^{\{\ln_e[R^F] + 1.96 * \sigma(\ln_e[R^F])\}} \quad (9.)$$

where,

$$\sigma(\ln_e[R^F]) = \sqrt{\left[\frac{1}{(I)}\right] + \left[\frac{\sigma^2((E))}{[(E)]^2}\right]} \quad (10.)$$

or, an alternative (but equivalent) formulation for $\sigma(\ln_e[R^F])$ is given by,

$$\sigma(\ln_e[R^F]) = \sqrt{\left[\frac{1}{(I)}\right] + \left[CV[(E)]^2\right]} \quad (11.)$$

$\ln_e[R^F]$ **is the natural logarithm (to the base e) of** R^F;

and,

$\sigma(\ln_e[R^F])$ is the **statistical 'one standard error'** measurement for the natural logarithm (to the base e) of the **frequency road travel basic risk estimator** R^F;
and,

$\sigma^2((E))$ is the **statistical 'variance'** measurement for the **kilometers of road travel done, (E),** by **target** entity **group i**, TG_i, under **target** travel **conditions j**, TC_j, during a specified **time period z**, T_z;
and,

CV(E) is the **statistical 'coefficient of variation'** measurement for the **kilometers of road travel done**, (E), by **target** entity **group i**, TG_i, under **target** travel **conditions** j, TC_j, during a specified **time period z**, T_z;

where,

$(I) = (I|TG_i,TC_j,T_z)$,
$(E) = (E|TG_i,TC_j,T_z)$,
$R^F = R^F(I|TG_i,TC_j,T_z)$.

The Interpretation of R^F

Assumptions and Limitations -- There are no assumptions required for justifying or interpreting the final value of the *frequency road travel basic risk estimator*. Similarly, there are no limitations or restrictions affecting the computation of this estimator, however severe limitations and restrictions with respect to its interpretation and usefulness do exist. These are discussed below.

Analytical Properties – The analytical properties associated with *the frequency road travel basic risk performance measure indicator* include:

$0 \leq (I|TG_i,TC_jT_z) < \infty$ -- the lower bound of the estimator is zero, and it has a logical upper bound;

$0 < (E|TG_i,TC_j,T_z) < \infty$ -- the *'exposure (to risk)'* must always be greater than zero for meaningful *risk estimation*, i.e., if there is *'zero/no exposure'* then there is *'zero/no travel'* which results in *'NO RISK OF INCIDENT ENCOUNTER'*;

$0 \leq R^F(I|TG_i,TC_j,T_z) < \infty$ -- the *frequency road travel risk performance measure indicator* has a logical 'upper bound';

$R^F(I|TG_i,TC_j,T_z)_{[L,95\%]}$ and $R^F(I|TG_i,TC_j,T_z)_{[U,95\%]}$ are 'near' symmetrical around $R^F(I|TG_i,TC_j,T_z)$ and represent logical 'lower' and 'upper' 95% C.L.s, respectively;

$R^F(I|TG_i,TC_j,T_z)$ are NOT UNIT-FREE, i.e., they are NOT DIMENSIONLESS. Since the estimators are not unit-free there is **no expected value or bench-mark** for ***comparing and assessing frequency road travel risk estimators.*** In the case of the *proportional road travel basic risk estimator* the 'expected value' is '1' -- the bench-mark for *identifying 'high' and 'low' road travel risk* entity groups. This is a desired and necessary property for the *risk estimator* to possess for differentiating among *road travel risk levels* for different entities (and their subgroups, as well) on the roads and highways. Unfortunately, the **frequency road travel basic risk performance measure indicator DOES NOT POSSESS this 'interpretative property'.**

As will be seen in subsequent sections, however, *the frequency road travel 'relative risk' and 'relative risk odds-ratio' performance measure estimators* are much more useful. These two estimators offer the same powers of interpretation as the *'proportional road travel 'relative risk' and 'relative risk odds-ratio' performance measure indicators*. This is because the dimensional units of the incident and *exposure (to risk)* frequency count data inputs used to compute the *frequency road travel 'relative risk' and 'relative risk odds-ratio' indicators* cancel one another in the estimation formulae resulting in UNIT-FREE estimators -- the 'desired analytical property' -- resulting in the ability to identify significant differences in *road travel relative risks* between and among entity groups, and significant differences in *road travel risks* between and among entity groups for specified road travel condition comparisons.

Interpretation(s) -- Unfortunately, there are **no meaningful interpretations available from the** $R^F(I|TG_i,TC_j,T_z)$ *frequency road travel basic risk estimator* as there were for $R^P(I|TG_i,TC_j,T_z)$ -- the *proportional road travel basic risk estimator.* In essence, $R^F(I|TG_i,TC_j,T_z)$ is simply ***an accident rate*** with no standard or bench-mark to compare it to. Unlike the *proportional road travel basic risk estimator* which had an **'expected standardized value' of 1** with which to compare for identifying ***'high'***, ***'low'*** and ***'expected' road travel risk level(s), the FREQUENCY ROAD TRAVEL BASIC RISK ESTIMATOR*** PROVIDES NO INFORMATION FOR ASSESSING THE ***LEVEL(S) OF ROAD TRAVEL RISK*** **ATTRIBUTABLE TO THE ENTITY GROUPS BEING ANALYZED AND EVALUATED.** As a result, *the frequency road travel basic risk performance measure indicator* is **of limited use** in differentiating among *road travel risk level(s)* and identifying characteristics of road travel entities and groups with *'high' road travel risk.* The only types of comparisons possible involve the comparisons of various target entity groups' *accident rates* with some other standard, e.g., *mean accident rate* for all entities, *accident rate for another control group* of entities, etc.. By their very nature, however, these types of comparisons are done through the use of *'relative risk' and 'relative risk odds-ratio' performance measure indicators* -- not *'basic road travel risk' estimators.* There are, therefore, **no meaningful interpretation(s) for assessing/evaluating the *frequency road travel basic risk estimator* or identifying *'high risk'* road travel entities.**

The examples provided in Figure 5 demonstrate the limited amount of information available for interpretation and assessment of the *frequency road travel basic risk performance measure indicators.* Hypothetical examples for five $R^F(I|TG_i,TC_j,T_z)$, indicated by [1], [2], [3], [4], and [5], are illustrated in the graphical results. Result [1] demonstrates an *accident rate* of about 1.50 *accidents per million driver kms. of travel* for target entity group TG_1. Similarly, results [2], [3], [4] and [5] depict *the accidents per million driver kms. of travel* for target entity groups TG_2, TG_3, TG_4, and TG_5 -- 0.75, 1.00, 0.50 and 1.20 respectively. From an interpretation point of view, all that can be said is that the *accident rates* vary between 0.50 and 1.5 *accidents per million driver kms. of travel* for the five target entity groups and, when the error levels (95% confidence limits) are taken into account, there does not appear to be any significant differences among the *accident rates* with the exceptions of: result [4] compared to result [5] -- it is possible that result [4] is statistically significantly different in value from result [5] ; and result [4] compared to [1]. This can be determined through the application of hypotheses tests and evaluating whether *significant differences in accident rates* exist by comparing the results among the five target entity groups. Although the methods for carrying out these types of comparisons is discussed in the following section, **the major problem with this method remains -- an inability to assess whether any of the (groups of) target entities being evaluated are *'high'* or *'low'* or *'at their expected level of' road travel risk.***

THE 'PROPORTIONAL ROAD TRAVEL RELATIVE RISK' PERFORMANCE MEASURE INDICATOR -- *RR^P : AN ESTIMATOR BASED ON PROPORTIONAL DATA INPUTS*

The concept behind the 'road travel *relative risk*' estimator seeks to compare the *risks of incident involvement* for two (groups of) entities represented on the roads and highway systems. In essence, the *'road* *travel basic risk' estimator* (as described in section 5) is computed for both (groups of) entities. Then, these *two road travel basic risk performance measure indicators* are then compared through the computation of a *relative risk*

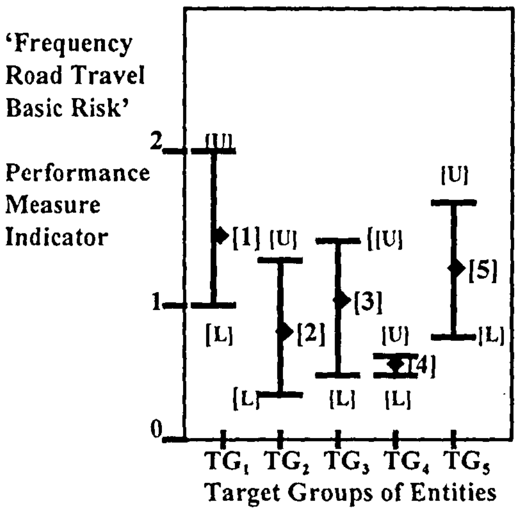

Figure 4. Interpretation of the '*Frequency Road Travel Basic Risk*' performance measure indicator.

ratio (i.e., the division of the one *basic risk* estimator by the other). The resultant *road travel relative risk performance measure indicator* is a measure of any *differential in road travel risk level(s) (i.e., level(s) of safety) existing between the two (groups of) entities.*

The mathematical formulation for detecting any *road travel risk differential* existing between the two entity target groups, say 'target group 1' -- TG_1, and 'target group 2' -- TG_2, is given by:

$$RR^P(I|TG_{1:2},TC_j,T_z) = \frac{R^P(I|TG_1,TC_j,T_z)}{R^P(I|TG_2,TC_j,T_z)} \quad (12.)$$

where,

$$R^P(I|TG_1,TC_j,T_z) = \frac{p(I|TG_1,TC_j,T_z)}{p(E|TG_1,TC_j,T_z)},$$

$$R^P(I|TG_2,TC_j,T_z) = \frac{p(I|TG_2,TC_j,T_z)}{p(E|TG_2,TC_j,T_z)},$$

and,

$RR^P(I|TG_{1:2},TC_j,T_z)$ is the *proportional* road travel *relative risk* performance measure estimator of the differential in road travel risk existing between entity groups TG_1 and TG_2, under specified target travel conditions j, TC_j, during an evaluation time period z, T_z

The Accuracy of *RR^P*

The **lower and upper 95% confidence limits** for the $RR^P(I|TG_{1:2},TC_j,T_z)$ estimator are given in equations (13.) and (14.) respectively.

$$RR^P(X)_{[L,95\%]} = e^{\{ln_e[RR^P(X)] - 1.96 * \sigma(ln_e[RR^P(X)])\}} \quad (13.)$$

$$RR^P(X)_{[L,95\%]} = e^{\{ln_e[RR^P(X)] + 1.96 * \sigma(ln_e[RR^P(X)])\}} \quad (14.)$$

where,

$$\sigma(ln_e[RR^P(X)]) = \sqrt{\sigma^2(ln_e[RR^P(X)])} \quad (15.)$$

and,

$$\sigma^2(ln_e[RR^P(X)]) = \sum_{k=1}^{2} \left\{ \left[\frac{1}{p(I_k)}\right]^2 * \sigma^2(p(I_k)) \right\} + \sum_{k=1}^{2} \left\{ \left[\frac{1}{p(E_k)}\right]^2 * \sigma^2(p(E_k)) \right\} \quad (16.)$$

where,

$X = (I|TG_{1:2},TC_j,T_z)$,
$I_k = (I|TG_k,TC_j,T_z)$,
$E_k = (E|TG_k,TC_j,T_z)$.

The Interpretation of *RR^P*

Assumptions and Limitations -- There are no assumptions that need to be made for justifying or interpreting the resultant values of the *proportional road travel relative risk estimator.* There are no limitations or restrictions affecting the interpretation of *the proportional road travel relative risk estimator.* Similar to the *proportional road travel basic risk estimator,* natural logarithms (to the base e) are used thereby ensuring that the RR^P can always be measured, has a logical upper bound and the confidence limits measuring its accuracy are 'near symmetrical' around RR^P and have a logical upper bound as well.

Analytical Properties -- The proportions of incidents and *exposure (to risk)* for both groups TG_1 and TG_2 must be greater than zero for meaningful *relative risk estimation and comparisons*, i.e., $p(I|TG_1,TC_j,T_z) > 0$, $p(I|TG_2,TC_j,T_z) > 0$, $p(E|TG_1,TC_j,T_z) > 0$, $p(E|TG_2,TC_j,T_z) > 0$.

$RR^P(I|TG_{1:2},TC_j,T_z)$ are UNIT-FREE, i.e., DIMENSIONLESS, ensuring that comparisons of RR^Ps are valid and meaningful.

$0 < RR^P(I|TG_{1:2},TC_j,T_i) < \infty$. The value of the *proportional road travel relative risk estimator* is always greater than zero and has a logical 'upper bound'.

The 95% lower and upper confidence bounds, $RR^P(I|TG_{1:2},TC_j,T_z)_{[L,95\%]}$ and $RR^P(I|TG_{1:2},TC_j,T_z)_{[U,95\%]}$, are 'near' symmetrical around $RR^P(I|TG_{1:2},TC_j,T_z)$ and have logical lower and upper bounds as well.

$RR^P(I|TG_{1:2},TC_j,T_z)_{[EXPECTED]} = 1$. The expected value of a *proportional road travel relative risk estimator* is '1' with the value of '1' meaning that *the road travel risk level of incident encounter of type I* is potentially equivalent for both target entity groups TG_1 and TG_2 under target travel conditions j, TC_j, during a specified evaluation time period z, T_z. This 'expected value' of 1 implies that if the ratio of the representation of entity group TG_1 in incident involvement to its *exposure (to risk) representation* on the roads is equivalent to target entity group TG_2's incident involvement to *exposure (to risk) representation ratio*, then *the road travel risk level* for the two target entity groups is *'relatively' the same.* In other words, the *level of safety* being experienced by the two groups of entities is equivalent. In a similar fashion as the *'proportional road travel basic risk' estimators*, however, the *proportional road travel relative risk estimators* must only be interpreted by taking into account their accuracy levels, i.e., 95% C.L.s.

Interpretation(s) – The following rules govern the decision-making from the computed road travel relative risk estimators:

If $RR^P(I|TG_{1:2},TC_j,T_z) < 1 \Rightarrow$ Then the ***road travel risk level of incident encounter of type I*** is potentially ***'lower'*** for the **target** entity or **group** of entities, TG_1, then it is for **target** entity **group** TG_2 under **target** travel **conditions** j, TC_j, during a specified **time period** z, T_z;

If $RR^P(I|TG_{1:2},TC_j,T_z) > 1 \Rightarrow$ Then the ***road travel risk level of incident encounter of type I*** is potentially ***'higher'*** for the **target** entity or **group** of entities, TG_1, then it is for **target** entity **group** TG_2 under **target** travel **conditions** j, TC_j, during a specified **time period** z, T_z;

If $RR^P(I|TG_{1:2},TC_j,T_z) = 1 \Rightarrow$ Then the ***road travel risk level of incident encounter of type I*** is potentially ***'equivalent'*** for **target** entity **groups** TG_1 and TG_2 under **target** travel **conditions** j, TC_j, during a specified **time period** z, T_z.

The above decision rules provide the basic guidelines for *interpreting the relative risk estimators*, but their results cannot be fully interpreted without taking into account their accuracy assessment measurements. The hypothetical examples given in Figure 5 that follow demonstrate the care that must be taken for properly interpreting the resultant *proportional road travel relative risk estimators.*

Five target group *relative risk comparisons* estimating the differential in *road travel risk* between target group 1 (TG_1) and target groups TG_2, TG_3, TG_4, TG_5 and TG_6 are illustrated. Result [1] shows an RR^P value of about 1.6 comparing entity target groups 1 and 2, implying that target group 1 has a *road travel risk level* that is about 1.6 times higher than that of target group 2. Even when the 95% C.L. error bounds for the *relative risk estimator* are taken into account it can be concluded that target group 1 is *a 'higher road travel risk' group* than entity group TG_2. Examining the *road travel relative risk comparison* between TG_1 and TG_3 -- result [2] = 0.75 -- it can be readily seen that TG1 has a *definitive 'lower road travel risk level'* than TG2, and this conclusion is true at a 95% level of statistical confidence. Result [3] measuring the *relative risk* of TG_1 compared to TG_4 is equal to 1.0 indicating that TG_1 appears to be *an equaivlalent 'road travel risk group'* to group TG_4. However, when the 95% C.L.s are taken into account it cannot be determiined which of the two groups is a *(statistically significant) 'higher risk group'* than the other, if either. Therefore, more and better (more accurate) data and/or further research are needed to make a definitive decision regarding whether a *significant road travel risk differential* exists between entity groups TG_1 and TG_4. The *relative risk estimator* comparing target groups 1 and 5 (result [4]) is 0.6 with the upper 95% C.L., [L,95%], smaller than the value of 1. The conclusion can therefore be drawn that TG1 is *definitively a 'lower road travel risk group'* than TG_5 -- this is known to be true at the 95% level of statistical confidence. Finally, the last example (result [5]) comparing entity groups TG_1 and TG_6 has *a relative risk estimator* value of 1.2 indicating that TG_1 *appears to be a higher road travel risk than group* TG_6. However, when the 95% C.L.s are considered it cannot be determined which group, if either, is *a lower risk group* compared to the other. In this instance more and better (more accurate) data and/or further research is necessary to make a definitive decision regarding any *road travel* *risk differential* that may exist between entity groups TG_1 and TG_6.

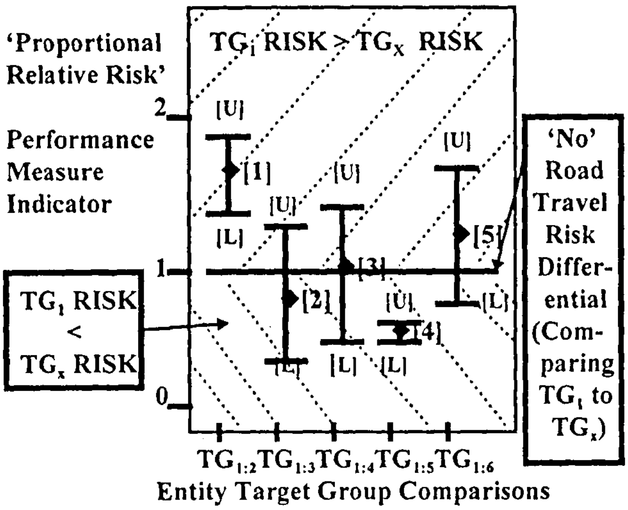

Figure 5. Interpretation of the '*Proportional Road Travel Relative Risk*' performance measure indicator.

An Example of the 'Relative Road Travel (Proportion) Risk' Estimator, RR^P --

Problem Formulation :
We would like to determine whether any significant road travel risk differential exists between two particular target groups of entities, TG_x and TG_y. The target conditions, TC_y , associated with the evaluation are for night-time travel only; on rural roads and highways; and the temporal period z, T_z, being covered is for the first six months of the calendar year in 1994. We have all of the necessary input data (proportion estimates of injury incidents -- injuries are being evaluated. proportion estimates of exposure (to risk), and measures of variability on all proportion estimates in terms of CVs -- coefficients of variation). The specific data inputs are given in the following section.

Data Input Requirements :
(1) $p(I|TG_x,TC_i,T_i) = 0.4$; (2) $p(I|TG_y,TC_i,T_i) = 0.5$;
(3) $p(E|TG_x,TC_i,T_i) = 0.2$;
(4) $p(E|TG_y,TC_i,T_i) = 0.3$; (5) $CV[p(E|TG_x,TC_i,T_i)] = 0.2$; (6) $CV[p(E|TG_y,TC_i,T_i)] = 0.1$;
(7) $n(I) = 200{,}000$ injuries.

The above information provides all of the 'data input requirements' for estimating the 'relative road travel (proportion) risk' performance measure estimator for measuring the road travel risk differential that exists between target entity groups TG_x and TG_y.

Estimation, Accuracy Assessment and Interpretation -- Applying the proportional data inputs to equation (12.) we get the estimate of the 'relative road travel (proportion) risk' performance measure indicator:

$$RR^P(TG_{x:y}, TC_i, T_i) = 1.2$$

Next, inputting the appropriate quantities into equation (16.) and computing it yields:

$$\sigma^2(\ln_e[RR^P(I|TG_{x:y},TC_i,T_i)]) = 0.0500125$$

Now, computation of equation (15.) gives:

$$\sigma(\ln_e[RR^P(I|TG_{x:y},TC_i,T_i)]) = 0.223635$$

And finally, computation of equations (13.) and (14.) yields the lower and upper 95% C.L.s for $RR^P(TG_{x:y}, TC_i, T_i)$ respectively, given by:

$$RR^P(I|TG_{x:y},TC_i,T_i)_{[L,95\%]} = 0.774140$$

$$RR^P(I|TG_{x:y},TC_i,T_i)_{[U,95\%]} = 1.860127$$

Summary of Results/Interpretations --

Conclusion :
The target entity group TG_x **appears to be a "higher road travel risk group" than group** TG_y . However, when the error limits for the risk differential estimator are taken into account, **it cannot be concluded that a significant differences in road travel risk differential** exists between the two groups of entities. **This statement is known to be true at a 95% level of statistical confidence.**

Recommendation :
It is **recommended that** more/better data be obtained and/or further research be conducted to determine whether a significant risk differential exists between the two entity groups. **No definitive decision for remedial treatment(s) (i.e. mitigative measures and/or countermeasure programs) for target entity group TG_x** to reduce their road travel risk of injury encounter for the target conditions and temporal periods evaluated **can be supported at the present time.**

NOTE: The 'Relative Road Travel (Frequency) Risk' Estimator, RR^F, is not presented in this paper. For its details see Stewart (1998b).

THE 'RELATIVE ROAD TRAVEL (PROPORTION) RISK ODDS-RATIO' PERFORMANCE MEASURE INDICATOR : AN ESTIMATOR BASED ON PROPORTION DATA INPUTS, $RROR^P$

The concept behind the RROR performance measure estimator involves the comparison of the relative road travel risks for a target entity group, say TG_x, during target travel conditions TC_i as compared to travel conditions TC_k to the relative road travel risks for a target entity group, say TG_y, during target travel conditions TC_i as compared to travel conditions TC_k. In essence, the final relative risk odds-ratio (RROR) performance measure estimators provide a measure of the differential in road travel risks being experienced by the target and comparison groups of entities for the selected target and comparison travel conditions being evaluated.

The mathematical and statistical formulation for the RROR estimators are given by:

$$RROR^P(I|TG_{1:2},TC_{1:2},T_i) = \frac{RR^P(I|TG_1,TC_{1:2},T_i)}{RR^P(I|TG_2,TC_{1:2},T_i)} \qquad (17.)$$

where,

$RROR^P(I|TG_{1:2},TC_{1:2},T_i)$ is the relative road travel risk odds-ratio proportion estimator measuring the differential in road travel risk of encountering incidents of type I, between entity groups TG_1 and TG_2 under travel conditions TC_1 compared to travel conditions TC_2, for a specified evaluation time period i, T_i;

$RR^P(I|TG_1,TC_{1:2},T_i)$ and $RR^P(I|TG_2,TC_{1:2},T_i)$ are the relative road travel proportion risk estimators of encountering incidents of type I for entity groups TG_1 and TG_2 respectively under travel conditions TC_1 compared to travel conditions TC_2 for a specified evaluation time period i, T_i.

Accuracy of the 'Road Travel (Proportion) Relative Risk Odds-Ratio' Estimator, $RROR^P$

The lower and upper 95% C.L.s for $RROR^P(I|TG_{1:2},TC_{1:2},T_i)$ are given in (18.) and (19.) .

$$RROR^P(X)_{[L,95\%]} = e^{\{\ln_e[RROR^P(X)] - 1.96 * \sigma(\ln_e[RROR^P(X)])\}} \qquad (18.)$$

$$RROR^P(X)_{[L,95\%]} = e^{\{\ln_e[RROR^P(X)] - 1.96 * \sigma(\ln_e[RROR^P(X)])\}} \qquad (19.)$$

where,

$$\sigma(\ln_e[RROR^P(X)]) = \sqrt{\sigma^2(\ln_e[RROR^P(X)])} \qquad (20.)$$

and,

$$\sigma^2(\ln_e[RROR^P(X)]) = \sum_{L=1}^{2}\left[\frac{1}{n(I,TG_L,T_i)}\right] x \left\{\sum_{J=1}^{2}\left[\frac{[1 - p(I|TG_L,TC_J,T_i)]}{p(I|TG_L,TC_J,T_i)}\right]\right\} + \sum_{L=1}^{2}\sum_{J=1}^{2}\left[CV[p(E|TG_L,TC_J,T_i)]\right]^2 \qquad (21.)$$

where,
$(X) = (I|TG_{1:2},TC_{1:2},T_i)$,
$n(I,TG_L,T_i)$ is the number of incidents of type I that entity group L, TG_L, is involved in during the evaluation time period i, T_i;
$p(I|TG_L,TC_J,T_i)$ and $CV[p(E|TG_L,TC_J,T_i)]$ are proportion data and coefficients of variation respectively for the various entity target groups and travel conditions being evaluated (as defined in previous sections).

Interpretation of the 'Relative Road Travel (Proportion) Risk Odds-Ratio' Estimator, $RROR^P$

As with the previous types of road travel risk estimators, logarithms (to the base e) are computed for all 'basic road travel risk' components of the $RROR^P$ estimator to ensure that logical lower bounds of zero exist resulting in a logical lower bound of zero for the $RROR^P$ estimator. Also, $RROR^P$ estimators possess the nice analytical property of being dimensionless -- i.e. unit-free, and therefore comparisons between and among them are always valid.

IF $RROR^P(I|TG_{1:2},TC_{1:2},T_i) < 1 \Rightarrow$ THEN the road travel risk level of incident encounter of type I is potentially lower for the target entity or group of entities TG_1 than it is for target entity or group of entities TG_2 for travel conditions TC_1 compared to travel conditions TC_2 during a specified evaluation time period i, T_i;

IF $RROR^P(I|TG_{1:2},TC_{1:2},T_i) > 1 \Rightarrow$ THEN the road travel risk level of incident encounter of type I is potentially higher for the target entity or group of entities TG_1 than it is for target entity or group of entities TG_2 for travel conditions TC_1 compared to travel conditions TC_2 during a specified evaluation time period i, T_i;

IF $RROR^P(I|TG_{1:2},TC_{1:2},T_i) = 1 \Rightarrow$ THEN the road travel risk level of incident encounter of type I is equivalent for the target entity or group of entities TG_1 and target entity or group of entities TG_2 for travel conditions TC_1 compared to travel conditions TC_2 during a specified evaluation time period i, T_i;

As in the case of the previous road travel risk estimators the relative road travel risk odds-ratio estimators must only be interpreted by taking into account their accuracy levels (i.e. 95% C.L.s) for deriving conclusions and making decisions for road travel safety improvements, as illustrated in the following example.

An Example of the 'Relative Road Travel (Proportion) Risk Odds-Ratio' Estimator, $RROR^P$ --

Problem Formulation :
We would like to determine whether any significant road travel risk (of injury) differential exists between two particular target groups of entities TG_x and TG_y with respect to their travel during conditions TC_i as compared to conditions TC_J. The travel conditions being compared for the two groups are nighttime vs. daytime travel. The temporal period z, T_z, for the evaluation period is the years 1992-1994 inclusive. The data inputs needed for carrying out the risk evaluation are given in the following section.

Data Input Requirements :
For target entity group TG_x : (1) $p(I|TG_x,TC_i,T_i)= 0.4$; (2) $p(I|TG_x,TC_J,T_i) = 0.2$;(3) $p(E|TG_x,TC_i,T_i) = 0.15$; (4) $p(E|TG_x,TC_J,T_i)=0.3$;(5) $CV[p(E|TG_x,TC_i,T_i)]=0.05$; (6) $CV[p(E|TG_x,TC_J,T_i)]=0.1$; (7) $n(I,TG_x,T_i) = 100,000$ injuries ; T_i = 1992-1994.

For target entity group TG_y : (1) $p(I|TG_y,TC_i,T_i) = 0.3$; (2) $p(I|TG_y,TC_J,T_i) = 0.5$;(3) $p(E|TG_y,TC_i,T_i) = 0.3$; (4) $p(E|TG_y,TC_J,T_i) =0.4$; (5) $CV[p(E|TG_y,TC_i,T_i)]= 0.15$; (6) $CV[p(E|TG_y,TC_J,T_i)]=0.05$; (7) $n(I,TG_y,T_i))= 50,000$ injuries ; T_i = 1992-1994.

Estimation, Accuracy Assessment and Interpretation :
Computation of equation (17.) yields the estimate for the relative road travel (proportion) risk odds-ratio performance measure indicator, given by:

$$RROR^P(I|TG_{x:y},TC_{i:J},T_i) = 5.0$$

Next, computing equations (21.) and (20.) (in that order) yields,

$$\sigma^2(\ln_e[RROR^P(I|TG_{x:y},TC_{i:J},T_i)]) = 0.037622,$$

and

$$\sigma(\ln_e[RROR^P(I|TG_{x:y},TC_{i:J},T_i)]) = 0.193964$$

And finally, computation of equations (18.) and (19.) yields the lower and upper 95% C.L.s for $RROR^P(I|TG_{x:y},TC_{i:J},T_i)$ respectively, given by:

$$RROR^P(I|TG_{x:y},TC_{i:J},T_i)_{[L,95\%]} = 3.418728$$

$$RROR^P(I|TG_{x:y},TC_{i:J},T_i)_{[U,95\%]} = 7.312663$$

Summary of Results/Interpretations :

Conclusion :
The road travel risks for target entity group TG_x are significantly higher than those of target entity group TG_y for travel under conditions TC_i compared to conditions TC_J. This finding is known to be true at the 95% level of statistical confidence.

Recommendation :
It is recommended that target entity group TG_x be considered for remedial treatment(s) (i.e. mitigative measures and/or countermeasure programs) for reducing their 'high road travel risk of injury encounter' during travel in conditions TC_i, in order to improve their level(s) of road travel safety.

NOTE: The 'Relative Road Travel (Frequency) Risk Odds-Ratio' Estimator, -- RR^{F}' is not presented in this paper. For its details see Stewart (1998).

CONCLUSIONS

In order to continuously work towards improving the levels of travel safety on our roads and highways it is first necessary to identify the circumstances under which 'unsafe levels' of road travel are occurring. To this end there is a requirement to continuously measure, monitor, assess, evaluate and compare the prevailing levels of road travel risks being experienced by various road users and their associated vehicle-road/infrastructure-environment-al-trip-temporal travel characteristics. As discussed this is only possible when compatible and consistent 'exposure to risk (amounts of travel)' and 'incident (accident, injury, fatality)' databases are both available for the various road users and their travel/use characteristics.

This paper presented methodologies for formulating the three main types of road travel risk performance measure estimators that lend themselves to measuring, interpreting and comparing the levels of risk on the roads for entities and their travel condition char-acteristics. The best methods require 'proportion' data on 'exposure to risk' and road collision incidents,-- the use of frequency counts (or rates) is not recommended due to the serious limitations in interpretation powers of the resultant estimators for assessing and evaluating the risk levels. This is also supported by Hauer (1983, 1995) discussing the potential flaws and limitations in using incident rates when non-linear relationships exist between incident and exposure frequencies, in which cases a he maintains 'safety performance functions' should be used. The key to proper interpretation of road travel risk estimators requires that accuracy estimates (e.g. confidence limits) be formulated and computed for them and taken into account to derive correct conclusions regarding the risk levels and subsequently to make sound decisions on any policy and/or programs (countermeasures/mitigative measures) to pursue for improving levels of road travel safety.

With these concepts and methodology in place, it is possible to incorporate them into a 'Risk Analysis and Evaluation System Model' (RAESM) [Stewart, 1998b]. A system such as this would provide the ability to measure, compare, monitor and evaluate the levels of risk (levels of safety) on the roads and highways on a continuous basis thereby providing the means for identifying and prioritizing 'high road travel risk' problems and issues for remedial treatment(s) in order to reduce road travel risk levels. Presently, the Evaluation and Data Systems Division, Road Safety Programs, Transport Canada is working on a project (entitled "The Design and Development of a 'Risk Analysis System' for Measuring and Monitoring Road Travel Risks") which has the expressed objectives of designing and developing an RAESM for future implementation.

In summary, **there are numerous benefits to be realized from the development of a comprehensive and continuous** ***national exposure (to risk) data collection system and database***, including:

- An ability to *analyze and interpret incident (collision, injury and fatality) data bases to the fullest extent possible, particularly the measurement of changes in incidents as the result of changes in: social and economic factors, existing and planned program measures and countermeasures, and exposure (to risk) levels*
- A significantly enhanced capacity to *develop models on accident causation and injury severity for determining the effects of contributing factors and countermeasure programs on accident and casualty risk levels, which is necessary in order to enhance our knowledge and understanding of the accident causation process*
- An ability to *implement a 'national risk analysis and evaluation system'*
- An ability to *effectively measure, monitor, compare and evaluate the levels (degrees) of risk / levels of safety* **for road travel factors and characteristics (i.e., human, vehicle, road/infrastructure, environment, trip and temporal)** *that cause the incidents of collisions, injuries and fatalities (i.e., the consequences of road travel risk levels) on Canada's roads and highways*
- An ability to *identify the 'high risk' road travel problems and issues* requiring remedial treatment(s) and/or action(s) in order *to reduce these risk levels and improve road safety*
- An ability to *conduct proper socio-economic impact analyses (SEIAs) and regulatory impact analyses (RIAs) for measuring and substantiating the benefits and costs of potential mitigative measures/countermeasures selected for reducing the risks on the roads and highways*
- An ability to *conduct proper cost-benefit analyses studies in support of SEIAs and RIAs*
- A significantly increased ability to *carry out effective assessments/evaluations of both present and potential impacts of various countermeasure programs and mitigative measures implemented for reducing road travel risks, or of projected changes in transport patterns*
- A significantly enhanced capacity to *provide expert and knowledgeable advice/guidance to senior management on the priority problems and issues that are adversely affecting the safety of travel on Canada's roads and highways*
- A significantly increased ability to *provide advice and guidance to senior management on the level of effort required for reducing road travel risk problems and issues, which could result in the inefficient use of the limited resources available for road safety work*
- An ability to *monitor the levels of transportation activity (and changes thereof) thereby reducing our effectiveness to address various transportation and safety issues whether it involves planning, design,*

operations, control, education, enforcement, management, or research

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OBSERVATIONAL STUDIES OF CAR OCCUPANTS' POSITIONS

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ABSTRACT

The use of current seat belts has been shown to be effective in reducing deaths and serious injuries to restrained car occupants by 50% compared to unrestrained. Real world accident studies have identified limitations to the performance of set belts. This has led to the next major evolution in restraint design which is the development of the intelligent restraints. The options for intelligent retraints include making the system variable, to take account of occupant age and sex, occupant weight, occupant sitting position (relative to forward structures) and the severity of the collision which is occurring thus changing the characteristics of the seat belt. Data are presented on how a population of drivers and passengers actually sit in cars, and accident analyses will illustrate how injury outcome varies with age and sex for restrained occupants. The implications of the position of the hands on the steering wheel during normal driving and the rotational orientation of the steering wheel during an impact for airbag design are also included.

INTRODUCTION

Current seat belts have been shown to be very effective in diminishing the frequency and severity of injuries to car occupants. So much so that high levels of seat belt use are a prime aim of all national transport safety policies in motorized countries. The limitations of the protective abilities of current seat belts have been well documented in many analyses of both field accident data and experimental studies (1).

Real world accident studies have identified five categories of limitations to the performance of current seat belts. These are:

1) Head and face contacts with the steering wheel by restrained drivers (2) - It is inherent in the kinematics of a restrained occupant that, in a severe collision at a velocity change of around 50 km/hr, the head will arc forwards and downwards, having a horizontal translation of some 60 to 70 cms Figure 1. If a normal steering wheel position is superimposed on such a trajectory, the head and face necessarily will strike the steering wheel. Such contacts usually produce AIS 1 to 3 injuries and are best addressed with the supplementary airbag systems becoming common throughout the new vehicle fleet.

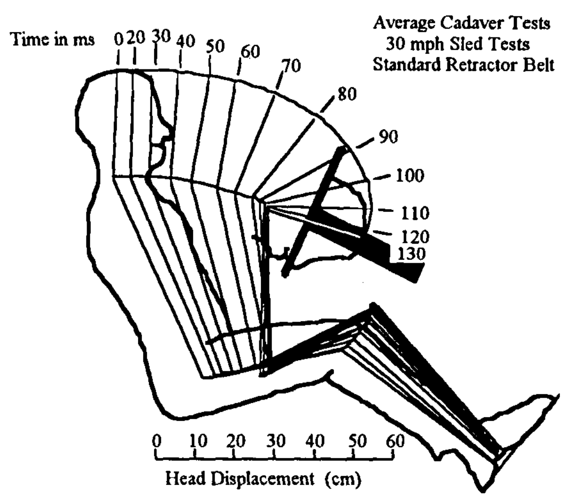


Figure 1 Seat Belt Excursion

2) Intrusion of Forward Structures - A seat belt requires a zone ahead of the occupant so that the occupant can be decelerated by the compliance of the restraint system. If intrusion compromises that space, then specific localized contacts can occur. The injury risk from such contacts may well be small if they are occurring with structures which have been engineered appropriately. Indeed, in the ultimate condition, it is better for the occupant to be decelerated not just by the seat belt alone but through a combination of belt loads and contact loads. Those contact loads are through the feet at the firewall, through the knees into the lower dash and through the airbag and belt at chest level. In severe collisions, however, major intrusions are destroying the passenger compartment so that exterior objects are

actually striking the occupants. This is a feature of restrained fatalities in frontal impacts (3).
3) Rear Loading - Correctly restrained front seat occupants can receive injuries from unrestrained occupants, luggage or animals from the rear seats. Such events contribute to some 5% of restrained front seat fatalities (4).
4) Misuse of the Seat Belt - Seat belts must be positioned correctly on the human frame to work effectively. Dejeammes (5) in a survey of belt use in France found that some 1.6% of front seat occupants had the shoulder belt under the arm or behind the back whilst some 3.3% had introduced slack because of the use of some clip or peg to relieve the retraction spring tension. A more important type of misuse relates to the positioning of the lap section. Many occupants, especially the overweight, place the lap section across the stomach instead of low across the pelvis. Indeed for the obese, it is often impossible to position the lap section so that it will engage on the iliac spines of the pelvis in a collision. These problems are reflected in abdominal injuries from the lap section of the seat belt (6).
5) Injuries from the Seat Belt Itself - As with any injury mitigating device there are limits to effectiveness. Those limits are when biomechanical tolerances are exceeded and thus the most vulnerable segment of the population begin to receive injuries. The usual thresholds are sternal and rib fractures occurring, especially in the elderly (7).

Current restraint design aims to achieve a compromise in the sense of optimizing protection for the largest number of people exposed in the largest number of injury-producing crashes. The end point, however, is a fixed design with single characteristics optimized around a single crash condition. That crash condition for most manufacturers is usually the 35 mph (56 km/hr) rigid barrier crash test.

The next evolutionary stage in restraint design is to move away from a restraint system with fixed characteristics which need to be considered if the concept of variability is introduced into restraint design.

POPULATION CONSIDERATIONS

The ideal restraint system would be tailored to the following variables:

- the specific weight of the occupant,
- the specific sitting position of the occupant,
- the biomechanical tolerances of the occupant,
- the severity of the specific crash which is occurring,
- the chances of specific passenger compartment intrusion occurring which might compromise restraint performance,
- the specifics of the compartment geometry and crush properties of the car.

ANTHROPOMETRIC CONSIDERATIONS

Current dummies and modeling cover the 5th percentile female to 95th percentile male range. Assuming for simplicity that males and females are exposed equally and that there are few males smaller than the 5th percentile female or females larger than the 95th percentile male, these conventional limits put 2.5% (1 in 40) of the small population and 2.5% of the larger population beyond those limits; 5% or 1 in 20 overall.

Table 1 gives the 1% and 99% ranges for height, sitting height and weight. These data show what would be required if the design parameters were extended to cover this wider range, so that only 1 in 50 of car occupants would be outside the design parameters (8).

Table 1
Population Ranges for Height, Sitting Height and Weight

Adult	Height		Sitting Height		Weight	
	ins	cm	ins	cm	lb	kg
1%ile female	57	145	28	72	82	37
5%ile female	59	150	29	75	90	41
95%ile male	73	185	37	93	225	102
99%ile male	75	190	38	96	236	107

More importantly, it is implicitly assumed in current designs that height (or sitting height) and hence sitting position are colinear with the weight of the occupant. In fact, there are data available to suggest that the relationship between height and weight are rather complex. For example, the body mass index (BMI) (i.e., the ratio of weight in kilograms to height in meters squared) varies to a greater degree in women than in men, and particularly at the 75th percentile and above, women have higher BMIs than men. In addition, the prevalence of overweight increases with age, more with females than males (9).

Therefore to optimize a restraint system it would appear appropriate that sitting position and body weight should be assessed independently if variability is to be introduced into restraint design.

POPULATION CHARACTERISTICS BY POSITION IN THE CAR

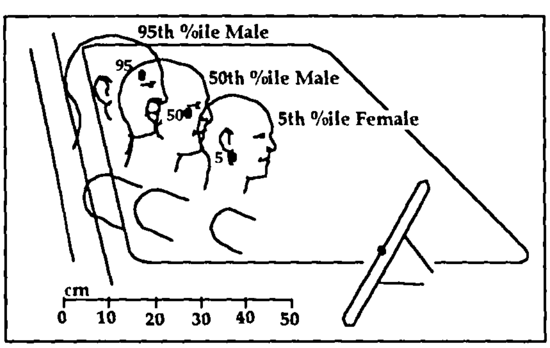
European data show that some 80% of drivers in injury-producing collisions are male, whilst some 65% of front seat passengers are female (10). Approximately one-third of rear passengers are children of 10 years of age or under (11). These simple frequencies suggest that restraint characteristics should not necessarily be the same for all sitting positions in the car.

Sitting Positions

Current design is predicated on the positions established for the three conventional dummies. Observational studies by Parkin et al (12) have demonstrated that there are substantial differences between those three positions and an actual population of drivers. Passive observations of drivers in the traffic stream have been made using video recording techniques, and drivers classified by sex and general age groups of young (35 years), middle (36-55 years) and elderly (56 years and older). Make and model of car were recorded and measurements made of the following distances:

- nasion to steering wheel upper rim and hub,
- top of head to side roof rail,
- back of head to head restraint, horizontally and vertically,
- shoulder in relation to 'B' pillar.

Such techniques allow thousands of observations to be made quickly and therefore population contours can be drawn. Figure 2 illustrates how particularly for the 5th percentile female population the actual sitting position is significantly closer than that of the 5th percentile dummy, by some 9.2cm. The 5th percentile, small female population sits some 38cm (15 inches) or closer to the hub of the steering wheel.



5th 50th and 95th %ile naison positions are illustrated for "real drivers" (head outlines) and dummies (black spots).

Figure 2 Drivers' Sitting Positions

BIOMECHANICAL VARIATION

An extensive literature exists concerning human response to impact forces, mostly conducted in an experimental context. A general conclusion from that body of knowledge is that for almost any parameter, there is a variation of at least a factor of 3 for the healthy population exposed to impact trauma in traffic collisions (13). That variation applies to variables which are relatively well researched such as the mechanical properties of bone strength, cartilage, ligamentous tissues and skin. It is likely to be even greater when applied to gross anatomical regions such as the thigh in compression, the thoracic cage, the neck or the brain.

How such variability is demonstrated in populations of collisions is less well understood. Data from a ten year period of the European Co-operative Crash Injury Study (CCIS) for restrained front seat occupants are given in Figures 3 and 4. The methodology of that work has been described elsewhere (14).

Figure 3 illustrates the effect of age on injury outcome in terms of the frequency of AIS 2 and greater injuries for three age groups. Data are presented for frontal impacts involving a principal direction of force (PDF) of 11 to 1 o'clock, controlling for crash severity by equivalent test speed (ETS). Injury severities were rated by Maximum Abbreviated Injury Scale (MAIS) (15).

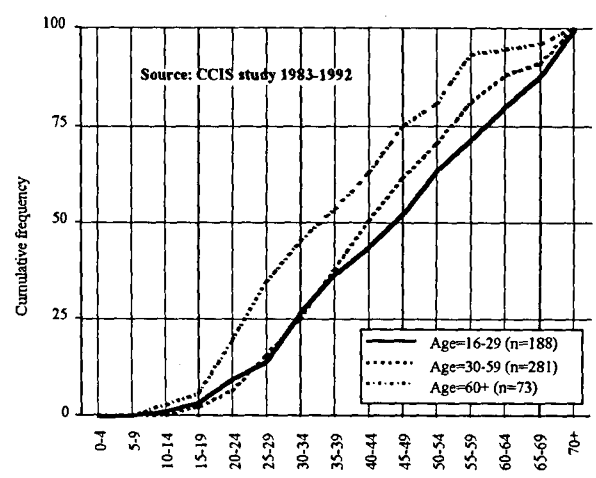


Figure 3 Crash speed distributions for frontal impacts (PDF of 11 to 1 o'clock) to drivers (by age groups) who experienced injuries with a MAIS > = 2

The 60+ age group especially shows greater vulnerability than the younger groups. As a broad generalization one may conclude that for the same injury severity, the younger age groups must have a velocity change of some 10 km/hr more than the elderly. The effect is more marked if a more severe injury level is chosen. Figure 4 illustrates the cumulative frequencies for the three age groups for injuries of AIS 4 and greater.

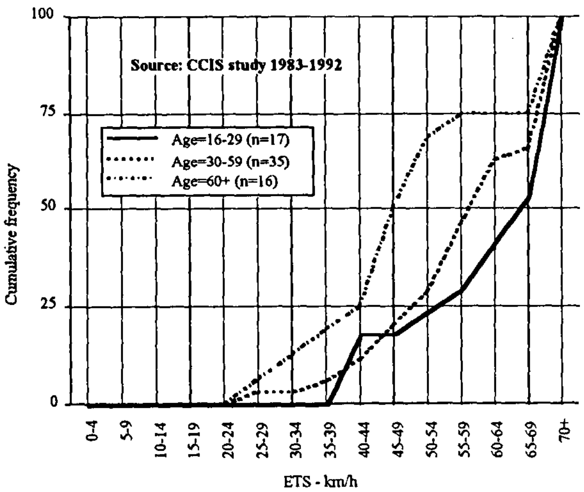


Figure 4 Crash speed distributions for frontal impacts (PDF of 11 to 1 o'clock) to front seat occupants (by age groups) who experienced injuries with a MAIS > = 4

Figure 5 shows similar frequency curves for crash severity by sex of occupant. Thus at a velocity change of 48 km/hr (30 mph), some 2/3 of male and some 80% of female AIS 2+ injuries have occurred. As a starting point, therefore, as well as specific body weight and sitting position, a combination of age, sex and biomechanical variation could be developed as a predictor of the tolerance of a specific person within the population range.

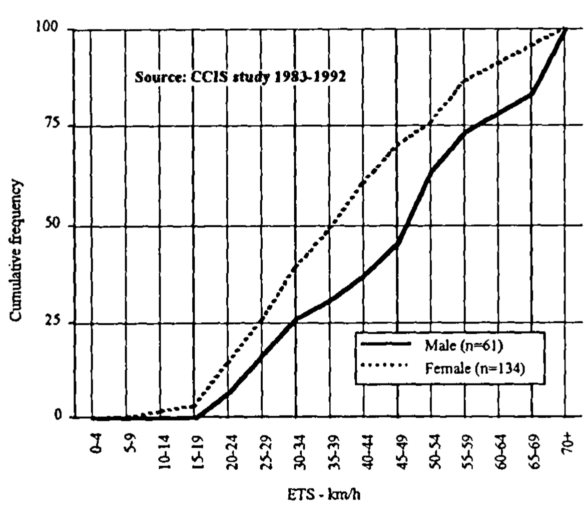


Figure 5 Crash speed distributions for frontal impacts to front seat passengers (by sex) who experienced injuries with a MAIS > = 2

An intelligent restraint system therefore would perhaps require a smart card, specifying the height, weight, age and sex of the occupant. On entering the card for the first time, the card would be read and the characteristics of the seat belt and airbag adjusted accordingly.

SENSING CRASH SEVERITY

Besides assessing the specifics of the occupant's characteristics before impact, protection could be enhanced if the nature and severity of the collision could be assessed early enough during the crash pulse so that the characteristics of the restraint system could be modified. That would require, for example, sensors to discriminate between distributed versus concentrated impacts, and between, for example, three levels of collision severity such as less than 30 km/hr, 30 to 50 km/hr, and greater than 50 km/hr. In addition, conceptually one might have an array of sensors which would detect the early development of compartment intrusion. Such electronic data could then instruct the restraint system to change its characteristics early enough during the crash phase to alter the characteristics of the restraint and thus the loads on and forward excursion of the occupant.

VARIABLE RESTRAINT CHARACTERISTICS

The advantages of a variable restraint system are illustrated by considering some examples. A front seat passenger, 70 years of age and female, weighing 45 kg sitting well back, in a 30 km/hr frontal collision with no intrusion, would be best protected by a relatively soft restraint system which would maximize the ride-down distance and minimize the seat belt loads. That would require a low pretensioning force, a long elongation belt characteristic provided by load limiters and a soft airbag.

Such a system is very different from what would be required by a 25 year old, 100 kg male, sitting close to the steering wheel in a 70 km/hr offset frontal collision. He would need a very stiff seat belt, an early deploying stiff airbag and a large amount of pretensioning load.

Consider thirdly a 9 year old girl, weighing 30 kg sitting in a rear seat in a 56 km/hr frontal impact. Maximizing her ride-down distance and minimizing the seat belt loads would require low pretensioning loads and a very soft belt system, but one which would still have a biomechanically satisfactory geometry at the forward limit of excursion. Possible techniques for introducing variability into restraint design are now discussed.

Variable Pretensioning Force

A retractor pretensioner might be devised which would have a variable stroking distance or perhaps two stages of pretensioning to address the population and crash severity requirements outlined above.

Combined Retractor Pretensioner & Buckle Pretensioner

Such a system of pretensioners might maintain good seat belt geometry especially for the small end of the population, such as the 9 year old girl in the rear seat, when soft restraint characteristics and hence large amounts of forward excursion are required.

Discretionary Web Locks

If the seat belt system needs to be stiffened for the heavy occupant with high biomechanical tolerance in a high speed crash, then the switching in of a web lock would be appropriate. Such a device would shorten the active amounts of webbing being loaded and diminish forward excursion at the expense of somewhat higher seat belt loads.

Discretionary Load Limiting Devices

One way of providing for biomechanical variability would be to have a load limiting mechanism which would be calibrated for the specifics of the occupant's age, sex and weight. Such a device could also be adjusted according to transient sitting position. Belt loads would be limited at the expense of increased forward excursion.

Variable Sitting Positions

Ultrasonic, infrared or other techniques of sensing might be used to monitor continuously the head position of each occupant. Such information could be used at a minimum to provide a warning that an occupant was sitting too far forward and in particular too close to the steering wheel. At a more advanced level it could be used to tune the seat belt and airbag characteristics to be optimized for that occupant in that specific position by adjusting the other restraint variables.

Variable Airbag Firing Threshold

The need for an airbag varies according to seated positions in the car and the characteristics and sitting position of the occupant. For most drivers in most sitting positions a supplementary steering wheel airbag becomes desirable in crash severities above 30 km/hr (2). For a front seat passenger however, particularly one who is towards the top end of the biomechanical tolerance spectrum and sitting well back, an airbag at 30 km/hr is unnecessary. For a child sitting a long way forward in such a crash, it might also be disadvantageous. Hence specific sensing techniques at a minimum could discriminate between the presence or absence of a passenger, and at the next level assess the need for the airbag to inflate or not.

Variable Airbag Characteristics

In response to the sensing data about the occupant's characteristics and transient sitting position, and the accelerometer data about the nature and severity of the collision which is occurring, the airbag properties could be varied. Specifically, gas volume and inflation rate could be changed. Compressed gas systems instead of chemical gas generators have the potential for providing those characteristics by having time-based adjustable inflation ports. This requires very advanced sensing and control systems but these aims could well be addressed through future research and development.

HAND POSITIONS AND STEERING WHEEL ORIENTATION

In addition to the seating position of the driver before impact, the position of the hands on the wheel and the orientation of the steering wheel at impact need to be considered. These factors may influence airbag characteristics.

Hand Positions on Steering Wheels

An observational study was carried out which looked at the position of the drivers hands on the steering wheel during normal driving condition on major roads with speed limits of 40 to 60mph (64 - 96km/h)in the UK and US, excluding motoways and freeways. Driving with only one hand on the steering wheel seems to be more common. Fifty eight percent of UK drivers used one hand only, while the proportion was much higher in the US at 70%.. Drivers were more inclined to hold the wheel in the upper semicircle, above the 3 and 9 o'clock positions. When two hand were used both tended to be at same height. The distribution of the positions of the hands on the steering wheel are shown in Figure 6 and Figure 7 where one and two handed positions have been counted together.

A quarter (26%) of the drivers were considered to be at risk of injuries because hands or arms were observed in very close proximity to the airbag module. The risk for US drivers was lower at 16%. Drivers were considered to be at risk of receiving injuries an airbag deployed while hands were (a) at the 1, 11 or 12 o'clock positions, or (b) at the 3 or 9 o'clock positions while resting inside the wheel rim on or near the airbag module. The risk of injury may be increased at junctions where 91% of the drivers in the UK and 98% of the drivers in the US were observed to cross arms while turning the wheel.

Therefore a significant group of the population may be at risk of injuries to the upper extremities if airbags deploy while the steering wheel is held near the top or while turning at a junction. The inclusion of sensors to assess arm position and tight steering manoeuvres at low speeds should be considered with smart restraints.

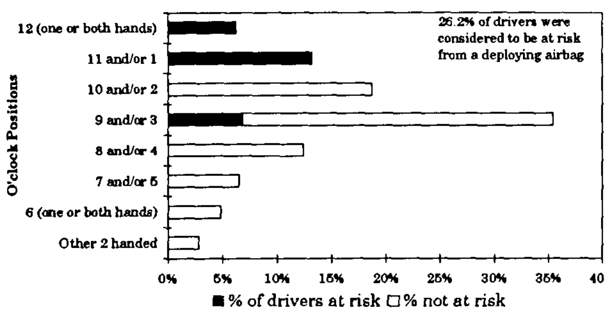


Figure 6 Hand positions on steering wheels observed for 850 U.K. drivers

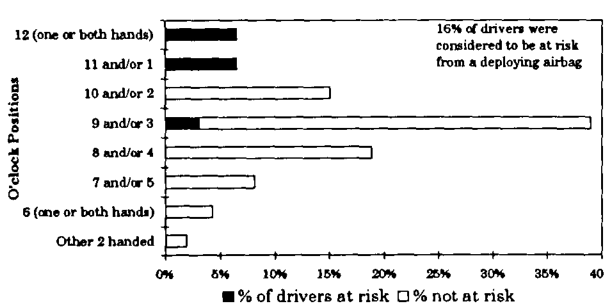


Figure 7 Hand positions on steering wheels observed for 850 US drivers

Steering Wheel Orientation

Accident records of cars, in the CCIS database, with steering wheels jammed by crushing at the time of impact were examined to determine the rotational orientation of the steering wheel. Only cars involved in single frontal impacts with a principle direction of force between 11 to 1 o'clock and with at least one front road wheel displaced rearwards (strutted) and firmly jammed by crush were included. Steering wheel orientation was assumed not to have changed post impact by considering factors such as degree of strutting, steering wheel damage, steering column damage and orientation of blood stains.

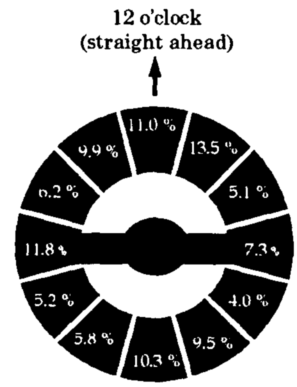


Figure 8 Observed steering wheel orientations grouped into 30° sectors (n = 272)

Wheels were more often orientated in the 11, 12 and 01 o'clock quadrant (Figure 8). However, over 65% of steering wheels were observed at other positions suggesting that steering wheels are in all possible rotational orientations at impact, and it can not be assumed that drivers crash their vehicles with the wheels in the straight ahead position.

There are implications for factors in airbag design including shape of the deploying bag, location of vent holes and port design. The airbag modules and their doors and inflating bags may activated when wheels are at any orientation. Their interaction with occupants may not be as predictable as the current design procedures imply. Symmetry should be incorporated so that components deploy in the appropriate manner and inflate over the wheel orientation.

OTHER CRASH CONFIGURATIONS

The discussion so far has focused on frontal collisions which constitute some 50% to 65% of injury producing collisions in most traffic environments. Lateral, rear and rollover crashes also suggest opportunities for optimizing protection through intelligent restraint systems.

Lateral Collisions

The technology is now developing for side impact airbags with two versions becoming available on 1995 model-year passenger cars. The observational data of Parkin et al (12) have illustrated the range of driver sitting positions which reflect the requirements of side impact airbag geometry to cover both the door and the B pillar. Because a significant part of the population, tall males, choose to sit as far rearward as possible, in a side impact in many four door vehicles the thorax would be loaded by the B pillar rather than the door.

A practical issue is the nature and position of the sensor for a side impact. Because of the extremely short time available for sensing, around 5 milliseconds, a simple switch system is appropriate (16). An analysis of a representative sample of AIS 3 plus lateral collisions has demonstrated that if a switch sensor is located in the lower rear quadrant of the front door then approximately 90% of all such side impacts would be sensed appropriately. A set of several sensors would be required to address the remaining few collisions, whilst rear seat occupant protection would also be addressed in large part by a sensor in the same position in the front door as is appropriate for front seat occupants (17).

Rear Impacts

Occupant protection in rear end collisions is addressed largely through the appropriate load deflection characteristics of seat backs and the provision of correctly positioned head restraints. The real world data of Parkin et al (12) demonstrates that head restraints are frequently positioned both too low and too far to the rear of the occupant's actual head position. The head position sensors discussed above could also be used for adjusting automatically both the vertical and horizontal position of the head restraint. Such a technology is relatively simple but the costs and reliability, as well as acceptability by the driving population, present serious practical problems.

Rollover Accidents

Actual mechanisms of injury in rollover accidents have been well researched by Bahling et al (18) for occupants in current seat belts. Conceptually one can suggest that a buckle pretensioner might have some benefits in rollover circumstances by diminishing the relative vertical motion of an occupant. However, in rollovers current dummies do not have the appropriate soft tissue or thoracic and lumbar spine response characteristics, in comparison to the human frame. The basic clearance of current bodyshell design and packaging limit intrinsically the ability of any restraint system to modify the nature of any roof contacts under the forces of actual rollover circumstances even with no roof deformation taking place. Raising current roof lines leads to many undesirable consequences. Nevertheless it would be of interest to explore occupant kinematics in rollovers using more realistic techniques with volunteer and cadaver subjects in the context of buckle pretensioners and the requirements of a sensor to detect incipient rollover.

CONCLUSIONS

This paper only attempts to outline in conceptual form some of the issues which need to be addressed in advancing from today's seat belts and airbags towards some form of intelligent restraint system. Of fundamental importance is to recognize the population issues of size, sitting position, biomechanical variation and changing crash exposures. Beyond these issues lies a larger amount of challenging research and development to actually produce the sensors and hardware to provide variability in a seat belt and airbag system. Proximity sensing has its advocates, and if radar techniques could actually discriminate an impending collision from a near miss or a passing object, then the provision of say 500 milliseconds warning would alter many of the restraint issues reviewed in this paper. However, the basic premise remains; the next generation of restraints must change from having single fixed characteristics towards variable ones which recognize the real world population variables of weight, sitting position, biomechanical tolerance and crash exposure.

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LOGISTIC REGRESSION ANALYSIS OF LOWER LIMB INJURIES IN FRONTAL CRASHES

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ABSTRACT

The objective of our study is to evaluate lower limb injuries in frontal crashes, identify the parameters that have significant influence on such injuries, and quantify their effect using logistic regression technique.

This paper contains a review of lower limb injuries literature. Later the data subset used for our study is described. It is followed by an exploratory analysis consisting of: The evaluation of lower limb injuries and the analysis of effects of different parameters on such injuries. The logistic regression analysis is presented in the end to quantify the effects of some significant factors on lower limb and leg-foot complex injury risk.

Two response measures, injury risk and average injuries per occupant, were analyzed during the exploratory analysis phase. Both measures showed similar effects of all factors.

Based on our logistic regression model, we have also predicted the probability of lower limb and leg-foot complex injury under certain conditions of intrusion, crash severity, seating position and gender.

INTRODUCTION

With increased seat belt usage and the introduction of supplemental inflatable restraint systems, the risk of injuries to the head, neck, and chest have decreased substantially in frontal crashes. As a result, more people are surviving accidents and the relative importance of upper and lower extremity injuries in vehicular crashes has increased [1, 2].

New crash test methods that focus on maximizing lower extremity interaction with vehicle structures have been developed. Early tests focused on 40%-50% offset frontal tests against a rigid barrier [7]. The barrier design was further improved by installing a deformable barrier face on the rigid barrier. A deformable barrier test that engages 40% of the frontal width of a vehicle has been adopted by European Community (ECE) for testing vehicles by 1998 and beyond. This test at higher than regulated speed has been adopted by several public information programs (European New Car Assessment Program (Euro NCAP), Insurance Institute of Highway Safety (IIHS), Australia NCAP).

In addition to studying vehicle crash tests (Regulatory and Public Information), a substantial amount of research is being conducted in the biomechanics of lower limb injuries and in the development of advanced test devices that would lead to changes in the lower extremity design of current dummies.

Although the biomechanical testing is essential to determine the responses, mechanisms, and impact tolerances, it is believed that empirical study of field accident data is necessary to gain understanding of complex mechanisms that exist in the real world crashes. This paper reports on such an empirical study of the NASS database.

LITERATURE REVIEW

Huelke, et al. and Pilkey, et al., have presented an excellent review of literature and summarized the effects of crash severity, offset, intrusion, occupant position, pedal interference, belt usage, and left-right foot on injury [1, 8].

Our review of the literature is summarized as follows:

- The risk of lower limb injuries increases with an increase in crash severity [4, 8, 9, 10, 11].
- A significant number of lower limb injuries are produced in crashes that do not involve intrusion [9].
- The risk of lower limb injuries is higher with intrusion than without it [9, 11, 12]. Such injuries increase with an increase in the level of intrusion [10, 11]. Results from both car-to-car and car-to-barrier crash tests, with

instrumented Hybrid III dummies, show that some of the loads acting on lower extremities have strong correlation with occupant compartment deformations, even when crash severity is controlled, though other factors also influence occupant loads [13].

- Drivers receive more injuries than front seat passengers [11]. Drivers had twice as many foot fractures as front seat passengers [4].
- There are mixed data, reported in the literature, about the effect of position of the foot. Some studies report that the drivers left foot has more injuries than the right foot, specifically at higher level of intrusion [2, 14]. While other studies report that there is no significant difference between left and right foot injuries [4] or left and right leg injuries [2].
- Belt usage does not influence the injury frequency of the foot [4] or the lower extremity, however, there are higher number of pelvic injuries in unbelted cases [15].
- Thomas, et al., report that footwell intrusion increases the risk of leg injury to a greater extent than crash severity and that intrusion is not a surrogate variable for delta-V [9].

DATABASE

The National Automotive Sampling System (NASS)-formerly, the National Accident Sampling System-is the mechanism through which the National Highway Traffic Safety Administration (NHTSA) collects nationally representative data on motor vehicle and highway safety countermeasures [26]. The NASS was originally designed and implemented in 1979 to support highway and motor vehicle safety programs. The NASS program was reevaluated in the mid-1980s.

To enhance its applicability in addressing crashworthiness issues, the NASS was divided into two parts: (1) the General Estimates System (GES), which collects data on an annual sample of approximately 50,000 police-reported traffic crashes; and (2) the Crashworthiness Data System (CDS), which collects additional detailed information on an annual sample of approximately 5,000 police-reported traffic crashes involving passenger vehicles towed from the crash scene due to damage resulting from the crash.

Data Subset Used for the Analysis:

- NASS CDS Data for calendar years 1988-94
- Frontal impacts of 11-1 O'clock position
- Crash severity (Delta-V total) of 15-25 mph
- Front seat occupants of 1986-95 model year passenger cars

This is a case study. Data were not weighted for generalization over the population due to concerns related to the use of Primary Sampling Unit (PSU) weighting factors.

EXPLORATORY ANALYSIS

A preliminary analysis of all data was conducted to evaluate the type and severity of lower limb injuries and to explore the significance of different factors.

Responses Analyzed

Lower limb injuries, excluding the pelvic injuries, were categorized as:

- Foot-ankle
- Tibia-fibula (leg)
- Knee
- Thigh
- Unknown/ others

The Abbreviated injury scale (AIS) of two or greater (AIS2+) are considered as moderate to serious injuries [26]. Injuries mentioned in this paper refer to lower limb AIS2+ injuries.

We selected the following two response measures for evaluation:

- Injury Risk (Percent of occupants who received maximum AIS2+ (MAIS2+))
- Average Injuries (Number of injuries / number of occupants)

Injury Risk is the probability of injury to an occupant involved in such crash. Average Injuries accounts for multiple injuries. It is the probability of count of injuries to an occupant. Our analysis showed that both response measures yield similar trends.

Factors Considered

The following exploratory factors were analyzed:

- Intrusion
- Location of intrusion
- Crash severity (Delta-V total)
- Seating position
- Gender
- Impacting object
- Belt usage
- Occupant's age

At this stage of the analysis, one factor was analyzed at a time ignoring the effects of all other factors. All factors were analyzed for the two conditions: With intrusion, and without intrusion. Subsequently, four factors (Intrusion, crash severity, gender, and seating position) were selected for logistic regression analysis to quantify the contribution of each factor and their interactions.

Results of the Analysis

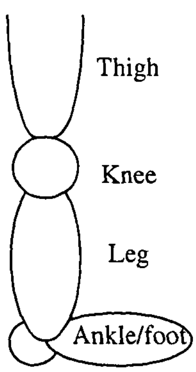
The data indicated that 11% of all front seat occupant involved in a 15-25 mph accident incurred MAIS2+ lower limb injuries. The occupants and the injuries considered in the study are summarized in Appendix (A).

Intrusion - Intrusion was defined as one inch or more of intrusion on the same side as the occupant.

Figure (1) shows the distribution of injuries by body region with intrusion and without intrusion. Table (1) compares injuries with and without intrusion.

Not controlling for any other factors, Injury Risk was found to be about three times higher with intrusion than without intrusion. Average Injuries were about four times with intrusion, compared to that without intrusion. Also, the severe injuries (AIS3) were slightly higher with intrusion (Table 1).

The frequency of the occupants involved in accidents with intrusion was relatively low, resulting in 30% less injured occupants with intrusion. Because of more multiple injuries with intrusion, however, total number of injuries were 8% more with intrusion.



Body Region	Intrusion Injuries N(%)	No-Intrusion Injuries N(%)
Thigh	39 (16)	23 (10)
Knee	47 (19)	59 (26)
Leg	62 (25)	74 (33)
Ankle/foot	74 (30)	66 (29)
Unknown	23 (9)	4 (2)
All	245 (100)	226 (100)

Fig. (1): Distribution of AIS2+ Injuries by body regions

TABLE 1. Comparisons of Injuries with and without Intrusion

	Intrusion	**No-Intrusion**
Frequency (N)	456	2056
Injury Risk (% of occupants considered)	27	8
Total Occupants Injured	122	158
Average Injuries/ Occupant	0.49	0.11
Total Injuries	245	226
AIS 3 Injuries (% of injured occupant)	35	29

Location of Intrusion - The occupants and injuries considered in this study are categorized by location of intrusion as follows (Appendix B):

- Floor and/or toe-pan (FLOOR) intrusion
- Instrument panel (IP) intrusion
- FLOOR and IP (COMPLEX) intrusion

FLOOR intrusion is more frequent than IP intrusion or COMPLEX intrusion, however, Injury Risk for FLOOR intrusion is far less (Table 2). The increased risk for IP intrusion is due to frequent leg and knee injuries compared to only frequent leg injuries with FLOOR intrusion. Also, the increased injury risk of COMPLEX intrusion may be due to knee entrapment. Occupants with IP intrusion had fewer multiple injuries than occupants with other categories of intrusion. There was no significant difference in the severity of injuries for any type of intrusion (Table 3 & 4).

Leg and foot/ankle injuries were more frequent with FLOOR intrusion while knee injuries were more frequent with IP intrusion.There was no significant difference in the frequency of thigh injuries in all three cases (Table 5).

Not controlling for other factors, it was found that:
Crash Severity - Injury Risk increased with the crash severity for both cases of intrusion and non-intrusion (Figure 2) when compared correspondingly.

Seating Position - Injury Risk for driver was 72% higher with intrusion and 30% higher without intrusion than that for front seat passenger.

Gender - Injury Risk for female occupant was 55% higher with intrusion and 110% higher without intrusion than that for male occupant.

Other Factors - Injury Risk was least in impacts with wide stationary objects than in impacts with vehicle-in-transport or with narrow objects for both cases of intrusion and no-intrusion (Figure 3).

TABLE 5. AIS2+ Injuries by Body Regions for Different Categories of Intrusion

Body Regions	FLOOR N (%)	IP N (%)	COM-PLEX N (%)
Thigh	16 (14)	3 (18)	20 (17)
Knee	17 (16)	8 (47)	22 (18)
Leg	32 (30)	3 (18)	27 (23)
Ankle/foot	36 (33)	1 (6)	37 (31)
Unknown	7 (6)	2 (12)	14 (12)
All	108 (100)	17 (100)	120 (100)

TABLE 2. Comparisons of Injury Risk for Different Categories of Intrusion

Intrusion	Frequency N	Injury Risk %
FLOOR	266	21
IP	34	32
COMPLEX	155	35

TABLE 3. Comparisons of Injury Severity (MAIS) for Different Categories of Intrusion

Intrusion	Occupants Injured (%)		
	MAIS 2	MAIS 3	Total
FLOOR	29 (52)	27 (48)	56 (100)
IP	7 (64)	4 (36)	11 (100)
COMPLEX	27 (49)	28 (51)	55 (100)

TABLE 4. Comparisons of Injury Severity (AIS) for Different Categories of Intrusion

Intrusion	Total Injuries (%)		
	MAIS 2	MAIS 3	Total
FLOOR	72 (67)	36 (33)	108 (100)
IP	11 (65)	6 (35)	17 (100)
COMPLEX	76 (63)	44 (37)	120 (100)

Note: In some tables percentages do not add to 100 because of rounding.

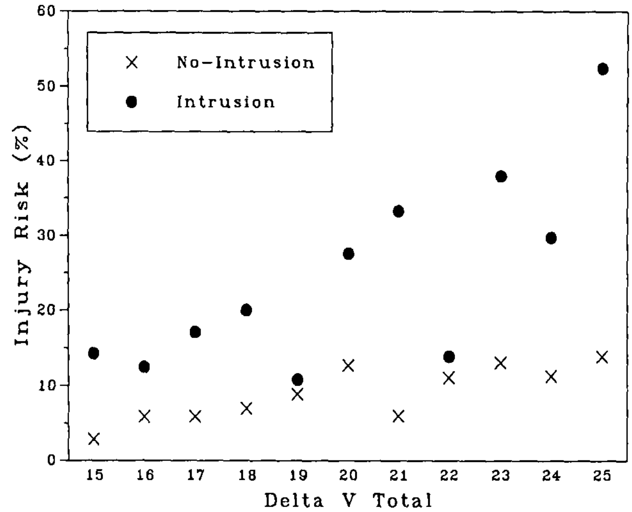


Fig. (2): Injury risk by Crash Severity

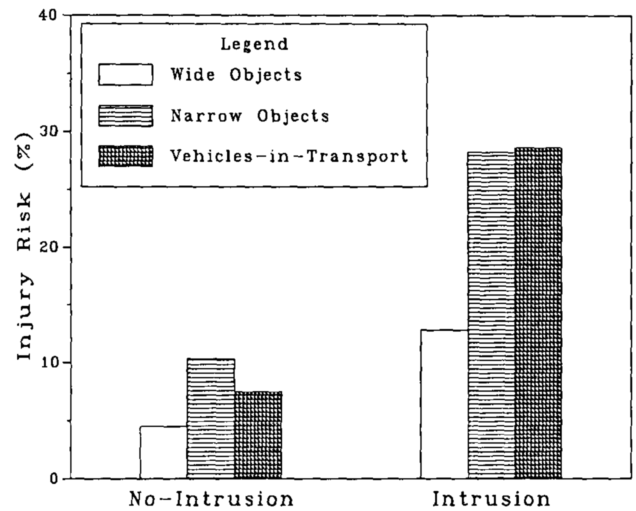


Fig. (3): Injury Risk by Impacting Object

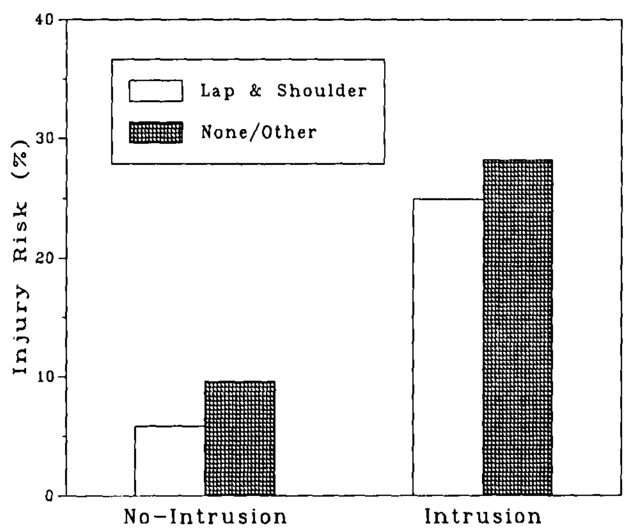


Fig. (4): Injury Risk by Belt Usage

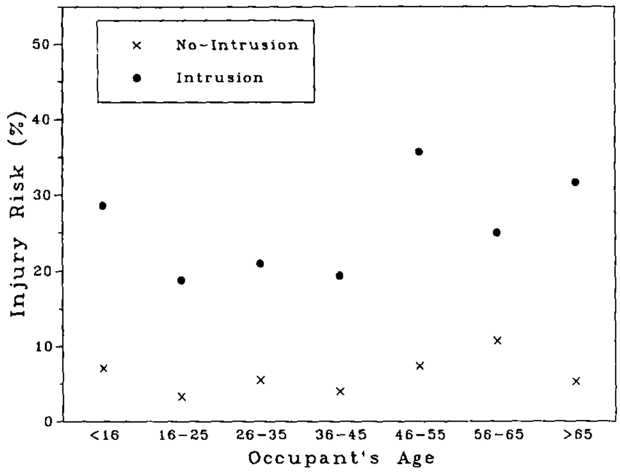


Fig. (5): Injury Risk by Age for Male

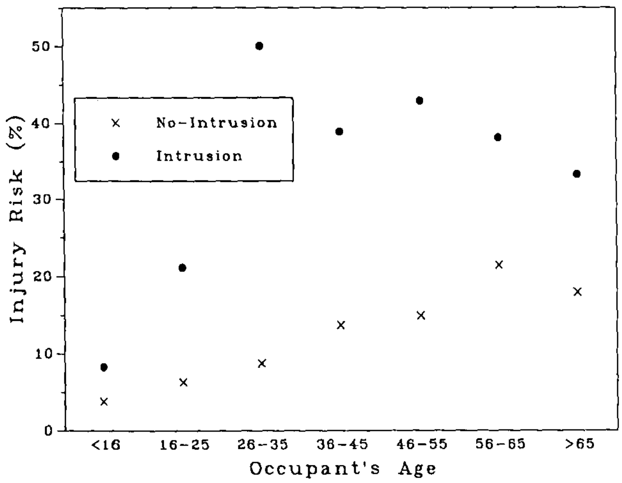


Fig. (6): Injury Risk by Age for Female

Injury Risk was reduced by (53%) when three point belt system was properly used in cases with no intrusion. There was no significant difference in injury risk for belted occupants with intrusion (Figure 4).

Figures (5) and (6) show the Injury Risk to males and females as it varies with their age. There was an increase in the risk with age of females with no-intrusion. There was no trend of injury risk with age of females with intrusion and with age of males with or without intrusion.

LOGISTIC REGRESSION ANALYSIS

Logistic regression is a form of statistical modeling that is appropriate for categorical outcome variables. It describes the relationship between a categorical outcome(response) variable and a set of explanatory variables. The response variable is usually dichotomous, but it may be polytomous, that is, have more than two response levels. The explanatory variables in logistic regression can be categorical or continuous.

For the present study, the following two dichotomous response variables were modeled:

1) leg-foot complex injury (yes, no), and
2) lower limb injury (yes, no) [excludes pelvic injuries]

A relationship of the response variables was described with a set of four categorical explanatory variables: intrusion, delta V total, seating position, and gender. The explanatory variables were categorized as follows:

- Intrusion (< 1 in, 1-6 in, >= 6 in)
- Delta V total (15-17 mph, 18-22 mph, 23-25 mph)
- Seating position (driver, right front passenger)
- Gender (male, female)

Two separate analyses were performed for leg injury and lower limb injury. The relationship between each response variable and the four explanatory variables was estimated by fitting a model of main effects only, because the interaction effects between explanatory variables were negligible. The main effect logit model has the form:

$$Logit(p) = \ln\left(\frac{p}{1-p}\right) = \alpha + (\sum \beta i X i)$$

where

p = the probability of the event that an injury occurred (response measure)

α = Intercept parameter (overall effect)

βi = Slope parameters (coefficients of Xi)

Xi = Explanatory variables (intrusion (X_1), delta V total (X_2), seating position (X_3), and gender (X_4))

The upper and lower 95% confidence limits for the predicted risks were calculated by using the following formulae:

$$UL = \frac{1}{1 + \exp(-(\hat{\eta} + 1.96\hat{\sigma}(\hat{\eta})))}$$

$$LL = \frac{1}{1 + \exp(-(\hat{\eta} - 1.96\hat{\sigma}(\hat{\eta})))}$$

where

$\hat{\eta} i = \hat{\alpha} + (\sum \hat{\beta} i X i)$ (Estimated logit)

$\hat{\alpha}$ = Estimate of α

$\hat{\beta} i$ = Estimate of βi

$\hat{\sigma}(\hat{\eta} i)$ = The standard errors of the parameter estimates derived from the logit analysis

The calculated values of Parameter Coefficients along with corresponding standard error are given in Table 7.

The figures 7-14 show the confidence limits along with the predicted values. Table 6 shows the values of all parameter coefficients and standard error.

The statistical software "PROC LOGISTIC" from SAS System was used for modeling logistic regression.

TABLE 6. Parameter Coefficients of Logistic Model

Variable	Instance	Parameter Coefficient Value($\beta_\iota X_\iota$)	Standard Error
Overall effect (α)	**	-4.4311	0.2792
Seating Position	Passenger*	0.	
	Driver	0.6356	0.2133
Gender	Male*	0.	
	Female	1.0171	0.1730
Intrusion	< 6 inch*	0.	
	6-18 inch	1.7671	0.2427
Velocity	15-17mph*	0.	
	18-22mph	0.6516	0.2044
	23-25mph	1.4321	0.2792

* Represents lowest level (risk) instance
** At the lowest level of all variables

Results of the Analysis

The effects of each of the four explanatory variables on the injury risks, as calculated from the main effects model are summarized below. The effects of each variable shown was calculated after adjusting for the effects of the remaining variables at some fixed levels. The effects of all levels of each variable and their 95% confidence limits were calculated from the parameter estimates and their corresponding standard error estimates, derived from the main effects model.

All four factors analyzed using logistic regression were found to be statistically independent and significant. Interactions of these factors were found to be insignificant.

The predicted values of both response measures derived from the main effect model for various conditions of occupant involvement are shown in appendices C and D.

<u>Lower Limb Injury Risk</u>

- As intrusion increases there is a significant increase in risk. Occupants with six inches or more of intrusion were nearly five times as likely to receive at least one moderate to serious leg injury than occupants with less than one inch of intrusion (Figure 7).

- As Delta V increases, there is a significant increase in risk. Occupants with higher Delta V (23-25 mph) were about three times as likely to receive at least one moderate to serious leg injury than occupants with lower (15-17 mph) Delta V (Figure 8).

- Females were twice as likely to receive at least one moderate to serious leg injury than males (Figure 9).

- Drivers were one and half times as likely to receive at least one moderate to serious leg injury than right front passengers (Figure 10).

<u>Leg-Foot-Complex Injury Risk -</u> The "Leg-foot-complex" response produced similar results as the "Lower Limb" response (Figures 11-14).

CONCLUSIONS

1. A significant number of lower limb injuries are produced without any residual intrusion.
2. Indications are that lower limb injury risk is higher with IP intrusion than floor/ toe-pan intrusion.
3. The crash severity, intrusion, seating position and gender are independent significant factors of lower limb injury risk. Statistically, interactions could not be extracted.
4. The injury risk is higher for higher crash severity and increased level of intrusion. Drivers have higher risk than front seat passengers and females have higher risk than males.

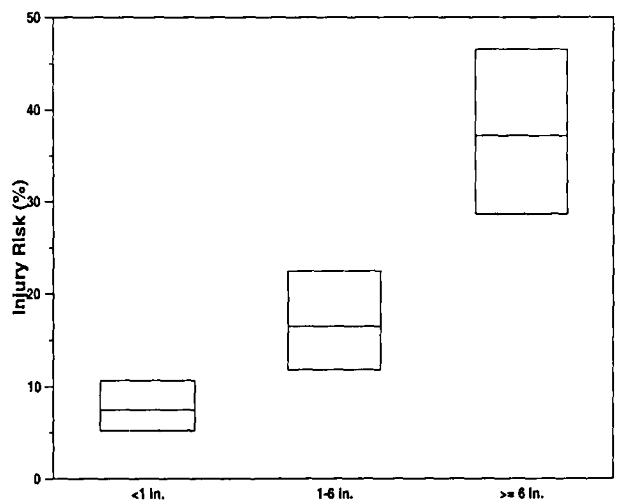


Fig. (7): Effect of Intrusion on leg-foot complex with 95% confidence intervals

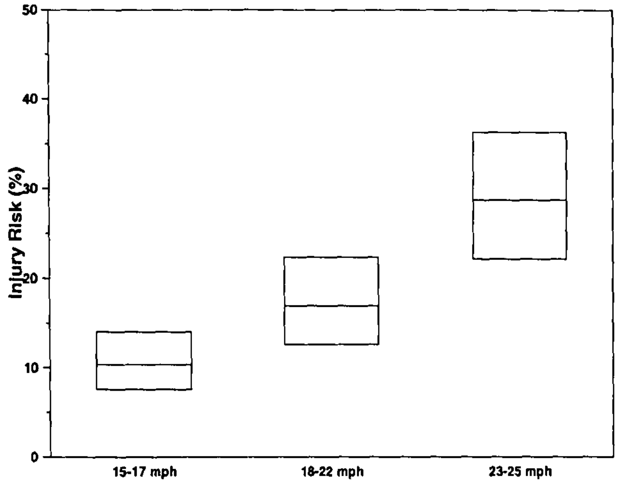


Fig. (8): Effect of impact severity on leg-foot complex with 95% confidence intervals

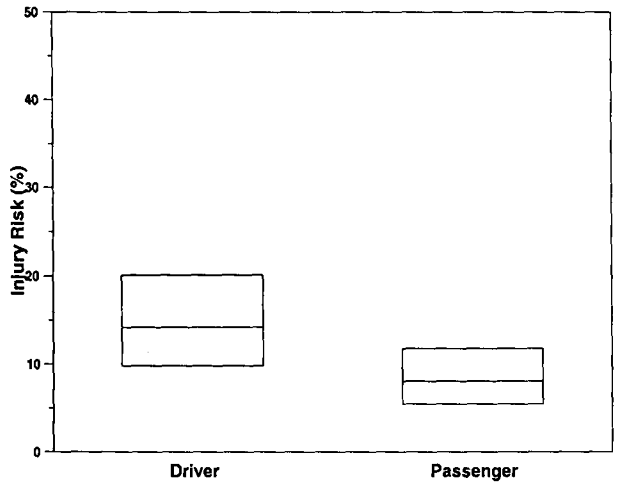


Fig. (9): Effect of seating position on leg-foot complex with 95% confidence intervals

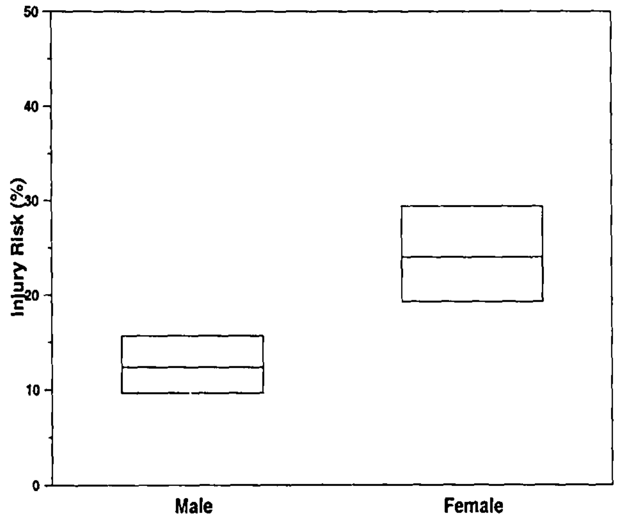


Fig. (10): Effect of gender on leg-foot complex with 95% confidence intervals

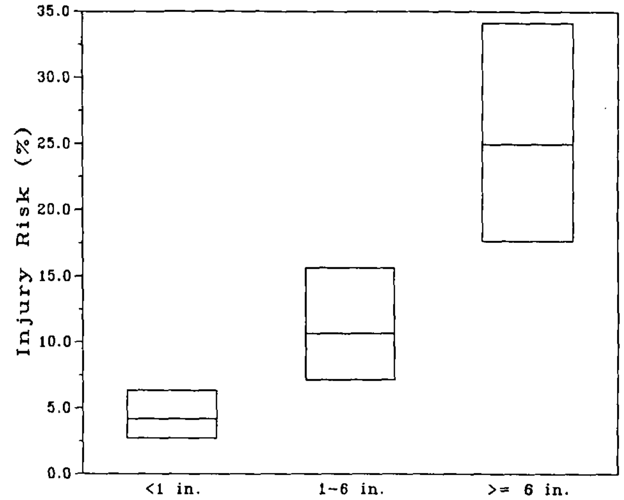


Fig. (11): Effect of Intrusion on leg-foot complex with 95% confidence intervals

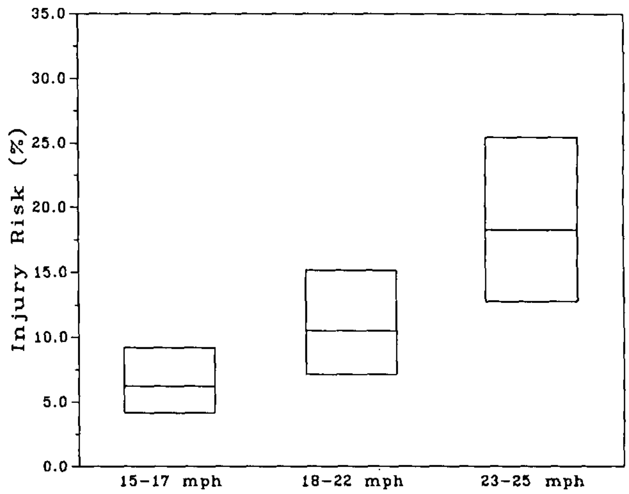


Fig. (12): Effect of impact severity on leg-foot complex with 95% confidence intervals

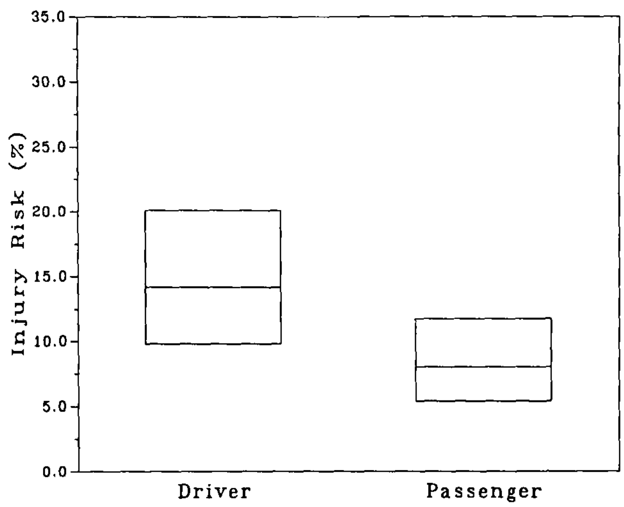


Fig. (13): Effect of seating position on leg-foot complex with 95% confidence intervals

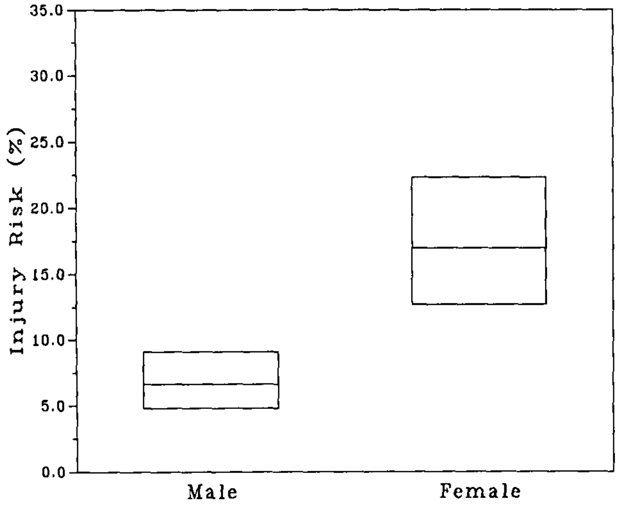


Fig. (14): Effect of gender on leg-foot complex with 95% confidence intervals

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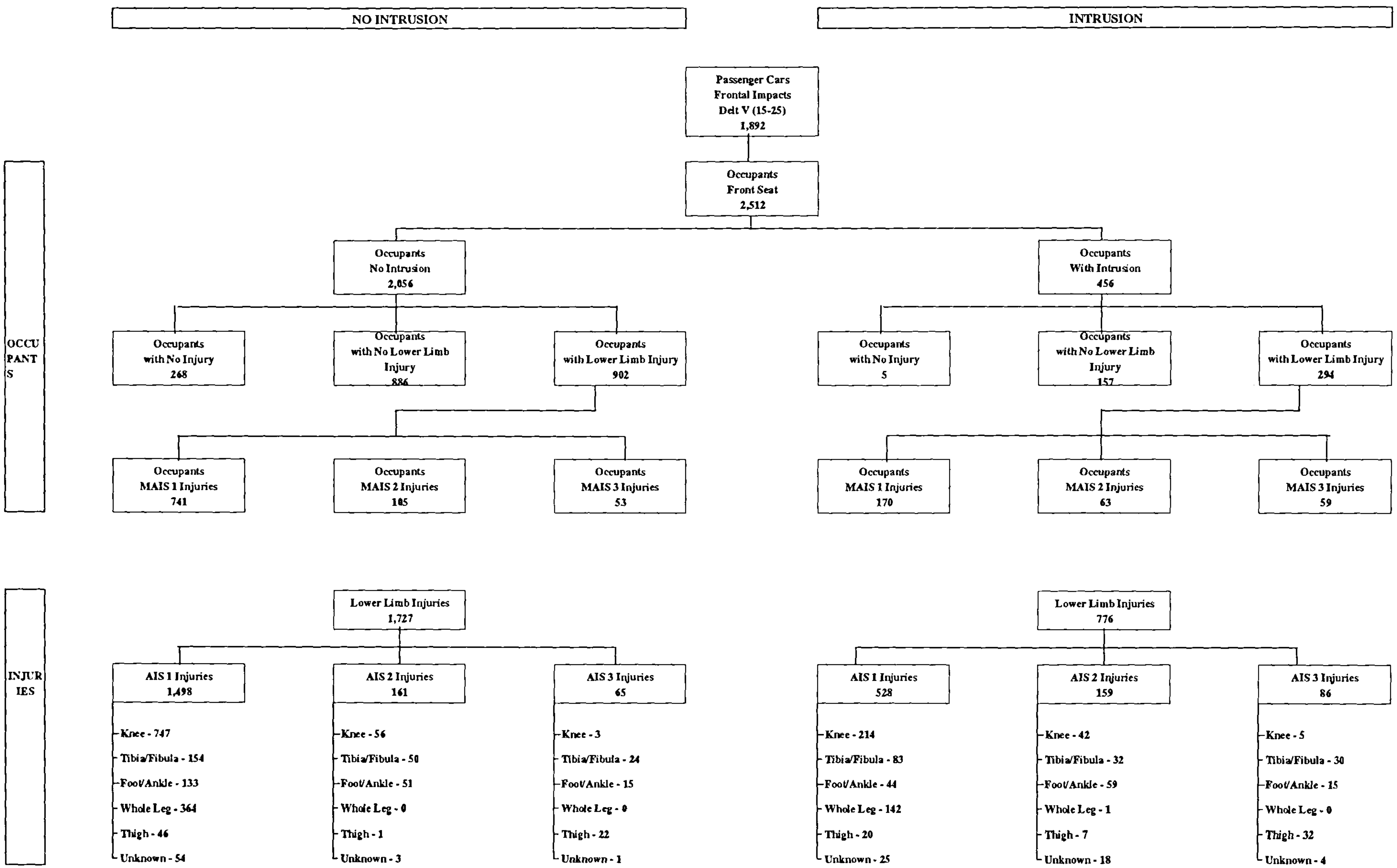
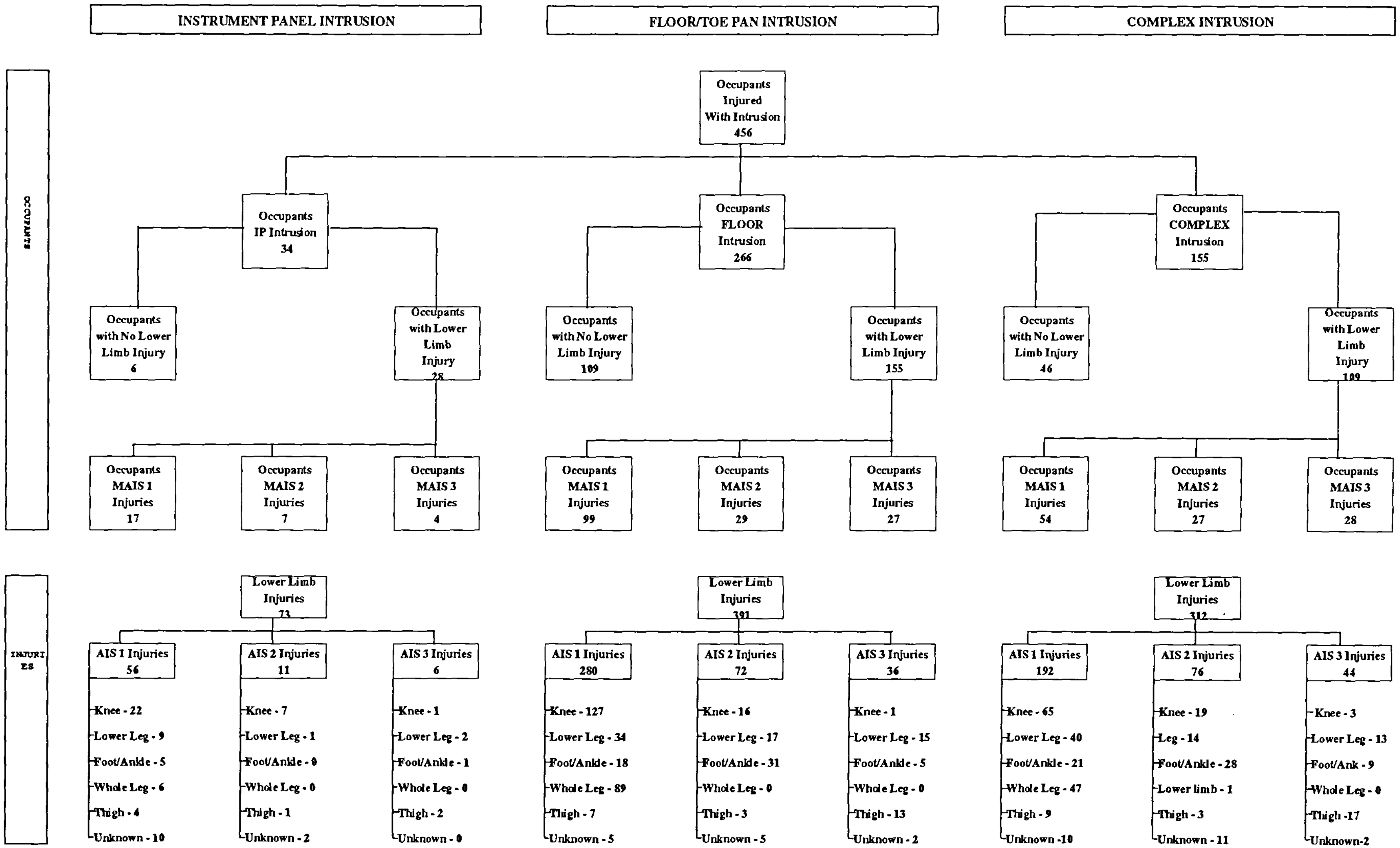
APPENDIX A. OCCUPANTS AND INJURIES CATEGORIZED BY INTRUSION



- 1988-94 NASS, 1986-95 Model Year Passenger Cars, Delta V Total 15-25 MPH, Frontal Impacts (clock position 11-1 O'Clock)
- Intrusion = Floor/Toe and/or I.P. Intrusion

APPENDIX B. OCCUPANTS AND INJURIES CATEGORIZED BY INTRUSION LOCATION



* 1988-94 NASS, 1986-95 Model Year Pass. Cars, Delta V Total 15-25 MPH, Frontal impacts (clock position 11-1 O'Clock)

APPENDIX C. PREDICTED INJURY RISK OF LEG-FOOT COMPLEX

					Observed Values		Predicted Values	
S. No.	Crash Severity	Position	Gender	Intrusio n	Events	N	Injury Risk	95% Confidence Interval
1	Low	Driver	Male	No	5	346	1.9	1.3 - 2.9
2	Low	Driver	Male	Low	2	31	5.1	3.1 - 8.2
3	Low	Driver	Male	High	3	14	13.0	7.8 - 20.8
4	Low	Driver	Female	No	20	350	5.3	3.8 - 7.4
5	Low	Driver	Female	Low	1	20	13.3	8.7 - 20.0
6	Low	Driver	Female	High	0	3	30.0	19.3 - 43.4
7	Low	Passenger	Male	No	0	105	1.0	0.6 - 1.8
8	Low	Passenger	Male	Low	0	4	2.8	1.5 - 5.0
9	Low	Passenger	Male	High	0	1	7.3	3.9 - 13.3
10	Low	Passenger	Female	No	7	137	2.9	1.8 - 4.6
11	Low	Passenger	Female	Low	0	14	7.5	4.4 - 12.7
12	Low	Passenger	Female	High	1	3	18.5	10.5 - 30.4
13	Mid	Driver	Male	No	13	336	3.3	2.3 - 4.7
14	Mid	Driver	Male	Low	4	61	8.6	5.7 - 12.8
15	Mid	Driver	Male	High	5	24	20.8	13.7 - 30.4
16	Mid	Driver	Female	No	31	327	9.0	6.9 - 11.7
17	Mid	Driver	Female	Low	7	46	21.4	15.3 - 29.0
18	Mid	Driver	Female	High	3	10	43.1	31.0 - 56.1
19	Mid	Passenger	Male	No	1	76	1.8	1.1 - 3.0
20	Mid	Passenger	Male	Low	0	12	4.8	2.7 - 8.1
21	Mid	Passenger	Male	High	0	5	12.2	7.0 - 20.5
22	Mid	Passenger	Female	No	7	127	5.0	3.3 - 7.6
23	Mid	Passenger	Female	Low	4	17	12.6	7.9 - 19.6
24	Mid	Passenger	Female	High	2	3	28.6	17.9 - 42.4
25	High	Driver	Male	No	8	107	6.2	4.2 - 9.0
26	High	Driver	Male	Low	8	42	15.3	10.5 - 21.8
27	High	Driver	Male	High	7	22	33.4	23.6 - 45.0
28	High	Driver	Female	No	10	97	15.9	11.7 - 21.3
29	High	Driver	Female	Low	18	38	34.2	25.7 - 43.8
30	High	Driver	Female	High	10	15	59.1	46.5 - 70.6
31	High	Passenger	Male	No	0	32	3.4	2.0 - 5.7
32	High	Passenger	Male	Low	1	14	8.7	5.2 - 14.4
33	High	Passenger	Male	High	2	5	21.0	12.8 - 32.6
34	High	Passenger	Female	No	3	35	9.1	5.8 - 14.0
35	High	Passenger	Female	Low	1	10	21.6	14.1 - 31.6
36	High	Passenger	Female	High	1	6	43.4	29.7 - 58.1

APPENDIX D. PREDICTED INJURY RISK OF LOWER LIMB

					Observed Values		Predicted Values	
S. No.	Crash Severity	Position	Gender	Intrusio n	Events	N	Injury Risk	95% Confidence Interval
1	Low	Driver	Male	No	10	345	3.7	2.7 - 5.0
2	Low	Driver	Male	Low	3	31	8.5	5.7 - 12.4
3	Low	Driver	Male	High	5	14	21.7	14.5 - 31.2
4	Low	Driver	Female	No	27	350	7.8	6.0 - 10.2
5	Low	Driver	Female	Low	2	20	17.1	12.1 - 23.8
6	Low	Driver	Female	High	1	3	38.3	27.2 - 50.8
7	Low	Passenger	Male	No	1	104	2.2	1.5 - 3.4
8	Low	Passenger	Male	Low	0	4	5.3	3.2 - 8.5
9	Low	Passenger	Male	High	0	1	14.3	8.7 - 22.6
10	Low	Passenger	Female	No	12	137	4.9	3.4 - 7.0
11	Low	Passenger	Female	Low	0	14	11.1	7.1 - 16.8
12	Low	Passenger	Female	High	1	3	27.2	17.6 - 39.6
13	Mid	Driver	Male	No	24	336	6.3	4.8 - 8.2
14	Mid	Driver	Male	Low	6	61	14.1	10.2 - 19.1
15	Mid	Driver	Male	High	7	24	33.0	23.9 - 43.5
16	Mid	Driver	Female	No	44	326	13.1	10.6 - 16.1
17	Mid	Driver	Female	Low	12	46	26.8	20.5 - 34.3
18	Mid	Driver	Female	High	3	10	52.4	40.8 - 63.8
19	Mid	Passenger	Male	No	2	76	3.9	2.6 - 5.8
20	Mid	Passenger	Male	Low	0	12	9.0	5.8 - 13.6
21	Mid	Passenger	Male	High	0	5	22.8	14.9 - 33.4
22	Mid	Passenger	Female	No	12	127	8.3	6.0 - 11.5
23	Mid	Passenger	Female	Low	5	17	18.1	12.5 - 25.5
24	Mid	Passenger	Female	High	3	3	39.9	28.1 - 53.0
25	High	Driver	Male	No	15	107	11.7	8.7 - 15.6
26	High	Driver	Male	Low	14	42	24.4	18.3 - 31.8
27	High	Driver	Male	High	10	22	49.3	38.5 - 60.2
28	High	Driver	Female	No	15	97	22.9	18.0 - 28.7
29	High	Driver	Female	Low	19	37	42.0	33.5 - 51.0
30	High	Driver	Female	High	13	15	68.5	57.6 - 77.7
31	High	Passenger	Male	No	3	32	7.4	4.9 - 11.0
32	High	Passenger	Male	Low	1	14	16.3	11.0 - 23.6
33	High	Passenger	Male	High	3	5	36.9	25.9 - 49.5
34	High	Passenger	Female	No	4	35	15.2	10.8 - 21.0
35	High	Passenger	Female	Low	2	10	30.4	22.0 - 40.3
36	High	Passenger	Female	High	1	6	56.7	43.7 - 68.9

FIELD DATA IMPROVEMENTS FOR FIRE SAFETY RESEARCH

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ABSTRACT

As part of the March 7, 1995 Settlement Agreement between General Motors and the U.S. Department of Transportation, General Motors sponsored analyses of various field collision data files maintained by Federal and State highway safety organizations. These analyses were performed to: 1) evaluate possible causes and effects of vehicle fire events; 2) assess the adequacy of existing databases for studying these events; and 3) recommend possible enhancements to these data files to assist safety researchers in studies of motor vehicle fires.

Results of this GM-sponsored research indicate that existing data sources contain insufficient information to enable researchers to satisfactorily understand the causes of vehicle fires. This paper describes some major deficiencies in current field accident databases (with respect to information about the causes and consequences of vehicle fires) and recommends enhancements to these databases which might provide researchers with better, more comprehensive information about the causes and effects of vehicle fires.

BACKGROUND

Researchers studying crash-related vehicle fires seek answers to the following types of questions:

1. How do vehicle type, vehicle age, driver age and gender, crash mode, and crash severity affect the likelihood of post-collision vehicle fire?
2. What are the sequential crash-related events associated with the fire?
3. What is the extent of vehicle damage associated with the fire?
4. If leakage occurs, what is the fuel and what is the source of the leak?
5. What is the source of ignition?
6. What are the injury (trauma/burn) consequences of the crash?

Typically, initial approaches to answering these types of questions involve analyzing vehicle fire-related data contained in various Federal and State traffic safety databases. This paper summarizes results obtained from GM sponsored analyses of various field collision data files maintained by Federal and State highway safety organizations.

Fatal Analysis Reporting System (FARS)

The Fatal Analysis Reporting System (FARS), maintained by the National Highway Traffic Safety Administration (NHTSA) has often been used as a starting point in efforts to gain an understanding of crash-related vehicle fires. FARS represents a census of motor vehicle crashes on public roads in the United States that result in at least one fatality within thirty days of the crash. Even though FARS' broad coverage of fatal crashes makes it a logical data source to begin quantifying the most extreme injury consequences of vehicle fire, there are limitations that make FARS a less than reliable source of data on fatal vehicle fires.

Some of the limitations of FARS for studying fire incidents are apparent from a cursory review of the variables that are coded in the FARS files. For instance, FARS provides no opportunity to code presence or absence of fuel leakage, let alone what the source of such fuel leakage might be. There is also no indication in FARS as to possible ignition source for the fire nor is there any indication of the origin of the fire (e.g. engine compartment, passenger compartment, fuel tank area, etc.).

Moving beyond questions about the vehicle to those dealing with the occupants of the vehicle, other difficulties are encountered. FARS only codes the most basic information about a person's injury severity. The coding for a person's overall injury severity is derived from police level injury scales (K-fatal injury, A-incapacitating injury, B-non-incapacitating evident injury, C-possible injury, 0-no injury). Other than providing only a rough measure of a person's overall injury severity, FARS provides no information on a person's injuries -- their type (e.g. laceration, fracture, burn, etc.), the part of the person's body involved (e.g. face, heart, left leg, etc.), or the contacts with objects associated with the injury (e.g. contact exterior to the vehicle, A-pillar, etc.). Even the cause of death is not contained in the FARS files.

To account for some of the limitations of FARS, researchers have used indirect methods to bound estimates dealing with fire related fatality. Tessmer relied on the FARS variable Most Harmful Event (MHE) to make projections about the number of people who had died as a result of vehicle fire (Tessmer 1994). The author recognized that not every occupant fatality in a vehicle which experiences a fire can be reasonably thought to have his/her death directly caused by the fire, as opposed to impact-induced trauma. To derive a lower bound, it was assumed that for vehicles with an occupant fatality and "fire or explosion" coded as the MHE, at least one occupant died as a result of the fire. To get an upper bound, it was assumed that all occupant fatalities in vehicles with fire died as a result of fire, with the exception of one occupant fatality in each vehicle with fire and a MHE coded as other than "fire or explosion". Bounding projections, using such an indirect approach, is perhaps the best one can do to overcome the lack of specificity in the FARS fire coding. However, evaluation of the FARS database calls into question the meaningfulness of these bounds, due to the inconsistency in the application of the coding from state to state.

State Accident Files

As part of their police reported crash databases, several states have data on the presence of vehicle fire either as an explicit variable or as a possible code value to variables dealing with harmful events associated with the crash. The degree of detail (never too great) and the way in which the fire data is presented vary from state to state.

National Automotive Sampling System (NASS) General Estimates System (GES)

The National Highway Traffic Safety Administration's National Automotive Sampling System's General Estimates System (NASS-GES), as its name implies, aims to serve as a resource for making general estimates about traffic crashes nationally. It relies on extracting common pieces of data from the reports of selected police agencies nationwide. NASS-GES' general outlook and underlying data sources prevent it from having very great detail in any one area, fire events being no exception.

National Automotive Sampling System (NASS) Crashworthiness Data System (CDS)

The National Highway Traffic Safety Administration's National Automotive Sampling System's Crashworthiness Data System (NASS-CDS) contains a relatively rich set of variables providing relevant data on crash-involved vehicles and occupants. The primary problem with NASS-CDS is not the lack of detail but rather the relatively low number of reports received annually. A NHTSA study of vehicle fires noted that "there are very few vehicles in the NASS database that had a fire, most likely less than 50 per year." (Tessmer 1994) This relatively small sample size results from the low frequency of fires in towaway crashes combined with a smaller number of cases selected compared with FARS.

National Fire Protection Association (NFPA) Survey Data

The National Fire Protection Association (NFPA) conducts yearly surveys of a random sample of U.S. fire departments to make national projections of fire occurrence. This survey does not capture any detailed information about vehicle fire incidents. NFPA estimates of vehicle fire and of fatalities in vehicle fires are based on a sample survey of fire departments and are subject to sampling error of approximately 10%.

National Fire Incident Reporting System (NFIRS)

The Federal Emergency Management Administration's (FEMA) U.S. Fire Administration established the National Fire Incident Reporting System (NFIRS) for the collection of fire incident and fire casualty data in the U.S. NFIRS was designed as a tool for fire departments to report and maintain computerized records of fires in a uniform manner. This system provides data that allows analysts to detect local, state, and national trends. However, the system is voluntary; not every U.S. fire department contributes to the system. Data from NFIRS must be combined with information from other sources (e.g., NFPA sample survey data) to produce national estimates of fire trends. NFIRS offers codes for injuries and fatalities in noncollision motor vehicle fires by vehicle make and model. In addition, the amount of direct property damage is estimated. Fire incidents can be detailed by area of fire origin, type of material first ignited, and form of heat of ignition.

RESULTS OF DATABASE EVALUATIONS

Research sponsored by General Motors as part of the March 7, 1995 Settlement Agreement between General Motors and the U. S. Department of Transportation examined the reliability of FARS data for fire research (Griffin 1997 & 1998). Some of the conclusions of this research include:

- A large amount of variation exists among the states in the coding of the presence of fire. Without getting beyond even the most basic level of data dealing with vehicle fire -- its presence or absence -- there is some reason to believe that the data input to FARS is not consistent nationwide.
- A large amount of variation exists among the states in the coding of "fire or explosion" as the most harmful event (MHE) for vehicles coded as having experienced a fire. Because of this variability in MHE coding, it is unlikely that the states are estimating the same phenomenon.
- Results of crosschecking coded injuries from the Multiple Cause of Death (MCOD) files with fire coding from FARS found:

- Occupants with burn type injuries in vehicles not having fire coding and
- Vehicles with "fire or explosion" coded as the MHE having none of their fatal occupants with burn type injuries.
- An evaluation of police reports underlying the FARS data illustrated the difficulty in properly pigeon-holing complex events such as vehicle fatalities, especially those associated with fire.

Additional research sponsored by General Motors as part of the same Settlement Agreement evaluated the strengths and weaknesses of a variety of state and federal data related to motor vehicle fire (Ray 1996). The principal findings of this study include:

- State-level databases vary widely in the accuracy and completeness with which they capture information about fire accidents.
- All databases reviewed lack adequate coded information for researchers to understand the cause of fire and to differentiate significant factors in a fire accident (e.g., engine fire versus fuel fire).
- The NASS-CDS provides detailed information on traffic accidents in which fire occurred. However, the small size of the database, coupled with the low rate of vehicle fire accidents, limits the usefulness of these data for the study of the causes of vehicle fire.
- The General Estimates System (GES) of NASS is a representative sample of all U.S. police-reported traffic accidents, containing information gleaned from police reports. This database is useful for an overview of vehicle fires and as a check on the consistency of the state databases.
- Because of limitations associated with each database examined, it is recommended that separate analyses should be performed for each database and the information be combined via statistical meta-analysis techniques.

Table 1 summarizes some of strengths and weaknesses of the databases evaluated by the two GM-sponsored data evaluation studies. Comments regarding database strengths and weaknesses refer to the adequacy of these different data sources for comprehensive vehicle fire research studies.

Table 1.
Summary of Databases Evaluated

Database	Strengths	Weaknesses
FARS	Census of all fatal accidents; information on many driver and environmental variables; contains limited information on presence or absence of fire.	Restricted to highest severity (fatal) accidents; cannot identify causes of fire; difficult to evaluate contribution of environmental and operator factors that result in severe crashes and vehicle design characteristics that may contribute to likelihood of fire.
State Data	Contains information on fatal and nonfatal accidents involving fire.	Accuracy and completeness of fire accident information varies widely; frequency of fire incidents may be significantly misrepresented.
NASS-GES	A sample of police-reported crashes; contains limited information on presence or absence of fire, which can serve as check on state data.	Relatively small sample size and infrequency of collision fire limit usefulness of these data for studying collision-related fire.
NASS-CDS	Contains detailed information on fire-related traffic accidents.	Small sample size and infrequency of collision fire limit usefulness of these data for studying collision-related fire.
NFPA Survey Data	Random sample of U.S. fire departments provides general picture of vehicle fire incidents.	Does not capture any detailed information about vehicle fire incidents. Survey sampling error is approximately 10%.
NFIRS	Provides vehicle fire-related data to enable analysts to detect local, state, and national trends. Fire incidents can be detailed by estimated area of fire origin, type of material first ignited and form of heat of ignition.	Voluntary; not every fire department in the U.S. contributes data to the system. Definition of vehicle fire fatalities differs from FARS.

RECOMMENDATIONS

Looking over the relative strengths and weaknesses of existing databases, it is clear that none has all the attributes that one would desire in an ideal database for studying vehicle fires. Among these attributes would be the presence of consistent, accurate, and sufficient data to make reasonable inferences about vehicle performance and occupant injury.

The infrequency of vehicle fires in NASS-CDS greatly limits its utility as a data source for fire research. NASS-GES suffers from the same problem, but to a lesser degree. FARS has proven to be a valuable resource for research efforts seeking to gain an understanding of fatal vehicle crashes on a national basis. However, FARS has some significant shortcomings as a resource for vehicle fire research.

One of FARS' great strengths is its comprehensive coverage of fatal crashes, which should allow good national assessments to be made about the frequency of fires in fatal crashes, but the inconsistency found among states in coding of fire-related variables keep FARS from achieving its potential in this area. Recognizing that underlying police reports form the basis of FARS, a step in the right direction would be for NHTSA to expand its efforts in promoting common data definitions and coding formats among the states to include fire-related variables, such as extent and source of fire. Even though it is difficult to promote even minimum standards for common data elements, the importance of fire safety research should support the need to add data elements related to fire to the array of essential data elements that should be common from state to state.

Short of a major redesign of the FARS program, a way of obtaining some injury data on occupants killed in crashes would be to link data on the reported cause of death from the National Center for Health Statistics' Multiple Cause of Death (MCOD) files to corresponding records in the FARS files. Linking these databases would not provide the last word on fatalities in crashes associated with fire, but it would present the possibility of gaining a better classification of these events.

The approaches suggested for FARS have some relevance to state data, as well. If states were persuaded to add common crash-related fire variables to their data systems, in addition to enhancing the utility of FARS, these enhanced state databases could serve as consistent and reliable sources of data for those fire-related crashes that are not captured by the FARS database. Going beyond mere consistency, the reliability of coded fire-related data would be further improved by implementation of field investigation programs (conducted by trained vehicle fire investigators using a standard incident investigation protocol). The importance of involving trained fire investigators in the process should not be understated given the difficulty of unraveling the chain of events in vehicle fires.

The direction that NHTSA has taken in their CODES program, shows potential for augmenting existing state crash databases, especially in the area of injury consequences. Undoubtedly, the lessons that NHTSA and their state partners have learned in piloting this process will be fed back into the process to improve the utility of the resulting linked databases. Building on what has been learned, if this linking approach could be extended to tie police-reported crash events to the reports of trained fire investigators in a representative set of states, researchers would begin to have the tools they need to get a more useful understanding of crash-related vehicle fires and their consequences.

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A SEARCHABLE TRANSPORTATION FIRE SAFETY BIBLIOGRAPHY

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ABSTRACT

Over 1,000 scientific and technical articles, specifically chosen for their relevance to transportation fires, were incorporated into a searchable bibliography. A searchable database was developed which incorporates the title, authors, source, publication year, associated keywords and, in many cases, an abstract for the citation. The database provides a mechanism to search the incorporated transportation fire safety literature for articles containing specific information. Transportation fire safety information that is reported in the scientific literature encompasses: the causes, propagation, severity and extinguishment of fires in passenger carriers, as well as, the flammability characteristics of the fuels and materials used in such vehicles. The advantage of this software package is that one can quickly locate scientific literature associated with a particular transportation fire topic (e.g., the radiant heat flux from a hydrocarbon pool fire or the critical heat flux required for the ignition of polypropylene). This is accomplished by searching the keywords that were selected for each citation. The software package is publicly available in a CD-ROM format for use on personal computers operating with Microsoft Windows® 3.1 or Windows® 95.

INTRODUCTION

Although fire safety bibliographic databases exist, to our knowledge none specifically address transportation. The Transportation Fire Safety Bibliography is a collection of scientific literature citations that is limited to articles relevant to transportation fire safety. The Transportation Fire Safety Bibliography cites over 1000 scientific articles published between 1911 and 1996. The bibliography is contained within a software package that enables users to both search and add citations. The software package is publicly available in a CD-ROM format for use on personal computers. This paper describes the development of this software package, conducted by the Fire Safety Research Group at General Motors Research and Development Center.

DISCUSSION

The Transportation Fire Safety Bibliography is designed to quickly and efficiently produce a list of publicly available scientific literature within a specified area of transportation fire safety. Developing the Transportation Fire Safety Bibliography required:

(1) locating scientific literature related to transportation fire safety,
(2) describing these works,
(3) storing this information in an easily retrievable format, and
(4) developing a PC-based stand alone software package with a user manual and help utility.

Locating Transportation Fire Safety Literature

Extensive literature searches were conducted to locate scientific literature relevant to transportation fire safety. This literature was reviewed and the appropriate citations were included in the bibliography. In general, transportation fire safety information within the scientific literature encompasses; the causes, propagation, severity, and extinguishment of fires in passenger carriers, as well as, the flammability characteristics of the fuels and materials used in such vehicles.

Both electronic and traditional resources were used to find scientific literature related to transportation fire safety. The electronic resources used include the following:

(1) on-line card catalogs at General Motors and 15 universities (all the Big Ten Universities, Eastern Michigan University, Wayne State University, Illinois Institute of Technology and the University of Illinois-Chicago),
(2) CD-ROM bibliographies (e.g., "BFRL Publications, 1994", developed by the Building and Fire Research Laboratory (BFRL)), and
(3) both commercial and public on-line electronic databases (e.g., FIREDOC,[1] developed by BFRL and RAPRA: Rubber and Plastics, supported by DIALOG Information Services[2]).

The traditional resources used to locate relevant scientific articles are: selecting references from the literature that was already incorporated into the Transportation Fire Safety Bibliography and requesting reprints from authors established in the fire safety field.

Transportation fire safety literature had to be extracted from thousands of fire safety research papers (most of which are related to building fires).[1] Topics relevant to transportation fire safety were defined, by the original project statement, as the following:

(1) flammability standards developed for transportation and related industries,
(2) ignition of vapor plumes and stratified mixtures,
(3) liquid pool fires and pool fire correlations,
(4) fire spread and fire spread correlations,
(5) large scale practical fires,
(6) flammability of interior and exterior materials used in transportation,
(7) flammability of fuels and other fluids used in transportation,
(8) flammability hazards associated with alternatively fueled vehicles, and
(9) the toxicological effects of off-gases produced by the combustion of vehicle materials.

The literature included in the Transportation Fire Safety Bibliography is limited to scientific articles addressing the above topics.

Describing the Scientific Literature

The selected literature is described by choosing a set of representative keywords for each scientific article and developing abstracts for the most important scientific papers.

Keywords were used to identify all the important concepts or data presented in an article. A complete set of keywords acts as a terse description of the article. The Transportation Fire Safety Bibliography incorporates keywords that are very specific to the study of transportation fire safety. These sharply defined keywords provide a mechanism to quickly locate information relating to specific transportation fire safety topics.

About 170 of the citations in the database include abstracts. This is due to the fact that abstracts developed by the original author are often subject to copyright protection. Abstracts subject to copyright protection are not included in this database. Therefore, the abstracts that are included in the Transportation Fire Safety Bibliography must meet one of the following two criteria:

(1) abstracts that are not subject to copyright protection, such as those provided by public institutions (i.e., NIST),[3] and
(2) abstracts that were written specifically for this project.

Abstracts could not be developed for all the citations in the Transportation Fire Safety bibliography, therefore, only those articles determined to be relevant to motor vehicle fires were abstracted. Literature selected as relevant to motor vehicle fire research examined the appropriate flammability properties of automotive materials or fluids. The flammability properties of interest are:

(1) ignition temperatures or critical heat flux,
(2) flame spread,
(3) rate of heat release,
(4) material or flame retardant chemistry and combustion or pyrolysis products, and
(5) the toxicological effects of combustion or pyrolysis gases.

Relevant automotive materials are defined as ABS, nylon, polyethylene, polypropylene, polyvinyl chloride, thermoset polyesters and urethane. These seven materials represent more than 75% of the total mass of polymers used in motor vehicles.[4] All automotive fluids are considered relevant, except gasoline. All of the abstracts developed for this project were written by students at Michigan State University.

Information Storage and Retrieval

Microsoft Access® was chosen as the software application to develop the Transportation Fire Safety Bibliography because it provides both efficient information storage and a mechanism to develop a specialized search engine.

The Microsoft Access® database incorporates the title, authors, source, publication year, associated keywords and, in some cases, an abstract from each scientific article. To avoid possible copyright conflicts information was not electronically manipulated from existing databases into the Transportation Fire Safety Bibliography. All the gathered and developed information was entered into the database by hand.

A search engine was developed to access the information stored in the database. The search engine searches most of the available data fields, including the: title, authors, source, publication year, associated keywords and abstract. The combination of the search engine and the sharply defined keywords provides a mechanism to search the database literature for articles containing very specific information.

Software Package Development

Microsoft Access® Developer's Toolkit enables software developers to produce a stand alone run-time software package of their Microsoft Access® database. All the necessary licenses are owned by GM and their contracting companies and the Microsoft License Agreement conditions have been fulfilled. The software package is distributed in a CD-ROM format. The files required to run the TFS Bibliography are installed from the CD-ROM to the user's hard disk.

The Transportation Fire Safety Bibliography is a dynamic database. In other words, the software includes the ability to add citations to the bibliography. Therefore, as the field of transportation fire safety grows, users can incorporate new publications. User-added citations are included in all searching and browsing operations. However, the user cannot edit any of the information (citations, authors, keywords, sources or abstracts) originally provided with the Transportation Fire Safety Bibliography.

Both a help utility and a manual are included with the Transportation Fire Safety bibliography. The help utility is an additional piece of software that is accessed when using the Transportation Fire Safety bibliography. The manual is a stand alone text document, included on the CD-ROM in Microsoft Word® versions 6.0 and 95. Note that the help file and the manual contain nearly identical text.

CONCLUSION

The Transportation Fire Safety Bibliography is a collection of scientific literature citations that is limited to articles relevant to transportation fire safety. The Transportation Fire Safety Bibliography operates as a stand alone, PC based software package. The advantage of this software package is that one can quickly locate scientific literature associated with a specific transportation fire research topic. Furthermore, a mechanism to add additional citations is included so that users can keep the database up to date as the transportation fire safety field continues to grow.

Use and Distribution Agreement

The Transportation Fire Safety Bibliography was created to assist researchers in their search for information. GM makes no claims regarding the accuracy or completeness of the software or accompanying information. GM is not responsible for any use or misuse of the software or accompanying information.

The information contained on the accompanying disks should not be altered in any way. Attempts to change the files will adversely impact the integrity of the information and its usefulness.

Searchable Transportation Fire Safety Bibliography is a database which contains citations to and abstracts of scientific literature. The database was prepared by General Motors Corporation pursuant to an agreement with the U.S. Department of Transportation. General Motors Corporation claims no copyright in the citations or abstracts which may be freely reproduced and used by the public, without limitation.

Searchable Transportation Fire Safety Bibliography was created using Microsoft Access® Developer's Toolkit, a copyrighted work of the Microsoft Corporation. The permission conferred above to reproduce or use portions of the database does not extend to any portion of the Microsoft Access® Developer's Toolkit.

Completion of this project partially fulfills the March 7, 1995, agreement between GM and the Department of Transportation.

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THE DEVELOPMENT OF THE CRASH INJURY RESEARCH AND ENGINEERING NETWORK

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ABSTRACT

The Crash Injury Research and Engineering Network (CIREN) has developed a computer database and wide area network for data sharing and analysis among the current seven trauma centers. The computer data base extends NHTSA's National Automotive Sampling System with medical and trauma related variables in a relational/object database system. The medical data includes injury location details, injury subclassification systems and medical images for better bio-mechanical injury evaluation.

Key data elements are migrated to a core repository so that all centers can review the status of case acquisition across the network. Cases, whole or in part, may be migrated between centers so that individual center expertise may be shared in evaluating the cause of injury. Electronic rounds where cases are reviewed simultaneously across multiple centers is possible.

MAIN BODY

History

The National Highway Traffic Safety Administration (NHTSA) has funded hospital-related studies since the 1980's. In 1991, NHTSA initiated the Highway Traffic Injuries Studies. Over the next two years research projects to collect detailed injury information on motor occupants were funded at four level 1 trauma centers. These were:

R. Adams Cowley Shock Trauma Center/National Study Center for Trauma & EMS
New Jersey Medical School/University of Medicine & Dentistry
Children's National Medical Center
William Lehman Injury Research Center/University of Miami

The Crash Injury Research & Engineering Network (CIREN) was established in 1996. With grants from General Motors, three additional level 1 trauma centers were added:

University of Michigan Medical Center at Ann Arbor
Harborview Injury Prevention & Research Center
County of San Diego, Department of Health Services

General Motors , also, funded the development of the computer network and system herein described.

Overview

CIREN cases are limited to people who are injured in motor vehicle crashes and transported to the participating trauma center. Other selection criteria includes a focus on frontal impacts involving late model year cars (current year less 8), any impact where a child is injured and transported to the trauma center, all fire related cases, and rollover with fewer than two quarter turns. The cases researched by these centers have been instrumental in the understanding of injury profiles associated with and without air bags and "hidden" injuries such as bowel perforations in children.

CIREN crash investigators depend on the participation and cooperation of law enforcement agencies, hospitals, physicians, medical examiners, coroners, tow yard operators, garages, city vehicle pounds, and the individuals involved in the crashes. Cooperation from law enforcement agencies enables CIREN researchers to obtain police accident reports which give key information on the location of the crash and vehicles involved in crashes.

CIREN crash investigators inspect and photograph vehicles, interview vehicle occupants, and inspect and photograph crash scenes in order to collect the core National Automotive Sampling System dataset via a field PEN computer which is subsequently uploaded to an Oracle Database Server. Additional data and crash reconstruction via WINSMASH, a deltav and trajectory calculation program, are input via a desktop computer directly into the Oracle Database Server. This data is collected independently of medical data collection.

CIREN researcher teams collect and input extensive medical data on the injured occupant as it is obtained during and after his/her hospitalization into the CIREN dataset stored on an Oracle Database Server. The medical data includes text, drawings, x-rays and other pertinent medical images and photographs.

CIREN research teams, crash investigators and, as required, additional experts meet periodically to review their cases and analyze the injury mechanisms. These review conferences associate injuries with vehicle intrusions, occupant contacts and bio-mechanical mechanisms. Additionally, system specific injury subclassification is performed to assist in elucidating injury mechanisms.

The Computer Network

The exchange of crash data among the trauma centers is essential for the sharing of individual center expertise. The first step in data sharing was the creation of a Wide Area Network (WAN). This WAN permits the individual trauma center computers to communicate and provides a back bone for the automatic migration of data from the centers to the central repository. The CIREN trauma centers were added to the NASS WAN and Oracle servers were placed at each center. The WAN is a frame-relay private TCP/IP network running on fractional T1 lines.

Each center is equipped with a Windows NT Pentium II server running Oracle 8.03 with adequate disk space to maintain 500 active cases. Storage includes images and text. A central repository is maintained at the Volpe National Transportation Systems Center (Volpe) in Cambridge, MA. The central repository is a SUN Enterprise 3000 system with optical jukebox with 180 gigabytes of on-line storage.

CIREN Data Set

The CIREN database consists of the NASS data set augmented with medical and injury variables. Oracle version 8.0 is the database engine. The NASS data set contains variables which describe an automotive crash including but not limited to:

- Crash Type
- Vehicle Make, Models and Body Types
- Crash deformation classification (CDC)
- Crush Profiles
- DeltaVs
- Intrusions
- Occupant Contacts

The medical and injury data elements includes tables for

- Co-morbidity
- Diagnostic Procedures
- Complications
- Operative Procedures
- Medical Images
- Disability Measurements
- Emergency Medical Response
- Emergency Medical Treatment
- Vital Signs
- Physiologic Measurements
- Injury Location
- Ventilation Periods
- Intensive Care Unit Stays

Each CIREN case is one injured occupant in a motor vehicle crash. The medical data listed above is linked to the crash data.

The principal table of the CIREN data set is the CIRENINJURY table. The design of this table permits the linking of injuries to its mechanisms, diagnostic procedures, patient history ,vehicle information, etc. The patient's injuries are stored in the CIRENINJURY table and initially coded using the 1990 Abbreviated Injury Scale (AIS). During a coding conference the injury is linked to appropriate subclassification systems, the crash intrusions and contacts, bio-mechanical descriptors and human mannequins. The human mannequins are a set of line drawings of organ systems. Labels and drawings are over-layered on the standard drawings to clarify position and mechanisms. Diagnostic and operative procedures are also linked to the appropriate injury.

The structure of the CIRENINJURY table permits the story of the injury. For example, an A-Pillar intrusion/contact causes a C1 fracture which in turn causes a spinal laceration via a sheer mechanism.

Data Migration

Each center may check the central repository for the current case types within the entire system. The central repository maintains core elements of every case within the system. Core elements include a preliminary injury list, accident type, vehicle make and model, CDC and the like. Any center may query the central repository , obtaining a list of cases both completed and active. Completed cases may be downloaded and reviewed. An active case may be requested from the originating center.

This core repository permits each center to rapidly look for trends and to compare data.

These functions are possible because of nightly data migration. The data migration algorithms were specifically developed for the NASS system and have ben adapted for the CIREN system. These processes maximize the speed of transfer and the synchronization of data copies across the network. Oracle Replication could not be used as data may be modified across multiple sites at different times. Our migration systems handle partial case ownership within and across centers.

Cross Center Expertise

Each center specializes in certain areas. For example the University of Maryland is expert in the Orthopedic Trauma Association (OTA) classification system, a detailed fracture classification system. Other centers may request their assistance for orthopedic classification of injuries.

The pertinent portions of the case are transferred to the "expert"center for analysis and coding. Both centers may simultaneously review the cases and education seminars around the case may be held across the two centers.

Electronic Rounds

Electronic rounds are the simultaneous viewing of the CIREN data across all centers in real time with the presentation driven by one center. The rounds are a core feature for the increased communication between centers.

Simultaneous data viewing across all centers is accomplished by migrating read only case copies across all the Oracle databases. As the data is local, the data is viewed real time at all the centers, even though driven by a single center. This eliminates the need for large bandwidth for group conferences.

Image Storage

The system stores all medical images, including x-rays, CT scans, etc. within the Oracle database. The images are stored in JPEG2 format. Images are imported directly in the case of digital cameras or through high resolution scanners.

Multiple images are viewable with the text data to assist in analysis and presentation.

Injury Localization

CIREN brings medical professionals and bio-engineers together. The bio-engineer requires a detailed localization of an injury in order to effectively analyze the mechanics and discover new relationships. The CIREN system includes line drawing mannequins which are mapped to area describers so that there are discrete elements linked to the graphic representation of the injury's locale. These discrete elements permit raw data analysis previously unable on the pure graphical representation.

Injury drawings are layered on top of the mannequin and not directly on the mannequin. This is transparent to the user. The injury layers may be added together or "clustered" so that patterns over several patients may be analyzed. This graphic "addition" highlights repetitive patterns, e.g. chest bruising from seat belts.

Conclusion

CIREN's computer system standardizes nomenclature across the seven centers, permits rapid identification of injury patterns, sharing of data and resources. As the system is implemented, the participating trauma centers may use the network to increase communication, share analytical expertise and work closer with bio-engineers. Hopefully, the system will assist in the early recognition of injury patterns and mechanism.

EPIDEMIOLOGY OF THE OLDER DRIVER -- SOME PRELIMINARY FINDINGS FROM DATA THROUGH 1996

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ABSTRACT

Although there is an ever increasing literature on older drivers, there is not available a comprehensive up-to-date epidemiologic presentation of the salient characteristics of how older drivers are impacted by traffic safety, and how they impact road safety for others. This paper presents preliminary results for such an undertaking, using data through 1996. The approach is to examine how many different measures (fatalities, fatalities per licensed driver, etc.) depend on age and gender. Risks drivers pose to other road users are estimated by driver involvement in pedestrian fatality crashes. It is found that renewing the license of a 70-year-old male driver for another year poses, on average, 40% less risk to other road users than renewing the license of a 40-year-old male driver. The fatality risks drivers themselves face generally increase as they age, with the increased risk of death in the same severity crash being a major contributor. If this factor is removed, crash risks for 70-year-old male drivers are not materially higher than for 40-year-old male drivers; for female drivers they are. For all drivers most risk measures increase substantially by age 80, in many cases to values higher than those for 20-year-olds. Given that a death occurs, the probability that it is a traffic fatality declines steeply with age, from well over 20% for late teens through mid twenties, to under one percent at age 65, and under half a percent at age 80.

INTRODUCTION

A comprehensive overview of how the risks faced by drivers change as they age, and the risks they impose on others change as they age, is the subject of Chapter 2 of Ref. [1]. The results presented there were based on data from the mid 1980's. Because of substantial demographic and other changes in US society, there is a need to examine how the effects reported in [1] may have changed. This paper uses data through 1996 to present how various rates related to safety depend on age (broken down by gender). In order to facilitate easy comparison of the present relationships with those of the mid 1980s, the present paper introduces topics in the same order as in [1].

Changes in driving risk with increasing age are best separated into two distinct components:-

Changing risks to the drivers themselves,

and

Changing risks they impose on other road users.

These risks are of a different nature. There is near universal agreement that society should take stronger measures to prevent its members from doing things that endanger others than to prevent them from doing things that endanger only themselves. Public safety makes a stronger claim on public resources than does personal safety, which can be supported often using personal resources. Differences between the risks we assume ourselves and those we impose on others impact on legislation, licensing policy, police enforcement, and so on.

These questions are addressed by plotting a number of rates versus age and gender (almost everything examined in traffic safety is a rate -- for example, the number of traffic fatalities per year, or per three years).

Data

The following data sets are used:

1. Fatality Analysis Reporting System (FARS), a census of all traffic crashes in the United States since 1975 in which anyone was killed on a public road [2].

2 Bureau of the Census estimates of the resident population on July 1 by age (in 1 year increments) and gender [3].

3 Federal Highway Administration (FHWA) data giving numbers of driver licenses [4].

4 National Personal Transportation Study (NPTS, run by FHWA) giving estimates of travel based on a diary approach [5].

5. Deaths from all causes [6].

6. Relationships between the risk of death from the same physical insult and gender and age, as presented in [1].

Relationships using the NPTS data will be for 1995. For all other cases averages over the three years 1994-1996 are computed. The resulting relationships have a center year of 1995, so that all the material presented may be interpreted as referring to 1995.

Unless stated otherwise, "driver" means a driver of any motorized vehicle, including a motorcycle, truck, bus, etc. This choice insures a simple categorization of all traffic fatalities as either drivers or non-drivers; pedalcyclists are considered non-drivers. The dependence of driver fatalities on age and gender examined below thus reflects choice of vehicle, how it is used and what the consequences of a crash are, given that one occurs, all factors which are themselves strongly influenced by age and gender.

Data for, say, 70-year-olds, is plotted at the (approximate) average age of 70-year-olds, namely 70.5 years, a practice that will be followed when the modes and medians of distributions are presented.

Some characteristics of the rates are displayed directly on the graph. The maximum value, and the age at which it occurs (the mode age), is given only if there is a clear maximum not at the extremes of very young or very old values. The median age, say, for driver fatalities, is defined such that half of fatalities occur to drivers of younger age and half to drivers of older age. This is estimated by linear interpolatioon between the cumulative distribution values just less than 0.5 and just greater than 0.5.

This paper relies exclusively on cross-sectional analysis, in which consecutive points refer to a different set of people, not to the same set, or cohort, growing older. Examining cohorts as they age (longitudinal analysis) requires collecting data over as many years as the age dependence is examined. In keeping with the practice in epidemiology, cross-sectional points are not generally joined by lines. However, the points are joined in a few cases to assist the eye in following the relationships.

CHANGING RISKS DRIVERS FACE AS THEY AGE

Fig. 1 shows the average number of driver fatalities per year versus age and gender for the three years 1994-1996. Fig. 1 exhibits the same general characteristics as Fig. 2-5 of [1], which showed data summed for the five years 1981-1985.

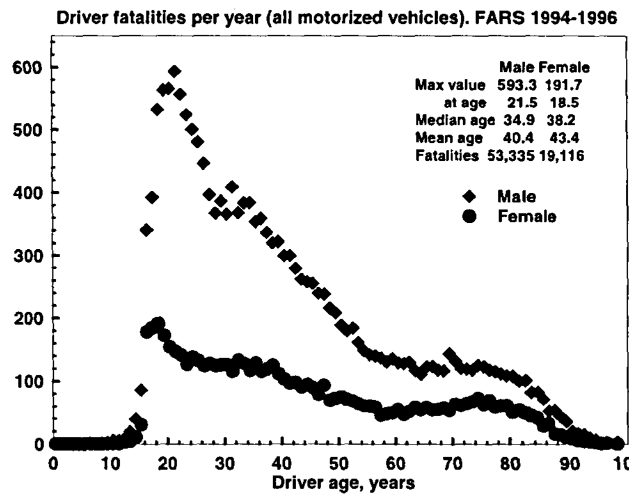

Fig. 1. Average number of driver fatalities per year (all motorized vehicles) versus gender and age, based on FARS 1994-1996

Fig. 2 shows the data in Fig. 1 normalized for population. The point plotted in Fig. 2 at (say) age 70 is the number of 70-year-old drivers killed from 1994-1996 divided by the sum of the number of 70-year-olds in each of these years. This plot is therefore an average, weighted by population, of graphs for individual years, all of which look similar (with more noise) to Fig. 2. Fig. 2 shows driver deaths per capita increase with age for males over about age 65 much more steeply than observed in 1980s data [1]. The moderate increase for females over about age 65 in Fig. 2 does not occur in the 1980 data.

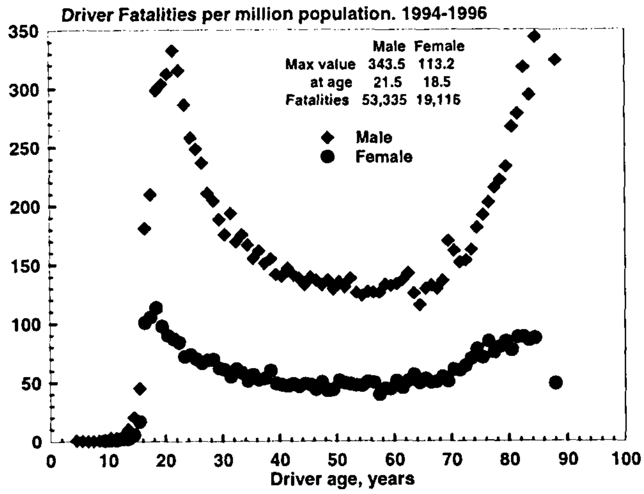

Fig. 2. Driver fatalities (all motorized vehicles) per million population versus gender and age. Based on FARS and US Bureau of the Census data, 1994-1996.

Fig. 3 shows driver fatalities per licensed driver. The general pattern differs from that in Fig. 2 only insofar as the fraction of the population holding driving licenses varies with age. In particular, older females are less likely than those in mid life to have driver licenses. Thus, in contrast to Fig. 2, the rates in Fig. 3 increase similarly with age for males and females older than about 65.

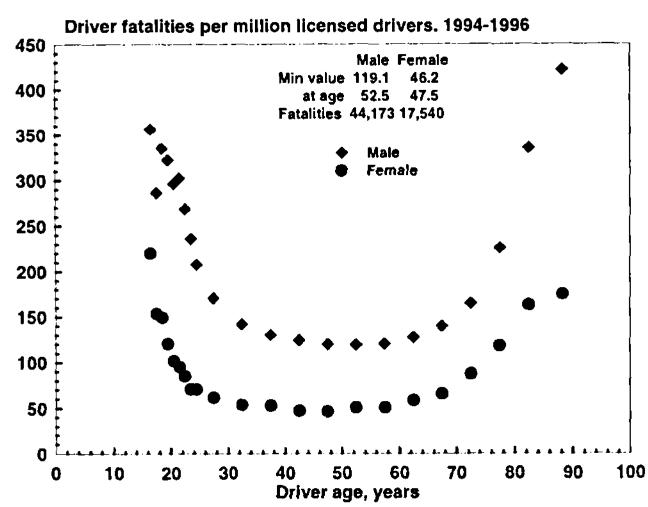

Fig. 3. Fatally injured drivers (all motorized vehicles) with valid driver licenses per million licensed drivers versus gender and age. Based on FARS and Federal Highway Administration data, 1994-1996

Fig. 3 reflects only fatally injured drivers with valid licenses. The percent of fatally injured drivers lacking a valid driver license depends strongly on driver age. This is shown in Fig. 4, in which a log scale shows that at very young and very old ages, a substantial majority of fatally injured drivers are unlicensed. As 15-year-olds cannot generally obtain licenses, nearly all 15-year-old drivers killed will not have licenses. The increase at older ages is consistent with the interpretation that as licenses are revoked, many older drivers continue to drive and are killed as a consequence.

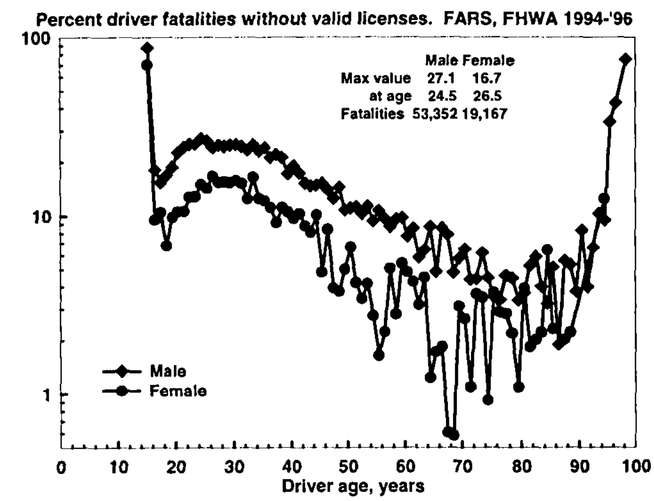

Fig. 4. The percent of fatally injured drivers without valid driver licenses at the time of their fatal crash. The denominator is those with valid or unknown license status. Based on FHWA, 1994-1996.

The number of driver fatalities per unit distance travelled, plotted on a log scale in Fig. 5, shows further elevation for older and younger ages above the average. The increases at older ages and younger ages are so much larger than the increasses in fatalities per licensed driver (Fig. 3) because older and younger drivers travel less than average drivers do (Fig. 6).

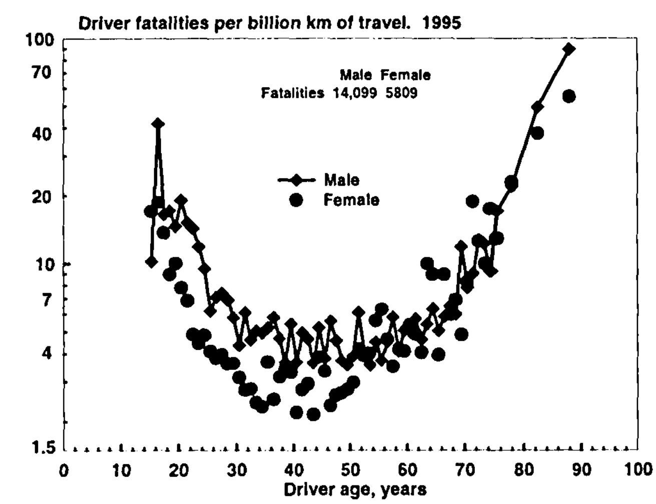

Fig. 5. Driver fatalities (all motorized vehicles except large commercial trucks) per billion km of travel versus gender and age. Based on FARS 1995, NPTS 1995.

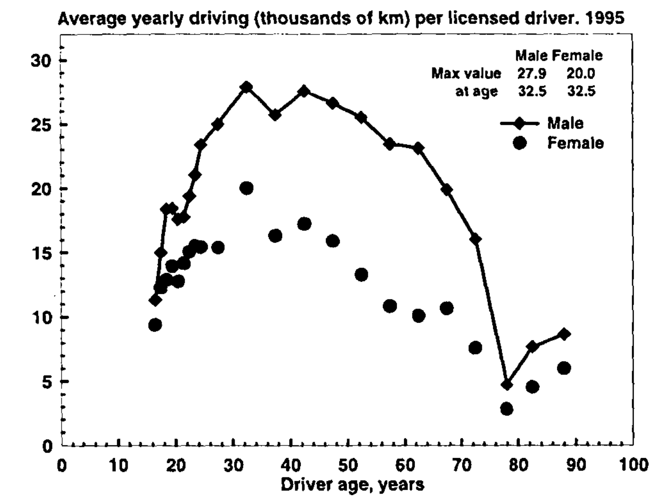

Fig. 6. Estimates of distance driven per year, based on FHWA 1995 and NPTS 1995.

Involvement rates in severe crashes

Increases with age like those in Figs 2, 3 and 5 have often been interpreted in terms of the drivers' risk of getting involved in a crash. Such an interpretation misses the crucial point that the number of drivers of given age and gender killed is the product of two factors:

1. The number of involvements in very serious crashes

and

2. The probability that involvement proves fatal.

The first factor reflects influences due to all use and behavioral factors, such as amount and type of driving, driver capabilities, type of vehicle driven, time of day, degree of intoxication, and driving risks. The second factor can be influenced also by such behavioral factors as safety belt wearing and alcohol consumption. Apart from such considerations, the probability that a given crash results in death is essentially physiological rather than behavioral in nature, and for the present purposes can be adequately approximated by the relationships given on page 26 of [1], which are:

$$R_{males}(A) = \exp 0.0231\,(A - 20) = 0.630 \exp(0.0231\,A) \qquad \text{Eqn 1}$$

and

$$R_{females}(A) = 1.3 \exp 0.0197\,(A - 20) = 0.877 \exp(0.0197\,A) \qquad \text{Eqn 2}$$

where R(A) is the fatality risk to an individual of age A compared to the risk to an individual of age 20 when both are subject to the same physical insult, or impact. When driver age is 16 to 20, we assume R = 1 for males and R = 1.3 for females; that is, the fatality risk from the same severity crash is the same as for a 20-year-old driver of the same gender.

Equations 1 and 2 are based on analyzing 80,000 fatalities in FARS 1975-1983. An update using recent data is planned as part of the ongoing work in this area.

Fatality rates focus on the outcome, not the severity of the crash that led to the death. Here we examine involvement rates in crashes of similar severity by considering crashes in a severity range greater than or equal to that sufficient to likely kill 80-year-old male drivers, for which case R has a value of 4.0 (Eqn 1). Consider the mix of crashes in which N fatalities occur to 80-year-old males. If these crashes were repeated keeping all factors the same except the drivers, then we would expect 0.25N fatalities for 20-year-old male drivers and 0.325N fatalities for 20-year-old female drivers (Eqn 2). In order to obtain the same number of fatalities, 4.0 times as many crashes by 20-year-old drivers, and 3.1 times as many crashes by 20-year-old female drivers are required. In this way we can use the observed numbers of fatalities to infer involvement rates in crashes in the severity range sufficient to likely kill 80-year-old male drivers.

Fig. 7 shows the number of involvements in crashes in the same severity range per licensed driver versus age and gender. In contrast to the earlier figures, the increase at older ages is much less, showing that a major component of increasing risk with increasing age is due to greater risk of being killed in the same crash.

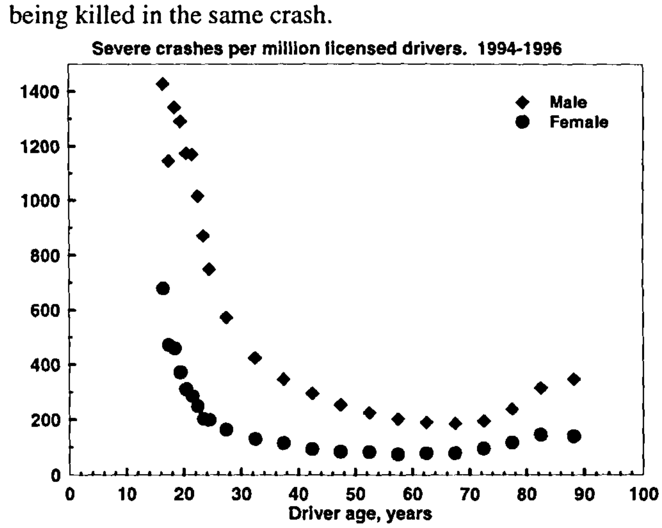

Fig. 7. Estimated licensed driver involvements (all motorized vehicles) per million licensed drivers in crashes of sufficient severity to likely kill 80-year-old-male drivers versus gender and age.

Severe crash involvements per unit distance of travel (Fig. 8) increase with increasing driver age for ages above about 60. However, the increase is smaller than in Fig. 5; even at the oldest age plotted, the rates for males and females are still less than those for male drivers under 30.

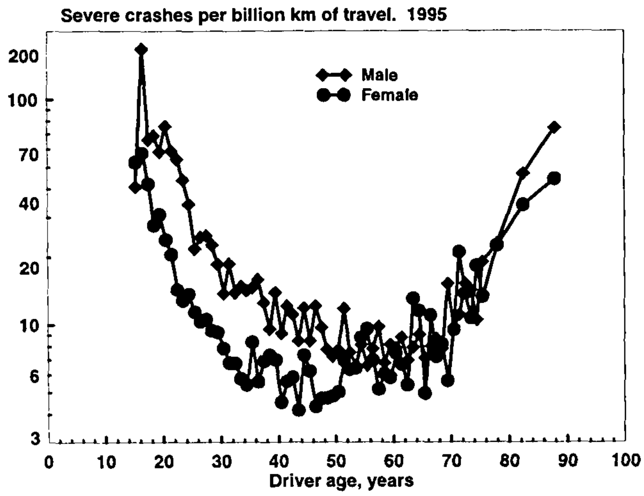

Fig. 8. Estimated driver involvements (all motorized vehicles) per billion km of travel in single-vehicle crashes of sufficient severity to likely kill 80-year-old-male drivers versus gender and age.

THREAT TO OTHER ROAD USERS

All the above focused on how the age and gender of a driver influence the threat to the driver's own life. In many ways this risk is presumed to be largely under the control of the driver. Here we address how the risk a driver poses to other road users depends on the driver's age and gender. This question raises a host of different issues which are relevant to discussion of driver licensing policy, in particular licensing test procedures that may make it more difficult for the elderly to obtain licenses. We investigate the threat to other road users by examining the number of crashes in which pedestrians are killed as a function of the age and gender of drivers (of any type of motorized vehicle) involved in the crashes. Attention is confined to single-vehicle crashes because when more than one vehicle is involved it is not always possible to determine from the FARS data which vehicle struck the pedestrian. In addition, involvement in multiple-vehicle crashes poses threats to drivers different from those of single vehicle crashes in which pedestrians are killed; the drivers of cars in single-vehicle pedestrian-fatality crashes are themselves usually not injured. No assumption is made regarding responsibility in pedestrian fatality crashes; the FARS data show about one third of fatally injured pedestrians have blood alcohol concentrations in excess of 0.1 percent by volume, the legal limit for intoxication in most US states.

Figs 9 through 12 show the variables for crashes involving pedestrian fatalities corresponding to those above for driver fatalities. The similarity between each corresponding set of curves reflects the extent to which driver involvement in pedestrian fatality crashes is proportional to driver fatalities, the basis of the pedestrian fatality exposure approach discussed in Chapter 4 of [1]. Only one of the four relationships, namely Fig. 12, which shows pedestrian fatality crashes per unit distance of travel, indicates an increase with age for older drivers.

Note particularly that the number of pedestrian fatality crashes per licensed driver does not increase at older ages. In terms of the decision to grant a license for a fixed period of time, a 20-year-old male is over 100% more likely to be involved in a crash in which a pedestrian is killed than is a male driver older than 70 years.

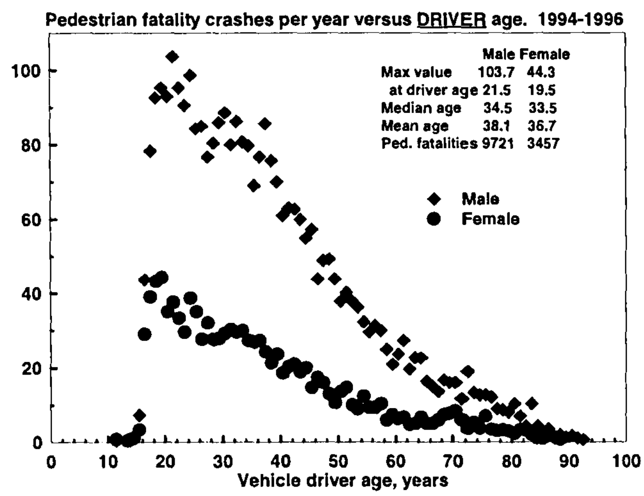

Fig. 9. Number of single vehicle crashes per year in which one or more pedestrians were killed versus the age and gender of the driver. FARS 1994-1996

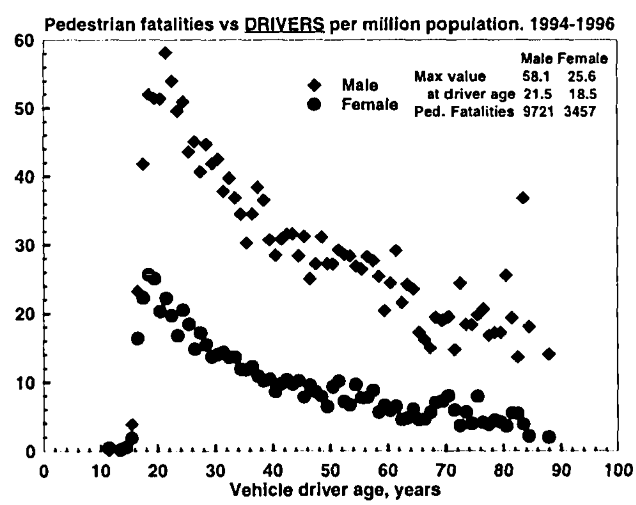

Fig. 10. Number of single vehicle crashes per million population in which one or more pedestrians were killed versus the age and gender of the driver. Based on FARS and census data for 1994-1996.

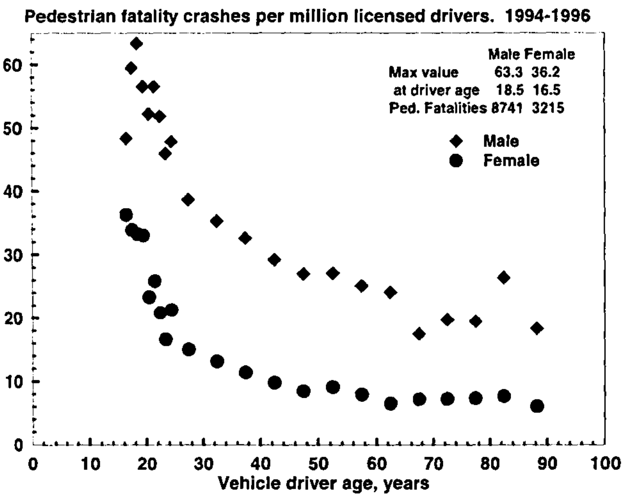

Fig. 11. **Number of single vehicle crashes per million licensed drivers in which one or more pedestrians were killed versus the age and gender of the driver. Based on FARS and Federal Highway Administration data for 1994-1996.**

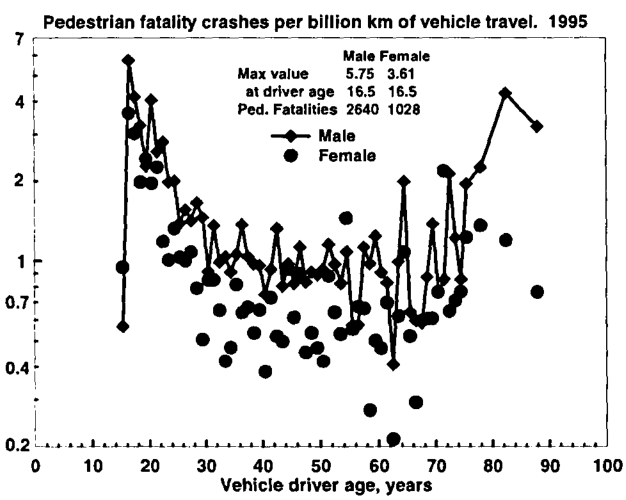

Fig. 12. **Number of single vehicle crashes per billion km of travel in which one or more pedestrians were killed versus the age and gender of the driver. Based on FARS, and Nationwide Personal Transportation Study data for 1995.**

PEDESTRIAN INVOLVEMENTS IN FATAL AND SEVERE CRASHES

Above we examined the age and gender of drivers involved in crashes in which pedestrians were killed. We now examine the age and gender of the pedestrians involved without regard to the characteristics of the involved drivers

Fig. 13 shows the distribution of pedestrian fatalities by pedestrian age and gender. The same data normalized by population are shown in Fig. 14.

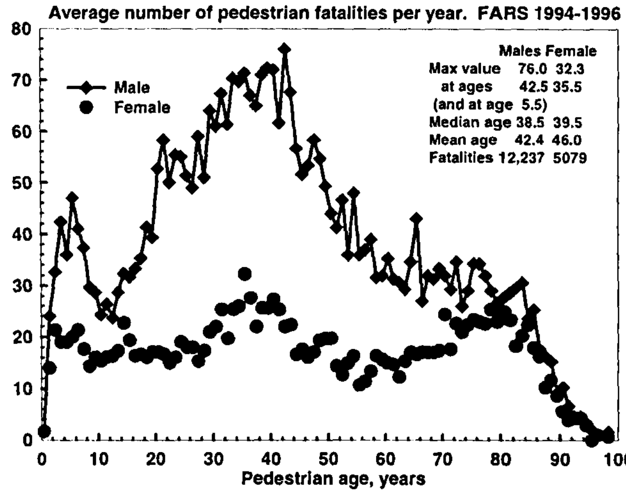

Fig. 13. **Average number of pedestrian fatalities per year versus gender and age, based on FARS 1994-1996. Distinct maximum values occur males at ages 5 and 42.**

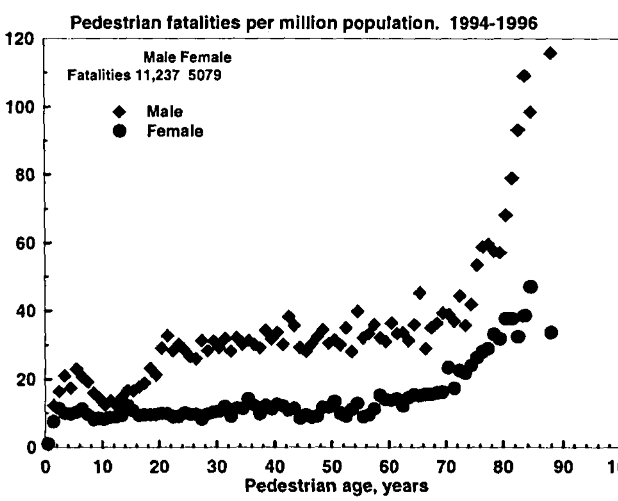

Fig. 14. **Pedestrian fatalities per million population versus gender and age. Based on FARS and US Bureau of the Census data for 1994-1996.**

Fig. 15 shows the ratio of male pedestrian deaths per capita to female pedestrian fatalities per capita. This figure, which uses FARS and Census data 1986-1996, is remarkably similar to Fig. 6-5 (p. 139) of [1], thereby offering additional support for the interpretation given there. Fig. 15 and Fig. 6-5 of [1] are derived using independent, non-overlapping data, and consequently reveal stable intrinsic behavioral differences at a fundamental level between the genders.

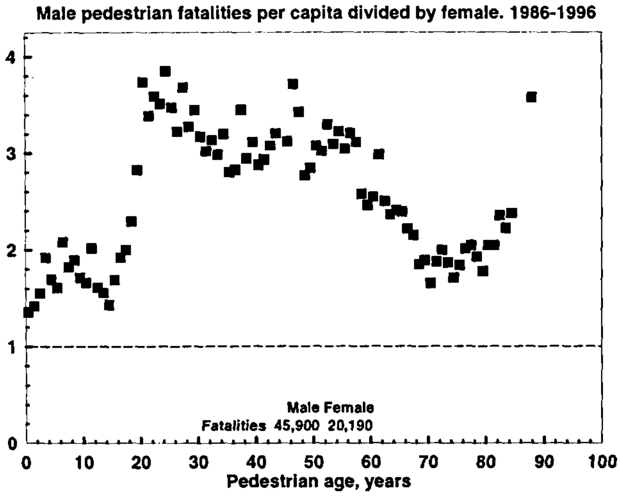

Fig. 15. Number of male pedestrian fatalities per capita divided by female pedestrian fatalities (of the same age) per capita based on FARS and census data for 1986 through 1996.

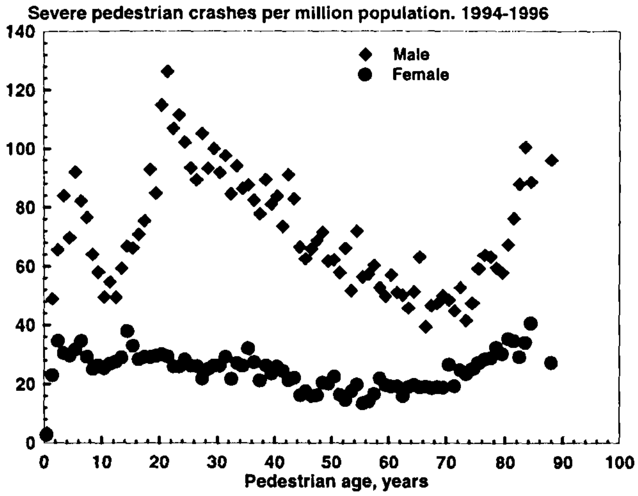

Fig. 16. Estimated pedestrian involvements per million population in crashes of sufficient severity to likely kill 80-year-old male pedestrians versus gender and age.

Part of the large increase in pedestrian fatalities per capita with increasing older ages in Fig. 14 is due to the greater likelihood that the older person is killed in a crash which a younger one would survive. In order to estimate the risk of involvement in a severe crash, as distinct from the outcome, we again use the relationships between risk of death from the same impact and gender and age given in Eqns 1 and 2. Fig. 16 shows the number of pedestrian involvements in crashes in the severity range equal to or greater than that necessary to kill an 80-year-old male pedestrian. Like the driver fatality data, the pedestrian fatality data show peaks at about age 21 for males. The increasing involvement in severe pedestrian crashes with increasing age at ages above about 65 is probably reflecting decreasing perceptual and agility skills, and also perhaps increased pedestrian exposure related to driving less.

TYPES OF CRASHES IN WHICH OCCUPANTS OF DIFFERENT AGES ARE KILLED

Over 90% of the 35,579 vehicle occupants killed in 1996 were occupants of cars or light trucks [7, page 18]. We here examine how the mix of crashes for these vehicles depends on occupant age.

Table 1 shows the number of occupants aged between 68 through 72 years old who were killed in crashes according to vehicle and crash type. We refer to this group as 70-year-old occupants (strictly, the center of the range is much closer to 70.5). Corresponding information is presented for 40-year-old (Table 2) and 20-year-old (Table 3) occupants. Table 4 shows the information for all occupants, regardless of age.

The fatality counts in tables 1-4 facilitate many comparisons. For example, substantially more 70-year-old occupants die in multiple-vehicle crashes than in single-vehicle crashes, the difference being so for cars and for light trucks. The effect is similarly consistent, but in the opposite direction for 20-year-old-occupants. Such comparisons cannot determine whether, say, the 70-year-olds are more involved in multiple vehicle crashes or less involved in single-vehicle crashes.

Given that a 70-year-old occupant is killed, the probability that the crash was a non-collision (most non-collisions are rollovers) is 2.3% for cars, and 7.6% for light trucks. The corresponding estimates for 20-year-olds are 10.1% for cars and 27.0% for light trucks. The larger values for light trucks reflects that in a given set of crashes, the portion that are rollovers tends to be greater for vehicles with higher centers of gravity. However, note that given that a fatality occurs, the probability that it is a rollover is lower for a 70-year-old in a truck than for a 20-yea-old in a car. This is likely a reflection of the overriding importance of driver behavior.

Table 1.
Distribution of vehicle occupants age 68, 69, 70, 71 or 72 (five year range centered at 70) killed in crashes in 1996.

1996 car-occupant fatalities
Age 70 – total 961

Single-car crashes	235	Multiple-vehicle crashes	726
Tree	52	Car / car	278
Utility pole	19	Car / LT	230
Guardrail	11	Car / Hvy T	109
Bridge structure	8	Car / Other	4
Rail train	7	3 or more vehicles	105
Parked motor veh.	10		
All other objects	106		
Non-collision	22		

1996 LT-occupant fatalities
Age 70 – total 355

Single-LT crashes	136	Multiple-vehicle crashes	219
Tree	28	LT / LT	59
Utility pole	8	LT / Car	58
Guardrail	8	LT / Hvy T	62
Bridge structure	5	LT / Other	3
Rail train	4	3 or more vehicles	37
Parked motor veh.	1		
All other objects	55		
Non-collision	27		

Table 2.
Distribution of vehicle occupants age 38, 39, 40, 41 or 42 (five year range centered at 40) killed in crashes in 1996.

1996 car-occupant fatalities
Age 40 – total 1385

Single-car crashes	610	Multiple-vehicle crashes	775
Tree	121	Car / car	249
Utility pole	48	Car / LT	255
Guardrail	29	Car / Hvy T	136
Bridge structure	16	Car / Other	9
Rail train	19	3 or more vehicles	126
Parked motor veh.	16		
All other objects	241		
Non-collision	120		

1996 LT-occupant fatalities
Age 40 – total 942

Single-LT crashes	579	Multiple-vehicle crashes	363
Tree	86	LT / LT	112
Utility pole	27	LT / Car	94
Guardrail	34	LT / Hvy T	98
Bridge structure	13	LT / Other	7
Rail train	19	3 or more vehicles	52
Parked motor veh.	9		
All other objects	173		
Non-collision	218		

Table 3.
Distribution of vehicle occupants age 18, 19, 20, 21 or 22 (five year range centered at 20) killed in crashes in 1996.

1996 car-occupant fatalities
Age 20 – total 3675

Single-car crashes	2057	Multiple-vehicle crashes	1618
Tree	486	Car / car	481
Utility pole	183	Car / LT	562
Guardrail	117	Car / Hvy T	300
Bridge structure	40	Car / Other	8
Rail train	32	3 or more vehicles	267
Parked motor veh.	31		
All other objects	796		
Non-collision	372		

1996 LT-occupant fatalities
Age 20 – total 1328

Single-LT crashes	940	Multiple-vehicle crashes	388
Tree	126	LT / LT	132
Utility pole	29	LT / Car	88
Guardrail	56	LT / Hvy T	116
Bridge structure	23	LT / Other	5
Rail train	10	3 or more vehicles	47
Parked motor veh.	6		
All other objects	331		
Non-collision	359		

Table 4.
Distribution of vehicle occupants of all ages killed in crashes in 1996.

1996 car-occupant fatalities
All ages – total 22,416

Single-car crashes	9302	Multiple-vehicle crashes	13,114
Tree	2092	Car / car	4191
Utility pole	781	Car / LT	4424
Guardrail	531	Car / Hvy T	2265
Bridge structure	236	Car / Other	75
Rail train	201	3 or more vehicles	2159
Parked motor veh.	226		
All other objects	3621		
Non-collision	1614		

1996 LT-occupant fatalities
All ages – total 9904

Single-LT crashes	5776	Multiple-vehicle crashes	4128
Tree	819	LT / LT	1300
Utility pole	215	LT / Car	1033
Guardrail	295	LT / Hvy T	1090
Bridge structure	138	LT / Other	44
Rail train	148	3 or more vehicles	661
Parked motor veh.	83		
All other objects	1954		
Non-collision	2124		

TOTAL TRAFFIC FATALITIES

Fig. 17 shows the average number of people killed per year in the United States in traffic crashes (sum of FARS values for 1994-1996 divided by 3). The total number of data, 123,842, differs from the total number of fatalities [7] in the three-year period, 40,716 + 41,817 + 41,907 = 124440 by the very small percent of occupants for which either age or gender was uncoded. The percent of all fatalities which were driver fatalities is shown in Fig. 18.

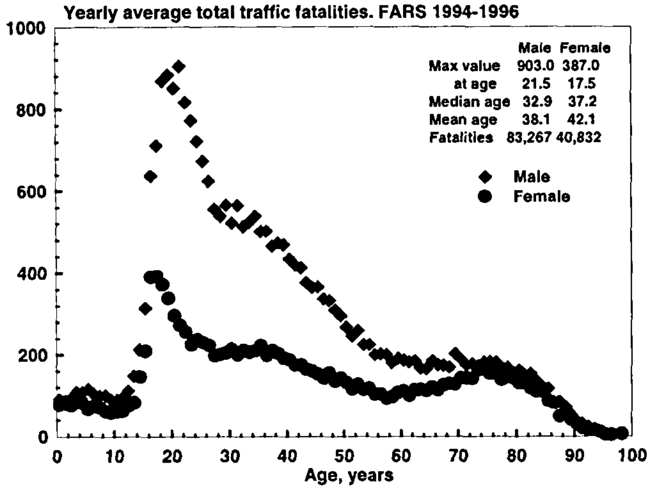

Fig. 17. The average number of people killed per year in US traffic crashes.

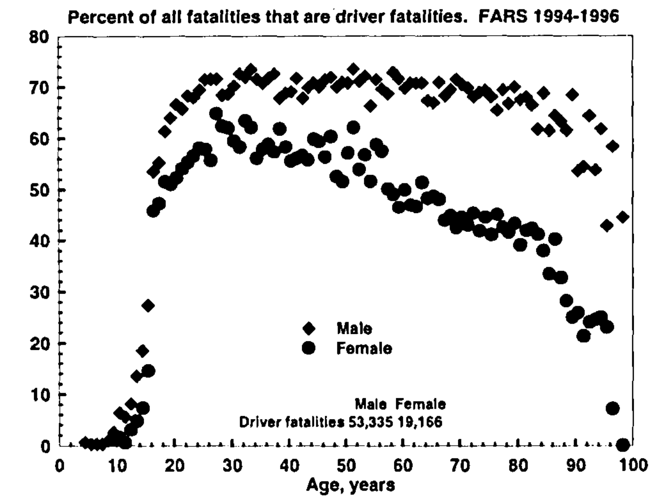

Fig. 18. The percent of all traffic fatalities (Fig. 17) that are driver fatalities. FARS 1994-1996.

Table 5 presents some of the actual fatality counts that contributed to the distribution in Fig. 17. One year, 1996, is selected to avoid the ackwardness of fractional fatalities per year; the values in 1994 and 1995 are quite similar.

Table 5

Number of 1996 traffic fatalities in Fig. 17 at selected specific ages. The first row refers to babies from birth to just prior to their first birthday (plotted at age = 0.5), the second row refers to children from their 5th birthday to just prior to their 6th birthday (plotted at age 5.5), and so on.

Age	Number of fatalities		
	Male	Female	Total
0	96	71	167
5	114	62	176
10	81	69	150
15	310	229	539
18	890	386	1276
25	716	237	953
30	449	231	680
40	439	201	640
50	262	122	384
60	168	117	285
70	196	145	341
80	153	139	292
90	39	39	78
95	5	6	11

Table 5 shows that 114 five-year-old boys and 62 five-year-old girls were killed in 1996 traffic crashes (over a thousand children aged 3 through 9 were killed.). One hundred sixty seven babies were killed before their first birthday.

TRAFFIC DEATHS RELATIVE TO ALL DEATHS

A noticeable feature of the ratio of traffic deaths to all deaths (Fig. 19) is the lack of a clear difference between the genders. Indeed, from the 20s through the 70s the fraction of all deaths that are traffic deaths declines at an approximately constant rate of 8 % per year for both genders. The percent of all deaths that are traffic fatalities fit extremely well the relationships 143.0 exp (-0.0775 age) for males and 135.8 exp (-0.0788 age) for females for ages from ages 27 to 70.

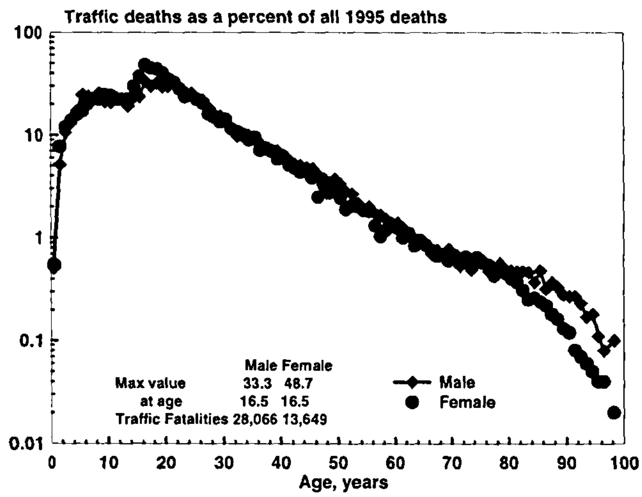

Fig. 19. Traffic deaths expressed as a percentage (on a logarithmic scale) of total deaths from all causes (including traffic). All data are for 1995.

Table 6 shows illustrative ages selected from the plotted data. Given that a death occurs in the teens through the twenties, the probability that it is a traffic fatality is over 20%. As drivers age, the risks from other causes of death increase much more rapidly than any increases of risk in traffic. Given that a 65-year-old dies, the probability that death is due to a traffic crash is less than one percent. For an 80-year-old it is less than half a percent.

Table 6
The percent probability that a death is a traffic fatality in 1995. Illustrative values from Fig. 19.

Age	Male	Female	Total
0	0.51	0.55	0.53
5	24.61	17.27	21.57
10	20.72	24.21	22.19
15	23.77	37.06	28.09
18	32.24	43.62	35.03
25	22.63	22.21	22.52
30	13.13	14.13	13.40
40	6.33	6.18	6.28
50	3.32	2.42	2.99
60	1.39	1.24	1.33
65	0.88	0.85	0.87
70	0.66	0.67	0.66
80	0.48	0.40	0.44
90	0.27	0.12	0.17
95	0.11	0.04	0.05

Traffic rates compared to crime rates

The top graph in Fig. 20 shows number of drivers involved in crashes of sufficient severity to likely kill 80 year-old drivers (computed as for Fig. 7 etc.). The bottom graph has nothing to do with traffic -- it is based on FBI compilations of arrests for all crimes except those relating to traffic. Figure 20 may be compared to Fig. 6-7, p. 142, of [1]. The interpretation presented there applies also to the present figure.

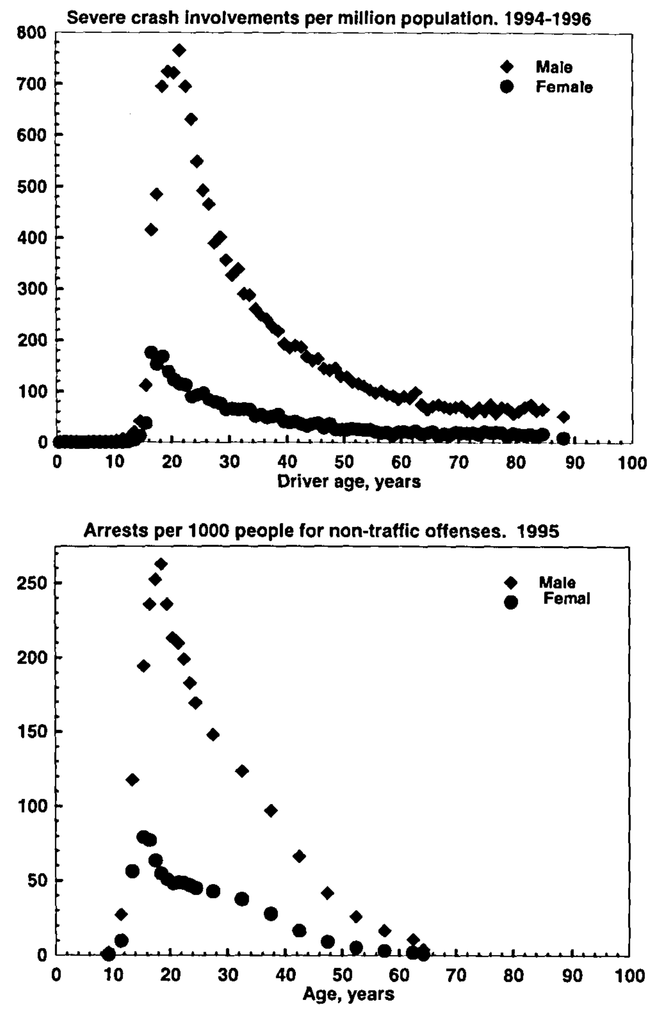

Fig. 20. *Top:* Estimated driver involvements per capita in severe single-vehicle crashes. *Bottom:* Number of arrests per capita for non-traffic-related offenses.

SUMMARY OF MAIN FINDINGS

Summary information from the graphs is presented below. When data are available in one year increments, the values are computed by averaging over three years (that is, the value for 70-year-olds is the average of the values at 69.5, 70.5 and 71.5. When data are available only in 5 year increments, the average of two values is used (the value for 70-year-olds is the average of the values for 67.5 and 72.5. In some cases the estimates at age 80 are based on relatively small sample sizes.

Risks older drivers impose on others

The risks that 70-year-old drivers impose on other road users is compared in Table 7 to the risks imposed on others by 40-year-old drivers and by 20-year-old drivers. The ages 40 and 20 were chosen to typify the generally safest age and a high risk age, respectively.

Table 7.

Risks 70-year-old drivers pose to other road users compared to the risks posed by 40- and 20-year-old drivers, as measured by involvement in single-vehicle crashes killing pedestrians. The first entry indicates that, on average, licensing a 70-year-old male poses 40% less risk than licensing a 40-year-old. Compared to licensing a 70-year-old male, licensing a 20-year -old poses 198% more risk to others.

	Male		Female	
	Age 70 / Age 40	Age 20 / Age 70	Age 70 / Age 40	Age 20 / Age 70
Per licensed driver (Fig. 11)	**0.60**	**2.96**	**0.68**	**3.81**
For same distance of driving (Fig. 12)	**1.14**	**2.98**	**2.02**	**1.87**

Renewing the license of a 70-year-old male driver for another year imposes, on average, 40% less risk to other road users than renewing the license of a random 40-year-old male driver. Renewing the license of a 20-year-old male driver compared to a 70-year-old male driver imposes an increased risk to others of 196%.

One of the reasons older drivers pose less of a threat per year to others is that they drive less (Fig. 6). In terms of risks for the same distance traveled, the 70-year-old driver poses a 14% higher risk than the 40-year-old. The female risks, with values much lower at 40, proportionally increase more even though their values are lower than for males at essentially all ages.

Table 8 shows information parallel to that in Table 7, but for 80-year-old drivers. Granting a license for another year to an 80-year-old driver poses substantially less risk to other road users than granting a license to a 40-year-old driver.

Table 8.

Risks 80-year-old drivers pose to other road users compared to the risks posed by 40-year-old and 20-year-old drivers, as measured by involvement in single-vehicle crashes killing pedestrians.

	Male		Female	
	Age 80 / Age 40	Age 20 / Age 80	Age 80 / Age 40	Age 20 / Age 80
Per licensed driver (Fig. 11)	**0.74**	**2.40**	**0.70**	**3.67**
For same distance of driving ((Fig. 12)	**3.71**	**0.91**	**1.88**	**2.01**

Risks older drivers themselves face

In general, as drivers become older, most measures indicate increases in risk as they age. A major contributor to this is that the same severity crash is more likely to lead to the death of an older person. In terms of the measures which best reflect the behavioral aspects of driving, namely, driver involvements in severe crashes per unit distance of travel (Table 9), and crashes in which pedestrians were killed per unit distance of travel (Table 7), the values for 70-year-old male drivers are not particularly different from those of 40-year-old male drivers. (Many factors could contribute to a lack of difference, such as the older drivers confining driving to safer periods, less alcohol use, etc.). By age 80 (Tables 8 and 10) there is a substantial increase in risk of involvement; for female drivers increases are also substantial by age 70.

The above discussion has focused on how various measures depend on average chronological age. Not only do various measures of driver performance decline with age, but variability among individuals also increases, underlying the importance of not judging an individual's fitness to drive on the basis of chronological age.

Table 9.
Risks faced by 70-year-olds compared to risks faced by 40- and 20-year-olds. The first entries indicates that, for males, a random 70-year-old in the population is 13% more likely to become a driver fatality than is a random 40-year-old, but a 20-year-old is 196% more likely than is a 70-year-old.

	Male		Female	
	Age 70 / Age 40	Age 20 / Age 70	Age 70 / Age 40	Age 20 / Age 70
Driver fatalities per head of population (Fig. 2)	1.13	1.96	1.19	1.61
Fatalities per licensed driver (Fig. 3)	1.20	2.02	1.53	1.39
Fatalities for the same travel distance (Fig. 5)	2.05	1.70	3.86	0.77
Severe crashes per licensed driver (Fig. 7)	0.59	6.35	0.84	3.71
Severe crashes for same travel distance (Fig. 8)	1.02	5.38	2.11	2.09

Table 10.
Risks faced by 80-year-olds compared to risks faced by 40- and 20-year-olds.

	Male		Female	
	Age 80 / Age 40	Age 20 / Age 80	Age 80 / Age 40	Age 20 / Age 80
Driver fatalities per head of population (Fig. 2)	1.82	1.22	1.75	1.10
Fatalities per licensed driver (Fig. 3)	2.21	1.10	2.82	0.76
Fatalities for the same travel distance (Fig. 5)	7.62	0.46	11.0	0.27
Severe crashes per licensed driver (Fig. 7)	0.87	4.36	1.27	2.45
Severe crashes for same travel distance (Fig. 8)	2.98	1.85	4.97	0.89

CONCLUSIONS

The relationships presented here suggest:

1. Licensing an older driver (data goes up to age 80) does not pose a greater threat to other road users than licensing younger drivers -- indeed it poses substantially less risk than licensing a 20-year-old.
2. As drivers age, most measures indicate that they face an increased risk of becoming a traffic fatality, with the increase accelerating at very old ages.
3. Given that a death occurs, the probability that it is a traffic fatality declines steeply with age, from well over 20% for late teens through mid twenties, to under one percent at age 65, and under half a percent at age 80.

ACKNOWLEDGMENT

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Technical Session 7

Biomechanics - Injury Criteria and Test Procedures

Chairperson: Rolf Eppinger, National Highway Traffic Safety Administration, United States

The International Harmonized Research Activities (IHRA) Status Report of the Biomechanics Working Group was presented at the onset of this Session during the 16th ESV Conference. This Report begins Technical Session 7.

INTERNATIONAL HARMONIZED RESEARCH ACTIVITIES (IHRA) STATUS REPORT OF THE BIOMECHANICS WORKING GROUP

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INTRODUCTION

This report gives a summary of the activities of the International Harmonized Research Activities (IHRA) Working Group on Biomechanics Research. The Working Group was formed in 1997 after the IHRA Steering Committee meeting in Washington, DC, where the United States presented the NHTSA plan for the harmonization of biomechanics research. The focus of the group is to obtain international agreement on a framework and to develop a five year agenda for the harmonization of biomechanics research.

The first meeting of the Working Group on Biomechanics Research was held in Hanover, Germany, September 22, 1997, in conjunction with the IRCOBI Conference. The delegates representing Japan, Europe, and North America were present with Mr. K. Ono representing Japan, Dr. J. Wismans and Dr. D. Cesari representing the EEVC, Mr. D. Dalmotas representing Canada, and Dr. F. Bandak representing the United States. The meeting produced agreement on the research priorities and on the development of a framework and a five year agenda for the world wide harmonization of biomechanics research.

PROCEEDINGS OF THE FIRST BIOMECHANICS WORKING GROUP MEETING

Each member opened with a discussion of his respective country's harmonization priorities and a brief description of on-going candidate research areas for harmonization.

Mr. Dalmotas emphasized the high priority of exploring sound alternatives as replacement candidates for the current HIC as a measure of closed head injury. He also reiterated the need for obtaining a biofidelic neck to alleviate the current response inadequacies that the current Hybrid III-type necks exhibit for rear impacts, child and small female representation, and combined neck loading assessment. Mr. Dalmotas informed the Working Group of Transport Canada's efforts to develop a means for interpreting output for Hybrid III legs to satisfy the current urgencies in light of the absence of an alternative.

Mr. Ono presented the harmonization priorities for Japan emphasizing the need for harmonization of injury criteria and dummy development for side impact, child injury, frontal, and rear impact. He highlighted the differences in evaluation criteria between dummies and the existence of multiple dummies for the evaluation of the same type of restraint system. Mr. Ono also pointed out that it is necessary to insure that the leg has higher biofidelity for full frontal and offset impact conditions. He also indicated the desire for further international cooperation facilitating the development and eventual adoption of the THOR dummy.

Dr. Cesari discussed on-going research addressing the need for the establishment of head/brain and neck injury mechanisms and tolerances for the purpose of proposing testing specifications for motorcycle safety helmets. Dr. Wismans emphasized the need for research to identify injury mechanisms and provide low level neck response characterization for whiplash injury. He described on-going research in that area and in the area of side impact dummy biofidelity evaluation and enhancement. He announced the start of SID-2000, a 26 month program that will produce side impact dummy design enhancements and injury risk functions. He updated the Group on the whiplash research and the Advanced Crash Dummy Research for Injury Assessment in frontal test conditions (ADRIA) programs to address injury biomechanics and dummy development for whiplash injury and frontal impact injury respectively.

Dr. Bandak emphasized the future needs for the development of advanced frontal dummies and the current needs for cooperation on a set of up-to-date harmonized injury reference values for the family of Hybrid III dummies. He discussed NHTSA's on-going projects on head/brain and neck injury, chest injury, and ankle injury. He informed the Group of NHTSA's side impact research and Hybrid III dummy (5^{th}, 95^{th}, 3 & 6 year old) testing and evaluation. He also emphasized the need for a harmonized biomechanics data exchange protocol and presented NHTSA's approach. Dr. Bandak also discussed the need for standardizing computer models and computer codes.

RECOMMENDATIONS AND RESEARCH PRIORITIES

The Working Group agreed on an order of biomechanics research priorities that best reflects the needs of the member countries as a group. A discussion of the priority research areas is given below.

Frontal Impact - In light of the areas of research on-going in the various member countries related to frontal impact biomechanics the Working Group recommended that high priority be given to head/brain/face, neck, chest/abdomen, and lower extremities injury research. The Group also recommended cooperation on the development and evaluation of the advanced frontal dummy (THOR) under development by NHTSA.

Side Impact - The Working Group recommended that high priority be given to the generation of a harmonized strategy for the development of advanced world side-impact dummies. Assessment of the state of the existing side impact dummies, supporting biomechanics, and injury data is on-going as part of programs within the member countries. This presents a significant leveraging opportunity for cooperation in the development of advanced dummies for side impact addressing the issues of injury criteria, biofidelity requirements, and dummy sizes.

Whiplash - The Working Group recommended cooperation in the area of neck injury criteria development including low level injury. Priority was recommended for research in injury mechanism, low level neck response characterization, dummy and test procedure development.

Child Dummies - The Working Group recommended evaluation of recent testing (conducted by the member countries) on current child dummies that will help form the basis for IHRA Working Group recommendations on the development of a family of advanced child dummies. The Working Group recommended a two year period for this evaluation.

Data Harmonization and Exchange - The Working Group recommended that the new database approach, under exploration by the NHTSA National Transportation Biomechanics Research Center, be evaluated by the member countries for possible acceptance as an additional mechanism for data exchange supporting harmonization.

Computer Modelling - The Working Group recommended the creation of a steering subgroup to work as part of the IHRA Biomechanics Working Group to oversee a two-year study for the evaluation of the current modelling activities on-going by the member countries. The Steering Sub-Group on Computer Modelling shall then recommend possible approaches to the harmonization of computer models and programs.

Industry Representation - The Working Group recommended that three industry representatives be invited as members of the IHRA Biomechanics Working Group with one member representing each of, North America and Australia, Japan, and Europe.

SECOND MEETING OF THE WORKING GROUP ON HARMONIZATION OF BIOMECHANICS RESEARCH

The second meeting of the IHRA Working Group on Biomechanics Research was held in Orlando, Florida, USA on November 12, 1997 in conjunction with the Stapp Conference. The meeting was attended by Dr. Wismans and Dr. Cesari representing the EEVC, Mr. Dalmotas representing Canada, Mr. Ono representing Japan, Mr. Seyer representing Australia, and Dr. Bandak representing the United States.

The topic of discussion at the second meeting of the IHRA Biomechanics Working Group was development of a harmonized side impact dummy. This topic was identified as a priority at the previous IHRA/BIO/WG meeting and was endorsed as an issue of priority at the IHRA Steering Committee meeting in Geneva in November, 1997. The position of the Working Group on this issue is given in the following section.

Harmonization of Side Impact Dummies - In the 1980's, the governments of the US and European countries developed dynamic side impact regulations, the US FMVSS 214 and the ECE Regulation 95. Intending to improve occupant side impact protection, these regulations produced different test procedures, test devices, and injury criteria with the US and Europe specifying the use of the USSID and EUROSID respectively. The two procedures and two dummies and substantially different making harmonization to one global side impact standard quite a non-trivial task.

The state of world side impact regulation today (two standards / two dummies) has significant disadvantages particularly with the associated increases in vehicle development, safety, and testing costs. While the recognition of such disadvantages associated with different regulatory standards for different markets is quite apparent, little or no advancement of an agreement on a harmonized side impact regulation has occurred until recently. There now exists a worldwide recognition of the need to harmonize on a single side impact dummy to facilitate more economical development of safe vehicle designs that can be sold in the global market. This is an essential step in the worldwide harmonization of side impact standards.

Over the past few years several efforts have been initiated in the US to develop new side impact dummies, the BIOSID (by General Motors) and the SIDIIs (through USCAR). These two dummies have been used primarily by the industry as research tools for the purposes of in-house evaluation of vehicle designs. There are currently two new initiatives to build on current side impact dummy technology to develop advanced side impact dummies. One of the projects, sponsored by a European Commission, involving government and industry organizations was recently introduced and is referred to as SID2000. This project is expected to start January 1, 1998 and continue for a period of 26 months to (1) evaluate the SIDIIs and EUROSID1 dummies against the current state of biomechanics knowledge on side impact. (2) make recommendations to improve EUROSID, and (3) examine the need for dummy sizes other than the 50th percentile male.

The other project is based on work conducted over the past few years in the US and sponsored by USCAR for the development of the 5th percentile female side impact dummy, SIDIIs. This project initially called for the use of this dummy to form a basis for the development of a new 50th percentile side impact dummy under the auspices of the ISO/TC22/SC12/WG5. The ISO WG5 project was initially moving on a separate track from the SID2000 project. However, a recent resolution passed during the November, 1997, ISO/TC22/SC12/WG5 meeting proposed the introduction of a stategy to merge these two initiatives for the purpose of producing a globally harmonized dummy.

The recommendation of the September, 1997, meeting of the IHRA Biomechanics Working Group to include side impact dummy development as a priority was taken up by the IHRA Steering Committee in November, 1997. Further steering committee discussions at that meeting resulted in acknowledgment that two separate dummy development efforts will lead to harmonization difficulties down the road. This is consistent with the notion that the issue of developing a harmonized SID should be a priority of the IHRA/BIO/WG. It is also believed that the IHRA/BIO/WG is the government forum that can enhance the likelihood of agreement on a harmonized dummy. The Working Group can facilitate the early development of an acceptable framework that serves as a basis for achieving a harmonized dummy. This allows the various contributions from all groups including ISO/TC22/SC12/WG5 and SID2000 to focus on a common plan of action. It is therefore recommended that the development of a world harmonized side impact dummy be conducted with the full participation of the IHRA Biomechanics Working Group as the representing body for IHRA.

DESCRIPTION AND PERFORMANCE OF THE HYBRID III THREE YEAR OLD, SIX-YEAR-OLD AND SMALL FEMALE TEST DUMMIES IN RESTRAINT SYSTEM AND OUT-OF-POSITION AIR BAG ENVIRONMENTS

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INTRODUCTION

With the introduction of air bags coming into the market at a brisk pace, and foreseeing the need for assessing the safety benefits of the air bag for all sizes of vehicle occupants, the Center for Disease Control (CDC) awarded in 1987 a contract to the Ohio State University under the title "Development for Multisized Hybrid III-Based Dummy Family." At the time the funding covered only the development of a small female and a large male dummies. Recognizing the need for dummies with improved biofidelity and extended measuring capability and capacity to evaluate the safety of children, CDC provided additional funding in 1989 to develop a design foundation for the Hybrid III-type child size dummies. To support this work, the Ohio State University asked the Society of Automotive Engineers (SAE) to form an appropriate working group that would provide advice and guidance from the automotive perspective. The SAE, through its Hybrid III Dummy Family Task Group and later, also through the Dummy Testing Equipment Subcommittee, has continued the development work since then, resulting in the construction of prototype Hybrid III-type 5th percentile female, 95th percentile male, six-year-old, three-year-old, and CRABI 12-month-old dummies.

In 1997, NHTSA, in cooperation with the appropriate technical committess of SAE, initiated an evaluation program for the prototype Hybrid III dummies prior to proposing them for incorporation into Part 572 as regulated test devices. This paper provides highlights of the Agency program which was used to evaluate the Hybrid III three-year-old and six-year-old child dummies and the 5th percentile female dummy for their sufficiency as measurement devices. It includes detailed anthropometry, biofidelity responses, and performance data for out-of-position static air bag tests and dynamic sled tests. Similar evaluations for the 95th percentile male and the CRABI 12-month-old are forthcoming.

Table 1 summarizes the overall weight and key dimensions for a number of current dummies including the three dummies described in this paper. The three dummies along with the 50th male are shown in the photograph of Figure 1.

Figure 2 illustrates a key feature that has been added to the thorax of each of these three dummies. Accelerometers have been added to the sternum and spine box to allow the determination of the viscous criteria (v*c). Two or three pairs of accelerometers (one accelerometer on the sternum and one on the spine box constitute a pair) are used to determine the velocity of the sternum relative to the spine.

To assess biofidelity, component tests were conducted with the head, neck, and thorax of each dummy. The component test responses were then compared to the appropriate biofidelity corridors which represent estimated typical human responses to similar test conditions. Given the absence of sufficient data for the three- and six-year-old children, and the 5th percentile female, the biofidelity corridors were developed by applying the appropriate mass distribution and geometric scaling factors to the H-III 50M corridors.

When evaluating biofidelity, one must consider the limitations imposed by the mechanical nature of the dummy. For example, the biofidelity requirements must be balanced with the equally important qualifications that the dummy be durable and that its responses are repeatable. These requirements make it necessary to construct the dummy from

Table 1
Comparison of Weight, Sitting Height, and Stature for Hybrid III Family

		12 month CRABI	3 YO Child	6 YO Child	5th %ile Female	50th %ile Male	95th %ile Male
Weight	lbs	22.0	34.5	46.00	108.7	171.3	223
Stature	in	29.4	37.2	47.30*	59.0*	68.7*	73.4*
Sitting Height	in	18.9	21.50	25.00	31.1	34.80	36.8
*Estimated							

Figure 1. Photograph of the Hybrid III Dummy Family: (left to right) three-year-old, six-year-old small female and mid-size male.

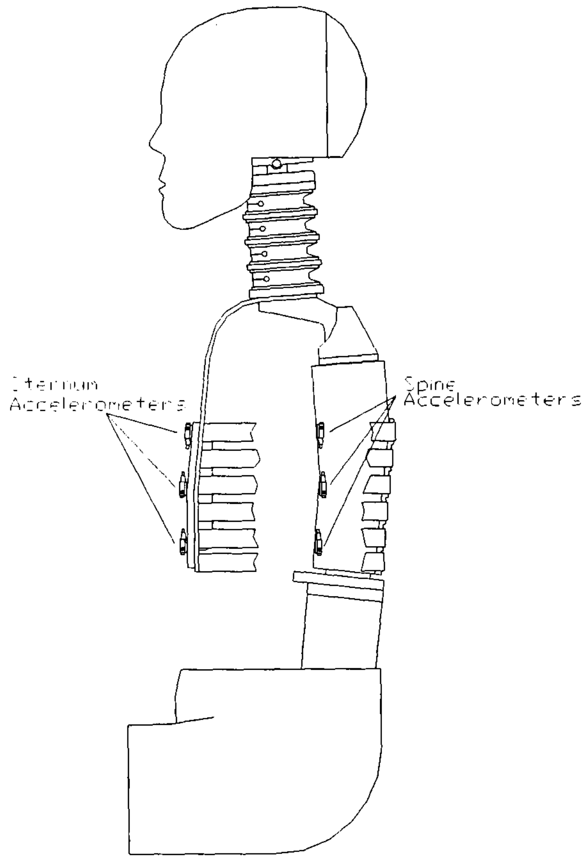

Figure 2. Accelerometer pairs in the thorax of the small female. (Middle ribs removed for clarity.)

engineering materials which can withstand repeated impacts of high energy, whereas the human body, consisting of frangible bones and soft tissue, cannot endure frequent exposures of this destructive nature. Given these limitations, it is not reasonable to expect that the dummies' responses can be tuned to fit perfectly within the biofidelity corridors. For the purposes of this evaluation, biofidelity has been deemed acceptable when the following subjective criteria have been met: (1) the area under the curve of the dummy's response is reasonably similar to that of the biofidelity corridor; (2) the hysteresis properties of the dummy's response are reasonably similar to those of the biofidelity corridor; (3) the maximum points of interest (force, deflection, rotation, etc.) are within the biofidelity corridor.

Each section to follow describes the features of the dummy, the instrumentation capability, the biofidelity responses of the major components, and key results of out-of-position and sled tests. All data presented in this paper conforms to SAE J-211 requirements for both filtering and sign convention.

HYBRID III THREE-YEAR-OLD DUMMY

Description of Dummy Features

The Hybrid III Three-year-old child (H-III3C) dummy was designed to be used in testing child restraints and assessing the injury risks associated with air bag interactions. The dummy's final design was based on a combination of designs from the Three-year-old "Air Bag" dummy, scaled-down versions of the Hybrid III 50th percentile male, and scaled-up versions of the Child Restraint Air Bag Interaction (CRABI) dummy. The dummy's current design includes some changes made by General Motors, First Technology Safety Systems and the Vehicle Research and Test Center (VRTC) to maximize permissable chest deflection and protect instrumentation, and further changes made by the SAE as a result of this evaluation. Some of the distinguishing characteristics of the H-III3C design are a segmented neck with a steel cable to limit elongation, a set of ribs and rib stiffeners made of 1095 steel for increased durability, upper and lower rib guides to deter vertical movement of the ribs for improved accuracy of chest deflection measurement and sternum-to-spine bumpers to prevent instrumentation destruction caused by metal-to-metal contact in the event of extreme chest deflection. As the dummy was intended to be used while properly restrained in child restraint systems as well as out-of-position with air bags, the dummy's pelvis allows sitting, standing and kneeling postures.

Anthropometry

Tables A1 and A2 in Appendix A show the measured segment weights and external dimensions of a Hybrid III Three-year-old dummy and provide a comparison to the published SAE guidelines (Draft Hybrid III Three-Year-Old Dummy User Manual dated May 13, 1997). The measurement data shows that the segment weights of the dummy measured at VRTC are all within the SAE specifications, with the exception of the head and torso with jacket, which are both only 0.03 lb. over the specified weight. All but two of the measured external dimensions made at VRTC fall within the specified range. The outstanding measurements were not significant enough to prevent testing.

Instrumentation

This dummy has numerous instrumentation capabilities including 19 accelerometers, 10 load cells and a rotary potentiometer in the chest, totalling 50 data channels. Unique instrumentation capabilities of this dummy include a pair of uniaxial accelerometers in the skull to calculate angular acceleration and rotation of the head, two sternal uniaxial accelerometer pairs for use in calculating the viscous criterion (VC), two triaxial configurations of accelerometers on the spine to allow calculation of angular acceleration and rotation of the thoracic spine, upper and lower neck and left and right iliac, acetabulum and shoulder load cells. The dummy also has the capacity to mount a pubic load cell to measure loads associated with child restraint systems. A table of instrumentation is included in Table 2.

Biofidelity

The Agency has conducted several tests with this dummy including component, static out-of-position (OOP) air bag and dynamic sled tests. Repeated component tests on the head, neck and thorax were conducted before, after, and throughout a series of OOP and sled tests to assess the dummy's biofidelity, repeatability, reproducibility and durability. Figures 3-6 show typical plots of component test data for the head drop, neck extension, neck flexion and thorax impact, respectively, with their biofidelity corridors as defined by Mertz[1].

Only a limited number of tests have been performed thus far on the latest versions of the head skin and neck as they have recently been modified to

Table 2
H-III3C Dummy Instrumentation Capabilities

Dummy	Type	Location	Measurements	# Channels
H-III3C	Accelerometers	Head	Ax, Ay, Az1, Az2	4
		Upper Thoracic Spine	Ax, Ay, Az	3
		Middle Thoracic Spine	Ax, Ay, Az	3
		Lower Thoracic Spine	Ax, Ay, Az	3
		Upper Sternum	Ax	1
		Lower Sternum	Ax	1
		Lower Spine Box	Ax	1
	19 max.	Pelvis	Ax, Ay, Az	3
	Rotary Potentiometer	Thorax	Dx	1
	Load Cells	Upper Neck	Fx, Fy, Fz, Mx, My, Mz	6
		Lower Neck	Fx, Fy, Fz, Mx, My, Mz	6
		Lumbar	Fx, Fy, Fz, Mx, My, Mz	6
		Anterior Superior Iliac Spine x 2	Fx upper, Fx lower	4
		Acetabulum x 2	Fy	2
		Pubic	Fx, Fz	2
50 max.	*30 max.*	Shoulder x 2	Fx, Fz	4

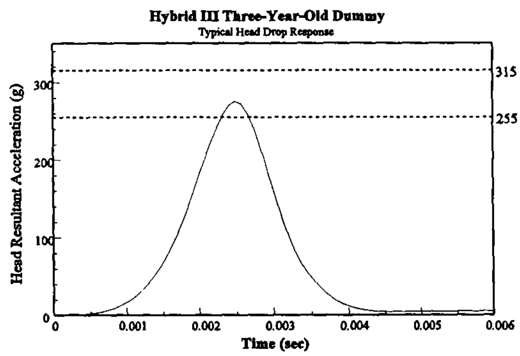

Figure 3. Typical head drop response with biofidelity corridor.

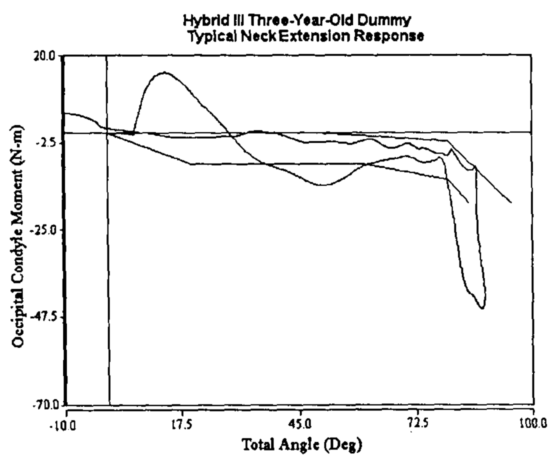

Figure 4. Typical neck pendulum response in extension with biofidelity corridor.

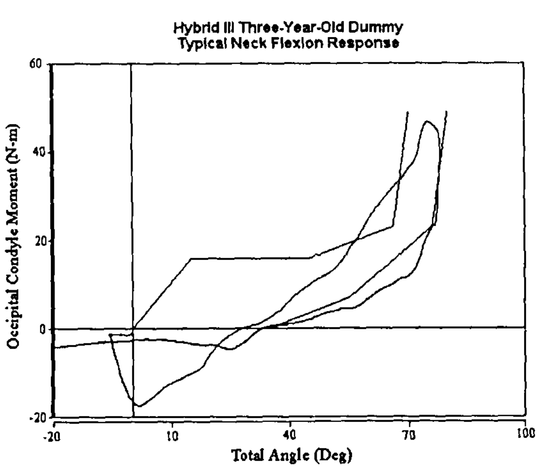

Figure 5. Typical neck pendulum response in flexion with biofidelity corridor.

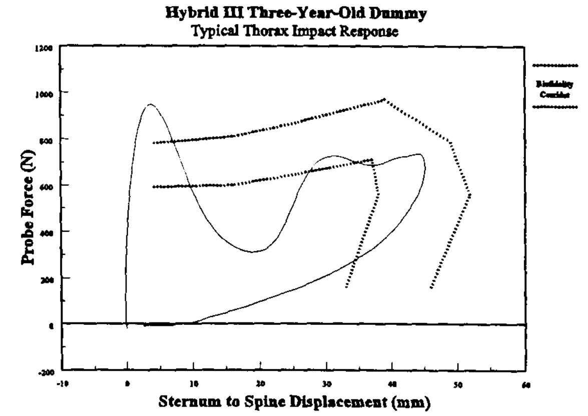

Figure 6. Typical thorax impact response with biofidelity corridor.

incorporate improvements. Insufficient component test data with the final dummy configuration prevents discussion of repeatability, reproducibility and durability of the head and neck. Note that the steep rise in moment during neck extension is caused by the segments of the neck contacting each other, resisting further rotation, producing a dramatic increase in the moment. This is a mechanical limit of the engineering materials and the geometry of the dummy neck. Both the neck flexion and extension responses show an inertial moment opposite to the direction of the primary response. For example, in the neck extension response, an initial flexion moment occurs. This response is observed in adult cadaver data and is due to the inertial response of the head during impact, but the biofidelity corridors do not include this inertial response.

Also note that the initial rise in force during thorax impact is due to the dummy skin slapping the ribs, is not an indicator of the response of the ribs, and is therefore disregarded when assessing the dummy's thorax biofidelity. This also is a mechanical limitation of the engineering materials, but one which is not seen in adult cadaver data. The thorax appears to show excellent repeatability and reproducibility and is reasonably durable.

Static Out-of-Position Air Bag Testing

The OOP and sled tests were performed to assess the dummy's durability and system performance. The OOP tests were conducted in several different vehicle configurations in ISO positions 1 and 2 to simulate pre-impact braking positions where severe interactions would occur with a deploying passenger air bag. The procedure for seating the dummy in the ISO positions is described in Appendix B. The air bag systems were selected based on the current trend toward depowered systems, in order to represent supplemental restraint systems which will be incorporated into vehicles in the future. The systems chosen were mildly aggressive and aggressive full-powered air bags which would subject the dummy to appropriate loads in order to evaluate its durability and system performance. It should be noted that the OOP and sled tests were conducted with a preliminary version of the dummy as some minor improvements were made to the dummy after the testing was completed. Additional tests with the latest dummy revisions are underway.

The tests were conducted in a generic setup, using actual vehicle seats, dash panels and passenger air bag modules to simulate front passenger environments. The orientation of each vehicle setup was representative of the actual vehicle including seat pan and seat back angles, windshield angle, air bag center height from the floor of the vehicle, and the relationship among these parts. Table 3 shows maximum responses from the primary channels during OOP tests.

Table 3.
H-III3C Out-of -Position Maximum Responses

Measurement/Calculation	Units	Peak Values
HIC		848
Head Resultant Acceleration	g	99
Upper Neck Force-X	N	-1771
Upper Neck Force-Z	N	2244
Upper Neck Moment-Y	N-m	-56
Chest Deflection	mm	-30
Resultant Chest Acceleration	g	53

Sled Testing

The dynamic simulation vehicle setup was the same as the OOP setup except two passenger seats were positioned next to each other, one on the driver side of the dash panel with the seat in the rearwardmost track position to keep the dummy from contacting the dash, and the other dummy on the passenger side of the dash panel with the seat in its forwardmost track position to ensure dummy contact with the air bag when deployed. The steering column was removed from the instrument panel for a more passenger-like setting, allowing more room for excursion. Again, it should be noted that the sled tests were also conducted with a preliminary version of the dummy. Additional tests with the latest dummy are being conducted.

The sled test set-ups included several different vehicle configurations with various child restraints, vehicle restraints and sled pulses. Three types of sled pulses were employed: (1) the FMVSS 213 pulse (approximately 47 kph, 23 g), (2) 208-type crash pulses (approximately 50-54 kph, 34-35 g), and (3) a 208 AAMA sled pulse (approximately 47 kph, 17.5 g). The dummy was typically properly restrained and seated in a child restraint system, except for some partially and completely unrestrained tests. The vehicle configurations were chosen to represent a range of aggressive environments in order to evaluate the durability of the dummy. The sled test matrix (Table C1, Appendix C) was designed to represent several sled pulses, two different vehicles, and a variety of restraint systems. Post-test dummy inspections were conducted to identify problems and/or ensure structural integrity before proceeding to the next test. In this way, dummy durability could be followed closely.

Table 4 shows the maximum responses from the primary channels during sled tests.

The loading of the OOP and sled tests was significant as demonstrated by the magnitude of the peak values in Tables 3 and 4. Overall peak chest deflection achieved 80% *(38/47 mm at the time; available space now is 41 mm, so overall peak deflection was 93%)* of the available clearance between the sternum and spine bumpers, illustrating that the test matrix provided chest loadings which were not inconsequential. The measured responses from the various conditions on the sled prove the dummy is able to provide useful and reasonable measurements using the different sled pulses, restraint conditions and vehicle setups as a basis for comparison. The dummy did not sustain significant damage throughout the test series, suggesting that the dummy is quite robust.

However, there were minor problems identified during the static and dynamic test series that have since been addressed by SAE and are in the process of being validated. For instance, the head skin began coming loose and shifting during both OOP and sled testing, which could potentially have affected head acceleration measurements and head injury criterion (HIC) calculations. Several modifications were made to the head skin and skull which resulted in a more secure attachment and better fit, as well as slightly

Table 4.
H-III3C Sled Test Maximum Responses

Criteria/Measurement	**Maximum Response**						
Sled Pulse Air bag deployed? Child Restraint Used?	213 W/AB* W/CRS$	208 W/O AB W/CRS	208 W/AB W/CRS	208 Sled W/O AB W/CRS	208 Sled W/AB W/CRS	208 W/O AB W/O CRS#	208 W/AB W/O CRS
HIC	757	1828	1003	444	218	3032	666
Neck Flexion Moment (N-m)	31	57	37	34	13	214	27
Neck Extension Moment (N-m)	-22	-25	-27	-13	-8	0	-59
Neck Shear Force (N)	933	837	726	-702	373	4078	813
Neck Axial Force (N)	-1735	2235	-1396	1178	-467	1564	1868
Chest Resultant Acceleration (g)	67	64	76	32	44	119	72
Chest Deflection (mm)	-13	-22	-13	-14	-13	-38	-13

*AB=Air Bag
$CRS=Child Restraint System
#W/O CRS=The dummy was not in a child seat and was not belted

improved biofidelity. In addition, the shoulder belts of the child restraint systems became lodged between the dummy's neck and shoulder, causing unrealistic loading. The shoulder load cell cover and structural replacement were modified with the addition of a belt guide to prevent such occurrences. The neck segments were shaved down to provide additional rotation as the neck response was short of the biofidelity rotation corridors in both flexion and extension. Concerns from members of the SAE Hybrid III Dummy Family Task Group prompted an increase in the depth of the sternum-to-spine bumpers from 4 mm to 10 mm as instrumentation had been destroyed using the thinner bumpers. It was thought that thicker bumpers would prevent such damage to instrumentation and a depth of 10 mm was chosen because it was the thickest depth which could be used without affecting thorax calibration deflection results.

HYBRID III SIX-YEAR-OLD DUMMY

Description of Dummy Features

The Hybrid-III6C dummy was designed for use in frontal impact testing and scaled from the Hybrid III 50th shape and biofidelity response. SAE and industry were further refining and revising the dummy in 1996 when NHTSA decided to use the dummy in research testing to evaluate the injury risks which full-powered passenger air bag systems posed for out-of-position children. In late 1997 NHTSA evaluated the suitability of the H-III6C dummy to be proposed for incorporation into the Part 572 standard. The dummy as received from the manufacturer was modified to include patches of skin under the chin and at the occipital condyles of the dummy head and around the shoulder to decrease the possibility of air bag punctures during testing. The dummy design included a neck and lumbar which were equipped with nylon inserts to prevent signal noise. The dummy's thorax was equipped with both a chest potentiometer and accelerometers and also has several structural enhancements to optimize it for use in the air bag environment. These enhancements included strong steel ribs and rib stiffeners, rubber sternum stops like the kind used on the HIII 50th percentile dummy, additional clearance in the thoracic cavity for travel of the chest deflection transducer arm, upper and lower rib stops to prevent vertical motion of the ribs and a metal strip with recesses to hold each rib from pivoting about the sternum area. A modified abdomen provided additional clearance for travel of the chest deflection transducer arm while maintaining posture.

Anthropometry

The dummy's design is based on established scaling procedures from the Part 572 Subpart E 50th percentile male Hybrid III crash test dummy matching anthropometry, mass distribution, sitting heights, and motion ranges of the average six year old[2,3,4]. Examination of the dummies' anthropometry and mass distribution and the SAE Task Group specified targets (Task Group minutes of May 10, 1991) are shown in Appendix A, Tables A.3 and A.4. A few of the components varied from the SAE specifications but were not considered sufficiently critical to preclude testing.

Instrumentation

The dummy's instrumentation capabilities shown below in Table 5 are particularly suited for assessing air bag induced injuries.

Biofidelity

Component tests[5] were performed throughout the test program to evaluate critical components, compare their response to the specified biofidelity corridors and determine repeatability after continuous testing of the dummy. The component tests were the head drop test, neck pendulum test, and thorax impactor test.

Typical responses of these three components overlayed onto their appropriate biofidelity corridors are shown in Figure 7 for the head, Figures 8 and 9 for the neck in flexion and extension, and in Figure 10 for the thorax.

The responses of the two dummies used in the test program were found to be excellent for both repeatability and reproducibility. None of the responses showed any tendency to drift in any specific direction.

Table 5.
H-III6C Instrumentation

Dummy	Type	Location	Measurements	Channels
H-III6C	Accelerometers	Head	Ax, Ay, Az	3
		Upper Thoracic Spine	Ax, Ay, Az	3
		Middle Thoracic Spine	Ax, Ay, Az	3
		Upper Sternum	Ax	1
		Lower Sternum	Ax	1
		Upper Spine Box	Ax	1
		Lower Spine Box	Ax	1
		Pelvis	Ax, Ay, Az	3
	Rotary Potentiometer	Thorax	Dx	1
	Load Cells	Upper Neck	Fx, Fy, Fz, Mx, My, Mz	6
		Lower Neck	Fx, Fy, Fz, Mx, My, Mz	6
		Lumbar	Fx, Fy, Fz, Mx, My, Mz	6
		Anterior Superior Iliac Spine	Fx upper, Fx lower	4
51 max.		Femur x 2	Fz Fx, Fy, Fz, Mx, My, Mz	2 12

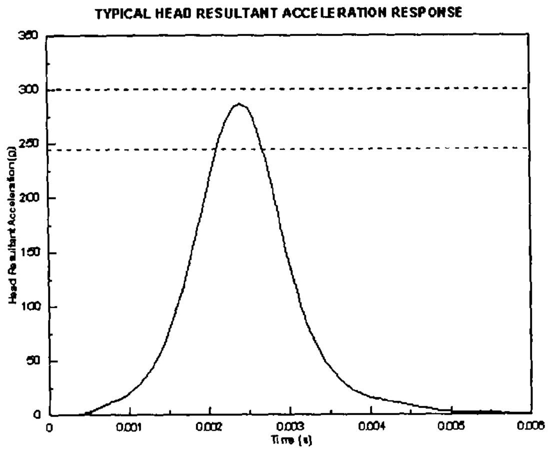

Figure 7. Typical H-III6C Head Response

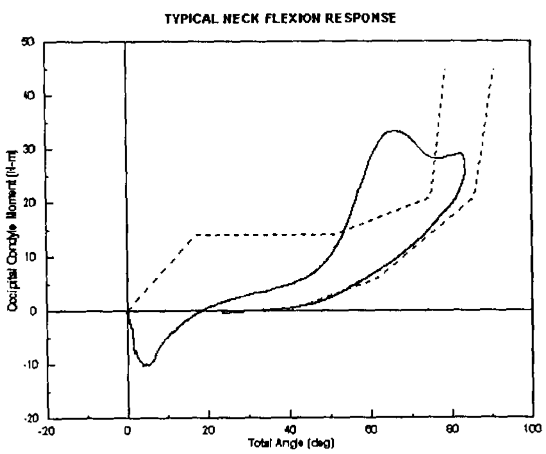

Figure 8. Typical H-III6C Neck Flexion Response

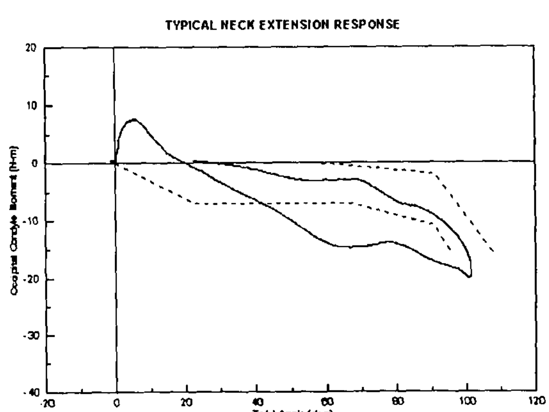

Figure 9. Typical H-III6C Neck Extension Response

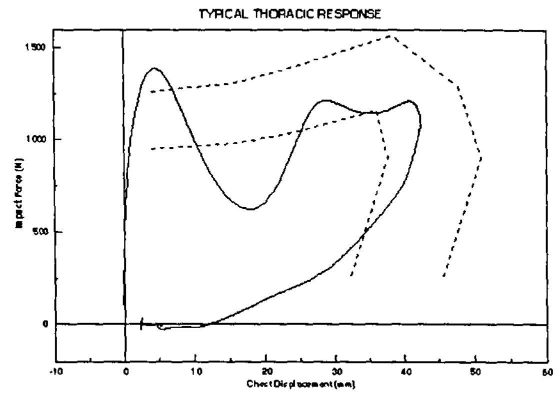

Figure 10. Typical H-III6C Thoracic Response

Static Out-of-Position Air Bag Testing

While the aim of the component level testing was primarily to determine the dummy's repeatability, the aim of the OOP test program was to determine the dummy's ability to provide useful and practicable measurements and to establish its structural integrity in a relatively severe air bag deployment environment.

Front passenger compartments of two popular compact vehicles were selected for OOP Tests. These systems were chosen as representative compact vehicles with top-mounted passenger-side air bag systems. The dummy set-up procedures for OOP tests are based on ISO child positions 1 and 2 modified to facilitate the placement of dummies within the vehicle as described in Appendix B. Sixteen tests were conducted and maximum primary dummy responses are shown in Table 6.

The OOP test program showed the dummy has the ability to provide useful and practicable measurements. The OOP test program tried the structural integrity of the dummy at the outset of the test program, requiring a modification to the metal strip in the front of the ribs. With this modification, the durability of the dummy in the relatively severe air bag environment was established.

Sled Testing

The purpose of the sled tests was to determine if the dummy (1) was capable of useful, consistent and repeatable measurements; (2) could distinguish among different crash pulses, seating configurations and restraint systems; and (3) had adequate durability.

Table 6.
H-III6C OOP Test Maximum Responses

CRITERIA/RESPONSE	VALUE
HIC	1085
Neck Flexion Moment (N-m)	62
Neck Extension Moment (N-m)	-94
Neck Shear Force (N)	2541
Neck Axial Force (N)	-3492
Resultant Chest Acceleration (g)	90
Chest Deflection (mm)	-34

The same vehicle configurations used in the OOP tests were used in HYGE sled tests. The dummy was positioned with various restraint conditions including booster seats, 3-point belts and air bags. The dummy was also tested unbelted and completely unrestrained. See Table C2 in Appendix C. Three types of sled pulses were employed: (1) the FMVSS 213 pulse (approximately 47 kph, 23 g), (2) 208-type crash pulses (approximately 50-54 kph, 33 g), and (3) a 208 AAMA sled pulse (approximately 48 kph, 17 g). Twelve sled tests were performed with two dummies. In two tests only one dummy was used, for a total of twenty-six dummy tests. Table 7 summarizes the maximum responses recorded for the various testing configurations.

The measured response values in the sled tests varied from very low to extremely high sensor outputs. Under extremely severe loading conditions, none of the measurements showed traces of contamination by unusual signals or distortions that would be a cause for questioning the response validity of the measurements. The patterns of measurements obtained from dummy-based sensors appeared to provide correct trends of comparative responses based on pulse aggressivity, seat locations and restraint conditions.

HYBRID III FIFTH PERCENTILE FEMALE

Description of Dummy Features

The H-III5F dummy is essentially a scaled-down version of the Hybrid III 50th (H-III50M) percentile dummy with several updated components to provide more human-like range of motion and improve performance and durability in the air bag

Table 7.
H-III6C Sled Test Maximum Responses

CRITERIA/RESPONSE	VALUE				
	213 W/O AB*	**213 W/AB**	**208 W/O AB**	**208 W/AB**	**208 SLED W & W/O AB**
HIC	694	906	1476	1119	313
Neck Flexion Moment (N-m)	31	21	28	34	24
Neck Extension Moment (N-m)	-42	-60	-46	-47	-15
Neck Shear Force (N)	-770	-940	-1439	-1172	-493
Neck Axial Force (N)	2544	-3016	3953	-2096	1806
Resultant Chest Acceleration (g)	55	58	85	70	40
Chest Deflection (mm)	-38	-33	-55	-38	-39
Excursion (mm)	624				
*AB = Air Bag					

environment. The thorax contains several significant modifications including rib guides which limit upward and downward movement of the ribs, similar to those found in the H-III3C and H-III6C. The pelvis contains features which reduce the likelihood of submarining when tested in a 3-point belt environment. Mounted on each upper femur is a hard plastic bumper which limits the amount of hyperflexion of the femur and prevents metal-to-metal contact in extreme conditions. A rubber bumper mounted on the ankle limits the range of motion of the foot and prevents metal-to-metal contact between the foot and ankle. Also incorporated into the heel of the foot is an Ensolite pad which provides a degree of heel compliance.

Anthropometry

The external dimensions and segment weights of an H-III5F dummy were measured and compared to design guidelines published by SAE. The results of these measurements appear in Tables A.5 and A.6 in Appendix A. The external dimensions meet the SAE guidelines and the segment weights meet all of the requirements except for one. The total dummy weight was well within the published guidelines.

Instrumentation

The dummy contains provisions for mounting a wide variety of electronic instrumentation. Similar to the H-III3C and H-III6C, the H-III5F has capacity for mounting three accelerometer pairs to the sternum and spine for computing the viscous criterion (V*C). Another unique feature is the anterior-superior iliac spine (ASIS) load cell which provides useful information relative to belt loading. Table 8 summarizes the available instrumentation for the H-III5F.

Biofidelity

The H-III5F biomechanical impact response requirements for the head, neck, and chest were

Table 8.
Available Instrumentation for H-III5F

Type	Location	Measurements	# Channels
Accelerometers	Head CG	Ax, Ay, Az	3
	Thorax	Ax, Ay, Az	3
	Pelvis	Ax, Ay, Az	3
	Sternum - Upper, Middle, Lower	Ax	3
	Spine - Upper, Lower, Middle	Ax	3
Rotary Potentiometer	Thorax (Chest Deflection)	Dx	1
Linear Potentiometer	Knee Slider*	Dx	1
Load Cells	Upper Neck	Fx, Fy, Fz, Mx, My, Mz	6
	Lower Neck	Fx, Fy, Fz, Mx, My	5
	Lumbar Spine	Fx, Fy, Fz, Mx, My	5
	Thoracic Spine	Fx, Fy, Fz, Mx, My	5
	ASIS*	Fx, My	2
	Femur - 1 channel*#	Fz	1
	Femur - 6 channel*#	Fx, Fy, Fz, Mx, My, Mz	6
	Upper Tibia Load Cell*	Fx, Fz, Mx, My	4
71 max.	Lower Tibia Load Cell*	Fx, Fz, Mx, My	4

** indicates that right and left load cells are required*
 # The two femur load cells are mutually exclusive; if one is used, the other is excluded.

obtained by applying the appropriate mass and geometric scale factors to the response requirements for the H-III50M[6]. Multiple head, neck, and thorax component tests were conducted to assess biofidelty and also to establish the repeatability and reproducibility of the responses. Tests were conducted throughout the duration of the evaluation to ensure the long term durability of the biofidelity responses.

The biomechanical head impact response requirements state that the peak resultant acceleration of the head c.g. for a 376 mm drop of the head onto a flat, rigid impact surface shall be between 240 and 295 g. Figure 11 shows a typical head drop response in comparison to the biomechanical response requirement.

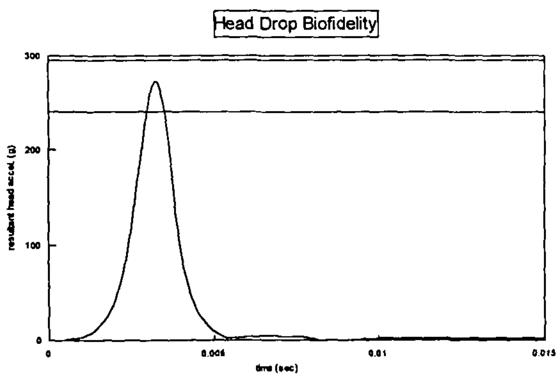

Figure 11. Typical H-III5F Head Impact Response

The biomechanical neck bending requirements are defined by the head and neck's response to a prescribed deceleration pulse resulting from a rigid pendulum drop into an energy absorbing material. A typical response for neck flexion and neck extension tests compared against their respective biomechanical corridors can be found in Figures 12 and 13, respectively.

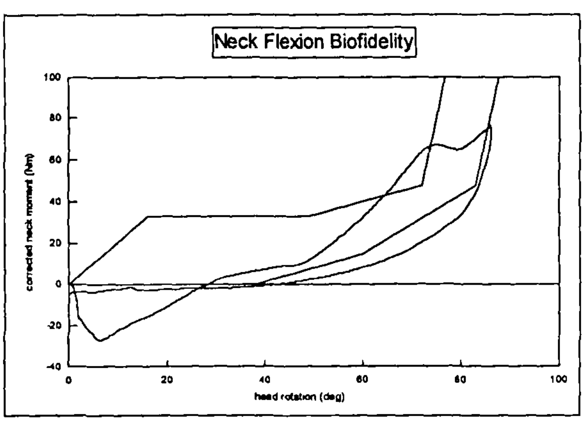

Figure 12. Typical H-III5F Neck Flexion Response

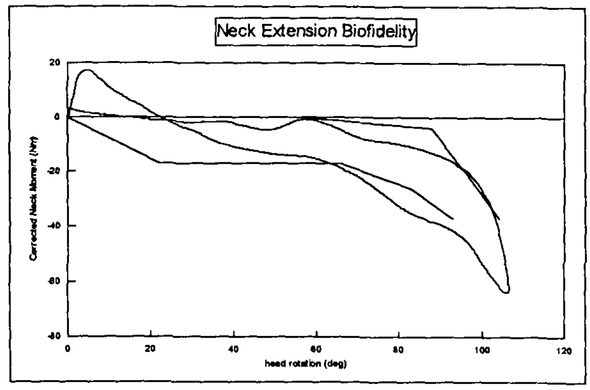

Figure 13. Typical H-III5F Neck Extension Response

The biomechanical requirements for the chest specify the force-deflection characteristics of the thorax in response to a mid-sternal impact of a 14 kg pendulum at 6.71 m/s. A typical response to a thoracic impact test compared against the biomechanical corridor can be found in Figure 14.

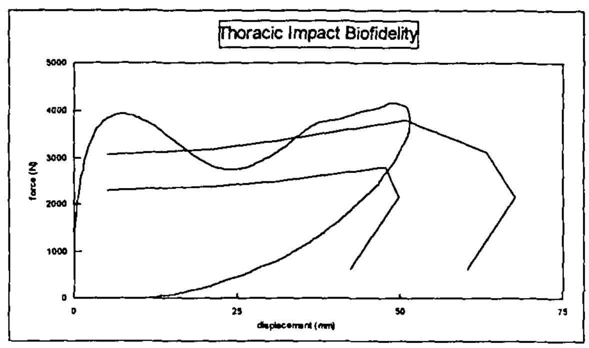

Figure 14. Typical H-III5F Thorax Impact Response

Static Out-of Position Air Bag Testing

Driver and passenger static out-of-position tests were conducted in several different vehicle systems. The OOP tests were primarily intended as an evaluation of the dummies' durability and the integrity of the instrumented measurements. Tests involving the driver systems were carried out in an actual vehicle using standard seats, dash panels, and air bags; for the passenger tests, however, the seats were removed to achieve proper dummy positioning. Tests involving the passenger systems were conducted in a generic setup. The driver test environment was made up of a flat, steel seat pan with a padded seat back, standard air bags and steering wheels, and a reusable steering column. The passenger tests utilized a standard dash panel and air bag. For all passenger OOP tests, the lower legs were removed to achieve proper dummy positioning.

For driver OOP tests, the International Standards Organization (ISO) seating procedures were followed. The procedures are contained in Appendix B. For the passenger tests, however, the ISO has not yet developed a standard positioning procedure for the H-III5F. Therefore, the dummy was positioned in what was considered to be a reasonable OOP testing configuration in close proximity to the air bag. An attempt was made to follow the driver positioning format, in that passenger position 1 is intended to maximize head and neck loading while passenger position 2 is intended to maximize chest loading.

A total of 16 driver and 6 passenger OOP tests were conducted and the dummies were thoroughly inspected after each test. The maximum driver and passenger OOP responses for all of the tests, including both ISO 1 and 2, are listed in Table 9. Table 9 indicates that the dummy can sustain significant loading to the head, neck, and chest without experiencing significant structural damage.

Table 9.
OOP Test Maximum Responses for H-III5F

Criteria	Units	Driver OOP	Pass. OOP
HIC		281	3319
Neck Force-X	N	-2739	-9918
Neck Force-Z	N	3324	9884
Neck Moment	N-m	-117	-152
Chest Displacement	mm	-62.4	-59.5
Chest Resultant	g	170	358
V*C	m/s	4.13	4.02

Sled Testing

Following OOP testing, 30 dynamic sled tests were conducted, 28 of which utilized two dummies simultaneously. Two different vehicle systems were employed in these tests: a compact car and a mid-size car. The tests were conducted in actual vehicle bodies using standard seats, instrument panels, steering wheels and columns, air bags, and 3-point belt restraints.

The test matrix was developed to evaluate the dummy's responses to several different restraint systems. Emphasis was placed on 3-point belt restraint tests because such an environment was considered to be the best condition for evaluating the repeatability of the dummies' response. See Table C3 in Appendix C.

Analysis of the dummy-based test measurements indicate reasonably consistent responses without any apparent tendencies to drift as a function of time or frequency to impact exposure. Post-test inspections of the dummy hardware did not reveal any damage, visual indications of wear or tendencies of the hardware to take on permanent deformation.

A repeatability and reproducibility analysis was completed for the dummies' responses in the sled environment. In order to make a reasonable comparison of responses, it was desired to analyze the results of those tests in which the dummy was subjected to repeatable test conditions. The most repeatable test condition was when the dummy was seated in the passenger seat of the mid-size vehicle and the 3-point belt system was the only restraint. The pulse of the mid-size car had a peak acceleraiton of approximately 25 g's. The peak velocity was approximately 49 kph. Table 10 contains a summary of the repeatability and reproducibility analysis for two different H-III5F dummies.

As Table 10 indicates, the measured responses exhibit good repeatability and reproducibility.

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2. Minutes of the SAE H-III Dummy Family Task Group of May 10, 1990.

3. Reynolds, Young, and McConville: "Development and Evaluation of Master Body Forms for Three-Year-Old and Six-Year-Old Child Dummies" 1976, US DOT contract NHTSA-5-1394.

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5. Society of Automotive Engineers Dummy Testing Equipment Subcommittee Draft Calibration Procedures for the Hybrid III Six-Year-Old Child, August 1996.

6. Mertz, H.J., et. al., "Size, Weight, and Biomechanical Impact Response Requirements for Adult Size Small Female and Large Male Dummies," Society of Automotive Engineers # 890756, March, 1989.

Table 10.
H-III5F Repeatability/Reproducibility Analysis for 3-Point Belt Sled Tests in Mid-size Buck

		Dummy A - Repeatability			Dummy B - Repeatability			Dummies A & B - Reproducibility		
		Avg.	Std. Dev.	%CV	Avg.	Std. Dev.	%CV	Avg.	Std. Dev.	%CV
HIC		881.3	60.5	6.9	832.2	57.6	6.9	854.0	60.8	7.1
Neck Fx	N	-1574.0	24.5	1.6	-1648.6	81.6	5.0	-1615.4	71.4	4.4
Neck Fz	N	2416.3	142.2	5.9	2278.4	86.0	3.8	2339.7	128.7	5.5
Neck Moc	N-m	70.8	3.3	4.2	70.6	2.4	3.5	70.7	2.6	3.6
Neck Moc-	N-m	-26.3	1.3	4.7	-24.4	1.9	7.2	-25.2	1.9	7.1
Chest Res.	g	53.8	1.0	1.8	53.6	1.7	3.4	53.7	1.3	2.6
Chest X	mm	-35.7	1.2	3.5	-33.2	2.4	7.4	-34.3	2.3	6.7
Pelvis Res.	g	55.3	4.0	6.5	53.4	3.4	6.3	54.2	3.6	6.2

ACKNOWLEDGMENT

The efforts reported in this paper were conducted by the Vehicle Research and Test Center of the National Highway Traffic Safety Administration and by the Transportation Research Center. We are indebted to the staff at these facilities for their support.

APPENDIX A

Table A1.
Segment Weights of H-III3C Dummy

Dummy Body Segment	Specification (lbs.)	Tolerance (lbs.)	Actual Measurement (lbs.)
Head	6.02	0.15	**6.20***
Neck	1.65	0.05	1.65
Torso w/jacket	14.32	0.50	**14.85***
Right Upper Arm	0.93	0.10	0.940
Left Upper Arm	0.93	0.10	0.940
Right Lower Arm	1.05	0.10	1.053
Left Lower Arm	1.05	0.10	1.004
Right Upper Leg	2.13	0.20	2.136
Left Upper Leg	2.13	0.20	2.222
Right Lower Leg	1.34	0.10	1.360
Left Lower Leg	1.34	0.10	1.346
Right Foot	0.60	0.10	0.670
Left Foot	0.60	0.10	0.646
Total Weight	33.83	1.20	**35.75***

*Not within specified tolerance

Table A2.
External Dimensions of H-III3C Dummy

Description	Specification (in.)	Tolerance (in.)	Actual Measurement (in)
Head Depth (length)	6.89	0.30	6.81
Head Width (breadth)	5.35	0.30	5.44
Head Height	6.89	0.30	6.94
Lateral Neck Breadth (width)	2.76	0.10	2.69
Chest Breadth at Axilla	6.77	0.30	6.56
Chest Depth w/o jacket	4.60	0.30	4.63
Waist Breadth (width)	6.93	0.30	6.83
Sitting Height	21.50	0.30	21.50
Shoulder Width (breadth)	9.61	0.30	9.50
Shoulder Pivot Height	13.15	0.30	**12.60***
Shoulder to Elbow Length	7.60	0.30	**8.38***
Back of Elbow to Fingertip	10.04	0.30	10.13
Buttock to Knee Length	11.61	0.30	11.50
Max. Hip Breadth (seated)	7.68	0.30	7.83
Thigh Depth (seated)	3.39	0.20	3.20
Standing Height	37.20	0.50	37.25
*Not within specified tolerance			

Table A3.
H-III6C External Dimensions

Feature	SAE Specification (in.)	Measured (in.)
Head Circumference	20.6	20.6
Head Width	5.6	5.6
Head Length	7.1	7.1
Erect Sitting Height	25	25
Shoulder/Elbow	9.2	8.13
Elbow/Fingertip	12.2	11.31
Buttock/Knee	15	15.5
Knee/Floor	14.1	12.44
Stature-erect standing (estimated)	47.3	44.9

Table A4.
H-III6C Segment and Assembly Weight

Feature	Specification (lbs)	Measured (lbs)
Head	7.66	7.65
Neck	0.91	1.27
Upper Torso	10.12	11.9
Lower Torso	13.56	13.2
Upper Arms (both)	2.21	2.1
Lower Arms and Hands (both)	2.15	2.6
Upper Legs (both)	4.35	6.6
Lower Legs and Feet (both)	5.04	5.4
Total	46	50.7

Table A5.
H-III5F External Dimensions

Description	Feb. '98 SAE Targets (inches)	Actual
Total Sitting Height	31.00 +/- 0.50	30.63
Shoulder to Elbow Length - right	11.30 +/- 0.40	11.3
Shoulder to Elbow Length - left	11.30 +/- 0.40	11.3
Buttock to Knee Length - right	21.00 +/- 0.50	21.4
Buttock to Knee Length - left	21.00 +/- 0.50	21.25
Head Breadth	5.60 +/- 0.20	5.6
Head Depth	7.20 +/- 0.20	7.2
Head Circumference	21.20 +/- 0.40	21.25
Knee Pivot Height - right	16.00 +/- 0.50	15.7
Knee Pivot Height - left	16.00 +/- 0.50	15.7
Stature	56.40 +/- 1.70	56.43

Table A6.
H-III5F Segment Weights

Segment	Feb. '98 SAE Target (lbs)	Actual Weight (lbs)
Head Assembly	8.10 +/- 0.10	8.13
Neck Assembly	2.00 +/- 0.20	2.09
Upper Torso Assembly with Torso Jacket	26.44 +/- 0.30	26.30
Lower Torso Assembly	30.40 +/- 0.30	28.88
Total Dummy Weight	108.74 +/- 2.00	107.63

APPENDIX B

SEATING POSITIONS - THREE- AND SIX-YEAR-OLD CHILD

Position 1 is designed primarily to evaluate contact forces of the deploying air bag on the chest. However, head accelerations and neck loading will typically be significant factors in this test position. The positioning is intended to represent a standardized worst case condition in which the child has been thrown against the frontal structures of the vehicle's interior due to pre-impact braking and/or vehicle impact. While possible, it is not assumed that the child will be seated, or resting on the seat, at the initiation of air bag deployment.

Position 2 is designed to primarily address the contact forces and loading forces of the deploying air bag on the head and loading forces on the neck. The Child Position Number 2 is intended to represent a standardized worse case scenario in which the child slides forward or is sitting forward on the seat while the upper torso jack-knifes downward into the dashboard. The final positioning may not necessarily place the head into direct contact with the air bag's cover but does reflect a reasonable positioning based on estimated body kinematics resulting from pre-impact braking. See Figures B1 and B2.

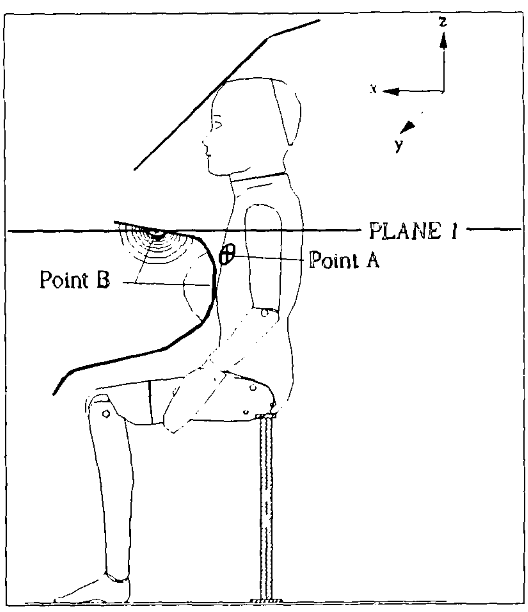

Figure B1. Position 1.

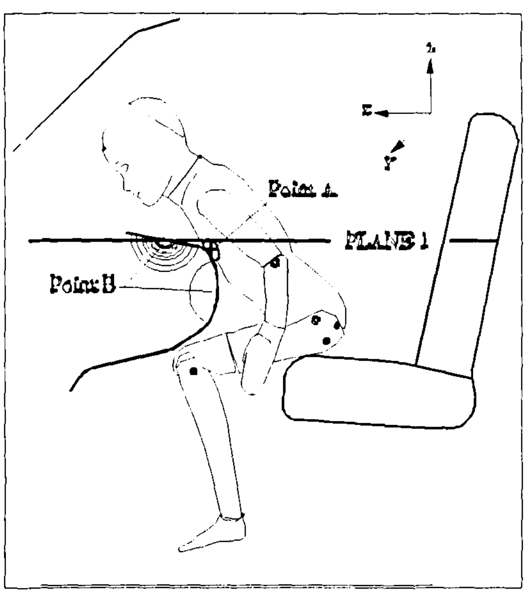

Figure B2. Position 2.

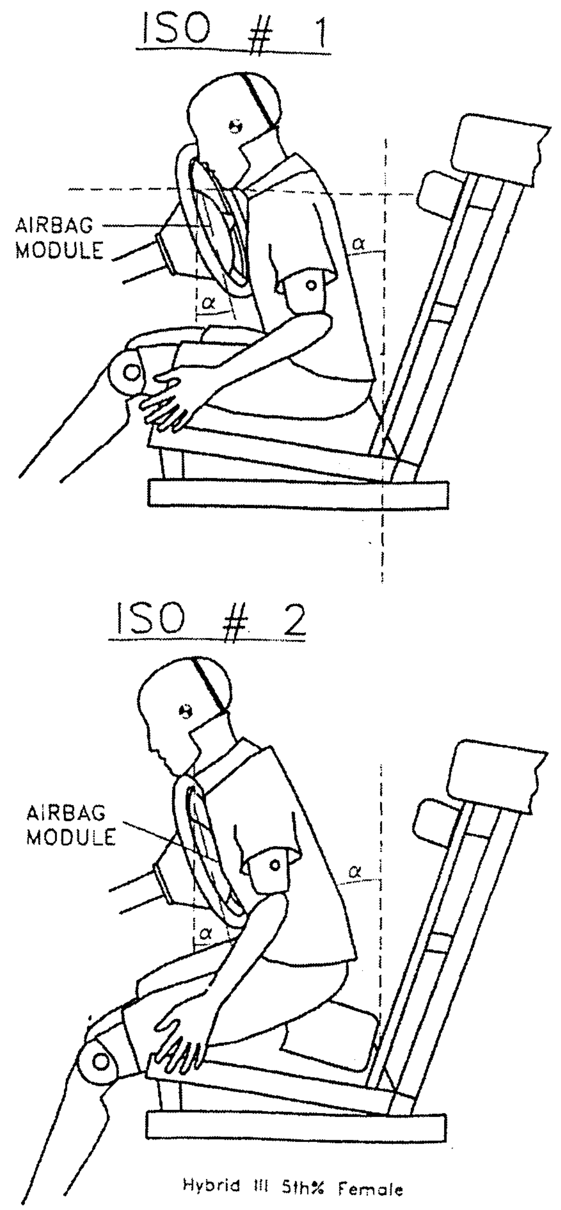

Figure B3. Hybrid III 5[th] percentile female.

HYBRID III 5th PERCENTILE FEMALE POSITIONS FOR OOP TESTING

The dummy positioning procedure used for the driver side air bag tests is based on the positioning procedure adopted by ISO.

Position 1

Position 1 is intended to position the dummy to maximize head and neck loading. For this seating procedure, the driver's seat is moved to the full forward position. The dummy is placed on the seat and the torso arranged so that the spine is parallel to the plane defined by the rim of the steering wheel.

Position 2

Position 2 is intended to position the dummy to maximize chest loading. This in turn will create significant neck and head loadings. The driver's seat track position is not specified and may be positioned to best facilitate the positioning of the dummy. The dummy is placed on the seat and the torso is arranged so that the spine is parallel to the plane of the steering wheel. The dummy is positioned so that the center of the chin is in contact with the uppermost portion of the rim of the steering wheel. Note: The chin is not hooked over the top of the rim of the steering wheel. It is positioned to rest on the upper edge of the rim. See Figure B3.

APPENDIX C

Table C1.
H-III3C Sled Test Matrix

Sled Pulse	Simulated Vehicle	CRS Belted No AB Dummy # 20	CRS Belted No AB Dummy # 18	CRS Belted AB Dummy # 18	No CRS Unbelted No AB Dummy # 18	No CRS Unbelted AB Dummy # 18
213	D-96 w/ 213 seat	1		1		
		1		1		
	D-96 w/ D-96 seat	1		1		
208 crash	D-96	1	1	1	1	1
		1				
		1				
	I-96	1	1			
		1	1			
		1		1		
208 sled	I-96	1		1		

CRS=Child Restraint System
AB=Air bag

Table C2.
H-III6C Sled Test Matrix

Test/seat	Occupant/Vehicle Restraint B[a]	3PT[b]	B/AB[c]	3PT/AB	None	AB	Velocity (KPH)
213	4[d]	2[d]	1	1			47
213/Veh. 1	1	1	1	1			47
208 sled Veh. 2	1		1				48
208 crash/Veh. 2	1	1	1	1			50
208 crash/Veh. 1	2	2	1	1	1	1	54

a - B indicates Booster Seat restrained by 3 point belt system
b - 3PT indicates 3 point belt restraint
c - AB indicates Air Bag
d- Number of tests evenly split between two dummies

Table C3.
H-III5F Dynamic Sled Test Matrix

	Mid-size Buck		Compact Buck	
Condition	**Driver**	**Passenger**	**Driver**	**Passenger**
3 pt. belt	20	20	4	4
3 pt. belt + air bag		1		
air bag	1	2	1	1
unrestrained	1	1	1	1

PERFORMANCE EVALUATION OF IMPACT RESPONSES OF THE SID-Ⅱs SMALL SIDE IMPACT DUMMY

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Paper Number 98-S7-O-02

ABSTRACT

A series of side impact tests have been conducted to evaluate the biofidelity of the latest prototype of a small side impact dummy, SID-Ⅱs β+(plus). The tests were lateral impacts for the thorax, shoulder, and pelvis, as well as lateral drops for the head, thorax, abdomen, and pelvis. The test data were compared to the response target corridors that were estimated by scaling the cadaver test data to a smaller occupant.

The test results show that the head, shoulder, thorax, abdomen and pelvis of the SID-Ⅱs β+ either completely or close to meets the response target corridors, and that its biofidelity has been improved from the previous dummy SID-Ⅱs β-prototype.

INTRODUCTION

Two side impact dummies has been specified as the test dummy to be used in side impact regulation, the SID for the United States, and the EUROSID-1 for EUROPE and JAPAN, respectively. Additionally, the EUROSID-1 and BIOSID has been recommended in the side impact test procedure of the ISO 10997. While all these dummies are representatives of a mid-size male, each has a different design. In recent years, development of an internationally harmonized mid-male side impact dummy is being discussed by the experts of the ISO.

Under these circumstances, an advanced small side impact dummy, named Side Impact Dummy second [Ⅱ] generation small (SID-Ⅱs) shown in Figure 1, has been developed in the United States. The dummy has been developed as a tool for evaluating advanced side impact countermeasures such as side airbags when the occupant is smaller than existing side impact dummies. In addition, the dummy has been developed for providing a basis for worldwide harmonization of side impact dummy design in the future. Specifications of the SID-Ⅱs were defined by the Occupant Safety Research Partnership (OSRP) of United States Council on Automobile Research (USCAR) formed by Chrysler, Ford, and General Motors. The dummy was designed and manufactured by First Technology Safety Systems (FTSS).

JARI/JAMA conducted a biofidelity evaluation test for the SID-Ⅱs named β-prototype in 1996, and reported the results to the experts meeting in the ISO in June, 1997. Recently, the SID-Ⅱs β-prototype has been updated to the SID-Ⅱs β+, for which JARI/JAMA are planning to continue the evaluation.

This paper describes the results of evaluation tests completed so far concerning the SID-Ⅱs β+ evaluations that JARI/JAMA are undertaking.

Figure 1. Small side impact dummy SID-Ⅱs.

GENERAL SPECIFICATION AND CURRENT STATUS OF THE SID-Ⅱs

The technical specifications and the biomechanical design targets for the SID-Ⅱs were published by OSRP in the 39th STAPP conference proceedings.

SID-Ⅱs has a similar anthropometry of a 5th percentile adult female. The structures of the shoulder, thorax, abdomen, and pelvis of the SID-Ⅱs were designed by incorporating the best features of exiting side impact dummies, SID, EUROSID-1, and BIOSID. For other body region, the components of the small female Hybrid-Ⅲ5F dummy were used with or without modifications. Maximum of 148 instrumentation channels are available, which can be chosen depend on the side impact countermeasures being evaluated.

The early prototype SID-Ⅱs dummy was called an α-prototype, and the first production version was called β-prototype(to be referred to as the β-type hereafter in this paper). In 1996-1997, the β-type dummy was evaluated by OSRP and JARI/JAMA and suggested to need to improve the biofidelity. Recently, the β-type dummy has been subjected to several modifications, then the dummy was called the SID-Ⅱs β+.

The description of the SID-Ⅱs and recent modifications towards the SID-Ⅱs β+ are briefly shown in Table 1. The recent modifications were intended to improve the biofidelity of the shoulder, thorax, abdomen and pelvis, as well as to obtain better measurement performance. Details of these modifications were reported by OSRP in ISO meeting in March 1998.

Table 1.
SID-Ⅱs and Modifications towards the β + dummy

	SID-Ⅱs	Modifications towards SID-Ⅱs β+
Head	Slightly modified Hybrid-Ⅲ5F head ·Shaved off skull sides ·Increased thickness of vinyl skin	No modifications
Neck	Slightly modified Hybrid-Ⅲ5F neck ·Plastic bushing installed to prevent metal contact	No modifications
Shoulder	Single far-side mounted rib with stub upper arm ·Upper arm on impact side only ·Linear potentiometer was used ·Rubber plug installed in the upper arm ·Arm positioned by using the detent stop	·Reduction of rib metal thickness ·Installation of support plate between the shoulder load cell and rib ·Arm plug hole was rounded corners ·Arm plug was molded on backing plate ·Enlargement of arm detent holes
Thorax, Abdomen	Asymmetrical spine box with 5 identical far-side mounted ribs ·High carbon spring steel ribs were used ·3 ribs for the thorax, 2ribs for the abdomen ·Ensolite® padding was placed inside the suits ·5 Linear potentiometers were used for each ribs ·4 load cells attached to the spine to measure rib to spine force	·Ribs were updated to Vascomax® Steel ·Reduction of rib metal thickness ·Redesigned rib-to-spine load cell ·Addition of accelerometer mounting hole on the non impacted side of the spine box ·Ensolite® padding was divided to the thorax and abdomen, and reduced padding thickness for the abdomen
Lumber Spine	Slightly modified Hybrid-Ⅲ5F lumber spine ·Cylindrical stepped shape rubber lumber ·Plastic bushing installed to prevent metal contact	No modifications
Pelvis	Bolted pelvic bone with removable pelvic Flesh ·Styrofoam® pelvic plug installed in the plug cup on the acetabulum ·Upper femur with rod end ball joints were used	·Plug material changed to a PP form ·Plug thickness and diameter were increased ·Plug retaining cup deleted ·Addition of rubber bumper to upper femur
Legs	Standard Hybrid-Ⅲ5F legs (The knee sliders were replaced with steel blocks)	No modifications

BIOFIDELITY EVALUATION TESTS

The biofidelity evaluation test procedures and the target responses for the SID-Ⅱs were proposed by OSRP in the 39th STAPP paper, based on the technical reports ISO TR9790-1 through 6. These technical reports describe the test procedures and response requirements for the head, neck, thorax, shoulder, abdomen, and pelvis for the mid-size male side impact dummy to asses their biofidelity. The response requirements of the ISO TR9790-1 through 6 were based on the test data on cadavers or human volunteers that were normalized to the mid-size male. It should be noted that a revised document N455-Rev.4 has been proposed to these technical reports.

OSRP has reviewed the cadaver data used to establishing the response requirements in the ISO TR9790-1 through 6, and scaled them to the SID-Ⅱs to establish the target responses. The test procedures and conditions are similar to those for the mid-size male provided in the ISO TR9790-1 through 6. However, the impactor mass for the thorax, shoulder, and pelvis has been reduced to amount in proportion to the total masses of the mid-size male and the SID-Ⅱs. Table 2 shows a matrix of the biofidelity evaluation test procedures for each body region of the SID-Ⅱs proposed by OSRP.

So far in this test series, JARI/JAMA have completed the impact tests for the thorax, shoulder, and pelvis, as well as the drop tests for the head, thorax, abdomen, and pelvis. The test data were compared to the response targets proposed by OSRP. Also, test data for the thorax, shoulder, and pelvis impacts were compared with those for β-type dummy previously tested. Future test plans include the 7.2 g HYGE neck sled test, and the WSU type sled tests for the shoulder, thorax, abdomen, and pelvis.

Some of the tests are not planned because the suitable test devices or paddings are not available in our laboratory (for example, neck 6.7g impact sled test and thorax 2m padded drop test). Further, tests for which the target response is established based on only one cadaver test data, or tests are considered too severe than necessary, are placed at a lower priority in the planning.

Table 2.
Biofidelity Evaluation Test Procedures for the SID-Ⅱs

Target	*Impact Tests*	*Drop Tests*	*Sled Tests*
Head	*No Target*	*200mm Rigid Drop* *1200mmm Padded Drop*	*No Target*
Neck	*No Target*	*No Target*	*7.2g HYGE Sled* *6.7g Impact Sled* *12.2g HYGE Sled*
Thorax	[illegible]	*1m Rigid Drop* *2m Padded Drop*	*Heidelberg- 6.8m/s Rigid* *WSU - 8.9m/s Padded*
Shoulder	[illegible]	*No Target*	*7.2g HYGE Sled* *12.2g HYGE Sled* *WSU - 8.9m/s Padded*
Abdomen	*No Target*	*1m Drop onto Rigid Armrest* *2m Drop onto Rigid Armrest*	*WSU - 6.8m/s Rigid* *WSU - 8.9m/s Rigid* *WSU - 8.9m/s Padded*
Pelvis	[illegible]	*0.5m Rigid Drop* *1m Rigid Drop* *2m Padded Drop* *3m Padded Drop*	*Heidelberg- 6.8m/s Rigid* *Heidelberg- 8.9m/s Rigid* *Heidelberg- 8.9m/s Padded* *WSU - 6.8m/s Rigid* *WSU - 8.9m/s Rigid* *WSU - 8.9m/s Padded*

(shaded) *; Completed.* (unshaded) *; Will be performed.*

Lateral Impact Tests

Lateral impact tests for the thorax, shoulder and pelvis were carried out by applying a pure lateral impact to the dummy, using a linearly guided impactor. The dummy (with suit) was seated in an upright position on a flat, rigid, horizontal surface, without back support. Two sheets of Teflon™ were placed between the dummy and the surface.

Thorax 4.3m/s and 6.7m/s Impact Tests – Five times thorax impact tests were carried out each for velocities of 4.3m/s and 6.7m/s. 14kg impactor having a flat face 120 mm in diameter was used. The centerline of the impactor was aligned to the center of the thorax middle rib. The upper arm of the dummy was removed because of possible interference with the impactor face. The thorax impact test setup is shown in Figure 2. In the test, the accelerations of the impactor and the upper spine (T1) of the dummy were measured. The impactor force was calculated by multiplying the acceleration of the impactor with its mass, 14kg.

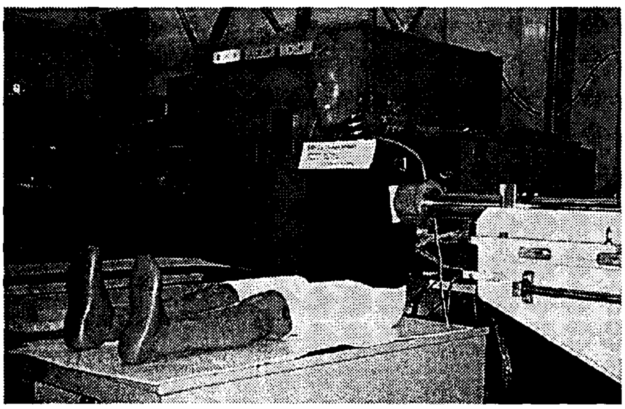

Figure 2. Test setup for the thorax lateral impact.

Figures 3 and 4 show the impactor force-time responses and the T1 acceleration-time responses for the 4.3m/s thorax impact tests, respectively. Figure 5 shows the impactor force-time responses for the 6.7m/s thorax impact tests. These figures also show that, the target response corridors estimated by OSRP, as well as the responses for β-type dummy previously tested.

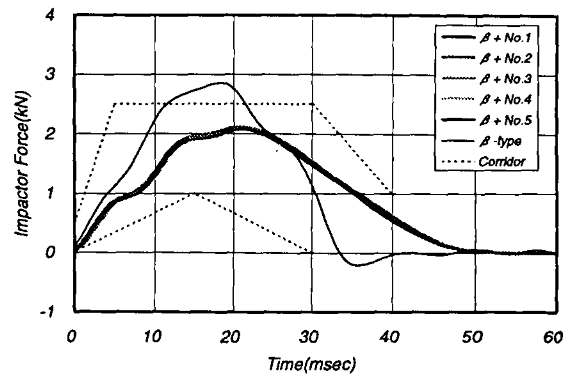

Figure 3. Impactor force-time responses with target corridor for the thorax 4.3m/s lateral impact.

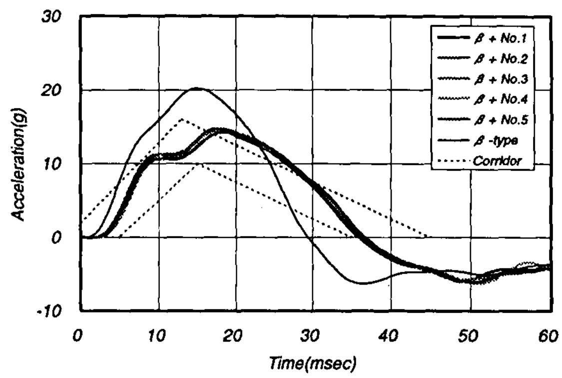

Figure 4. T1 acceleration-time responses with target corridor for the thorax 4.3m/s lateral impact.

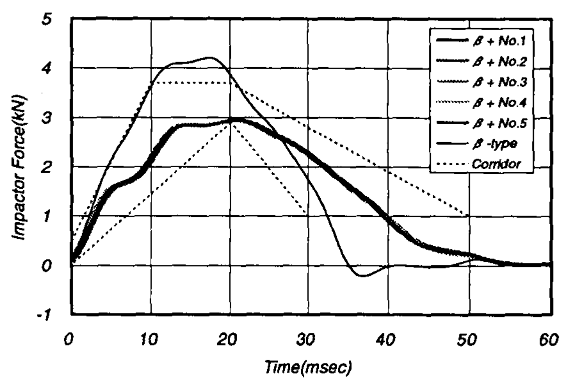

Figure 5. Impactor force-time responses with target corridor for the thorax 6.7m/s lateral impact.

In the 4.3m/s test, impactor force–time responses for the β + dummy are completely within the target corridor, while the β-type dummy shows higher peak force than the upper limit of the corridor. For the T1 acceleration, although the responses of the β + dummy are slightly above the upper limit of the corridor, the general shape and time duration are closer to the corridor than those of the β-type dummy.

In the 6.7m/s test, unlike the β-type dummy of which the peak impactor force exceed the upper limit of the corridor, the responses of the β + dummy are within the corridor close to the lower limit.

These test responses show that the modifications to the thorax rib have improved the rib deflection characteristics. In addition, it can be noted that the repeatability of the thorax impact test responses for the β + dummy appears to be very good.

<u>Shoulder 4.5m/s Lateral Impact Test</u> - Five times 4.5m/s shoulder impact tests were performed using an impactor identical to that in the thorax impact tests. The centerline of the impactor was aligned to the center of the shoulder pivot, and the upper arm was placed vertical beside to the thorax. The acceleration of the impactor and the shoulder rib deflection of the dummy were measured in the tests. The impactor force was calculated by multiplying the acceleration of the impactor with its mass, 14kg.

Figure 6 shows the impactor force-time responses for the shoulder impact tests, and Table 3, the peak shoulder rib deflections, together with the target responses estimated by OSRP and corresponding test results for the β-type dummy.

The peak impactor forces for the β + dummy are almost within the target corridor at the upper limit. While the time duration for the β + dummy is slightly shorter than the corridor, general shape is closer to the corridor than the β-type dummy. The peak shoulder rib deflections of the β + dummy are within the response target at the upper limit. These values considerably differ from those of the β-type dummy which shows values slightly below the lower limit of the response target.

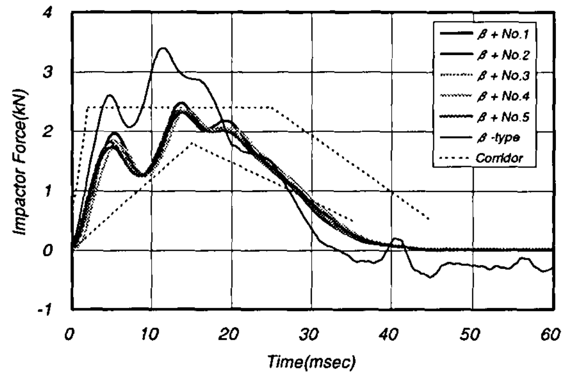

Figure 6. Impactor force-time responses with target corridor for the shoulder lateral impact.

Table 3.
Peak Shoulder Rib Deflections with Response Target for the Shoulder lateral Impact

Response Target	Test Results						
		No.1	No.2	No.3	No.4	No.5	Mean
Shoulder Rib Defl.	β-type	21.5	21.7	21.4	21.6	21.7	21.58
22 - 30 (mm)	β +	28.4	28.6	28.0	29.4	29.2	28.71

These test results indicate, just as in the case of the thorax, that the modifications in the shoulder rib have improved the rib deflection characteristics. In addition, as is for thorax, the test data repeatability can be described as well in the shoulder impacts.

<u>Pelvis 6 – 10m/s Lateral Impact Test</u> - The pelvis impact tests were conducted using a 10.0kg impactor having a spherical face of 175mm-radius and a diameter of 120 mm. The test for the β + dummy was repeated twice at each velocities of 6m/s and 6.7m/s. (For the β-type dummy, two tests each were conducted for velocities of 6m/s, 6.7m/s, and 7.5m/s). The center axis of the impactor was aligned to the H-point of the dummy. In the test, the acceleration of the impactor was measured, and multiplied with its mass, 10.0kg to obtain the impactor force.

Figure 7 shows the peak impactor force versus impact velocity relationship together with the target corridor and corresponding test results for the β-type dummy.

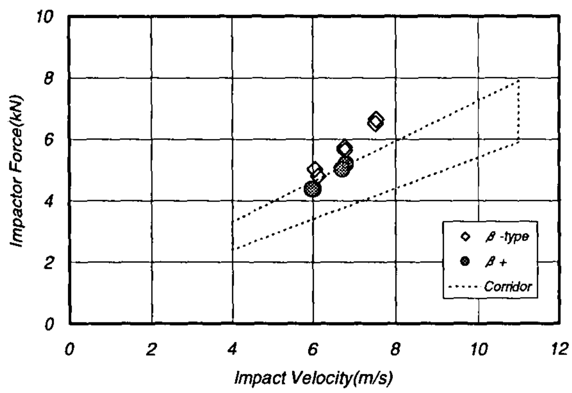

Figure 7. Peak impactor force vs. impact velocity with target corridor for the pelvis lateral impact.

The impactor peak forces for the β+ dummy are within the corridor for 6m/s and right at the upper limit for 6.7m/s, while the β -type dummy shows higher responses than the upper limit of the corridor.

These test results were achieved by modifying the material, diameter, and thickness of the pelvic plug that is installed into the sides of the pelvis. However, since this pelvic plug presently needs to be renewed after each test, development of a re-useable plug is expected.

Drop Tests

Drop tests were conducted for the dummy's head by itself, as well as for the thorax, pelvis, and abdomen using a whole dummy.

In the head drop test, a dummy head is suspended at a certain height and allowed to free-fall onto a flat surface to impact the upper side portion of the head. Only the 200mm rigid drop was conducted; the 1200mm padded drop was not performed because the test conditions were considered too severe than necessary.

Two types of drop tests were conducted to the whole dummy, one for the thorax and pelvis, other for the abdomen. In the tests, the dummy (with suits) was suspended with its midsagittal plane horizontal, and a quick release device was used to provide a free fall onto the impact surface. For the thorax and pelvis, the 0.5m and 1m rigid drop tests were conducted, but the 2m and 3m drop tests were not carried out because the required APR form padding was not available. For the abdomen, only the 1m drop test was conducted; the 2m drop was not performed because the test conditions were considered too severe than necessary.

Head 200mm Drop Test - The head was suspended with its midsagittal plane making an angle of 35° to the horizontal. Then the head was dropped onto a flat, rigid and horizontal surface from a height of 200mm. The test was repeated five times, to the upper left side of the head. Figure 8 shows the test setup for the head 200mm drop. The triaxial accelerations were measured at the non-impact side of the head cavity on the left-right axis passing through the center of gravity.

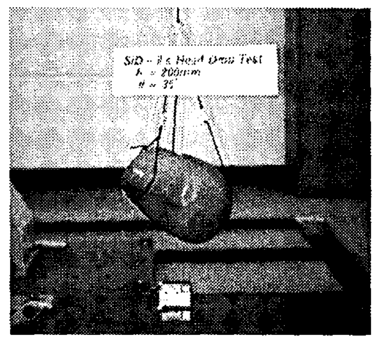

Figure 8. Test setup for the head 200mm drop.

The test results and the target response are given together in Table 4. The resultant accelerations of the head slightly exceed the upper limit of the target response for all five tests.

According to OSRP, the head response will improve if powder is applied between the skin and the skull. Although powder was used in the tests, the skin might have been outdated and hardened slightly. Accordingly, head tests will be rerun using a new skin.

Table 4.
Peak Head Resultant Accelerations with Response target for the Head 200mm Rigid Drop

Response Target	Test Results					
	No.1	No.2	No.3	No.4	No.5	Mean
Head Res.Acc. 106 - 158 (g)	162.3	167.9	167.3	165.5	167.6	166.12

Thorax and Pelvis Drop Test - In the thorax and pelvis drop tests, the whole dummy was dropped onto a flat, rigid, horizontal surface from a height of 0.5m and 1m. Two tests for 0.5m drop and three tests for 1m drop were carried out, respectively.

The impact surface consists of four separated force measuring surfaces correspond to the shoulder, thorax, pelvis and thigh, respectively. An edge of the thorax impact surface was aligned to the lower edge of the thorax lower rib. The upper arm of the dummy was rotated 20° forward to the spine. Figure 9 shows the setup for the thorax and pelvis drop tests. In the tests, the forces at the shoulder and thorax impact surfaces, thoracic rib deflection and the pelvic accelerations were measured. The target responses for the thorax were specified as the force-time response of the thorax impact surface (including the shoulder) and the peak thoracic rib deflection at the 1 m drop test. The peak pelvic resultant accelerations were specified to the 0.5m and 1m drop tests as the pelvis targets.

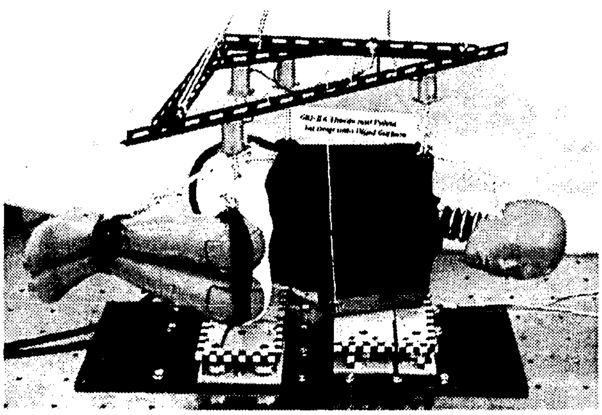

Figure 9. Test setup for the thorax and pelvis drop.

Figure 10 gives the force-time responses of the combined thorax and shoulder impact surfaces for the 1m drops together with the target response corridor. Table 5 shows the peak thoracic rib deflections for the 1m drops, and Table 6, the peak pelvic resultant accelerations for the 0.5m and 1m drops, together with the corresponding response targets.

For the impacted surface force for the thorax, while slightly exceeding the upper limit of the corridor at the beginning of the curve, peak forces are close to meet the lower limit of the corridor. However, the time duration is longer than the corridor. For the peak thoracic rib deflections, all three ribs within the response target near the upper limit for the three tests.

The peak pelvic resultant accelerations within the response target for the 0.5m drops but show values below the lower target limit at the 1m drops.

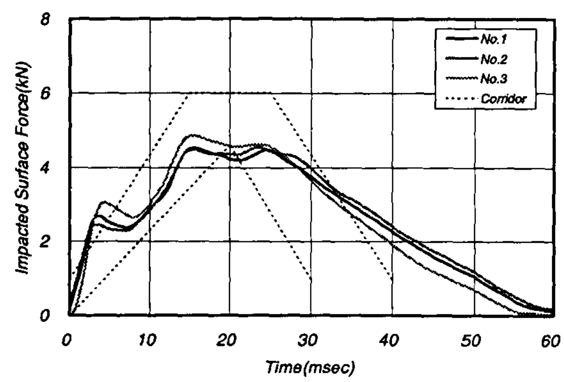

Figure 10 Impacted surface force-time responses with target corridor for the thorax 1m drop.

Table 5.
Peak Thoracic Rib Deflections with Response Target for the Thorax 1m Drop

Response Target	Test Results		
	No.1	No.2	No.3
Thorax Rib Defl. 24 - 32 (mm)	Upper ; 31.0	Upper ; 30.0	Upper ; 30.9
	Middle ; 30.9	Middle ; 30.2	Middle ; 32.0
	Lower ; 28.0	Lower ; 27.7	Lower ; 30.6

Table 6.
Peak Pelvic Resultant Accelerations with Response Targets for the Pelvis 0.5m and 1m Drops

	Response Target	Test Results		
		No.1	No.2	No.3
0.5m Rigid	Pelvis Res.Acc. 41 - 55 (g)	41.5	46.8	
1m Rigid	Pelvis Res.Acc. 70 - 94 (g)	58.1	55.1	56.9

In the whole dummy drop tests, it is very difficult to maintain the proper posture of the dummy at the moment of impact. Slight differences in the contact area at the impacting face or in the impact timing could cause data variation. Taking these factors into consideration, the drop tests for both 0.5m and 1m can be regarded as showing good repeatability.

Abdomen Drop Test - In the abdomen drop test, the whole dummy was allowed to free fall from a height of 1m to impact abdomen with a simulated armrest. The test was repeated three times. Figure 11 shows the setup for the abdomen drop test.

The simulated armrest is 70mm wide and 300mm long, protruding 33mm above the surrounding surface, and mounted on the two load cells. The centerline of the armrest was aligned to the center of the gap of the two abdominal ribs. The upper arm of the dummy was positioned upward. In the tests, the force applied to the armrest, the deflection and acceleration of two abdominal ribs, and the acceleration of the T12 spine were measured.

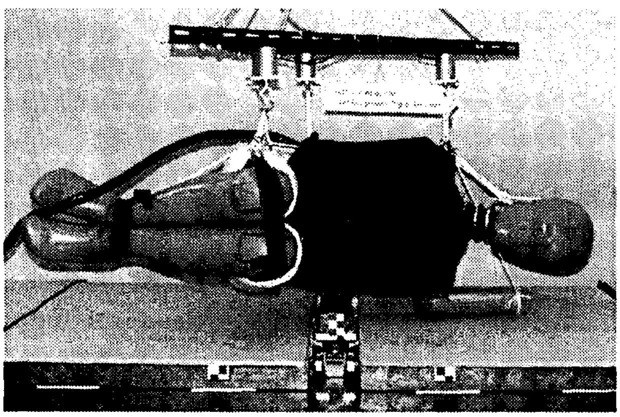

Figure 11. Test setup for the abdomen 1m drop onto rigid armrest.

Figure 12 shows the force-time responses of the armrest for the abdomen 1m drop tests with the response target corridor. The peak accelerations of T12 and the abdominal rib as well as peak abdominal rib deflections, with the response targets are given in Table 7.

The peak armrest forces are close to meet the lower limit of the corridor, and the time duration is slightly longer than the corridor in the abdomen 1m drops. The peak accelerations for the abdominal upper rib and the peak deflections for the upper and lower abdominal ribs within the response targets. However, the peak accelerations of T12 and the lower abdominal rib show values slightly exceeding the upper limit of the response targets.

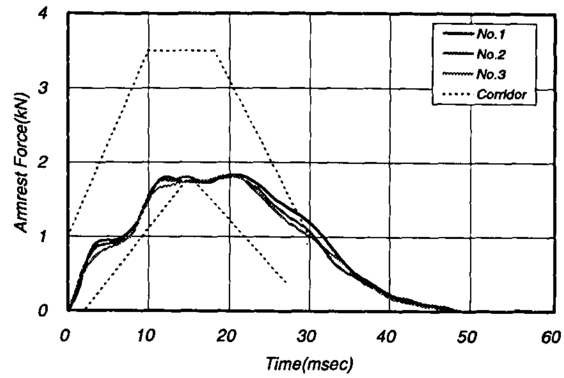

Figure 12. Armrest force-time responses with target corridor for the abdomen 1m drop.

Table 7.
Peak Abdominal Responses with Response Targets for the Abdomen 1m Drop

Response Target	Test Results		
	No.1	No.2	No.3
T12 Acc. 29 - 39 (g)	46.7	43.6	50.3
Abdominal Rib Acc. 112 - 152 (g)	Upper; 145.7	Upper; 129.9	Upper; 113.6
	Lower; 169.1	Lower; 162.9	Lower; 160.3
Abdominal Rib Defl. > 33 (mm)	Upper; 44.1	Upper; 43.7	Upper; 43.4
	Lower; 52.4	Lower; 51.9	Lower; 54.3

As with the thorax and pelvis drop test, it is also difficult to maintain the proper posture of the dummy for the abdomen drop test. Moreover, the small size of the contact area at the armrest is apt to cause data variations. In particular, as the peak acceleration of the abdominal ribs occurs in an early in the impact, slight differences in the dummy's posture or position at the moment of impact could translate into significant data variations.

SUMMARY

A series of side impact tests has been conducted by JARI/JAMA to evaluate the biofidelity of the latest prototype of a small side impact dummy, SID-Ⅱs β+. The dummy has been developed as a tool for evaluating advanced side impact countermeasures when the occupant is smaller than existing side impact dummies, and for providing a basis for internationally harmonized side impact dummy design in the future.

The tests conducted were lateral impacts for the thorax, shoulder, and pelvis, as well as lateral drops for the head, thorax, abdomen, and pelvis. The test data were compared to the target response corridors and values that were estimated by OSRP after scaling the cadaver data to smaller occupant.

The test results show that the SID-Ⅱs β+ either completely or nearly meets the targeted responses for the head, thorax, shoulder, abdomen, and pelvis. Then the biofidelity of the SID-Ⅱs β+ has been improved over the previous dummy called the SID-Ⅱs β-prototype. In addition, the responses of the shoulder, thorax, and pelvis have shown very good repeatability in the lateral impact tests. For the drop tests, although a substantial difficulty exists in the preparatory setting of the dummy, the test responses showed comparatively reasonable repeatability.

An outline of the test results for each part of the dummy are as follows:

1. For the head, the peak resultant accelerations of the head exceed the upper limit of the response target in the 200mm rigid drop test. However, since this may be due to the old head skin used, a retest would be required using a new head skin.
2. For the thorax, although the T1 acceleration responses slightly exceed the upper limit of the target corridor, the impactor force-time responses are within the target corridor in the 4.3m/s and 6.7m/s impact tests. In addition, in the 1m drop test, the thorax impacted surface force-time responses are close to meet the target corridor and the peak thoracic rib deflections are within the targets.
3. In the shoulder impact test, the peak forces of the impactor are almost within the corridor at the upper limit, and the peak shoulder rib deflections are within the response targets.
4. In the abdomen 1m drop test, the armrest forces are almost within the target corridor at the lower limit. In addition, the peak deflections of the abdominal ribs and peak accelerations of the abdominal upper rib are within the response targets. However, the peak accelerations of T12 and the abdominal lower rib show values slightly exceed the upper limit of the response targets.
5. In the pelvis impact test, the peak impactor forces are within the target corridor at 6m/s impact, and right at the upper limit of the corridor at 6.7m/s impact. The peak pelvic accelerations are within the response target for the 0.5m drop test, but show values lower than lower limit of the target in the 1m drop.

TASKS IN FUTURE

The SID-Ⅱs evaluation tests by JARI/JAMA are still continuing on with future test plans including the 7.2 g neck sled test, and the WSU type sled tests for the shoulder, thorax, abdomen, and pelvis. After these tests have been completed, biofidelity ratings of the dummy will be calculated based on the ISO biofidelity rating procedure. Further, JARI/JAMA intend to co-operate in the establishing the calibration corridors for the SID-Ⅱs that has been not defined yet.

The study results of JARI/JAMA will be reported at the experts meeting of ISO, when those become available. It is the opinion of JARI/JAMA that by publishing our study results the two organizations should be able to make contributions toward the development and research of the side impact dummies to be harmonized under worldwide specifications.

The SID-Ⅱs is a dummy on which development effort continues even now, and as such could be subjected to further improvements. The evaluation test program by JARI/JAMA needs to respond flexibly to such improvements.

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HUMAN THORAX BEHAVIOUR FOR SIDE IMPACT. INFLUENCE OF IMPACT MASSES AND VELOCITIES

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ABSTRACT

This study deals with the knowledge of human behaviour under impact conditions close to those of the real world and the verification of the sensitivity of the lateral criteria deflection and V*C to mass and velocity variation. A series of 11 tests were conducted on unembalmed cadavers with a guided horizontal impactor. The impactor masses used were 12 and 16 kg and the velocities were 6 to 8.5 m/s. The impact surface was flat, rigid and of 15 cm diameter. Identical tests were carried out with a Eurosid-1 dummy.

In these tests conditions, the behaviour of the Eurosid-1 thorax could be improved.

The V*C and the defelction criteria are sensitive to the variations of the impact masses and velocities.

INTRODUCTION

The improvement of occupant protection in side impact crashes is of constant concern in automotive safety. The basis for product improvements is an understanding of crash types and interior contact. The goal of this study is to look for the effects of mass and velocity variations on the biomechanical criteria used for the thorax in the lateral impact.In all previous studies using cadaver lateral impacts, the tests were carried out with an impactor mass of 23.4 kg and impact speeds of less than 9 m/s or against a rigid wall. The analysis of crash tests showed that the effective impacting masses with regard to the thorax were lower than 23.4 kg and the impact velocities were higher than 8 m/s. This study deals with the knowledge of human thorax behaviour and response under impact conditions close to those of the real world ($m = 12$ kg and $m = 16$ kg; $5.9 \text{ m/s} \leq V \leq 8.5 \text{ m/s}$.) since this information forms the basis for the development of applicable injury criteria and for setting human tolerance levels.

MATERIALS AND METHODS.

- **Specimen selection.**

Unembalmed cadavers were provided by the Department of Anatomy at Lyon-Nord Medical University.

They were all aged between 53 and 93 years; the average age was 72 years and mean body mass 59 kg. Anthropometric data were compiled for each subject prior to testing. The anthropometric data are shown in table 1.

Table 1 : Subject anthropometrics.

Subject	Sex	Age	Mass (Kg)	Height (cm)	Thorax width (cm)	C/L gr/cm
LCT01	M	65	55	176	29.0	0.20
LCT02	F	53	78	164	27.7	0.15
LCT03	F	80	30	157	24.5	0.53
LCT04	F	93	43	157	25.2	0.15
LCT05	M	84	42	160	28.5	0.14
LCT06	M	77	68	175	32.5	0.24
LCT07	M	72	82	181	34.0	0.21
LCT08	M	66	59	173	30.0	0.24
LCT09	M	65	66	165	30.0	0.20
LCT10	M	69	56	180	29.7	0.30
LCT11	M	71	71	169	29.0	NA*

*NA : Not available

The criteria for selection of subjects were their condition and cause of death, which limited the selection to specimens not having had a long period of bed rest or to specimens without infectius deseases. For each of the specimens, the time between death and testing was 4 to 6 days.

- **Preparation and instrumentation.**

Cadavers : The subjects were exposed to room temperature for several hours during instrumentation and preparation. Just before the test, the lungs were pressurized by means of a vent tube inserted in the trachea. The subjects LCT01,LCT02 and LCT03 were partially injected because of the atherosclerosis. The other subjects were not injected.

The subject instrumentation was defined to obtain the kinematics of seven points on the head, the spine and pelvic during the impact. The cadaver was instrumented with an array of accelerometers attached to the ribs, spine and pelvis. A triaxial accelerometer was attached to the first, eigth and twelfth thoracic vertebrae and a similar triaxial accelerometer was attached to the sacrum. An angular velocity sensor was attached to the eighth vertebra and another to the sacrum. Uniaxial accelerometers were attached to the fifth, the sixth and the seventh rib on the impacted side.

Double targets separated from one another by 6 centimeters were attached to the head, the first, the fourth, the eighth and the twelfth vertebrae, similar targets were attached to the third lumbar vertebra and to the sacrum (Figure 1). The double target system allowed the calculation of the vertebrae rotation during the impact.

Dummy : All cadaver tests were duplicated by Eurosid-1 tests. Table 2 gives the entire instrumentation used for the cadavers and Eurosid-1 tests.

Table 2 : Instrumentation used for the tests.

	Eurosid-1	Cadaver
Head acceleration	X,Y,Z	
Acceleration (T1)	X,Y,Z	X,Y,Z
Acceleration (T8)		X,Y,Z
Acceleration (T12)	X,Y,Z	X,Y,Z
Pelvic acceleration	X,Y,Z	X,Y,Z
Rib acceleration (1,2,3)	Y	
Rib acceleration (5,6,7)		Y
Pubic force	Y	
Rib deflection (1,2,3)	Y	
Angular velocity (T8)	ω	ω
Angular velocity (Sacrum)	ω	ω

- **Autopsy**

Autopsy was performed by a qualified physician and special attention was paid to chest injury.

In order to assess the subject mineralization, a 6 centimeter sample was taken from the fourth, the fifth and the sixth ribs.

- **Test configuration**

Impactor : The tests were carried out with a linear impactor. The impactor masses were 12 kg and 16 kg. The impactor interface was a rigid, flat, 15 centimeter diameter disc. The impactor was propulsed by bungee cords. The impact speed was calculated by a time interval counter and a known distance on the impactor.

Subject positioning : The subject was seated on a sheet of teflon. A suspension system, which held the neck, ensured that the subject was positionned, as required, with a straight back. The longitudinal axis of the impactor was aligned with the xiphoïd process. The arm was not involved in the impact. Each subject was impacted on the right side. Figure 1 shows a general view of the test configuration

Determination of the test matrix :

To determine the test conditions, that is to say, the impact masses and velocities, an analysis was made from vehicle tests with dummies used under ECE95 regulation conditions. The European side impact test procedure is a global test on a stationary vehicle struck laterally by a deformable moving barrier. The barrier velocity was 50 km/h.

This analysis was carried out to calculate the impact velocity of the inner side of the door during the crash. The impact velocities were obtained by integrating the acceleration of the door at a point located at the level of the middle rib of the dummy.

The analysis of several tests showed that impact velocity values were from 8 to 12 m/s with an average value of 10.9 m/s. These variations were due to the different stiffnesses of the doors of the vehicles tested.

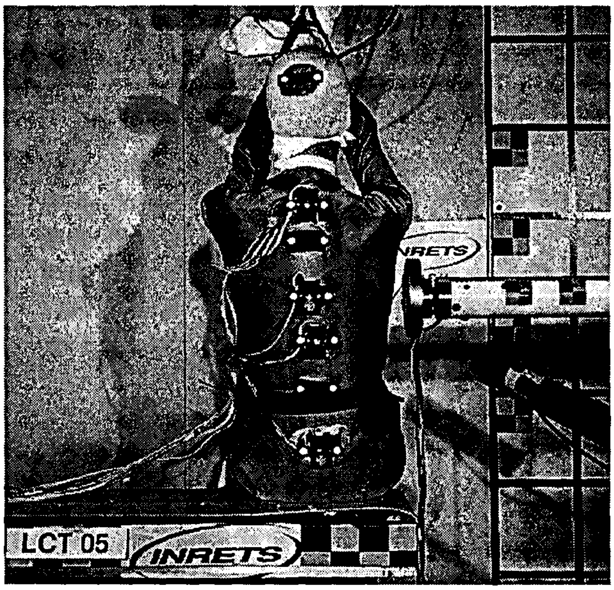

Figure 1 : General view of the experimental set-up.

Eleven cadaver tests and eighteen Eurosid-1 tests were carried out. Tables 3 and 4 respectively give the test conditions for cadavers and Eurosid-1.

Data analysis :

The tests was filmed at 1000 frames per second from behind the subject.

The half thorax deflection was considered to be equal to the displacement of the impactor with respect to the spine displacement at the eighth vertebra. For these tests, two methods of computing the deflection were used. The first method was the difference between the double integration of the T8 and impactor accelerations. The second method was a film analysis.

Table 3 : Experimental test conditions for the cadaver tests.

Test	Mass (kg)	Velocity (m/s)	Energy (J)
LCT01	12	5.96	213
LCT02	16	5.93	281
LCT03	16	6.06	294
LCT04	12	6	216
LCT05	12	8.19	402
LCT06	12	8.48	431
LCT07	16	7.16	410
LCT08	16	7.03	395
LCT09	16	5.7	260
LCT10	12	5.32	170
LCT11	12	8.53	436

A frame by frame analysis of the impact formed the basis for the instantaneous deflection data. These two methods allow the comparison of the data obtained and permit the validation of the results. Figure 2 shows a comparison of the deflections obtained from the two methods. The deflection value of the LCT02 test is 87.2 mm and this value is validated by the two methods. In all the results analysis, the deflection curves used are from the accelerometric method.

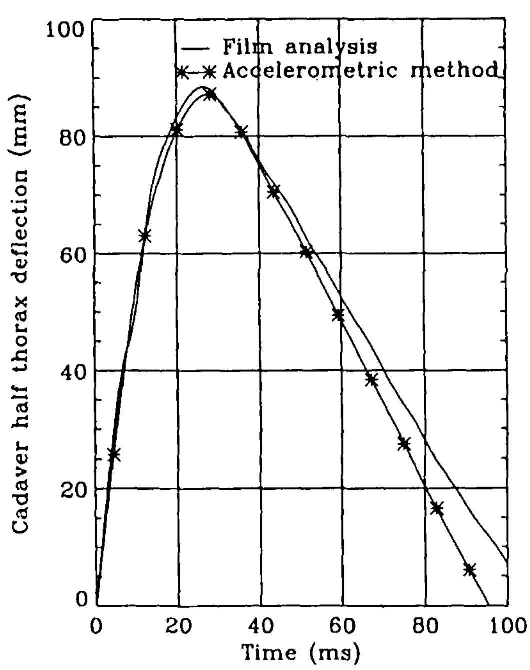

Figure 2 : Comparison of the deflection curves from accelerometric and film analysis.

The deflection data were processed using an established algorithm by Viano and Lau [1] and Lau and Viano [2] to derive the viscous response (V*C).
Contact was indicated by a flash on a movie frame and a simultaneous electrical signal from a switch. This defined time zero.

Table 4 : Experimental test conditions for Eurosid-1 tests

Test	Mass (kg)	Velocity (m/s)	Energy (J)
LMT01	12	6.10	223
LMT02	12	7.46	334
LMT03	12	5.39	174
LMT04	12	6.06	220
LMT05	12	9.02	488
LMT06	12	8.97	483
LMT07	16	5.90	278
LMT08	16	5.78	267
LMT09	16	8.32	554
LMT10	16	8.33	555
LMT11	12	4.81	139
LMT12	12	8.21	404
LMT13	11.4	6.00	205
LMT14	11.4	6.02	207
LMT15	11.4	8.58	420
LMT16	11.4	8.58	420
LMT17	16	7.18	412
LMT18	16	7.17	411

RESULTS

- Cadaver tests : Biomechanical responses.

The acceleration channels were filtered at CFC 180.
For the cadaver tests, peak biomechanical responses, in terms of force, deflection and viscous criterion, and resulting injuries are summarized in table 5.
The injury evaluation is given by the number of fractured ribs and the severity is given by the A.I.S. (Abreviated Injury Scale). All the subjects were injured. The injuries were essentially rib fractures. All subjects sustained one or more fractures on the 5th, the 6th and the 7th ribs. Some of them can be attribuated to the accelerometer mounting. That's why fractured ribs number is more able to avaluate the severite of the impact. Two subjects sustained more than rib fractures : (LCT02 and LCT07). These injuries were liver lacerations (stared wound of 4

centimeters in diameter for test LCT02 and a hemorrhagic wound of the right part of the liver for test LCT07). Comparisons between the number of fractured ribs and the energy, force and deflection were made. There were no relationships between these parameters and the number of fractured ribs.
The cadaver responses in terms of forces and deflections were gathered for energy values of 190 ± 26 J , 278 ± 18 J and 415 ± 20 J.

Table 5 : Cadaver responses and injuries for a lateral impact.

Test	Force (daN)	Deflection (mm)	V*C (m/s)	NRF	NFR	AIS
LCT01	223	62.5	1.33	3	3	2
LCT02	288	87.2	1.75	10	5	3
LCT03	187	63.6	0.93	18	7	4
LCT04	176	72.6	1.36	16	8	4
LCT05	294	102	2.59	9	7	3
LCT06	379	85.4	2.15	14	6	4
LCT07	394	96.8	1.70	11	6	4
LCT08	281	99.3	1.77	16	6	4
LCT09	262	73.9	1.26	6	6	3
LCT10	250	73.6	1.79	8	4	3
LCT11	384	80.5	2	6	4	3

* NFR = Number of fractured ribs
* NRF = Number of rib fractures

The results are given in figures 3 and 4. Figure 3 shows the thorax deflection curves versus time and figure 4 shows the impactor force versus time. On figure 4 and for the energy of 190 ± 26 J, we have added the iso corridor obtained from [4]. This corridor was obtained with the HSRI impact tests [5] with an impacto mass of 23.4 kg and a velocity of 4.3 m/s. For this level of energy, the impactor force curves are within the corridor.
Figure 5 shows the force/deflection curves. These curves represent the characteristic responses of the biomechanical behaviour of the thorax subjected to lateral impact. For those test conditions, response corridors were defined for each level of impact energy.

- Eurosid-1 tests : Biofidelity.

The Eurosid-1 biofidelity was assessed by comparing the responses of the dummy with those of the cadaver.
The characteristic responses of the Eurosid-1 thorax in terms of force versus deflection were obtained.
Figure 6 shows the curves of force/deflection for the three energy levels; to evaluate the biofidelity of the Eurosid-1, corridors obtained from cadaver tests were added to the graphs in figure 6.
For these impact energies and for the test configurations of this study, the Eurosid-1 behaviour was not biofidelic compared to the cadaver behaviour.

The force response of the Eurosid-1 thorax is twice as high as that of the human being. whereas the thorax deflection response of the dummy is half that of the human.

Criteria sensitivity.

To study the sensitivity of the impact response parameters to the test conditions, tests at isoenergy and tests at isomass were analysed.

- **Isoenergy tests**

Cadaver and Eurosid-1 tests at isoenergy level (but different masses and velocities) were analysed.
Table 6 gives,with the test conditions, the peak values of the force, the deflection and the V*C for the cadavers and table 7 gives the results for the Eurosid-1 tests for the same energy.

Table 6 : Cadaver tests at isoenergy (415 ± 20 J)

Test	Mass (kg)	Velocity (m/s)	Force (daN)	Deflection (mm)	V*C (m/s)
LCT05	12	8.19	294	102	2.59
LCT06	12	8.48	376	85.4	2.15
LCT11	12	8.53	384	80.5	2
LCT07	16	7.16	394	96.8	1.7
LCT08	16	7.03	281	99.3	1.77

From the results presented in table 6, it can be seen that for the higher velocity tests (LCT06 and LCT11) the V*C values are higher than (16.6 % higher) at the lower velocities. Furthermore, for the lower velocity tests (LCT07 and LCT08), the deflection values are higher than at the higher velocity tests.
For the same energy of impact, the V*C and d responses are sensitive to mass and velocity variations. Thus, the V*C increases with the impact velocity whereas the deflection decreases.

Table 7 : Eurosid-1 tests at isoenergy.

Test	Mass (kg)	Velocity (m/s)	Force (daN)	Deflection (mm)	V*C (m/s)
LMT12	11.4	8.21	873	48.2	1.37
LMT15	11.4	8.58	1135	47.2	1.30
LMT16	11.4	8.58	950	49.5	1.26
LMT17	16	7.18	827	46.9	0.99
LMT18	16	7.17	864	47.5	1.02

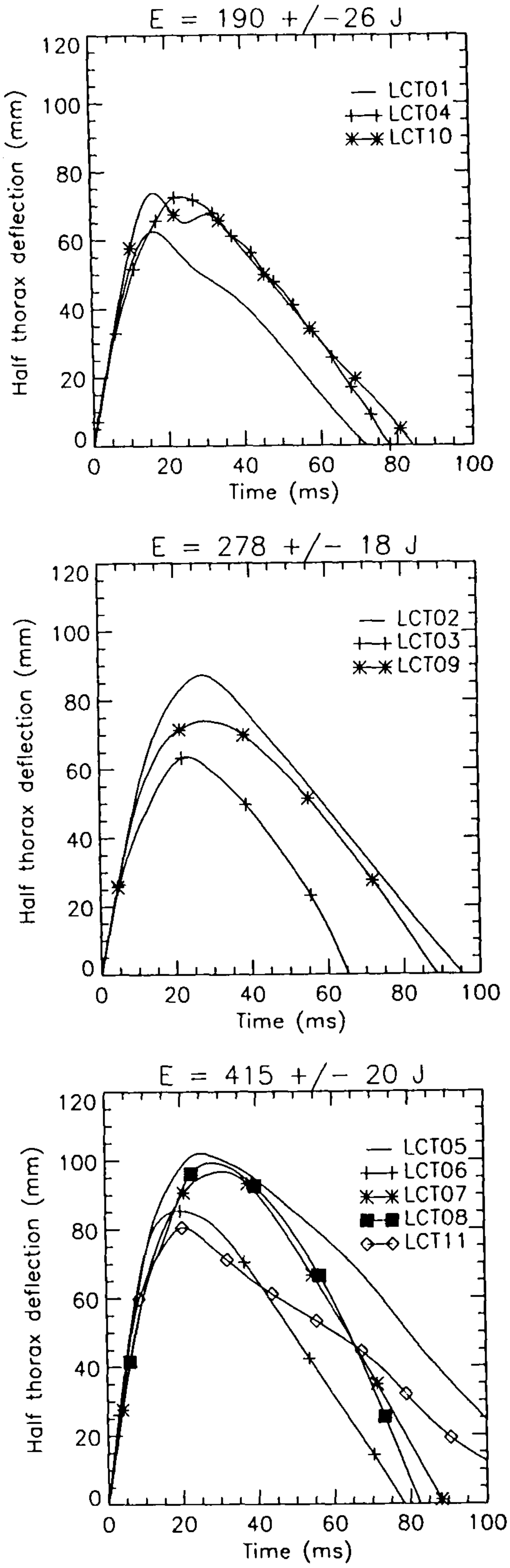

Figure 3 : Result of cadaver deflections for different energies

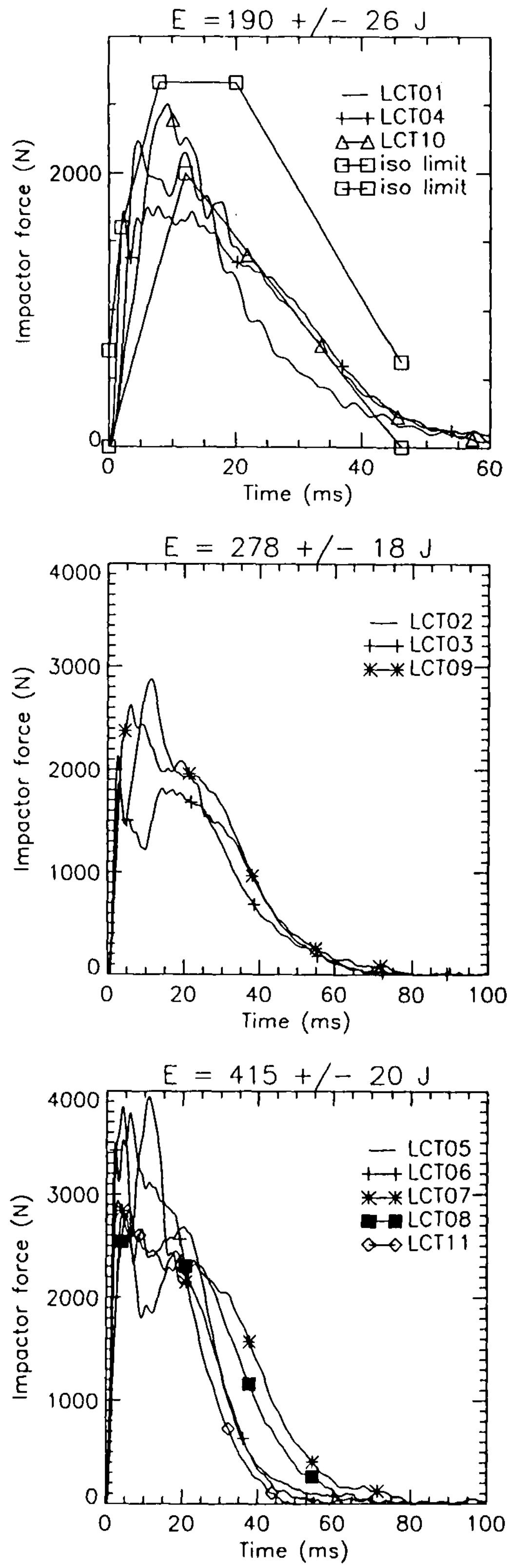

Figure 4 : Result of impactor forces for different energies

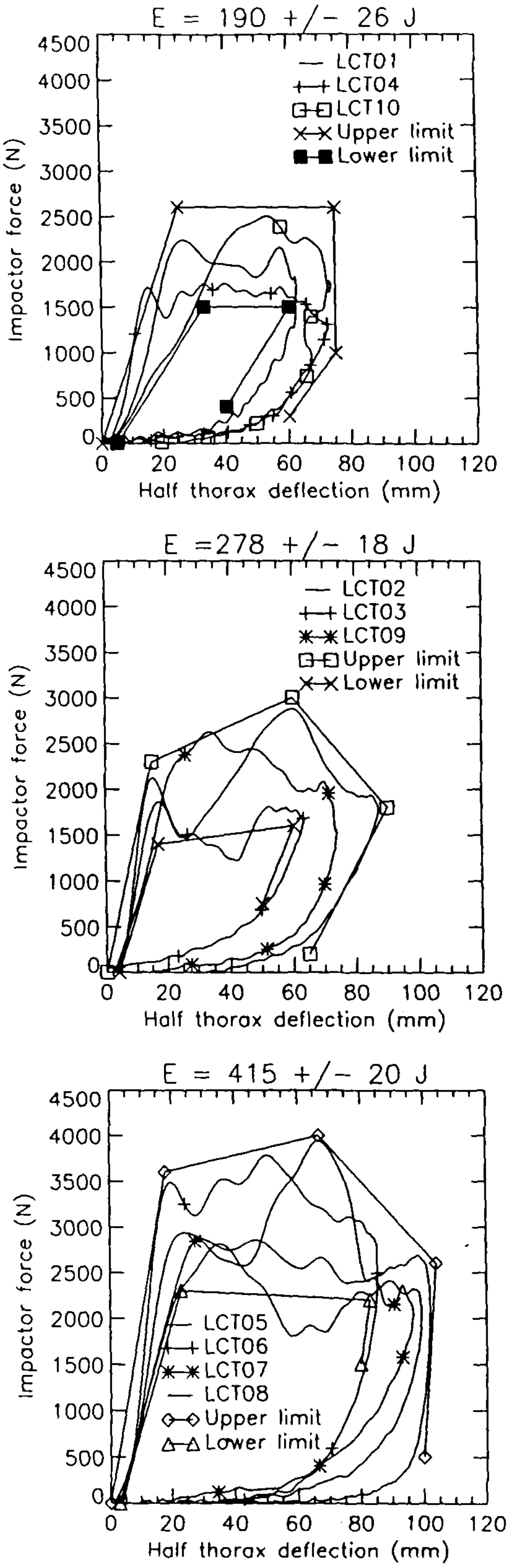

Figure 5 : Cadaver corridors
for different energies.

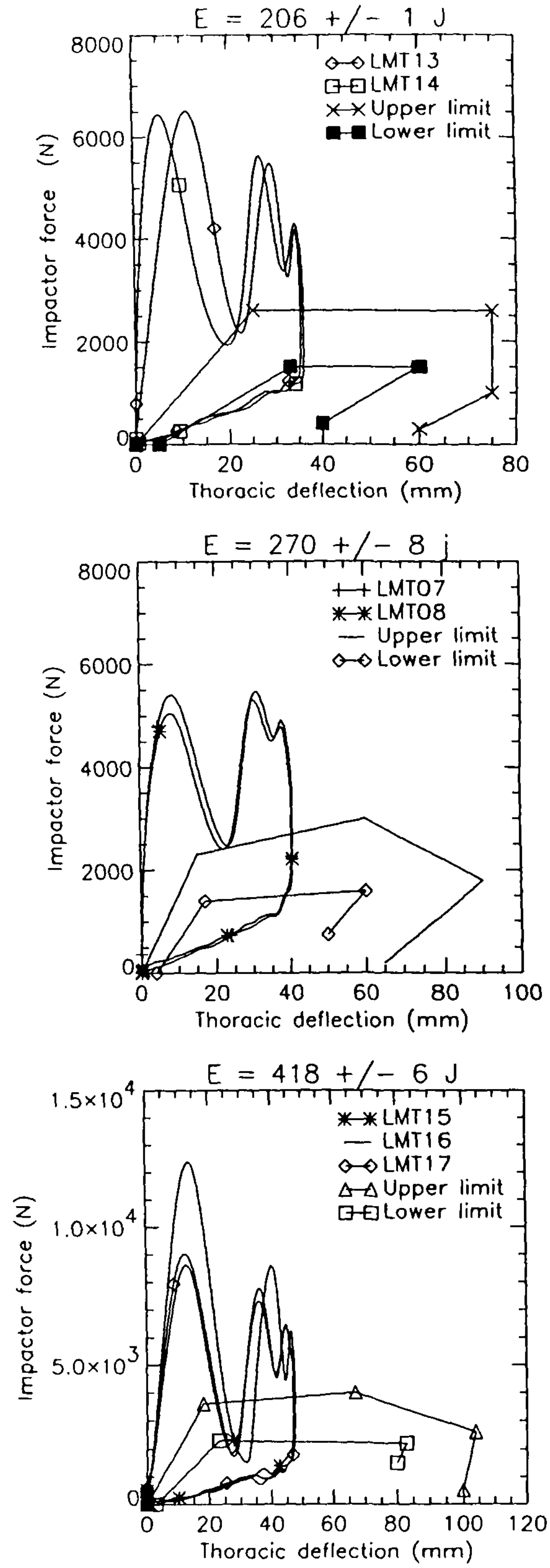

Figure 6 : Comparison of cadaver data
versus Eurosid-1 data for different energies.

The same reasoning was applied to the Eurosid-1 tests. The analysis showed that (as for the cadaver tests), tests with a lower mass (LMT12, LMT15 and LMT16 with m = 12 kg) have a V*C values greater than those of higher mass (LMT17 and LMT18 with m = 16 kg). The force values show a limit between the tests at the two velocities: ($V \geq 8.21$ m/s $\Rightarrow F \geq 873$ daN and $V \leq 7.18$ m/s $\Rightarrow F \leq 864$ daN).

The V*C value is very sensitive to the impact velocity. The Eurosid-1 thorax deflection is less sensitive to the impact variations. The mean value of the deflection for those tests is 48 mm.

Comment

A parametric study showing the energy distribution and (d) and (V*C) criteria sensitivity has been carried out with a mathematical model of Eurosid-0. The results of the tests with isoenergy showed that when the velocity increased and the mass decreased, the V*C increased and the deflection was constant. Those tendancies on the model are close to our experimental results on the dummy.

- **Isomass tests.**

The aim of this analysis was the obtention of a set of curves V*C = f(d) for different impacting masses.

This would help to understand why for each test condition, there is a different V*C = f(d) and different values of parameters (V*C,d). For the cadaver tests, figure 7 shows three curves of V*C versus deflection for impacting masses of 12, 16 and 23.4 kg. One can note that for the same deflection, the more the mass decreases, the more the V*C increases. However, for a constant value of V*C, the deflection increases when the impacting mass increases. That is to say that there is different criteria values for different impacting masses and velocities.

For example, simulations have been made with the mathematical model of the Eurosid-1 thorax. The result is that the criterion values V*C = 1 m/s and d = 42 mm (which are the values obtained for the ECE95 regulation conditions) are obtained with an impacting mass of m=7kg and a velocity V = 11 m/s.

The result of this analysis is, for each test condition (a given impacting mass and velocities) there is a different V*C = f(d). Thus the V*C and the deflection can't describe the same kind of injury .

For the Eurosid-1 tests, figure 8 gives the curves for m = 12 kg and m = 16 kg. The tests with m=23.4 kg are not available

The results of the analysis of the other physical parameters like force are given in figures 9 and 10. Figure 9 shows, for cadaver tests, a group of curves of force versus impact velocity. Figure 10 shows, for cadaver tests, a group of curves of force versus half thorax deflection for different masses. The force is a function of the test conditions and is correlated with the impact velocity. When the forces applied to the thorax are linked to the thoracic deflection (figure 10), we can see a weak correlation between these 2 parameters (r = 0.25 for tests with m = 23.4 kg; r = 0.25 for tests with m = 12 kg and r = 0.62 for tests with m = 16 kg).

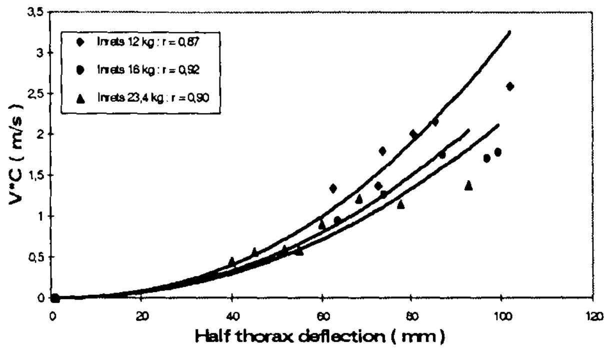

Figure 7 : Cadaver tests on thorax.
Sensitivity of the criteria to the mass.

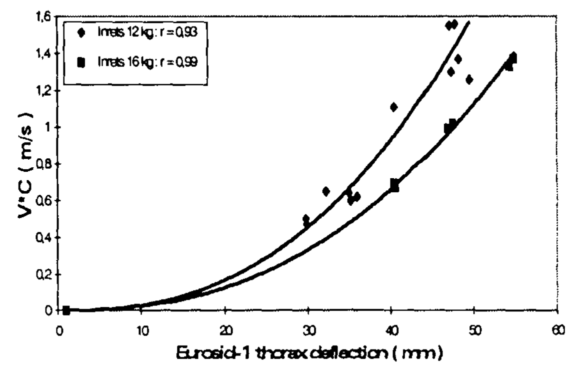

Figure 8 : Eurosid-1 tests on thorax.
V*C versus the deflection.

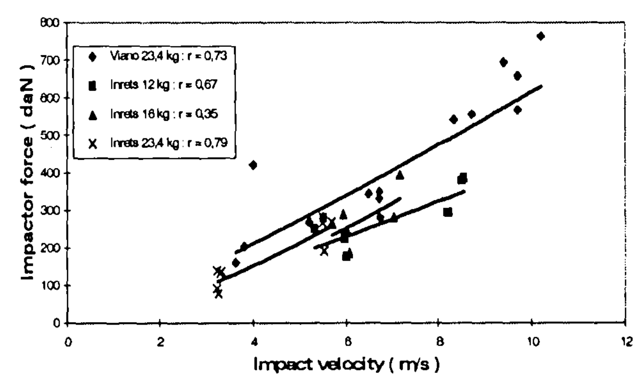

Figure 9 : Cadaver tests on thorax.
Impactor force versus the impact velocity.

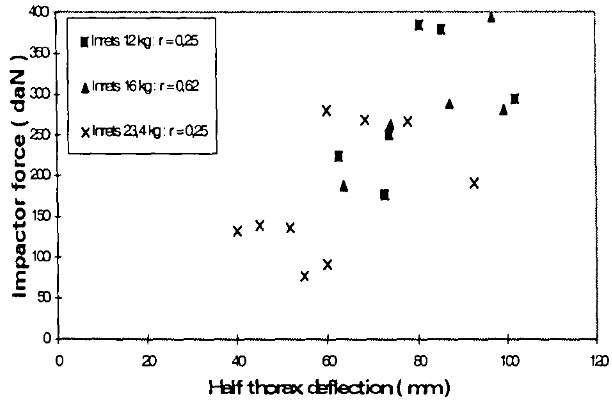

Figure 10 : Cadaver tests on thorax.
Impactor force versus the deflection.

Tolerance limit value :

Comparison has been made between the cadaver test results and Eurosid-1 test results. This comparison was made for tests under identical conditions. The values of (V*C) were related to the injury obtained.

Table 8 gives the peak values for the deflection, the V*C and the corresponding A.I.S. From these results and for cadaver tests, one can see that the lowest V*C value for AIS3 is 1.26 m/s. On the other hand, subject LCT01 who sustained AIS2 level injury has a V*C value of 1.33 m/s.

Table 8 : Cadaver and Eurosid-1 results comparison.

Test	Mass (kg)	Velocity (m/s)	Deflection (mm)	V*C (m/s)	AIS
LMT12	11.4	8.2	48.2	1.37	-
LCT05	11.9	8.2	102	2.59	3
LMT15	11.4	8.6	47.2	1.3	-
LCT06	11.9	8.5	85.4	2.15	4
LMT17	16.0	7.2	46.9	0.99	-
LCT07	16.0	7.2	93.8	1.70	4
LMT18	16.0	7.2	47.5	1.02	-
LCT08	16.0	7.0	99.3	1.77	4
LMT01	11.7	6.1	34.6	0.63	-
LCT01	12.0	6.0	62.5	1.33	2
LMT07	16.0	5.9	40.5	0.68	-
LCT09	16.0	5.7	79.8	1.26	3
LMT11	11.9	4.8	29.9	0.47	-
LCT10	11.9	5.3	73.6	1.79	3

CONCLUSIONS

- The isoenergy cadaver tests analysis show that the V*C and the deflection are sensitive to mass and velocity variations. The V*C increases when the velocity increases and the mass decreases. The deflection decreases when the velocity increases and the mass decreases. The isonergy Eurosid-1 tests show that V*C increases when the velocity increases whereas the deflection is constant when the velocity and the mass vary.
- The isomass test analysis shows that for given test conditions, a V*C = f(d) curve, and different values of the criteria can be established. To establish realistic values of V*C and d criteria, tests have to be carried out with test conditions close to those of the ECE95 regulation conditions.
- The response of the cadaver in terms of forces versus time is within the ISO corridor defined for the lateral impact conditions.
- Kinematic and dynamic analyses have permitted the determination of the response corridors in terms of force/deflection. They allow the assessment of the biofidelity of the Eurosid-1. The behaviour of the Eurosid-1 could be improved.

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PREDICTION OF THORACIC INJURIES IN FRONTAL COLLISIONS

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ABSTRACT

The frontal collision is the most frequent collision type observed in real accident investigations. The impact severity depends on the overlap of the vehicle with the obstacle which also determines the average deceleration of the car and subsequently the loading of the car occupant. The injury severity depends upon anthropometric parameters and the mechanical response. To investigate these relationships 46 frontal collisions with cadavers were performed. The impact velocity was 47-55 km/h, the average sled deceleration 10-20 g. The subjects, 36 males and 10 females, were aged between 19 and 65 years and were protected with 3-point standard belts, driver air bag - knee bolster, 3-point belt combined with air bag. The injuries were defined through medical investigation during the autopsy in situ or on isolated body parts in a more detailed manner later; the injury severity was coded in accordance with the AIS 90.The most injured body part was the thorax, usually rib fractures were found. The number of rib fractures includes uninjured cases up to 17 rib fractures with thoracic injury severity between AIS 0 and AIS 4. The fracture pattern was characteristic for the restraint system used. Logistic regression analysis was used to predict the probability of injury severity for the explanatory variables. To further restrain the subset of predictors Kruskal-Wallis and F-test were applied. Chest accelerations are suitable parameters to predict thoracic injury severity. By modelling the data with logistic regression models the best biomechanical predictor for the thoracic injury severity according to different goodness of fit criteria was the acceleration measured at the 1st thoracic vertebra. These evaluations take into account only the injury severity and the mechanical response, independent of the restraint system used and the impact severity.

INTRODUCTION

The frontal collision is the most frequently occurring accident type and is the accident type towards which the majority of safety measures have been directed. Due to extensive developments in passive safety and the effective combination of active and passive safety systems, a high standard of injury reduction for frontal collisions has been achieved. The aim of this study is to investigate the behaviour of the standard 3-point belt, an air bag only, and belt plus air bag systems in frontal collisions. The collision characteristics of 47 km/h to 55 km/h with a mean sled deceleration between 10g and 20g were chosen to represent common accident severities.

Method

<u>Test Subjects</u> - The test subjects were 46 unembalmed cadavers in the age range 19 to 65 years.

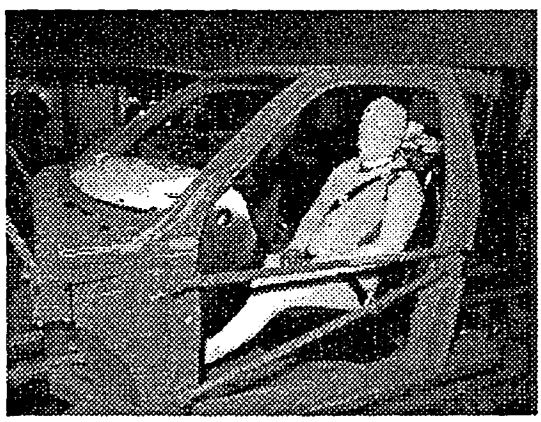

Figure 1:Test configuration

<u>Test Equipment</u> - The tests were performed on the University of Heidelberg's deceleration sled. Mounted to the sled was the front part of a passenger compartment of a mid-sized car. Test subjects were positioned in the driver's seat and restrained by either a 3-point belt, a driver side air bag-knee bolster, or a 3-point belt with supplemental driver side air bag combination. Figure 1. illustrates the experimental configuration. Frontal collisions were simulated with impact velocities of 47 to 55 km/h and a trapezoidal deceleration pulse with an average value of 10 g to 20 g. A test matrix according to the restraint system is given in table 1.

Table 1: Impact conditions according to the restraint system used

Restraint system		3-pt-belt	Air bag	3-pt-belt & Air bag
n		29	7	10
Impact speed [km/h]	range	48-55	47-50	47-53
	mean	50	49	49
Average sled dec. [g]	range	10-20	10-17	10-18
	mean	15	14	13
Age [years]	range	19-63	25-55	32-65
	mean	36	37	49

Instrumentation - In a part of the tests, the subject's thorax was instrumented with a twelve-accelerometer array (Eppinger et al., 1978). In some of the tests, a tri-axial accelerometer array was attached to Th 6. Furthermore tri-axial accelerations at the pelvis and shoulder belt forces were measured.

Autopsy / Injury Severity - For each cadaver, a full autopsy was performed. The injuries were coded according to the AIS 1990.

Statistical Methods

The statistical analysis aims at investigating the factors which influence the thoracic injury severity (AIS-level) and explain it on the basis of the cadaver anthropometric data and the most relevant biomechanical data (anthropometric and mechanical predictors).

As the different AIS values are measured on the ordinal scale (0 to 5), the analysis of variance based on rank scores (F-Test) (Agresti, A., 1984; Lehmann, E.L., 1979) has first been performed in order to determine whether the distribution of the predictors have the same location parameters across the injury levels. The Kruskal-Wallis chi-square approximate statistic (H-Test) (Bikel, P. J. and Doksum, K.A. ,1977; Hosmer, D. W. Jr. and Lemeshow, S., 1989), based on the empirical distribution has also been considered. Further, graphical statistical methods (box plots, Agresti, A., 1984) have been used for making distributional comparisons.

For modelling the data, logistic regression models (Draper, N. and Smith, H., 1981) have been applied to the most suitable explanatory variables. The regression part of these models, i.e. a linear combination of the values of the explanatory variables and the regression coefficients, is a logistic transformation of the probabilities of the response categories given by the function:

$$Y=ln(x/(1-x)),$$

which transforms the interval between 0 and 1 on the real axis $(-\infty; +\infty)$, so that probabilities transformed by the logistic function will be *stretched* out over the complete real axis. For a binary response probability p the linear regression model becomes:

$$logit(p)=ln(p/(1-p))=\alpha+\beta\cdot x.$$

Therefore, letting $LOW=(AIS\leq 2)$ and $HIGH=(AIS\geq 3)$ our model reduces to:

$$logit(p(HIGH))=\alpha+\beta\cdot x.$$

For the ordinal response AIS with values $0,1,2,...,5$ the logistic model has the form:

$$logit(p(AIS<=i))=\alpha i+\beta i\cdot x \qquad 0<=i<=4$$

where $\alpha 0$, $\alpha 1, ... \alpha 4$ are the intercept parameters of the four parallel regression lines and is based on the cumulative distribution probabilities of the AIS levels. For a value of the independent variable x in the fitted model, the estimated probability of the response is given by replacing the regression coefficients α, β, αi, βi *by their Maximum Likelihood Estimator.*

Prediction Ability and Quality of Fit Criteria (Cox, D.R. and Snell, E. J., 1989, Draper, N. and Smith, H., 1981, Linhart, H. and Zucchini, W., 1977). For comparing different models and assessing model fit the following criteria have been considered.The *-2log Likelihood* statistic:

$$-2log\ L=-2\sum_j log(pj)$$

where the estimate pj of the probability $P(Y=yj)$ is obtained by replacing the regression coefficients by their Maximum Likelihood Estimate (MLE). *-2log L* has a chi-square distribution under the hypothesis that the explanatory variables in the model are zero, therefore the p-value for this statistic gives a test for the effects of the covariates.

For assessing the predictive ability of a model, the following indexes of rank correlation between the observed responses and predicted probabilities have been calculated: *Somers'D, Goodman-Kruskal Gamma* and *Kandall's Tau-a.* For the binary response models, *HIGH/LOW* the 2x2 frequency table of observed and predicted responses has been calculated. The response *HIGH* is predicted to be an event if the estimated probability p is greater than, or equal to the critical level 0,5 otherwise it is predicted to be a no event. The classification table is therefore obtained by counting the number of observations for each of the following four categories:

	Observed	Predicted
1	event	event
2	event	no event
3	no event	event
4	no event	no event

Sensitivity is the proportion of event responses that were predicted to be *event.*

Specificity is the proportion of *no event* that were predicted to be *no event.*

A pair of input observations with different response *LOW/HIGH* is, said to be concordant if the observation with response *HIGH* has the lower predicted event probability. Therefore, the association between predicted probabilities and observed responses can also be measured on the basis of the number of concordant and discordant pairs carried out by categorizing the predicted probabilities into intervalls of lenght 0.002.

To compare different models it is important of course to look at different criteria simultaneously, since a good model should not be too bad in any one of the choosen criteria.

RESULTS

<u>Mechanical Response</u> - Figures 2 & 3 show the mean maxima and 3ms values of the measuring locations. The highest values were found at the lower sternum by using air bag restraint systems. The highest values at the left lower rib were measured by using 3-point-belt systems. Generally the values measured at the spine and pelvis are higher for airbag restraints. Also the measuring location upper sternum shows higher mean values for air bag restraints. The lowest mean values were observed at the left and right upper ribs for all restraint systems used. The combination 3-point-belt and air bag show generally the lowest values of the restraint systems used.

Medical Findings

<u>Injury Pattern</u> - Figures 4 - 6 show characteristic fracture patterns for the three restraint systems used. By using 3-point-belt systems the fractures are located mainly at the shoulder belt path, whereby by using only air bag restraints the front axillar line is involved. By using a standard belt in combination with a driver air bag the shoulder belt mainly defines the fracture pattern.

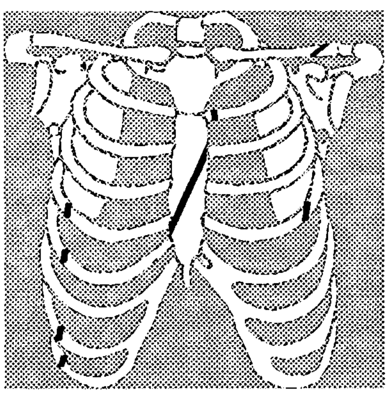

Figure 4: Injury pattern 3-point belt

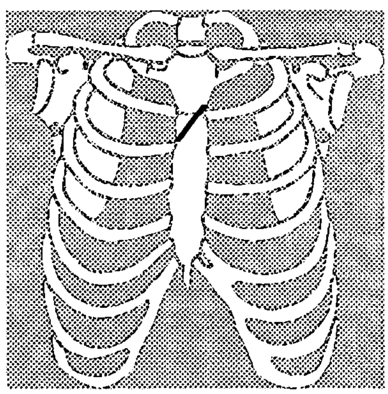

Figure 5: Injury pattern 3 point belt-air bag

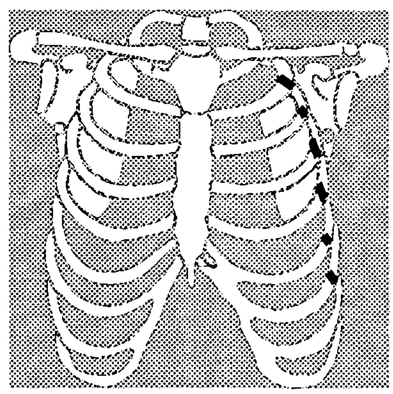

Figure 6: Injury pattern driver air bag

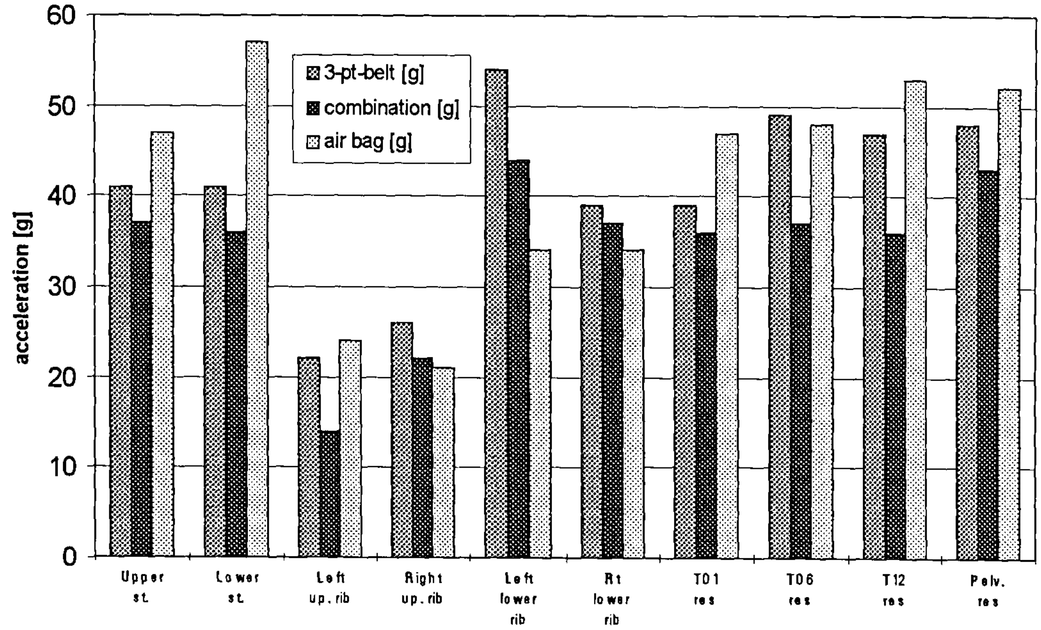

Figure 2: Maxima mean values of the measuring locations for the restraint system used

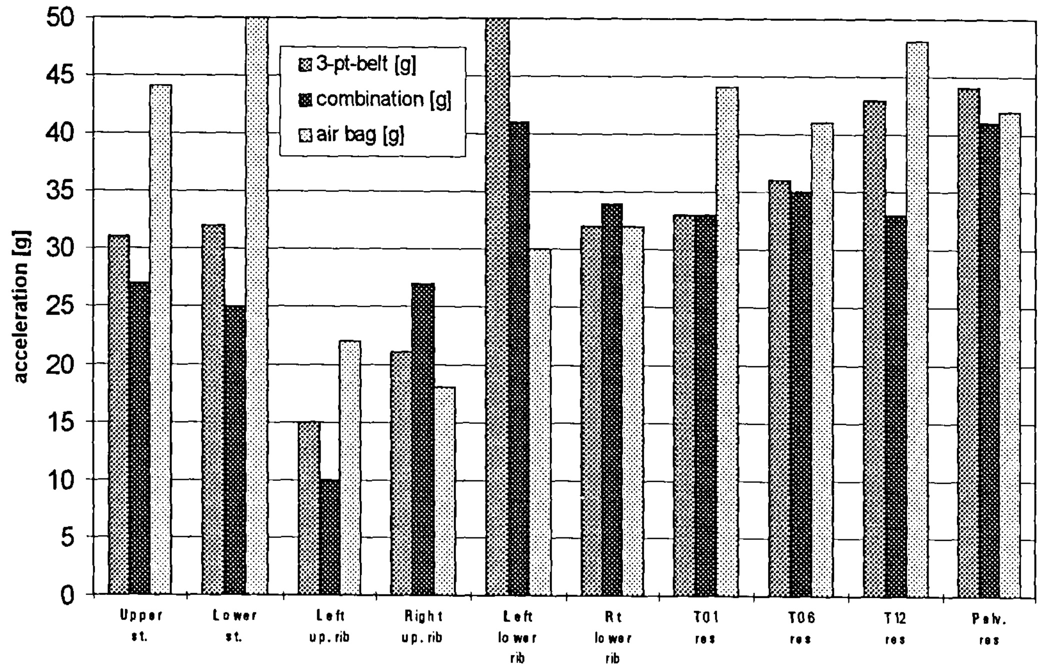

Figure 3: 3ms mean values of the measuring locations for the restraint system used

Skeleton Fractures - Thirty-four of the fourty-six tests conducted show thoracic injuries. The most frequent injury type were rib fractures, which also defined the thoracic injury severity; up to 17 rib fractures were observed, which were usually incomplete fractures.The number of rib fractures and the injury pattern is influenced mainly by the type of restraint system used. Figure 7 shows the frequency of the fractures of each rib for the three restraint systems used. The highest numbers of the rib fractures were observed when a 3-point belt was used. The first to ninth rib are involved, whereby the most fractured ribs were the second and the third one. By using only an air bag restraint system in one case the 2nd to 7th left rib at the front axillary line were broken, in a further case a fracture of the 6th right rib at the front axillary line was observed. The second most frequently fractured bones were the sternum and in some cases also the clavicle; in both of these bones the fracture pattern was defined through the belt path.

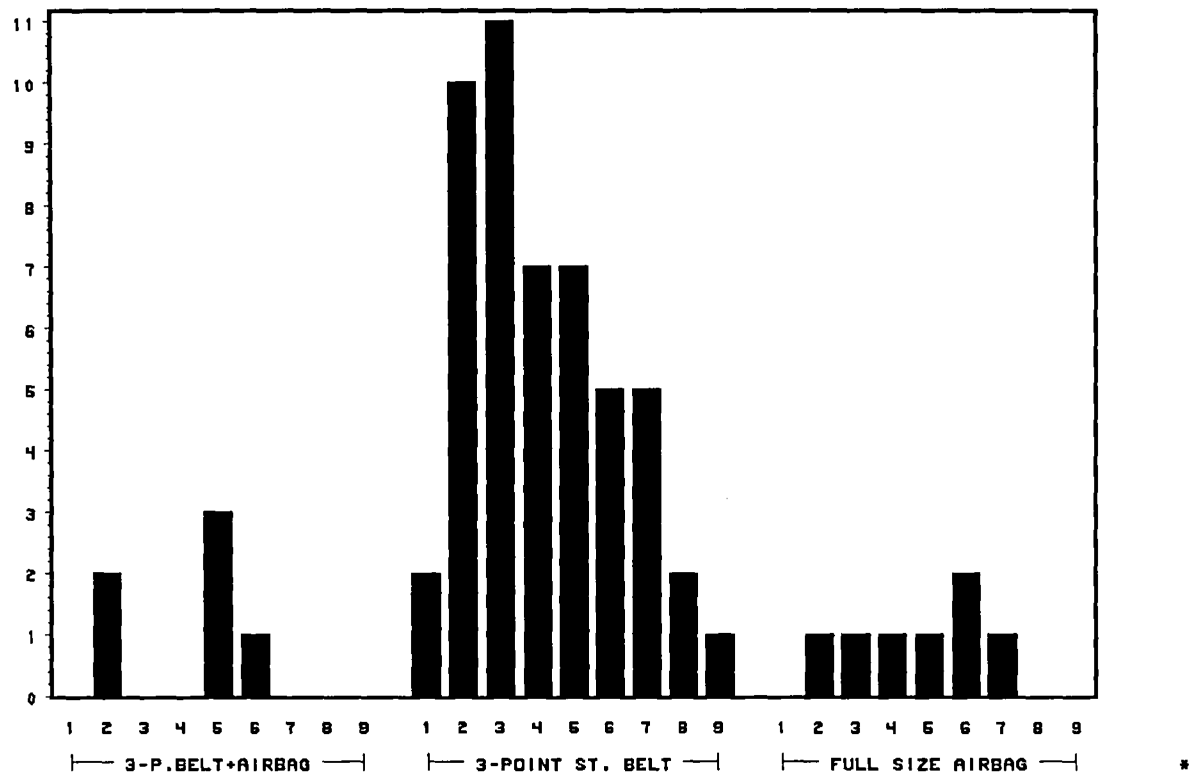

Figure 7: Frequency of the number of rib fractures according to the restraint system

Thoracic Injury Severity - The thoracic injury severity was rated according to the AIS 90 and our own biomechanical experience. Essential for the injury severity was the number of rib fractures. Soft tissue injuries like transfixing of the pleura or the lungs were rare. The collective with the 3-point belts is the most frequently injured sample and includes AIS severities between 2 and 4, whereby the AIS 2 and AIS 3 degrees are more frequent, the AIS 4 was concerned in 17% of the whole group. In the collective using only the air bag a case with AIS 1 (one rib fracture) and a second one with AIS 3 (six rib fractures) were observed. The sample using the combination of 3-point belt and air bag shows also lower thoracic injury severities than the one using only 3-point belt (Fig. 8).

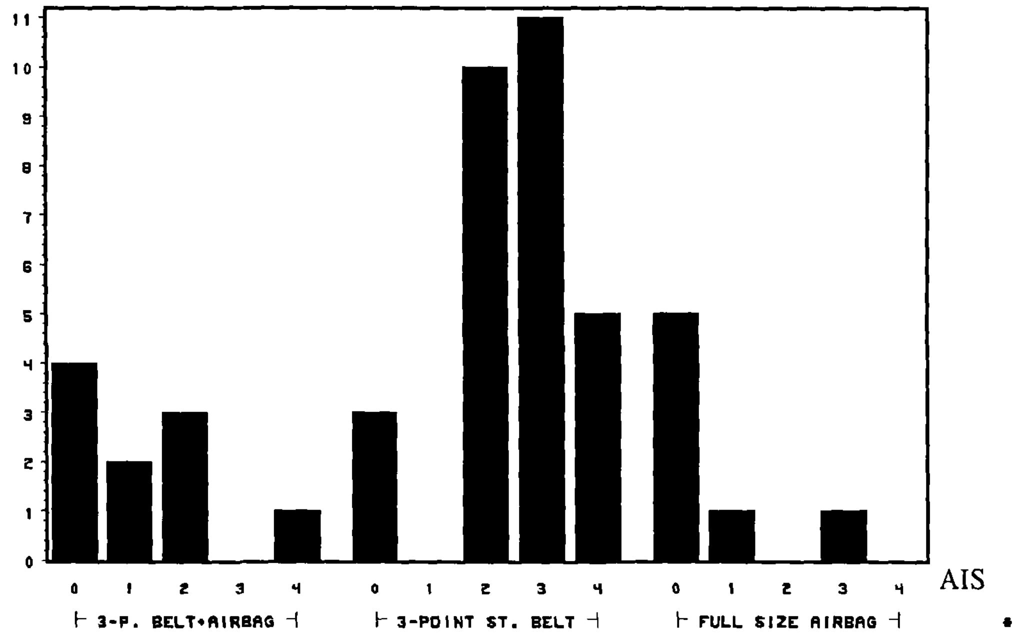

Figure 8: Frequency of the thoracic injury severity according to the restraint system

<u>Location of the Thoracic Skeleton Fractures</u> - Fig. 9 shows the location of the thoracic skeleton fractures. By using 3-point standard belt the complete front of the skeleton beginning at the front axillar line left to the front axillar line right includes fractures. The highest frequencies were observed at the sternum (M11, Fig. 10) and the parasternal region left and right (L09, R06, Fig. 10).

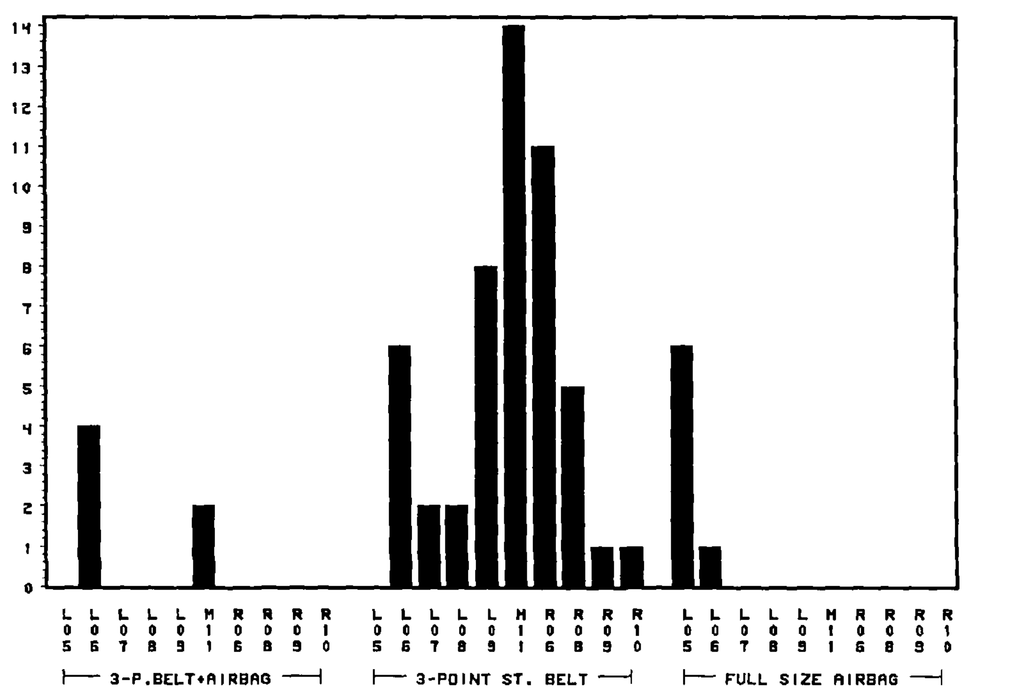

Figure 9: Frequency of the location of the rib fractures according to the restraint system

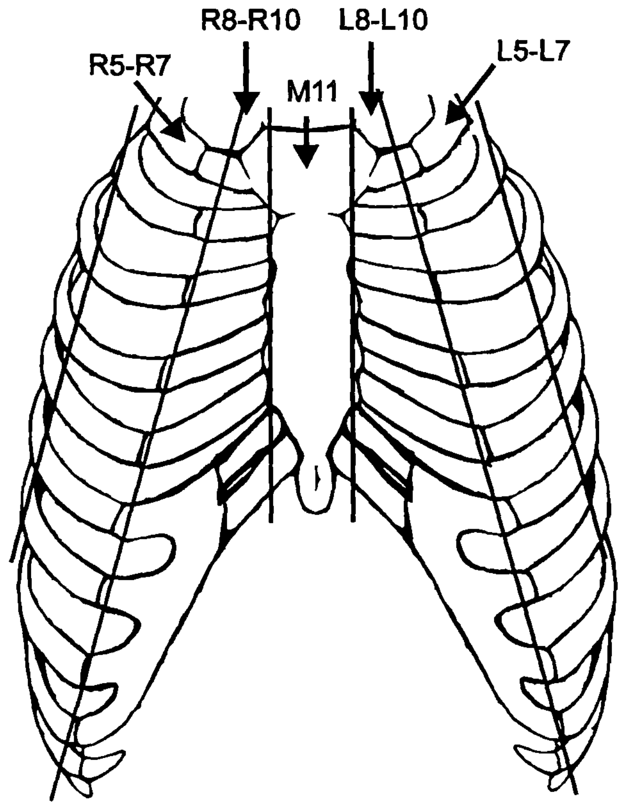

Figure 10: Location of the skeleton fractures by using 3-point belts.

Spinal Column Injuries - The second frequent type of injuries observed were the vertebral column injuries. They were located from the middle cervical spine to the upper thoracic vertebral column. The most frequent injuries were haemorrhages of the intervertebral discs, lacerations of the ligaments and compression fractures of the vertebral bodies. Also for this type of injuries the collective of the 3-point belt usage shows higher frequencies, the lowest numbers were found, if an air bag was used.(Fig.11). The injury severity was scaled according to the AIS 90 for the vertebral column and ranged from AIS 0 to AIS 3.

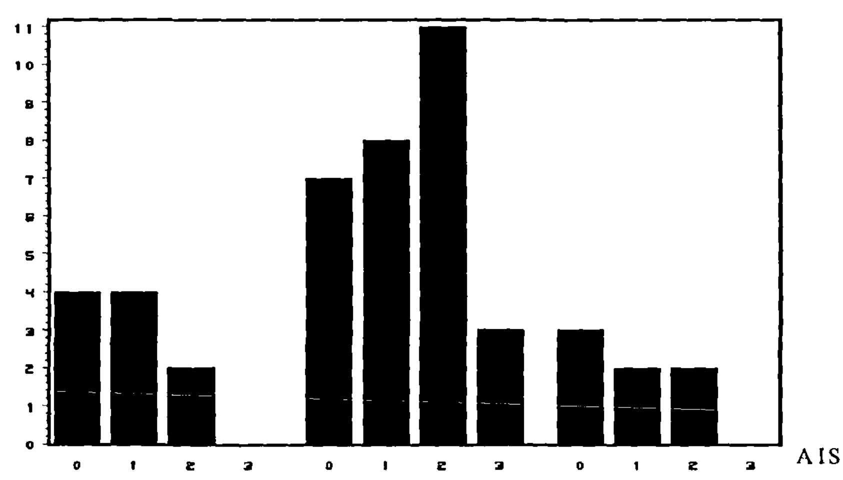

Figure 11: Frequency of the spinal column injury severity according to the restraint system

Abdomen Injuries - Only in 5 cases abdominal injuries were observed if a 3-point belt was used. In four tests liver ruptures sized between 2 cm long and 5 mm deep to 30 cm long (laceration of the capsule) and 3 cm deep were found, in one case a 1*1 cm sized laceration of the small intestinal mucosa was observed.

Statistic Evaluations

Figure 12 illustrates the parallel box plots of some of the variables which show good correlations with the thoracic AIS levels. The plots indicate the median (AIS levels, bold line), the upper and lower quantiles Q(.5), Q(0.25) (box) of the empirical distributions over the AIS levels. The mechanical response maximum acceleration at the fourth left rib (RIUGA_MX) shows distribution differences among the AIS levels: the median values increase clearly with the thoracic injury severity degree

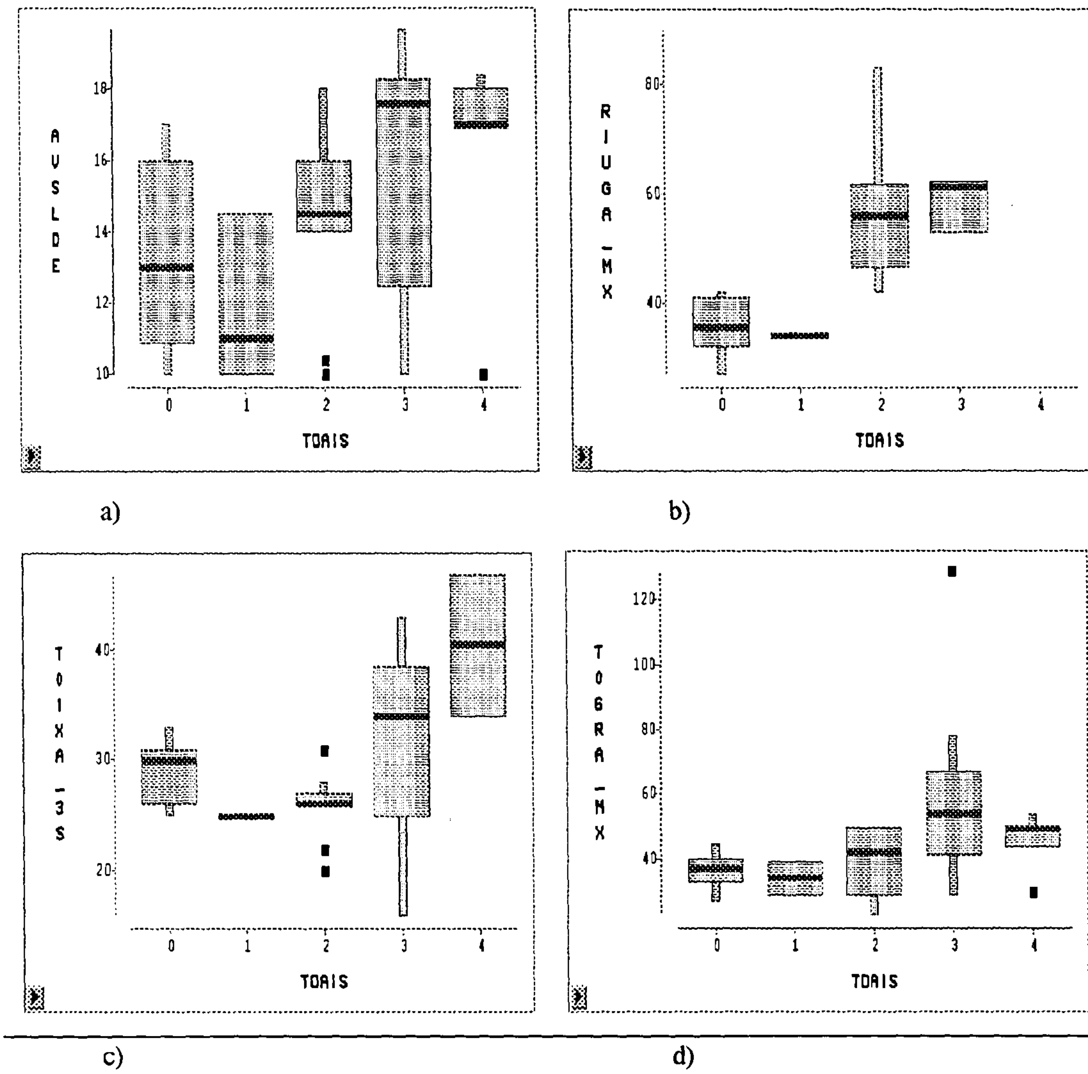

Figure 12: Box plots over the thoracic Injury Severity levels (TOAIS) for
a) Average Sled Deceleration (AVSLDE)
b) Max. Acceleration at Left Upper Rib (RIUGA_MX)
c) 3ms X-Acceleration at the 1st thoracic vertebra (T01XA_3S)
d) Max Res. Acceleration at the 6th thoracic vertebra (T06RA_MX)

The results of the statistical analysis suggest that the thoracic injury severity does not depend on the cadaver anthropometric parameters. Table 2 shows the significance levels of the Kruskal-Wallis and F-Test for the choosen variables.

Variable Name	Variable Label	Kruskal-Wallis Test:Prob>CHISQ.	F-Test: Prob>F
AGE	Age	0.0175	0.0014
AVSLDE	Average Sled Deceleration	0.0471	0.0570
RIUGA_MX	Max. Acceleration at upper Left Rib	0.0088	0.0007
T01XA_3S	3ms X-Acceleration at 1st vertebra vertebra	0.2374	0.0532
T06RA_MX	Max. Acceleration at 6th vertebra	0.1380	0.2020

Table 2: Analysis of variance, Tests results: Kruskal Wallis Chi square and F Test for the more relevant covariates.

We have found that, while the parameter **Age of Test Subject**, is for the thoracic injury severity significant at level 0.02 according to both Tests, modelling the data using only this parameter does not provide good prediction results.

The Kruskal-Wallis Test is not significant for **T01XA_3S** (3Ms X-Acceleration at the 1st thoracic vertebra) and **T06RA_MX** (Max. Res.-Acceleration at the 6th thoracic vertebra), which indicates that, because of high number of missing values, statistics based on empirical distributions schould not be considered.

Table 3 shows the M.L.E. for α and β in the logistic regression model by predicting thoracic injury severity $\geq$3. For all covariates the Estimates β are below 0.3 which means that the considered covariates influence the prediction of thoracic injury severity $\geq$3.

Model	Estimate α	Estimate β
TOAIS3=AVSLDE	-4.7668	0.2925
TOAIS3=RIUGA_MX	-5.7512	0.0797
TOAIS3=T01XA_3S	-7.2478	0.2067
TOAIS3=T06RA_MX	-4.1978	0.0991

Table 3: M.L.E Estimates for α and β, prediction of thoracic injury severity $\geq$3.

Tables 4 to 5 show the probability analyses according to the choosen criteria.

Variable	-2 Log L	Prob>CHISQ
AVSLDE	63.866	0.0071
RIUGA_MX	14.967	0.0322
T01XA_3S	19.892	0.0152
T06RA_MX	27.342	0.0070

Table 4: Prediction of thoracic injury severity $\geq$3, regression analysis: Testing Global Null Hypothesis: $\alpha=\beta=0$.

Table 4 shows that for all the choosen covariates the global null hypothesis $\alpha=\beta=0$ should be rejected.

Variable	Prob>CHISQ for Estimate α	Prob>CHISQ for Estimate β
AVSLDE	0.0299	0.0701
RIUGA_MX	0.0099	0.0139
T01XA_3S	0.0323	0.0579
T06RA_MX	0.0412	0.0374

Table 5: Prediction of thoracic injury severity $\geq$3, regression analysis: analysis of MLE

Table 5 shows that for all the covariates the Chi square test for the estimates α and β is significant, which means that the null hypothesis $\alpha=0$ or $\beta=0$ should be rejected.

Among all the accelerations at ribs and spine the best predictors for **Injury Severity $\geq$3** are **RIUGA_MX** (Max. Acceleration at Left Upper Rib), **T06RA_MX,** and most notably **T01XA_3S** which achieved by *81.8%* the highest proportion of correct predicted *event/no event* by critical probability level 0.5 (Table 6). As shown in Table 6 the model has also the highest specificity value.

Variable	Sensitivity%	Specificity%	Correct predicted
AVSLDE	68.4	85.7	78.7
RIUGA_MX	25.0	93.3	78.9
T01XA_3S	33.3	100.0	81.8
T06RA_MX	76.9	75.0	76.0

Table 6: Prediction of thoracic injury severity ≥3, regression analysis: classification table at critical probability level 0.5.

The highest correlation between predicted and observed probabilities according to both Sommers'D and Gamma statistics has been reached by modelling the data with **RIUGA_MX** (Table 7).

Variable	Concordant %	Discodant %	Sommers' D	Gamma
AVSLDE	72.9	22.7	0.502	0.525
RIUGA_MX	83.3	13.3	0.700	0.724
T01XA_3S	83.3	16.7	0.667	0.667
T06RA_MX	78.2	21.2	0.571	0.574

Table 7: Prediction of thoracic injury severity ≥3, regression analysis: association of predicted probabilities and observed responses.

An other important predictor is also the **Average Sled Deceleration**. Although values of correlation between predicted and observed probabilities remain below the value of 0.53 the model has a high sensitivity and provide also good results according to the other choosen criteria (Table 7).

Figures 13-16 show the logistic regression plots with the upper and lower confidence curves of probability of thoracic injury severity ≥3 modelled by the choosen covariates. Looking at the confidence bands, one can notice that the prediction accuracy remains good over all values of the average sled acceleration. For the other covariates because of the number of missing observations the accuracy goes down by higher values.

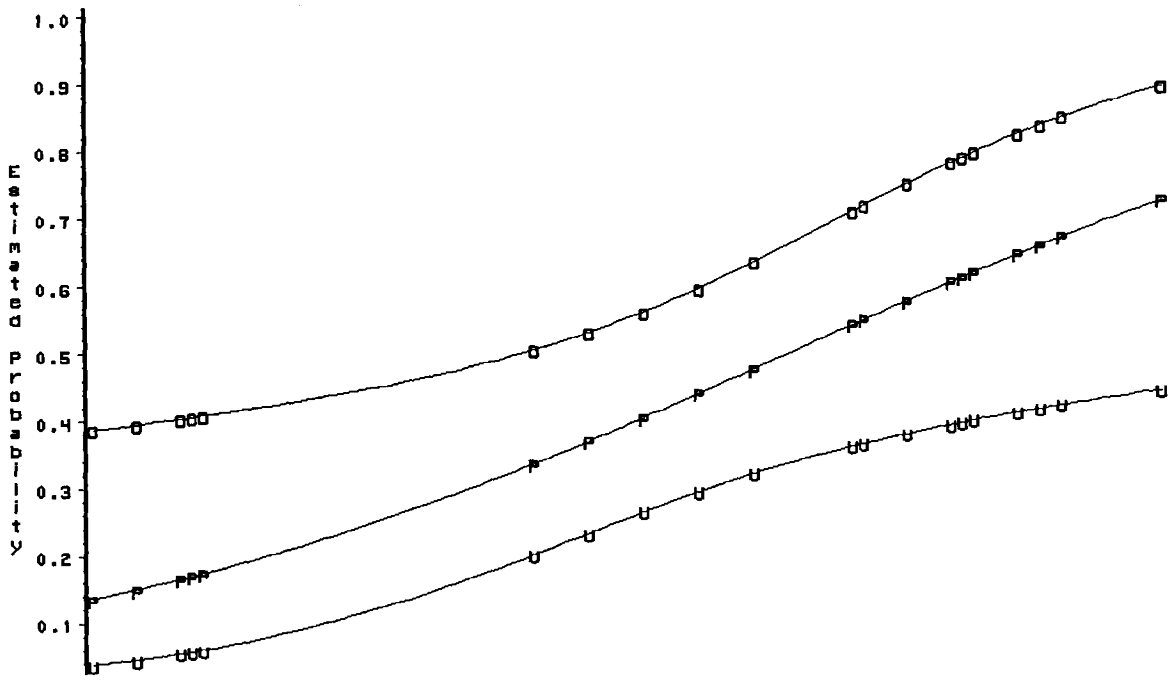

Figure 13: Logistic Plots of probability of thoracic injury severity ≥3 modelled by the Average Sled Deceleration (AVSLDE).

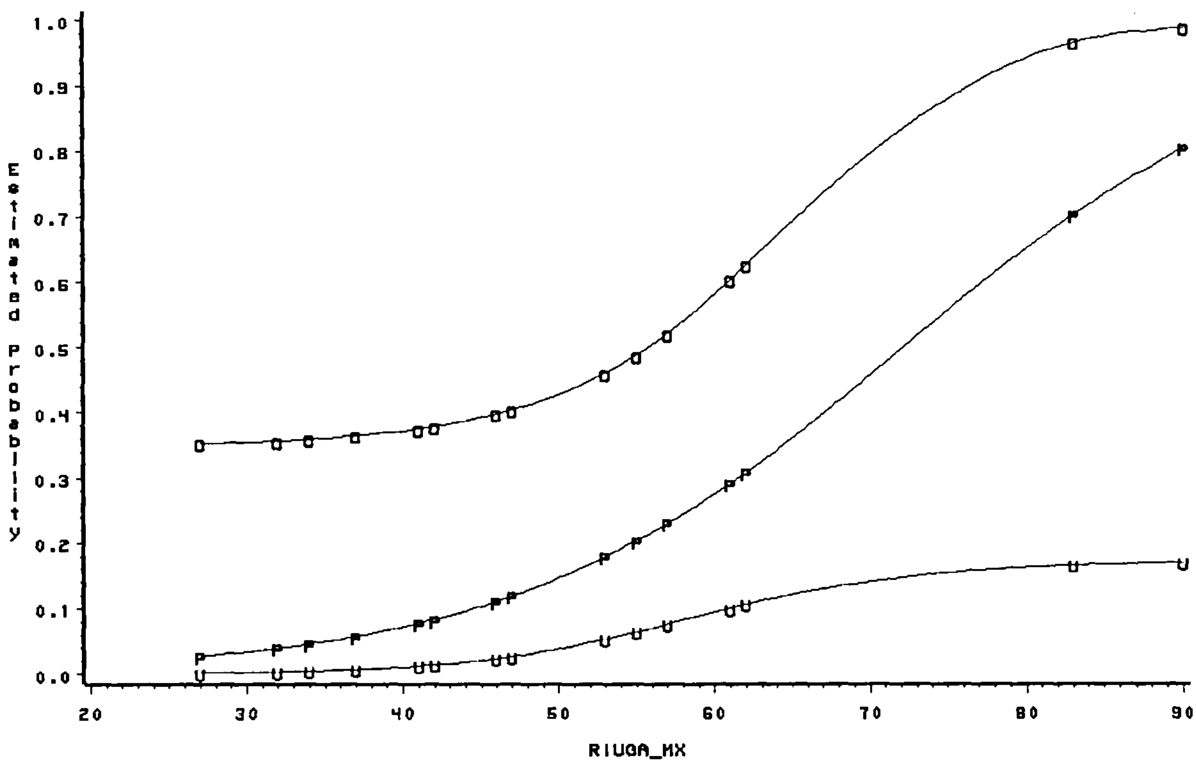

Figure 14: Logistic Plots of probability of thoracic injury severity ≥3 modelled by the Max Acceleration at Upper Left Rib (RIUGA_max).

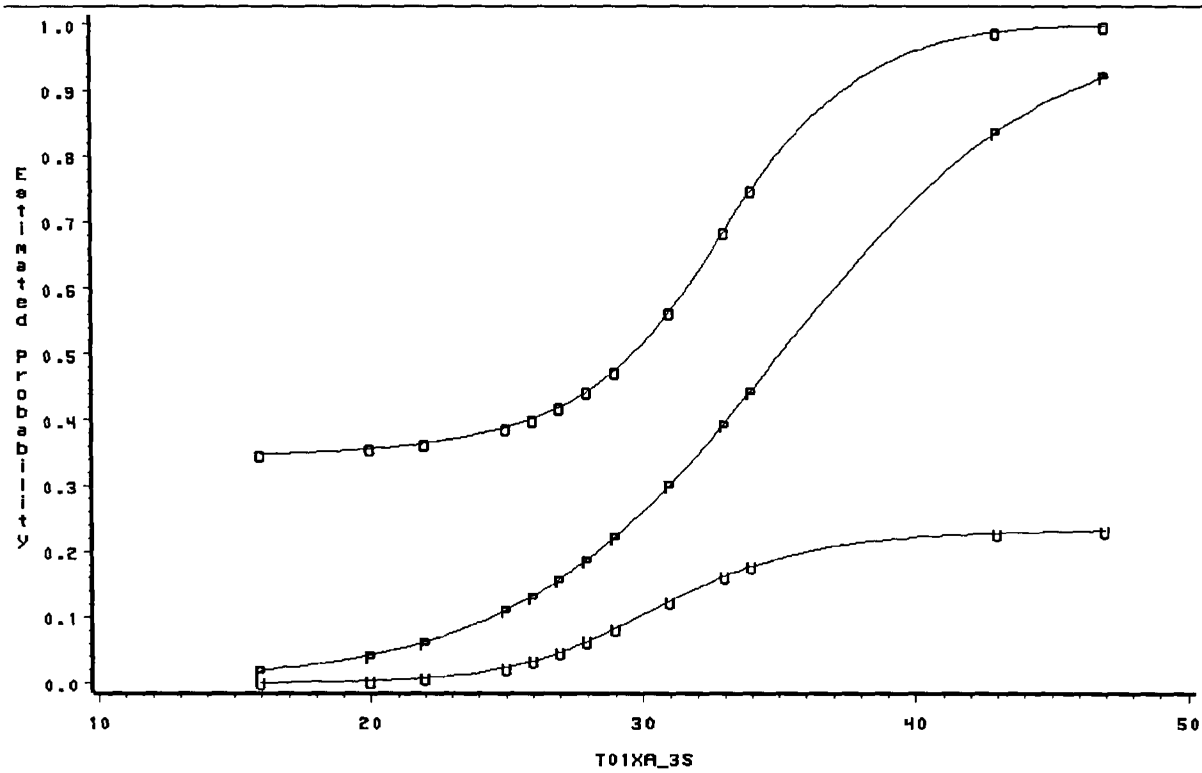

Figure 15: Logistic Plots of probability of thoracic injury severity ≥3 modelled by the 3ms Acceleration at the 1st thoracic vertebra(T01XA_3S).

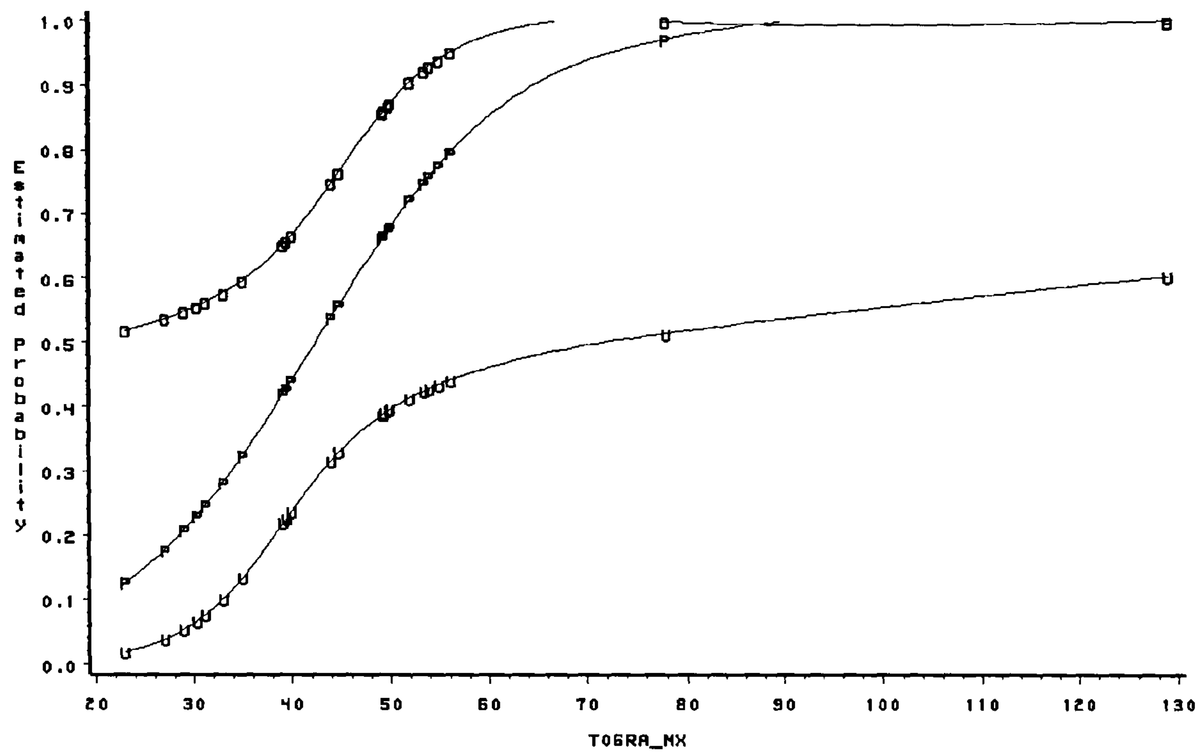

Figure 16: Logistic Plots of probability of thoracic injury severity ≥3 modelled by the Max R-Acceleration at the 6th thoracic vertebra (T06RA_MX).

Although we primarily focused on the mechanical parameters at the thorax for predicting an **Injury Severity ≥3,** other models have also be considered. Among these, one of the most relevant predictor for **Injury Severity ≥2** is **RIUGA_3S** suggesting that the 3ms-acceleration value at Left Upper Rib can be in general considered a reliable predictor for the thoracic injury severity.

DISCUSSION

A collective of 46 frontal collisions with 3-point belt, air bag and combined 3-point belt - air bag protected cadavers was investigated. The impact conditions ranged according to the velocity and the chosen sled deceleration with 47 to 55 km/h and 10 to 20 g in a wide area. The accelerations measured at the different locations of the chest are between 45 g and 60 g for all three restraint systems used.According the restraint system used , characteristic fracture patterns were observed. By using 3-point belts the fractures are located mainly at the shoulder belt path, whereby by using only air bag the front axillar line is involved.

By using the combination 3-point belt/driver air bag, the injury pattern of the 3-point belt predominated; this is thought to be a result of both the stiffness and path of the shoulder belt. The rib fractures resulting from air bag use are located at the front axillar or medio-clavicular line; this is in agreement with findings of Yoganandan et al. (1993).

The most fractures that were observed were infractions, a fracture type which is not visible at the chest front when using the conventional x-ray examination; these findings are now possible through autopsy and the touching of the ribs.

The most frequent fractured rib by usig 3-point belt was the 2nd and the 3rd rib. According the chest location the central front (sternum), the right axillar line and the left cartilage region were involved; more or lesser the fractures were distributed at the whole front of the chest.

Independed of the restraint system used; the statistics show good correlations between the mechanical responses, „ average sled deceleration, maximum acceleration at the left upper rib, maximum resultant acceleration at T6 and the 3 ms acceleration at T1in x-direction " with the thoracic injury severity.

In the study no good correlations between the age of the cadavers and the thoracic injury severity were found as observed in side impact investigations (Kallieris et al., 1996). According to Kruskal-Wallis and F-test the thorax injury severtity seems to be influenced by the age of the subject. But using this covariate to predict the injury severity in the logistic model yielded no good results according to the choosen goodness of fit criteria. The reason is the large range of the sled deceleration.

The highest correctly predicted observations (82%) shows the 3 ms acceleration at T1 in x-direction for the prediction of the thoracic injury severity ≥ 3. The next most reliable predictors, with the same correctly predicted observations were the average sled deceleration and the maximum acceleration at the right upper rib.

The 50% probability of thoracic injury of AIS ≥ 3 differs for the spinal accelerations and the acceleration at the left upper rib. It is associated for T1 with an acceleration of 35 g, for T6 with 43 g in comparison to the left upper rib with 70 g. The T1 value is in agreement with those given by Morgan et al., (1994) by using belt restraints. The acceleration values at the spine are significant lower than those proposed in the FMVSS 208 as chest acceleration criterion of ≤ 60 g.

CONCLUSIONS

- Injury patterns indentify the restraint system used.
- The subject's age was not a relevant predictor for the thoracic injury severity.
- Chest accelerations are suitable parameters to predict thoracic injury severity.
- The best biomechanical predictor for the thoracic injury severity was the acceleration measured at the 1st thoracic vertebra, based on the logistic regression model.
- Spine accelerations seem to be the most reliable parameters to predict thoracic injuries.

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BIOMECHANICAL IMPACT TOLERANCE CHARACTERISTICS OF THE HUMAN NECK

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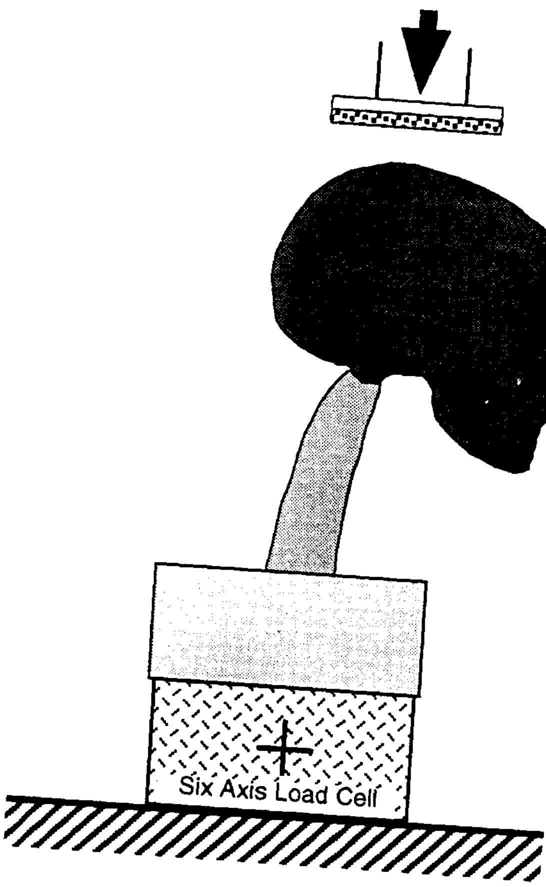
INTRODUCTION

Cervical spinal column injuries secondary to vehicular crashes can be severe and costly to the individual and to the society as a whole. Injuries involve bony damage in the form of fractures with or without dislocations and/or soft tissue ruptures such as intervertebral disc disruption and ligament tear. Our understanding of the mechanism and the biomechanics associated with these injuries comes from an analysis of epidemiological, clinical and experimental research [1, 4, 6-11, 14, 17]. Epidemiological studies have classified these injuries in a vehicular environment based on factors such as incidence, type of impact and occupant seating location. Databases such as the National Automotive Sampling System and Fatality Analysis Reporting System have been traditionally used to further analyze injuries. Clinical studies have included the retrospective evaluation of the patient using modalities such as radiography, computed tomography and magnetic resonance imaging. These studies can provide important information regarding the physiological and anatomical status of the patient, and the determination of the mechanisms of injury on a retrospective basis. However, from these studies it is difficult to quantify the actual load vector responsible for the production of the injury and the associated biomechanical variables. Depending on the extent and severity of the external load vector applied during the crash event, different types of injuries can occur to the human neck structure. Commonly encountered cervical injuries are classified into noncontact related (inertial loading) and contact related (with head impact) trauma. For example, cervical spine injuries resulting from a low speed, rear-end vehicular-collision caused by inertial loading are often considered to be of the noncontact type. In contrast, injuries arising from contact of the human head with the vehicular interior or the exterior surfaces belong to the contact category. Bony damage such as burst and wedge fractures associated with the disruption of the posterior ligaments are typical examples of contact induced neck injuries in a motor vehicle environment. This paper focuses on the correlation between the loading mechanisms and biomechanical quantities associated with cervical spine injury due to head impact.

MATERIALS AND METHODS

Unembalmed human cadaver head-neck complexes were used in the study. The specimens were selected through an evaluation of medical records and radiographic examination to eliminate bone disease, spinal disease or cancer. The subjects were screened for HIV; and Hepatitis A, B and C. Standard guidelines and laboratory practices were adopted in the biomechanical study. The demographics of the subjects were obtained which included documentation of age, height and weight. After procurement and selection, the head-neck complexes were isolated by transecting at the T2-T3 intervertebral disc space. Radiographs of the specimen in the frontal and lateral projections were obtained. Two-dimensional computed tomography (CT) images were obtained in the axial and sagittal planes (High-Speed Advantage, General Electric, Waukesha, WI). The head-neck complexes were sealed in double plastic bags and kept frozen at -70 degrees Centigrade. Handling and storage of human cadaver material in this manner, routinely used in biomechanical investigations, does not alter the material characteristics of the bone and soft tissues including ligament and cartilage [15-18, 20]. The cranium and its contents were left intact. The inferior end of the preparation was fixed in polymethylmethacrylate. The distal end of the fixation was rigidly mounted to a six-axis load cell and firmly affixed to the platform on an electrohydraulic testing apparatus. The head was held in place using pulleys and dead-weights or masking tape to achieve the initial head-neck orientation. A flat metallic plate covered with an Ensolite padding was fixed to thc piston of the electrohydraulic testing device. This served as the impact surface for contacting the preparation during dynamic loading. A schematic of the experimental set up is included in Figure 1.



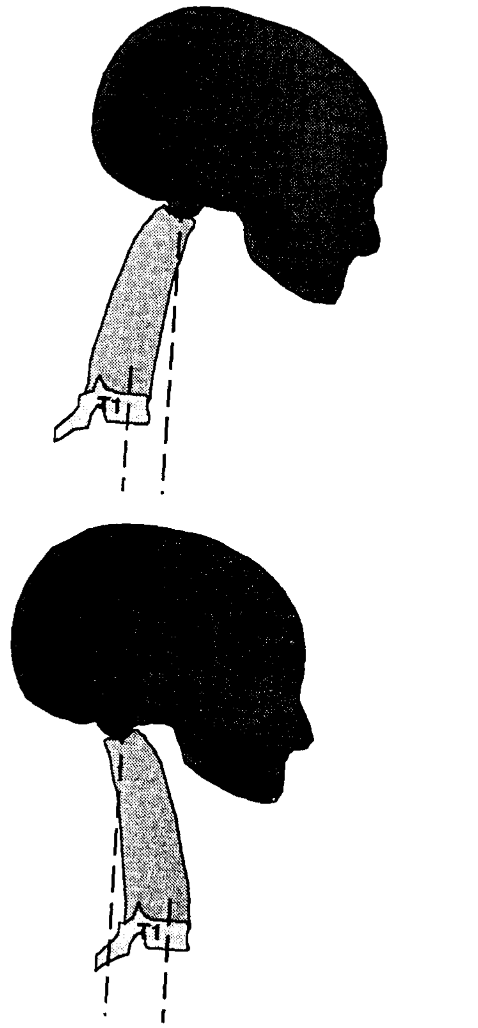


Figure 1: Schematic of experimental setup (left). Eccentricities measured from the occipital condyles to the thoracic vertebra; positive eccentricities (right top), negative eccentricities (right bottom).

Dynamic loading to the cranium was applied by the piston at rates ranging from 3 to 8 m/s. The maximum piston excursions were set at 25 to 100 mm. The head-neck specimens were tested at varying eccentricities. Zero eccentricity was defined as the position of the occipital condyles aligned with respect to the center of the first thoracic vertebral body along the direction of loading. In this position the head was flexed forward to remove the Lourdes's of the cervical spine. Eccentricities were defined as positive when the occipital condyles were aligned anterior to the first thoracic vertebra (Figure 1). When the occipital condyles were posterior to the first thoracic vertebral body the eccentricities were considered to be negative. The eccentricities were measured using radiographs taken prior to head impact. Each specimen was impacted once with the above initial conditions. Following the dynamic impact, the specimens were macroscopically examined, radiographs were taken, and CT images were obtained in the sagittal and axial planes. The pathology was determined using these images.

The six-axis load cell placed at the inferior end of the preparation recorded the forces and moments in the three directions. The coordinate system of reference was such that the x, y and z axes referred to the posteroanterior, right-left lateral and inferior-superior directions. A load cell (Model 9251, Kistler Corp., Amherst, NY) was attached in series with the piston of the testing device to measure the applied forces. In addition, a built-in linear variable differential transformer recorded the input displacements as a function of time. All biomechanical data were collected according to the Society of Automotive Engineers SAE J211 specifications using a digital data acquisition system. High-speed photographic images were obtained using a 16 mm high-speed camera or a digital video camera.

The failure force and bending moment at the level of injury were determined using the generalized force histories at the inferior load cell, geometry data from the radiographs and/or highspeed images, equations of equilibrium, and pathological information from post test evaluation. The bending moment at the level of injury was computed for the time when the compressive force was at its maximum. In this initial study, the compressive force and bending moment sustained by the cervical spine were considered as the primary biomechanical parameters to quantify the cervical spine injury. In order to associate these two biomechanical parameters to the initial loading conditions, one factor ANOVA statistics were performed to determine the number of data grouping cases separated according to their corresponding eccentricities. The optimal number of groups and the range of eccentricities for each group were determined when the one factor ANOVA statistics gave the lowest p values for both force and moment. Student t-tests were performed to determine the differences (significance level was chosen to be $p < 0.05$) in the force and moment parameters between any two groups.

RESULTS

A total of 28 specimens were included in the present study. Table 1 includes a summary of data.

Pathology identified by radiography and CT images included bony fractures of the cervical vertebrae with and without dislocation of the joints. Bony injuries included wedge, burst, vertical and tear drop fractures. Ligamentous injuries ranged from tear of the posterior or anterior ligaments to disruption of the entire intervertebral joint. In a majority of cases the injuries were concentrated at one level of the cervical spine; this was primarily in the mid to lower spinal areas. In general, irrespective of the eccentricity of the external load vector, bony/soft tissue damage occurred during the loading process. With the piston dynamically contacting the head-neck complex, the cervical spine experienced deformations during the loading sequence. Following the completion of the loading process (maximum piston excursion), the cervical spine sustained additional deformations secondary to inertial effects of the head. These observations were made using the highspeed photographic images. For the entire ensemble, the peak load to failure measured by the inferiorly placed load cell ranged from 650 to 6431 N (mean: 3055 N ± 267). The moments at the level of injury ranged from -37 to 127 Nm (mean: 37 Nm ± 6).

Table 1: Summary of Data

Age (years)	Height (cm)	.Weight (kg)	Sex (M/F)	Eccentricity (cm)	Mechanism
39 - 95	152 - 178	50 - 91	1 / 3	- 0.5 to -0.1	CE
29 - 76	152 - 183	41 - 98	8 / 4	0.0 to 1.0	VC
39 - 82	152 - 193	48 - 98	5 / 2	1.1 to 4.0	CF
46 - 61	153 - 178	64 - 102	4 / 1	4.1 to 11.0	HF

Statistical analyses revealed the following groups to have significant ($p < 0.05$) differences in the biomechanical variables. Compression-extension (CE), vertical compression (VC), compression-flexion (CF), and hyperflexion (HF) were found to have the eccentricity in the range of -0.5 to -0.1, 0.0 to 1.0, 1.1 to 4.0, and 4.1 to 11.0 cm, respectively. The compressive force and moment were significant biomechanical factors for differentiating these groups (ANOVA factorial test). The vertical compression group sustained the greatest compressive force (mean: 3680 N ± 258; this force was significantly greater than the force sustained by the specimens in the compression-flexion (mean: 2786 N ± 182) and hyperflexion (mean: 1275 N ± 292) groups based on unpaired Student t-test. The force sustained by the specimens in the compression-flexion group were significantly greater than the forces sustained by the specimens in the hyperflexion group (unpaired t-test). However, the forces sustained by the specimens in the compression-extension group were not statistically different from that of the other three groups ($p > 0.1$). The mean bending moment at the injury level sustained by the specimens in the compression-extension group (-7 Nm ± 15) was significantly smaller than the mean moments sustained by the specimens in the vertical compression (30 Nm ± 4), compression-flexion (65 Nm ± 16,) and hyperflexion (47 Nm ± 11) groups. The bending moment sustained by the specimens in the vertical compression group was significantly lower than the bending moment sustained by the compression-flexion group.

The kinematics of the cervical spine in response to head impact had different patterns among the four groups. The spinal column in the vertical compression group generally deformed axially. In the compression-flexion group, the upper portion of the vertebral column deformed axially, while the mid or lower portion bent into flexion. The kinematic response in the hyperflexion group demonstrated a continuous increase in flexion in the cervical column. In the compression-extension group, the spine deformed axially accompanied by an increasing extension movement.

DISCUSSION

In order to quantitatively determine the biodynamics of the human cervical spine secondary to contact induced forces, several experimental approaches have been used. They include conducting dynamic tests using whole-body human cadavers employing drop techniques, pendulum impact methods, or applying loads with an electrohydraulic testing device [2, 3, 6-8, 11, 19]. Tests have been conducted using intact head-neck complexes (without the underlying human torso and extremities) employing drop techniques or loading with an actuator [3, 6, 11]. In addition, experiments have been conducted using isolated segments of the cervical spine [12]. These studies form the primary database on this topic. While the testing of intact cadavers provides a unique opportunity to include all load bearing structures in the human body, experimental difficulties exist particularly with regard to the consistent reproduction of clinically seen motor vehicle related trauma and the associated quantification of the biomechanical variables. The use of segmented regions of the cervical spine limits the extrapolation and applications of the experimental protocol since factors such as the effects of spinal curvature and orientation cannot be included in the model. Consequently, the use of the intact head-neck complex appears to be a viable alternative to produce clinically seen injuries and at the same time measure the appropriate biomechanical variables to quantify trauma. Because of these reasons, the present study used an intact head-neck model.

The fundamental mechanical parameters investigated in the present study to quantify injury and contribute to the determination of human tolerance included forces and moments. In order to measure such biomechanical variables, several controls have to be exercised while applying the dynamic load to the head-neck complex. In this study, the insult was applied to the intact cranium using the electrohydraulic testing device and the specimen was rigidly fixed at the inferior end. The vertical travel of the piston applied dynamic load to the specimen in vertical or preflexed positions. The loading condition was varied by adjusting the location of the occipital condyles with respect to the first thoracic vertebra, i.e., the eccentricity of load application. This was achieved by suitably orienting the cervical spinal column with respect to the head. All specimens were configured such that the occipital condyles were aligned at eccentricities ranging from -0.5 to 11.0 cm. The resulting forces and moments were measured by the inferiorly placed six-axis load cell. Due to the interspecimen variability of the specimen position with respect to the load cell, the bending moments measured at the load cell include the influence from the shear and compressive forces. Such moment contribution from the forces masks the real moment load experienced by the cervical spine. This effect was minimized by determining the bending moment at the injury level such that a comparison could be made in the biomechanical parameters. Cervical spine injury may be quantified by the axial compressive force alone (e.g., burst or vertical fractures of the vertebral body), by bending moment alone (e.g., tear of the posterior ligaments without fracture), or a combination of the force and moment variables.

The effects of the initial and boundary condition on the cervical spine responses have been observed by a number of studies in literature. The alignment conditions were found to affect the loads and injuries sustained by the cervical spine [8, 11, 13]. For example, the positions of the head, neck and torso with respect to the loading direction affected the strains sustained by the cervical spine [8]. The injury outcome was found to be dependent on the position of the occipital condyles with respect to T1 vertebra [11]. Other studies reported strong influences of the boundary conditions on the resulting neck forces and injury outcomes [5, 6, 19]. The force and injury severity sustained by the cervical spine increased with head restraint in drop testes [6, 19]. Although these previous studies provided evidence of such effects, quantitative correlation between the head-neck alignment condition and the resulting load vector sustained by the cervical spine has not been reported. The present study quantified such correlation between the geometric parameter and the load vector using experimental data from 28 head-neck cadaver specimens. Statistical analyses of the forces and moments demonstrated a strong correlation between the biomechanical variables and eccentricity. The specimens with eccentricities of 0.0 to 1.0 cm sustained the greatest compressive force (mean: 3680 N $\pm$ 258) while those with much larger eccentricities (4.1 to 11.0 cm) sustained the least force (mean: 1275 N $\pm$ 292). The compressive force was determined to be a biomechanical parameter that significantly differentiated the three test groups according to their pre-test eccentricities in the range of 0.0 to 11.0 cm. The compressive force was not effective however, in differentiating between groups with negative and positive eccentricities. The bending moment, on the other hand, was determined to be sensitive to the sign of the eccentricity and differentiated the test group with negative eccentricities from any of the other three groups with positive eccentricities.

A measurement of compressive force and bending moment therefore is required to determine the loading condition in terms of the eccentricity. For example, a 3000

N compressive force sustained by the cervical spine may indicate any of the following: vertical compression, compression-extension, or compressive-flexion. The sign of the bending moment can help to select or eliminate the compression-extension group. The moment magnitude can help to differentiate the vertical compression from compression-flexion groups. Similarly, a 65 Nm bending moment may suggest compression-flexion or hyperflexion. A compressive force greater than 2000 N can then indicate compression-flexion as a more likely loading mechanism than hyperflexion. The demarcation between the four groups for the forces, moments and eccentricities will become more definitive when the experimental sample size increases to cover the range of testing conditions. Additional experiments are needed to increase the accuracy of the grouping demarcations and extend the results into greater negative eccentricities. Likewise, additional tests are needed to include the effects of parameters such as age, bone condition and gender on the biomechanics of cervical spine injury. Nevertheless, this study has provided an important framework to guide future studies of cervical spine injury.

The results in this study suggest that a general tolerance criterion for the human cervical spine injury due to head impact should include force and moment parameters, and different tolerances for different mechanisms. The present study has demonstrated that the forces and moments sustained by the cervical spine are strongly dependent on the eccentricity. Four distinct groups were identified according to their eccentricities in the range of -0.5 to 11.0 cm. Each group was associated with a particular pattern of kinematic responses. Therefore, such groupings may be associated with different loading mechanisms of the cervical spine. A single force parameter may be adequate to quantify the tolerance under vertical compression where vertebral body fractures are predominant [11]. For hyperflexion injuries however, where bending of the spine is the predominant response, the same single force parameter may not only be too high, but may also not represent the resulting injury pattern. A single bending moment may effectively quantify hyperflexion or hyperextension injuries where only the ligaments are torn. A universal moment tolerance criterion derived from hyperflexion injuries will not effectively quantify vertical compression injuries. The compression-flexion and compression-extension injuries may involve ligamentous disruption and vertebral fracture as primary structural failure and therefore, may need to be quantified with both force and moment parameters. The application of such a tolerance criterion to a particular type of cervical spine injury case involves the determination of the loading or injury mechanism, and selection of the appropriate tolerance parameters and values according to the mechanism.

Acknowledgment: This study was supported in part by DOT NHTSA Grant DTNH22-93-Y-17028, PHS CDC Grant R49CCR 507370 and the Department of Veterans Affairs Medical Research.

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SEAT DESIGNS FOR WHIPLASH INJURY LESSENING

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ABSTRACT

The purpose of this study is to evaluate the potential for the reduction of occupants neck injuries, so called "whiplash injuries" (whiplash associated disorder), in rear end collisions. Based upon new biomechanical research, an effort was made to design head restraints and seats to help lead to a reduction of such injuries. This resulted in a concept which involves the motion of the head and torso in harmony during a rear end collision. Consequently a newly designed seat based upon this concept is evaluated in low speed rear impact dummy sled tests, and additionally offered in volunteer sled tests using X-ray cinemas conducted by Japan Automobile Research Institute and University of Tsukuba, who investigate the influence of seat characteristics to human head and torso kinematics and cervical vertebra movement to reveal the mechanism of whiplash injuries. As a result, it was found that the motion between head and torso as well as the movement between each cervical vertebra was reduced.

INTRODUCTION

Whiplash injuries which occur mainly in rear end collisions are the most frequent injuries reported in traffic accidents. In Japan, approximately 40% (approximately 200 thousand occupants in struck vehicles per year) of all injuries are caused by rear end collisions [1], and approximately 80% of rear end collisions are neck injuries of varying severity [2]. Its by-product is a very high social and economic cost, for example $4.5 billion per year in the USA [3].

The majority of whiplash injuries result in no objective evidence such as X- rays, MRIs, or electric signals (EEG, EMG, SEP, etc). However subjectively they can present pain, numbness, headache, and so on. Furthermore, they can potentially lead to long term disability of which approximately 40% require more than one year treatment according to the investigation of Galasko et al. [4]. Therefore, it is understood that complicated circumstances are behind whiplash injuries.

Up to this time, head restraints have been thought to prevent whiplash injuries caused by hyper-extension of neck. However biomechanical studies in recent years, by Matsushita et al. [5], who investigated cervical spine movements in volunteer sled tests using X-ray cinemas, found that whiplash injuries could be caused within a normal range of neck motion. The same theory was reported by McConnell et al. [6].

At present there are several hypotheses explaining the mechanism of whiplash injuries. Svensson et al. [7] suggested that a swift motion of neck can cause nerve damage in a spinal ganglia of lower cervical regions due to the pressure changes experienced in pig tests. The same trauma was reported by Miyoshi [8] from rabbit pendulum tests using X-ray cinemas. Matsushita et al [5] concluded that discomfort symptoms are from micro-injuries of musculature or soft tissues caused by a passive stretching in resistence to inertial loads. Ono and Kaneoka [9], who investigated each cervical vertebra movement from volunteer sled tests using X-ray cinemas, suggested that an abnormal crash extension of C5/C6 could cause facet impingement injuries.

The Concept- Though the mechanism of whiplash injuries is not completely understood, a decrease in neck motion is thought to lessen whiplash injuries. Expressing the above ideas visually, Figure.1 shows the concept for reducing the likelihood of whiplash injuries or lessening the severity.

In 1982 Kahane [10] reported that the effectiveness of integral and adjustable head restraints, reducing neck injuries in rear end collisions, was 17 and 10 percent, respectively. Viano et al. [11] reported that from H-III dummy sled tests a 28.3% injury reduction in risk could be achieved by merely adjusting all head restraints to the extended position. By contrast, in 1996 NHTSA [3] questioned how, for example, head restraints and seating systems can be improved to reduce neck injuries.

This study attempts to present some solutions, for not only the head restraint but also the seat back. Yet other factors have much to do with whiplash injuries such as age, physique, gender of occupants, and medical diagnosis and treatment by doctors.

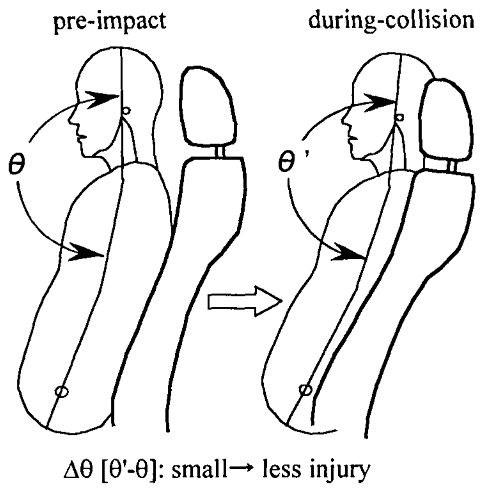

Figure 1. Desirable occupant motion during impact in low-speed rear end collision.

COMPLEMENT TO ACCIDENT DATA

Crash severity in which whiplash injuries occur is examined from the 1993 NASS data of rear end collisions involving AIS=1 neck injuries (Figure 2), Compared with the investigation by Eichberger et al. [12] of Graz University, NASS data is concentrated toward higher velocity change. This is because severe crash accidents are more frequently sampled than soft ones in the NASS data (samples over 50km/h are disregarded in this study).

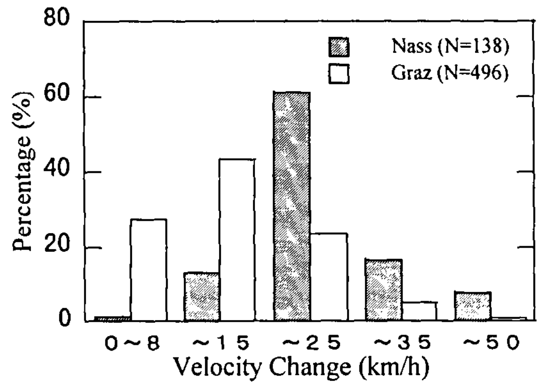

Figure 2. Distribution of velocity change (ΔV) of the struck car in rear end collisions involving whiplash injury.

Considering this data, it is clear that whiplash injuries occur most often in low speed collisions within 25 km/h of velocity change, so to evaluate whiplash injuries, low speed tests are suitable.

DESIGN CONCEPT

It is important to arrange the sitting posture of the occupant as straight up as possible, because a slouching posture will keep the occupant's head distant from the head restraint. The locus of adjusting the head restraint is designed to move almost vertically. This is because, when driving, the backs of head, depending upon the body size of the occupants, are located almost on the same vertical axis as shown in Figure 3 on the left, which represents the head of AM95, AM50, and AF05 from the top.

Geometry of The Head Restraint and Seat Back

First, for the low-speed rear end collisions, the head restraint, especially the metal frame, is moved forward and upward. But it has some limitations, because if the head restraint is too near the head it interferes with the occupant's head and causes discomfort while driving. Second, the upper part of the seat back frame is moved rearward away from the upper torso with the seat surface remaining to support the upper torso the same way as in the original seat design, and also raised along with the head restraint. During rear end collisions the upper torso mildly sinks into the seat back, and when the upper torso stops and starts to rebound, at the maximum deformation of the seat back, the head is restrained naturally by the head restraint (Figure 3). Therefore head and torso move in harmony, and head stops and starts to rebound simultaneously with the torso (less whiplash movement). The pelvic support at lower part of the seat back frame initiates the lower torso to rebound first, and therefore helps to prevent the neck extension motion through its relative flexion motion.

To position the head restraint as high as the top of the occupant's head is not quite necessary. The reason is because it is not the pad but the frame of the head restraint which sustains the occupant's head during rear end collisions. The head restraint height (H) of approximately 800mm parallel with the torso line is considered sufficient even for AM95 if the insert frame of the head restraint sustains the head center of gravity.

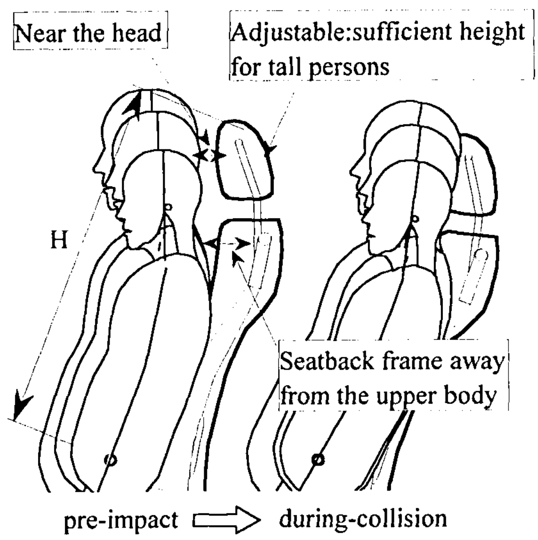

Figure 3. Geometry of the seat structure.

DUMMY SLED TESTS

Modified Dummy Neck

There is no doubt that H-Ⅲ original neck is too stiff to evaluate neck extension motion in low speed rear impact dummy sled tests simulating low-speed rear end collisions. So H-Ⅲ original neck is modified as shown in Figure 4 in order to achieve higher bio-fidelity, referring to TNO RID neckⅡ [13].

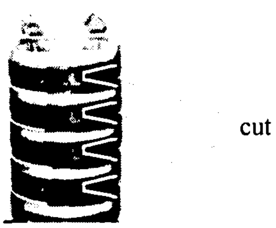

Figure 4. Modified H-Ⅲ neck.

Figure 5 shows performance of modified neck as compared with human necks. These tests were performed without head restraints. TNO's reference line [13] in Figure 5, represents the border between relaxed and tensed human before impact, determined by various volunteer and cadaver tests. Even if results are somewhat influenced by various seat performance, the modified neck roughly located on the border line. The stiffness difference between the modified neck and the original H-Ⅲ neck, also shown in Figure 5, is approximately 30%.

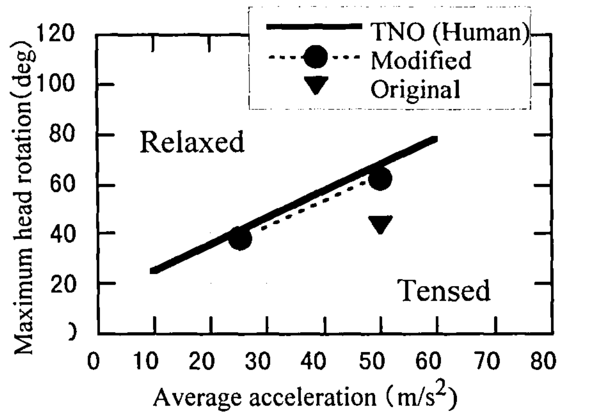

Figure 5. Maximum head rotation of modified and original H-Ⅲ neck compared with human.

Test Method

To evaluate the new seat design, low speed rear impact dummy sled tests were performed using AM50 H-Ⅲ dummy (Table 1).

Table 1. Summary of Dummy Sled Tests

Test No.	Head-restraint	Velocity Change(km/h)	Neck
D01	Yes	8	Modified
D11	Yes	12.5	Modified

one sled pulse was derived from the acceleration pulse of car to car rear end collisions and resembles by the half sin-curve to be approximately 12.5 km/h velocity change. The other 8 km/h velocity change sled pulse was also derived from JARI's data of actual car rear end impact experiments.

In each test the dummy was positioned with Hip point determined by SAE mannequin, and a initial gap (a horizontal distance between head and head restraint) determined by human driving postures was set. The center of head restraint was adjusted to be level with the gravity center of the dummy head. The dummy was belted by normal 3- point belts. This sled needs initial velocity before impact, so two pieces of urethane pads were installed to support dummy's head and chest while accelerating to reach required initial velocity. Dummy accelerations were measured and dummy motions were filmed with a high speed video camera.

Results

In each test the dummy's pelvis, chest, lower head and upper head stop and start to rebound one after another. However, in spite of soft crash, each rebound time of D01 is slower than that of D11.

The dummy's resultant acceleration and motion data are time- historically shown in Figure 6 and Figure 7. Here the reference point is on the sled, and all numerical values are initially zero. As a fact, in D11 rearward head rotation angle is larger than that of D01 for the high velocity change, however Δθ max (maximum relative rotation angle between head and torso) of D11 is smaller than that of D01 because in D11 the rearward torso rotation is larger than in D01.

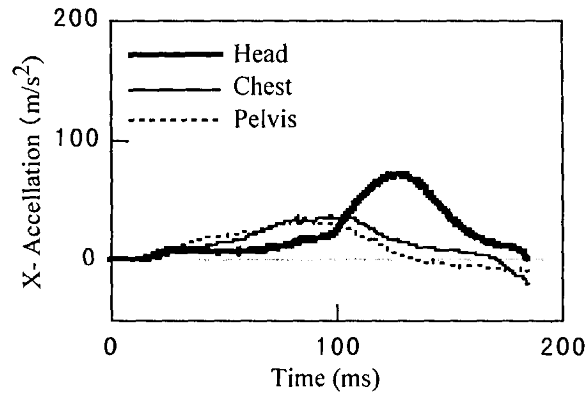

Figure 6A. ΔV= 8 dummy response (D01).

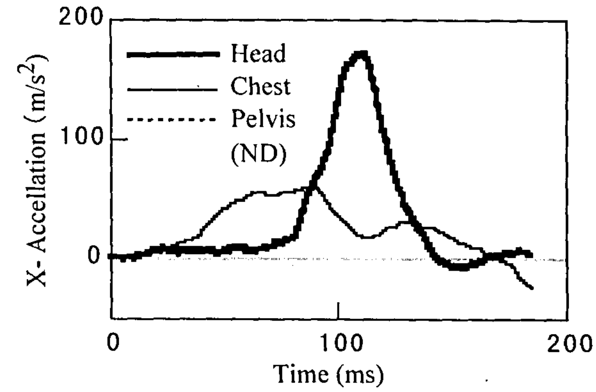

Figure 7A. ΔV= 12.5 dummy response (D11).

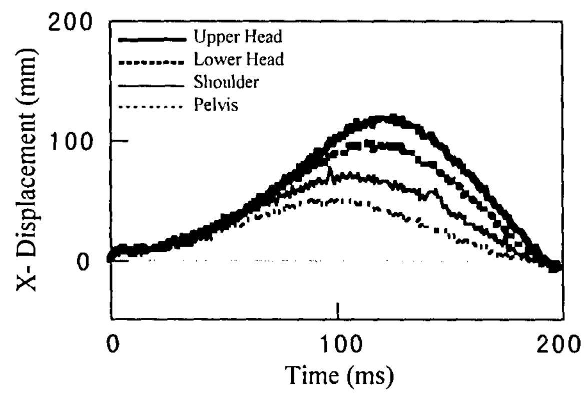

Figure 6B. ΔV= 8 dummy response (D01).

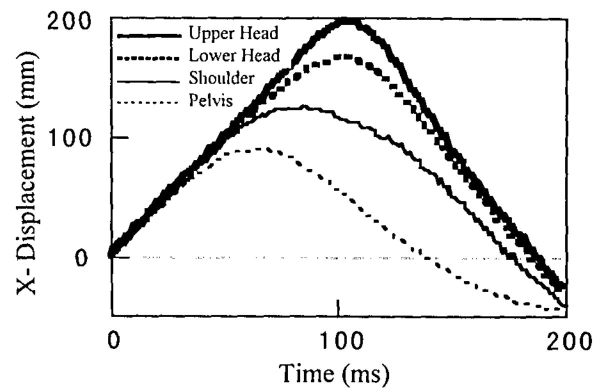

Figure 7B. ΔV= 12.5 dummy response (D11).

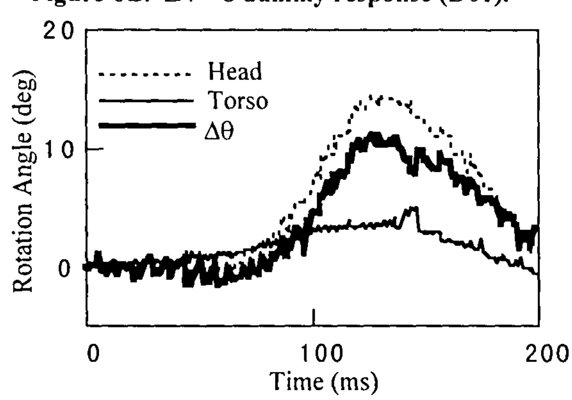

Figure 6C. ΔV= 8 dummy response (D01).

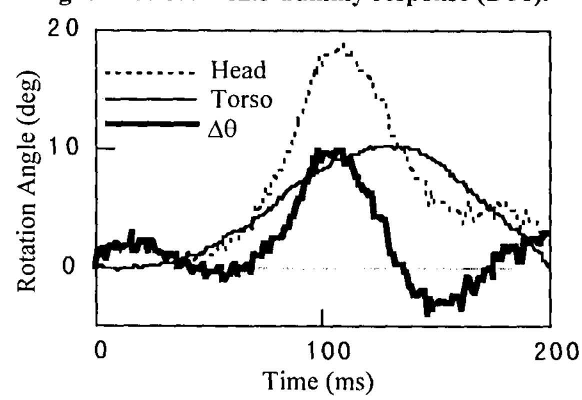

Figure 7C. ΔV= 12.5 dummy response (D11).

The rearward torso rotation is a flexion motion for the neck, and therefore able to cancel the rearward head rotation and lead to a reduction of Δθ max.

Eichberger et al. of Graz University [12] who also performed volunteer sled tests indicated that a Δθ exceeding 30 degrees caused cervical distortion and exceeding 15 degrees caused pain. Compared with this investigation, Δθ maxs of the newly designed seat are not high enough to cause pain, in both sled tests.

VOLUNTEER SLED TESTS

Human cervical vertebra movement cannot be simulated by the dummy. And consequently, volunteer sled tests using X-ray cinema was planed to observe cervical vertebra movement. JARI and University of Tsukuba have concentrated on the investigation of the influence of seat characteristics to human head and torso kinematics and cervical vertebra movement, after their examinations by volunteer sled tests [9], [14].

Table 2 shows a summary of these tests. The newly designed seat is also used and velocity change is 8 km/h. The seat position was identical to dummy sled test. The head restraint was adjusted so that the center was level to the ear center of the subject. Seat belts were not used. Test series V01, V02 evaluates volunteers' head and torso motion, and was performed at JARI. Test series V03, V04 evaluates cervical vertebra movement, and was conducted by JARI at University of Tsukuba. The cineradiographic system of Tsukuba University Hospital obstructs to film the volunteer's total motion. Observation of volunteers' cervical vertebra movement and observation of volunteers' head and torso motion can't be performed simultaneously.

A more detailed configuration and method of these sled tests were referred in Ono and Kaneoka [9], [14].

Table 2.
Summary of Volunteer Sled Tests

Test No.	Volunteer	Head-restraint	X-ray
V01	a	Yes	No
V02	b	Yes	No
V03	a	Yes	Yes
V04	b	Yes	Yes

Table 3 shows physical data for the volunteers. Volunteers, whose physiques resembled AM50 and without history of cervical spine injury, participated. It was confirmed through X- rays that they had no degenerative cervical spine irregularities.

Table 3.
Physical Data of Volunteers

Volunteer	a	b
height (cm)	174	172
sitting height (cm)	94	90
weight (kg)	70	61
age (year)	22	22

Head and Torso Motion

Figure 8 shows one subject's sequential motion in V01, and shows the target points for the analyses of the subject's head and torso motion. Time- historical volunteer motion in V01 test are shown in Figure 9. Here the reference point of the x- displacement is on the sled, and all the numerical values are initially zero.

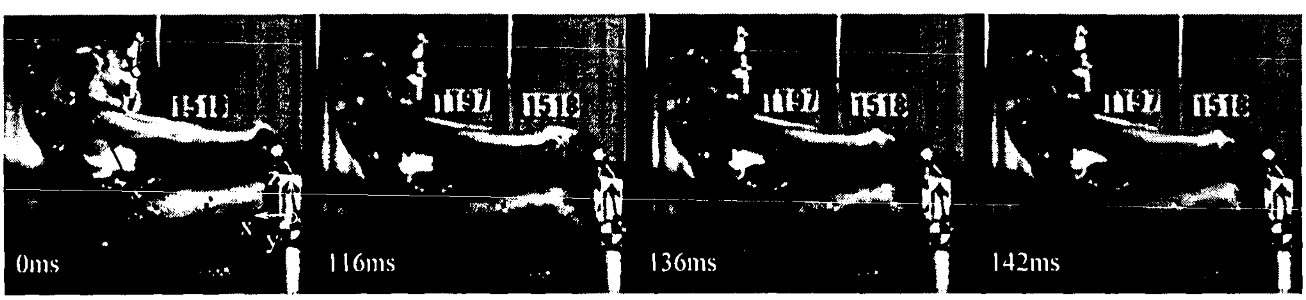

Figure 8. Volunteer sequential motion during impact (V01).

The rearward head rotation is almost the same as the dummy's head rotation (Figure 6C and Figure 9C). However the rearward torso rotation is larger than the dummy's torso rotation, resulting in cancellation of rearward head rotation and a reduction of Δθ max.

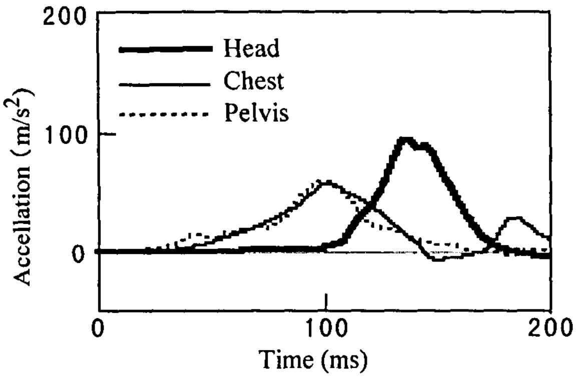

Figure 9A. Volunteer response (V01).

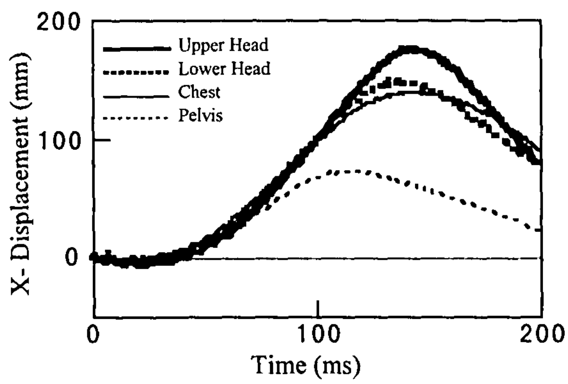

Figure 9B. Volunteer response (V01).

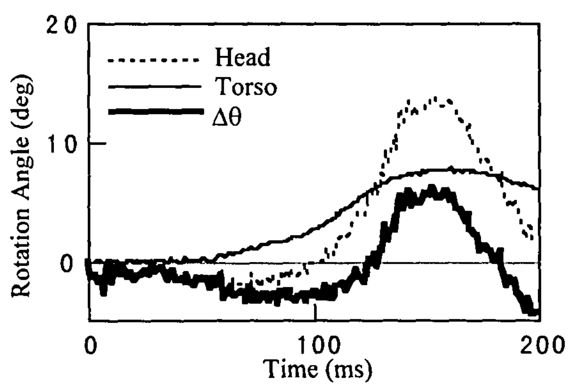

Figure 9C. Volunteer response (V01).

According to smoother spines curvature, more flexible shoulder joints and softer lumber spines of the human subjects, their upper torsos sink into the seat back and rebound much slower than pelvis, also resulting in cancellation of the rearward head rotation relative to the torso. Figure 10 shows time- historical electromyographic activities, arising approximately 60ms after impact, proves that the subject remained relaxed before impact.

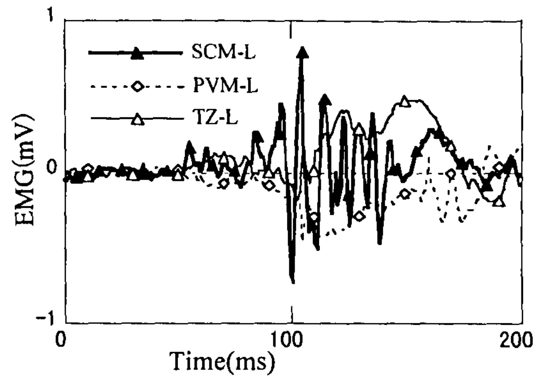

Figure 10. Electromyograph (V01).

On the other hand in V02 test (Figure 11) subject's head rotation and torso rotation showed all smaller values than in V01. Consequently Δθ max is identical to V01. The initial flexion mode of neck was clearly observed in V01, however only slightly observed in V02 as in the dummy sled tests. (Figure 6C, Figure 9C and Figure 11). In these tests even if only two cases, it is observed that each subject's head and torso motion was small.

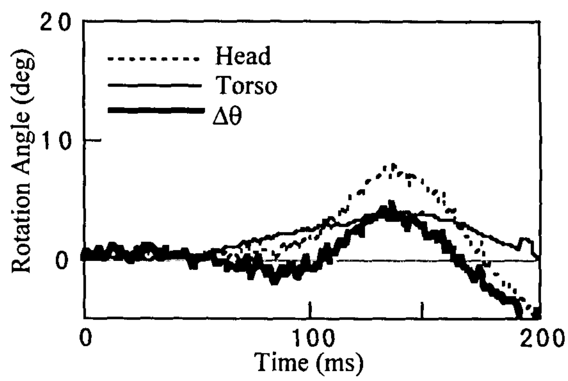

Figure 11. Volunteer response (V02).

In addition, each head and torso motion of the dummy is almost in the same range as the volunteers' motion. Considering the difference of initial gaps between head and head restraint, the dummy with the modified neck can be a surrogate in these low speed rear impact conditions except for the cervical vertebra.

Cervical Vertebra Movement

Figure 12 shows one subject's cervical vertebra sequential movement in V03, the same subject as in V01 test. In the case of V03 the maximum rearward rotation of the head is time- historically a little later than in V01. In the two tests the subject intend to sit identically, but might have had different seating positions, especially with regard to the initial gap.

Figure 13 shows time- historical cervical vertebra movement in test V03, and Figure 14 in test V04. The picture of cineradiography can't be obtained from the impact timing, because the field of cineradiographic vision is limited. So the initial picture is determined by the appearance of the subject's neck within the analyzable range.

Cervical vertebra response of the two subjects is in contrast with each other. In test V03, middle vertebra rotate rearward, followed by C6 and C2 vertebra. When the maximum rotation of C6 occurs cervical vertebra move in alignment, with C5- C2 in almost initial alignment. In test V04, lower vertebra rotate rearward, followed by upper vertebra. When the maximum rotation of C6 occurs the cervical vertebra move in alignment. In this case total neck motion shows extension however cervical vertebra movement shows flexion. This is because the torso moves rearward but the head moves forward supported by the head restraint.

In both tests cervical vertebra rotations between C6 and C2 are small, approximately only 10 degrees. Moreover it is observed that the human cervical vertebra behaved diversely. One is extension and the other is flexion.

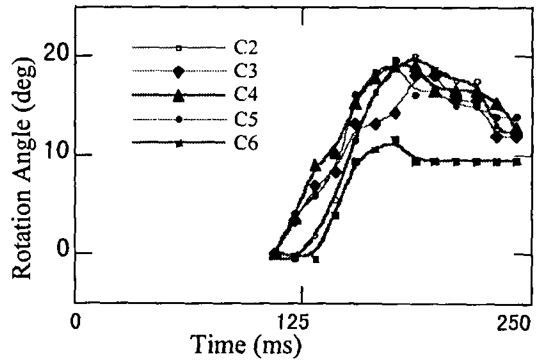

Figure 13. Cervical vertebra response (V03).

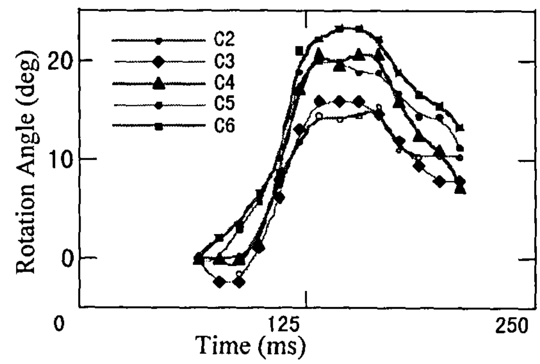

Figure 14. Cervical vertebra response (V04).

Maximum rotation angles of these two subjects' cervical vertebra are compared with the average maximum extension angle of human cervical vertebra in ordinary neck extension motion [15]. Each cervical vertebra in these two tests is within the normal range of movement, see Figure 15. Of course test V04 shows flexion motion as described.

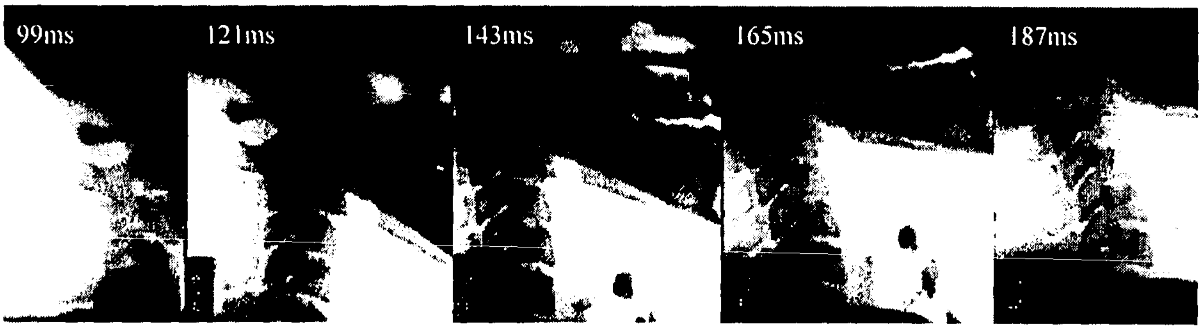

Figure 12. Volunteer cervical vertebra sequential movement during impact (V03).

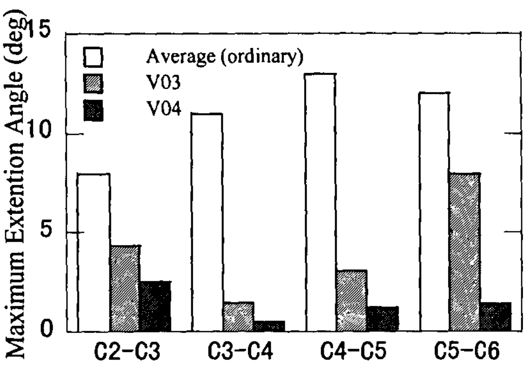

Figure 15. Maximum cervical vertebra rotation of these tests compared with ordinary neck extension.

Finally it must be mentioned that two volunteers suffered no injury to their necks in these tests.

CONCLUSIONS

The seat, which has new design concept for reduction in whiplash injuries, allows less motion between head and torso in the modified dummy sled tests, and also allows less motion in volunteer sled tests. Moreover there is less movement between each cervical vertebra.

Further research is required whether any other mechanism of whiplash injuries exists.

With head restraints, human motion between head and torso is similar to the modified dummy. Consequently a evaluation of head and torso motion is possible using a modified dummy, if limited to low-speeds. However, real human's neck motion, especially cervical vertebra movement, is too complicated and diverse to simulate by current dummies.

A more sophisticated rear impact dummy with higher bio-fidelity is needed for more accurate evaluation. Smoother spines curvature, softer lumber spines, more flexible shoulder joints are needed.

It. is important to remind occupants to adjust their head restraints properly according to manufacturers' recommendations so as to take advantage of the protection offered by the available head restraint.

Prius- Toyotas' brand new car. Its seats have the design concept as described in this paper.

ACKNOWLEDGEMENTS

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A SLED TEST PROCEDURE PROPOSAL TO EVALUATE THE RISK OF NECK INJURY IN LOW SPEED REAR IMPACTS USING A NEW NECK INJURY CRITERION (NIC)

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ABSTRACT

Today's cars do not sufficiently prevent neck injuries in rear end impacts. So called whiplash injuries are often sustained at low velocities. According to Swedish road casualty statistics, the risk for whiplash injuries increases dramatically with the velocity change (Δv) of the impacted car in the interval between 10-20 km/h. During recent years, much progress has been made in research concerning this issue. This includes new findings from injury statistics, better knowledge of injury mechanisms (even if they are not yet fully understood) and development of suitable rear impact dummies.

This paper describes a new sled test procedure involving two levels of rear impact severity. In the proposed procedure, a new neck injury criterion (NIC) which is a measure of the effect of violence to the neck, is used to evaluate the level of neck protection.

Seats, from two cars with different neck injury-risk rating (according to Swedish statistics), have been tested according to the new procedure and compared with a new seat concept. The results indicate that a seat back with a low yielding limit has a lower risk of neck injury, which is reflected in lower NIC-values.

INTRODUCTION

When designing car seats to prevent injuries in high Δv rear-end collisions (Δv above 25 km/h and 10 g in crash pulse), there already exist sled test procedures including risk evaluation criteria (Viano, 1994). For this level of severity most researchers agree that neck hyper extension and occupant ramping up the seat back (with the potential for secondary impact of the occupant with the rear seat and the rear window) must be avoided. By improving the head rest and stiffening the seat, the occupant may be protected from life threatening injuries. On the other hand, AIS 1 classified neck injuries, sustained mostly at low speed rear-end collisions (Eichberger et al. 1996, Parkin et al. 1995) have been given increased attention over the last ten years. According to Nygren et al. (1984), Lundell et al. (1998) and v Kock et al. (1995, 1996), these injuries are by far the most common injury type in rear end impacts and cause long term disability in 1 out of 10 injury cases (Nygren, 1984). Despite these facts, there are no established test methods nor evaluation criteria for low speed rear impacts. A reasonable requirement for a test procedure, evaluating disabling neck injuries in these impacts, would be the ability to discriminate between circumstances with different injury risk (Jakobsson et al., 1994).

According to an in-depth study of neck injuries by Olsson et al. (1990) the shape of the crash pulse has a greater influence on the severity of the neck injury than the amount of transferred energy. Recent work by Krafft (1998) shows that the existence of a tow bar as well as being hit by a car with a transversely mounted engine significantly increases the risk of long term disability in rear impacts. It is tempting to believe that, in a rear impact these two factors influence the mean or peak struck car acceleration.

Boström et al. (1996) proposed a new neck injury criterion (NIC) based on a hypothesis of Aldman (1986) and the findings of Svensson (1993). The idea of NIC is to measure the effect of the violence to the neck (normally not life threatening) during the initial retraction phase, phase 1 in Figure 1.

The scientific basis for the NIC-criterion has been further substantiated in recent work, where NIC-values in simulated real-life rear-end collisions have been compared with the actual injury outcome (Boström and Krafft et al., 1997a). The NIC has been found to be sensitive to the seat structure characteristics, the car Δv, and the car crash pulse.

The aim of this paper was to propose and evaluate a new sled test procedure to characterize a car seat from neck injury risk point of view. The design of the test method is based on real-life crash data and research in biomechanics as well as experience from various sled tests and full-scale car tests.

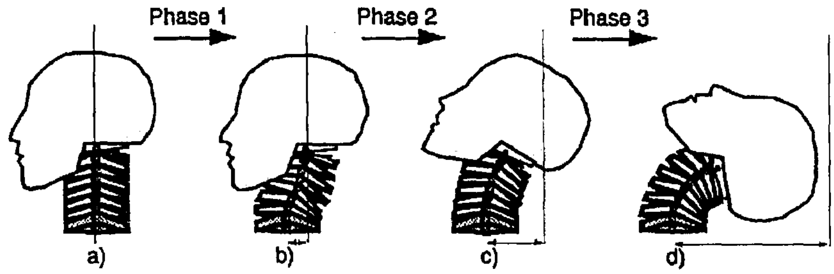

Figure 1 - Schematic view of four parts of the head-neck motion during a rear-end collision: a) initial posture, b) maximum retraction, c) maximum rearward angular velocity of the head is reached, d) hyper extension. The vertical line represents a reference plane in rest. (from Svensson, 1993)

PROPOSED SLED TEST PROCEDURE

The most appropriate crash pulse to use in a sled test with a car seat to simulate a rear impact, should be based on a large set of full scale crash tests with the particular car model. However, the purpose of this study was to evaluate the properties of a seat independently of the corresponding car structure. That is, the ambition was that a seat performing well in this study should perform well in any car regardless of the car structure properties.

In the proposed sled test procedure the seats are exposed to acceleration pulses giving the same Δv but with different acceleration time-history. The difference between the chosen acceleration levels represents the difference between the striking/struck car having a stiff or soft frontal/rear structure, or the difference between a struck car with or without a tow bar. The influence on occupant loading due to such differences have been investigated by Håland et al. (1996) and Boström et al. (1998) by means of full scale crash tests. According to Krafft (1998) these factors indicate a difference in disability risk.

The expected effect of the violence to the neck of a human occupant is measured by the NIC response. The NIC and the tolerance level are defined according to equations 1 - 4.

$$NIC = a_{relative} * 0.2 + v_{relative}^2 \quad [m^2/s^2] \quad (1.)$$

calculated at maximal retraction (posture b in Figure 1)

$$a_{relative} = a_{T1} - a_{C1} \quad [m/s^2] \quad (2.)$$

local x-acceleration, T1=lower neck, C1=upper neck

$$v_{relative} = \text{time integral of } a_{relative} \quad [m/s] \quad (3.)$$

$$\text{Tolerance level of NIC} = 15\ m^2/s^2 \quad (4.)$$

In eq. 1, 0.2 [m] is a length parameter. Depending on the biofidelity of the dummy response, these equations may have to be changed, for example by making assumptions about the upper neck (C1) acceleration.

The hypothesis is that a seat which is tolerant to different rear impact crash pulses and has low NIC values, up to maximal retraction, is a good seat with low risk of neck injury.

METHOD

Two standard production seats, seat B ("Bad") and G ("Good"), and an anti whiplash seat, AWS, were tested with a Hybrid III (HIII) 50th percentile male dummy. The AWS has a force controlled yielding of the seat back to give the neck a gentle acceleration until maximum retraction is passed. According to real-life disability data analysed by Krafft (1998), in rear impacts, the seat G car model is much safer than the seat B car model. This agrees with the ranking based on police reported accidents presented by Boström and Krafft et al. (1997a).

The chosen Δv in the sled tests was 15 km/h representing an impact speed of approximately 25 km/h (for equal masses of the target/bullet cars). Two pulses, from now on called the 4g and the 8g pulse, were used in the tests (Figure 2).

The seat back angle was measured by the use of an SAE H-point machine (dummy). It was placed in each seat model and the seat back angle was adjusted so the torso-line was 25 degrees to the vertical. The resulting seat back angle for each seat model was measured and used in the sled tests. The H-point of the HIII was positioned according to the H-point machine and the upper torso was pushed into the seat back with the same force as with the H-point machine. Finally the baseline of the head was placed in a horizontal position.

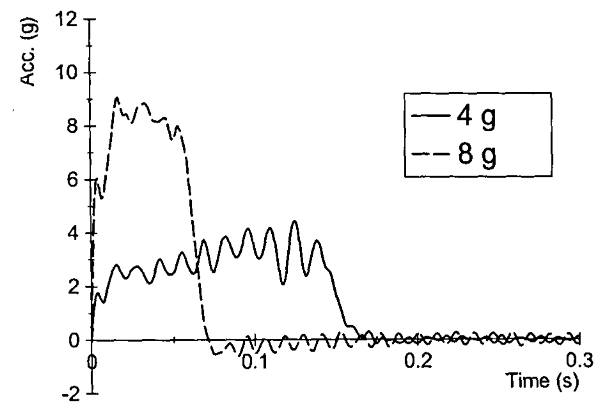

Figure 2 - For the evaluation of the proposed test concept, these pulses were chosen; the 4g and the 8g pulse.

For seat G, the test was repeated with a 5th percentile HIII female dummy seated on a child cushion. The purpose was to evaluate the weight influence on the test results. The reason for the child cushion was to prevent the 5th percentile female dummy from sinking into the seat below the transverse upper seat back beam.

The neck injury criterion (equations 1-4), was configured for the use of the HIII dummy. The neck (as well as the complete spine) of the HIII dummy is far from biofidelic regarding the initial retraction phase. Therefore, the relative acceleration in equation 2 is not applicable for a HIII dummy. On the other hand, the upper neck (C1) acceleration of an unaware human occupant is relatively low until the moment of maximal retraction (eq. 1 and posture b in Figure 1). This is true as long as the head is not accelerated by the head rest during the retraction phase. In order to evaluate the risk of injury/level of protection for a given seat, NIC50 as defined in eq. 5 - 9 was used as a criterion in the current evaluation.

$$NIC50 = a_{lower\,neck} * 0.2 + v_{lower\,neck}^2 \quad [m^2/s^2] \qquad (5.)$$

calculated when

$$d_{lower\,neck} = 50\text{ mm} \qquad (6.)$$

$a_{lower\,neck}$ =
(local) x-component of the lower neck acc. [m/s^2] (7.)

$v_{lower\,neck}$, $d_{lower\,neck}$ = time integral and double time integral of $a_{lower\,neck}$ (8.)

$$\text{Tolerance level, } NIC50 = 15\ m^2/s^2 \qquad (9.)$$

Equations 5-9 are the conformed alternative to eq. 1-4 with the assumption of zero upper neck (C1) acceleration during the initial retraction phase (phase 1 in Figure 1) and the occurrence of maximal retraction after 50 mm of lower neck displacement relative to a non accelerating head.

In addition to NIC50, the upper neck extension moment and shear force (My and Fx) were also measured. To evaluate the rebound effect of the seats, the relative upper torso rebound was calculated as follows:

$$\text{Relative upper torso rebound} = (\text{max. lower neck speed} - \Delta v)/\Delta v \qquad (10.)$$

If for example the interaction between occupant and seat-back in a rear impact is totally plastic (non-elastic), the maximum neck speed in eq. 10 becomes approximately Δv and the relative upper torso rebound becomes zero. If on the other hand, the interaction is totally elastic, the maximum neck speed becomes approximately $2\Delta v$, with a relative upper torso rebound close to 1 (100%).

RESULTS

The performance of seat G and of seat AWS compared to seat B were quite different. The lower neck acceleration of the HIII in seat B was considerably affected by the difference in pulse, which was not the case for seat G and the seat AWS (Figures 3-5). The resulting NIC50 values for the production seats were in agreement with the disability analysis made by Krafft (1998). It was found that the level of the pulse influenced the NIC value significantly for seat B, but not for seat G (Figure 6). Actually, only the 8g pulse for seat B resulted in NIC values well above the injury threshold of 15 m^2/s^2.

There was no correlation found between the relative upper torso rebound values and the expected injury outcome (Figure 7). Actually it seemed as seat G was even more elastic than seat B.

For all tests, the traditional neck criteria, upper neck extension moment and shear force, were well below the AIS2+ tolerance levels (57 Nm/1100 N) proposed by Backaitis and Mertz (1994) (Figures 8-9). However, for seats G and B, the shear force (Fx) values were lower in the 4g pulse tests compared to the 8g pulse tests. For the 8g pulse, the seat B Fx value was higher than the corresponding values for seat G and seat AWS.

The results of the test with the elevated HIII 5th percentile female dummy were comparable with the results with the HIII 50th percentile male dummy. There was no substantial difference regarding the NIC response for the two pulses (Figure 10). The lighter dummy experienced, however, slightly higher NIC50 values.

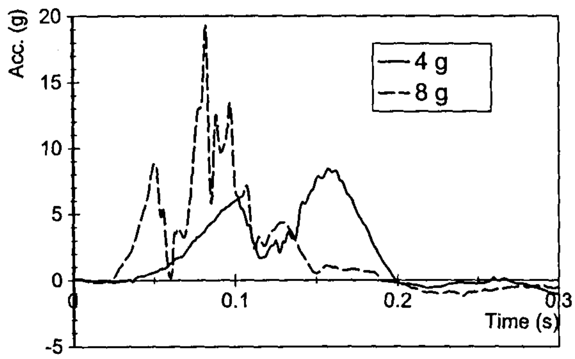

Figure 3 - Lower neck acceleration for seat B for the two crash pulses.

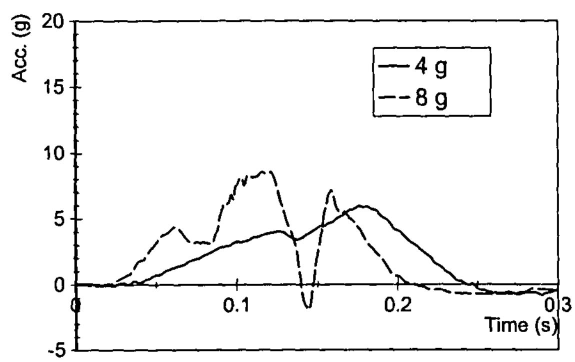

Figure 4 - Lower neck acceleration for seat G for the two crash pulses.

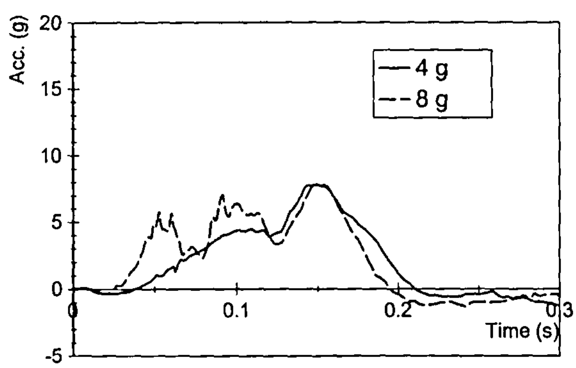

Figure 5 - Lower neck acceleration for seat AWS for the two crash pulses.

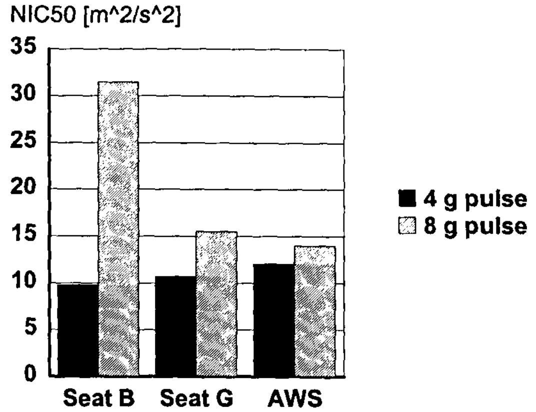

Figure 6 - NIC50 values for the HIII 50th percentile male dummy for the two pulses for seat B, G and AWS. The tolerance level is 15 m^2/s^2.

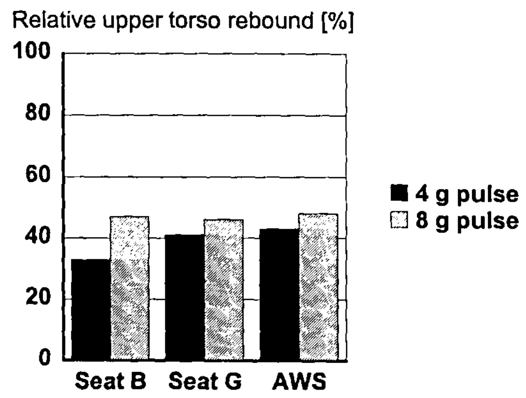

Figure 7 - Relative upper torso rebound, defined in eq. 10, for the HIII 50th percentile male dummy for the two pulses for seat B, G and AWS.

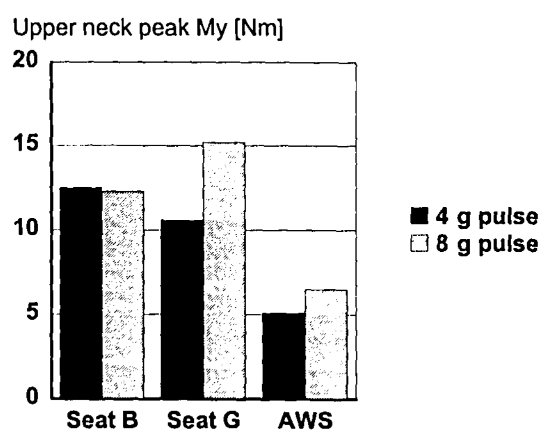

Figure 8 - Peak upper neck torque, My, for the HIII 50th percentile male dummy for the two pulses for seat B, G and AWS.

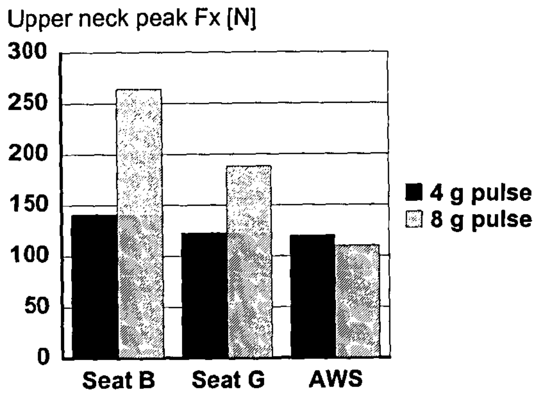

Figure 9 - Peak upper neck shear force, Fx, for the HIII 50th percentile male dummy for the two pulses for seat B, G and AWS.

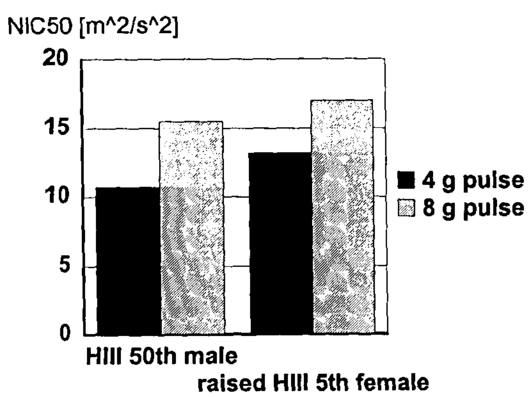

Figure 10 - NIC50 values for the HIII 50th percentile male dummy compared to the values for the raised HIII 5th percentile female dummy for the two pulses for seat G.

DISCUSSION

The pulses (the 4g and 8g pulses) and the Δv (15 km/h) used in this study were chosen on the basis of full scale rear impacts, where the impact speed was 25 km/h. If it is determined that the 8g pulse is not an accurate representation of an average injurious impact, the level of pulse and/or the Δv will have to be changed in the sled test procedure.

The explanation for the lower NIC50 values and the insensitivity to the shape of the acceleration pulse for seat G and seat AWS is clearly the "softer" performance indicated by the lower neck accelerations shown in Figure 3-5. In addition, the "softer" performance of seat G and seat AWS also resulted in decreased upper neck shear forces. This is in agreement with the analysis of a series of sled tests with a HIII dummy equipped with a Rear Impact Dummy (RID) neck developed by Svensson and Lövsund (1992), where the *initial* upper neck torque and shear force maxima were shown to correlate with the NIC values (Boström et al., 1997b). However, in contrast to the NIC values, for all sled tests in this study as well as in the study by Boström et al. (1997b), the peak upper neck moment and shear force were well below the tolerance levels (57 Nm/1100 N; Backaitis and Mertz, 1994). In this study only the NIC50 values, in agreement with disability data, prove seat B being worse than seat G.

The major limitations of the seat test procedure (performed) seem to be the disregard of the seat geometry, the restriction to low velocity and the focus on AIS 1 injuries. The motivation for a test with these limitations is the fact that head rests of car seats have a low efficiency (Nygren 1984, Brault et al. 1998) and that high velocity rear impacts and AIS2+ injuries are rare (Otte et al., 1997). The proposed sled test procedure seems to evaluate the risk of neck injury and the level of protection in an elementary way. That is, the test is able to discriminate between cars (seats) with rather different disability rankings. In order to evaluate a seat more precisely, taking the seat geometry into account, a dummy with more human like properties regarding spinal motion is needed. Such a dummy is under development in Sweden and will be presented later (Davidsson et al., 1998).

The use of a dummy representing an average female instead of an average male would be more appropriate since females are at higher risk (Krafft et al., 1996). In this study, the 5th percentile female dummy was elevated with a cushion in order to simulate a light (compared to an average) female with an average seating height. As a result, the NIC values were slightly higher. However, no *more* information was gained. It appears, on the basis of this limited dummy weight study, that a seat that accelerates a dummy representing an average male in a gentle way (low NIC values), regardless of the acceleration profile, will accelerate a 50th percentile female dummy in a similar manner.

CONCLUSION

The proposed seat test procedure evaluates the risk of neck injury and level of protection in typical low speed rear impacts. It includes two different acceleration pulses and uses the NIC as the main injury risk indicator. To conclude the findings of this study:

- The proposed sled test procedure with the HIII dummy appears to be relevant for an elementary evaluation of car seats regarding the risk of neck injury in low velocity rear-end impacts.
- Seats (seat backs) with low yielding limit are tolerant to different rear impact crash pulses and have low NIC50 values.
- A gentle neck acceleration, until maximal neck retraction is passed (posture b in Figure 1), could prevent neck injuries with a risk of permanent disability from occurring, as the NIC50 value would be below the tolerance level.

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THE WHIPS SEAT - A CAR SEAT FOR IMPROVED PROTECTION AGAINST NECK INJURIES IN REAR END IMPACTS

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ABSTRACT

Neck injuries resulting from rear end car impacts have attracted increasing attention in recent years. Although usually not life-threatening these injuries can have long-term consequences. The exact mechanism of injury has not yet been established. Several probable mechanisms occurring at different phases during the crash sequence have been suggested by researchers.

Biomechanical guidelines and test methods are presented, being part of the results of Volvo's Whiplash Protection Study (WHIPS). The biomechanical guidelines are based on an extensive review of accident experience and biomechanical research aimed at reducing the risk of neck injuries in rear end impacts.

A new seat concept, the WHIPS seat, developed using these guidelines and requirements, is explained in detail. The WHIPS seat comprises new recliners as well as a modified backrest and head restraint. The WHIPS recliner is designed to give a controlled rearward motion of the backrest in a rear end impact; thereby improving the closeness to the occupant's head and back, absorbing energy and reducing the occupant's forward rebound.

Test results are summarized, and, seen in relation to the suggested engineering guidelines, show a considerable potential for improved neck injury protection in rear end impacts.

INTRODUCTION

Neck injuries, often called whiplash injuries or whiplash associated disorders (WAD, Spitzer et al. 1995) and classified as AIS 1 (AAAM, 1990) are not life-threatening, but nevertheless are the most important injury category with regard to long-term consequences (Nygren 1984). Statistics from several countries have reported an increase in the occurrence of neck injuries during the last decades. (Ono et al. 1993, van Kampen 1993, von Koch et al. 1994 and Morris et al. 1996). Due to their long term consequences, these injuries are very costly for society (v Koch et al. 1994). Consequently, there is much to gain in terms of avoidance of human suffering and costs for society by reducing the occurrence of AIS 1 neck injuries.

At Volvo, a study has been performed, with the aim of reducing the risk of neck injuries in rear end impacts. The working name for the study was Whiplash Protection Study, with the acronym WHIPS.

WHIPS combines experiences from accident research and computer modeling with existing biomechanical knowledge, summarized into three biomechanical guidelines, see Figure 1. In order to be able to evaluate design concepts, the biomechanical guidelines are broken down into engineering requirements and test methods.

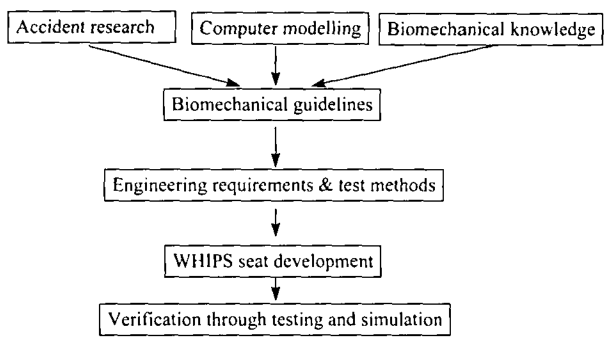

Figure 1. Volvo's Whiplash Protection Study (WHIPS)

The Volvo Whiplash Protection Study has previously been described in detail by Lundell et al. (1998).

This paper focuses on the seat design and test performances of the WHIPS seat. As an introduction, the background for the requirements is briefly described, comprising mainly accident research and the biomechanical guidelines.

The WHIPS seat will come into production in the new S80 Volvo model which is introduced in 1998.

ACCIDENT RESEARCH

AIS 1 neck injuries (also called whiplash injuries) are reported in all crash configurations (Morris et al. 1996 and Jakobsson, 1997). However, the risk of sustaining a neck injury is higher in rear end impacts as compared to other crash types (Morris et al. 1996). Volvo accident data indicates a neck injury risk for rear end impacts which is approximately double the rate for frontal or side impacts (Lundell et al. 1998).

The frequency of different bodily injuries in rear end impacts is shown in Figure 2. The graph is based on a subset of 605 belted drivers, in Volvo 700 and 900 models between 1985 and 1995 (Volvo Accident Data Base, ref. Lundell et al. 1998).

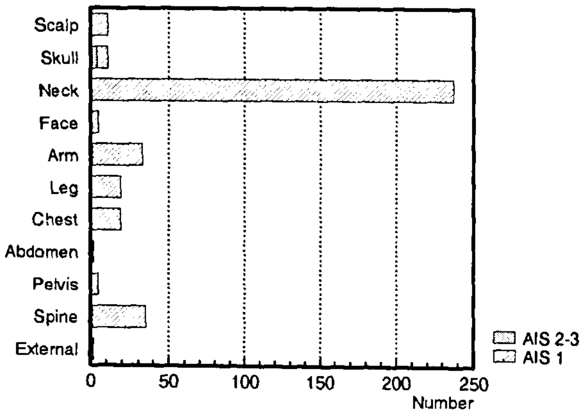

Figure 2. Injury distribution for rear end impacts.

As can be seen in Figure 2, AIS 1 neck injuries are by far the most common injury type in rear end impacts. Nygren (1984) has reported similar findings.

Neck injuries are reported at all impact speeds (Jakobsson 1997 and Otte et al. 1997). From accident research as well as tests with volunteers, it is shown that people sustain neck injuries frequently even in impacts with very low severity (Olsson et al. 1990, Morris et al. 1996, Siegmund et al. 1997). An example of this was presented in Lundell et al. (1998), as shown in Figure 3. The graph is based on a subset of 1467 belted drivers in Volvo cars involved in a rear end impact.

In Figure 3, the injury risk is shown to be almost constant irrespective of the degree of vehicle deformation. Severity measures based on deformation depth are obviously not good predictors of neck injury risks. Other factors, such as whether stiff vehicle structures have been involved or not, have shown to be more related to neck injuries in some studies (Olsson et al. 1990). Figure 3 also tells that in order to significantly help reduce the number of AIS 1 neck injuries in rear end impacts, minor and moderate crash severity must be the main focus since they account for the majority of the incidences.

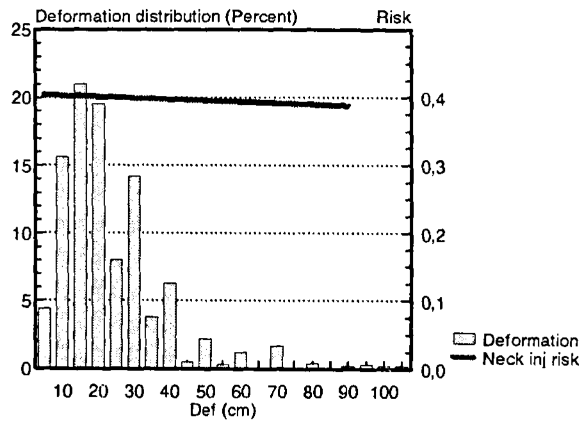

Figure 3. Vehicle Deformation Distribution and Neck Injury Risk vs. Vehicle Deformation.

Knowledge of the individual differences are important when analysing accident data as well as designing protection systems. Women are more likely to sustain a neck injury in the event of a rear end impact (Lövsund et al. 1988, Spitzer et al. 1995, Krafft et al. 1996, Morris et al. 1996, Minton et al. 1997, Otte et al. 1997, Lundell et al. 1998). There is also an increase of neck injury risk for taller occupants (Lundell et al. 1998). However, this becomes only clear when considering the occupants by gender, since the height distribution for men versus women differs and these two factors interfere.

Volvo accident data shows that medium height women are at the same level of risk as tall men (Lundell et al. 1998). This indicates that the height of the head restraint is not the only issue related to the reduction of neck injuries. Although head restraints are important, the height of the head restraint is, however, not a guarantee that the occupant will not be injured. This is also supported by volunteer tests (Brault et al. 1998).

Another factor influencing the risk of neck injury in rear end impacts is seating position in the car. Volvo accident statistics report a significantly higher risk of the driver sustaining a neck injury than the passengers (Lundell et al. 1998). Lundell et al. hypothesized that the differences between the driver and front seat passenger could be mainly due to different seating postures. Drivers are probably more prone to bend forward and away from the seat backrest and head restraint than passengers, who are more relaxed and probably more likely to rest their head against the head restraint. The relationship between increased distance to the head restraint and risk of neck injury has been shown, both in accident studies (Olsson et al. 1990, Jakobsson et al. 1994) as well as in studies based on tests with volunteers (Deutscher 1996). Also, several studies indicate that the front seat occupants are at a higher risk than rear seat occupants (States et al. 1972, Carlsson et al. 1985, Lövsund et al. 1988). One reason for this could be a more rigid, uniform and less elastic design of the rear seats than the front seats.

Accident studies have found that lumbar spine injuries occur together with cervical spine injuries (Minton et al. 1997). The exact relationship is not stated, but it stresses the importance of regarding the whiplash problem as an issue concerning the whole spine, and thus neck injury protection systems must include the support of the whole spine.

There are some studies indicating that the seat belt system increases the risk of neck injury (Spitzer et al. 1995, Morris et al. 1996, v. Koch et al. 1995, Krafft et al. 1996). This may be so, in some cases, but rather than discussing what to do about the seat belt system in a rear end impact, the objective should be to design a system that will help reduce the occupant's rebound into the seat belt.

The WHIPS study is based mainly on experience from accident research. More than ten years of concentrated effort by Volvo, on the study of whiplash, has shown that it is important to consider the whole spine of the occupant and, accordingly, the whole seat when addressing whiplash injury resulting from rear end impact. Minor and moderate severity crashes should also be focused on in order to achieve a true injury reduction in real world accidents.

The individual differences between occupants (gender, height and other), the seating position and the variety of seating postures must also be considered in order to get a true injury reduction in real world accidents. All these areas were considered when defining the design guidelines, as presented below, and when the guidelines were broken down into requirements.

BIOMECHANICS AND GUIDELINES

The exact injury mechanism has not yet been established. Several mechanisms have been suggested by different researchers. In order to be able to know what engineering efforts to make, the accident experience and the results of all realistic injury mechanism research need to be condensed. An effort to do this resulted in the following three guidelines. The guidelines summarize a holistic approach to the whiplash problem, aiming to address all existing theories and cover all possible situations.

The three guidelines are:

- <u>reduce occupant acceleration</u>
- <u>minimize relative movements between adjacent vertebrae and in the occipital joint, i.e. the curvature of the spine shall change as little as possible during the impact</u>
- <u>minimize the forward rebound into the seat belt</u>

The first guideline, aiming to reduce occupant acceleration, does not have a direct connection to experiences from accident data, nor any traditional injury mechanism for neck injuries. The rationale for this guideline is basic crash dynamic knowledge, and the fact that if zero acceleration is reached no injury would be suffered. Volunteer tests have also shown that below certain occupant accelerations the likelihood of sustaining an injury is expected to be minor for most healthy persons. The fact that the proposed Neck Injury Criterion (NIC), is based on acceleration, supports the importance of monitoring occupant acceleration (Boström et al. 1996 and 1997).

Relative motion of the spine as a cause for whiplash injuries has been suggested by several researchers (Aldman 1986, Svensson et al. 1993b, Jakobsson et al. 1994, Boström et al. 1996, 1997, Ono et al. 1997a, 1997b). The knowledge gained from space technology, and also from the performance of rearward facing child seats in a frontal impact (Aldman 1964), tells us that the ultimate aim is to keep the spine as evenly supported as possible. If the spine is completely intact, no injuries are likely to occur.

The third guideline aims at reducing the rebound after rear end impact, in order to minimize the interaction with the seat belt. Seat belt interaction has been suggested as injury-producing, as already mentioned. The exact mechanism of these findings is not known. That discussion, however, is not necessary for rear end impact cases if the goal is to eliminate seat belt interaction in rear end impact.

We believe that if these guidelines are followed, the seat design will reduce the risk of neck injuries in rear end impacts. Since they are not conventional biomechanical criteria, described by biomechanical mechanisms, it is impossible, at this stage, to determine certain thresholds. The ultimate goal would be to reach zero loading as the output of the guidelines. And every reduction can be regarded as a step in the right direction. In order to be sure that improvements will also reduce the injury risk, all three guidelines should be addressed, since they are related, to some extent, to different theories.

ENGINEERING REQUIREMENTS

Having formulated the guidelines described above, the next task was to design a seat concept along these guidelines. In order to be useful in practice, the guidelines had to be further refined to a level which could easily be verified in testing.

Unfortunately, existing standard anthropomorphic test dummies have not proved to be applicable for studying human like spine movements in rear end impact testing (Scott et al. 1993, Szabo et al. 1994). The Hybrid III dummy family can, however, be used for evaluating the response of the seat in a rear end impact, but need to be complemented with other test methods in order to cover all the biomechanical guidelines. A more biofidelic neck, the RID-neck, to be used with the Hybrid III dummy for low speed rear end impact testing, was developed by Svensson et al. (1992), but the performance of the neck is restricted by the rigid thoracic spine of the HIII dummy (Lövsund and Svensson 1996). In volunteer testing, it has been found that an essential part of neck kinematics is due to the torso push-up motion exerting compression forces in the cervical spine, and the angling of the T1 and the lower cervical vertebrae (Mc Connell et al. 1993, Siegmund et al. 1997, Ono et al. 1997a, 1997b). Therefore, in order to obtain correct responses, especially with regard to the neck behavior, a test dummy with an anthropomorphic spine, enabling study of the effect of torso push-up motion, is required (Lövsund and Svensson 1996). A dummy for this purpose, with a segmented spine with humanlike curvature, is currently being developed as a Swedish joint venture and will be presented in the near future (Davidsson et al. 1998, Linder et al. 1998).

A mathematical occupant model with a segmented spine simulating human-like motion was developed (Jernstöm et al. 1993 and Jakobsson et al. 1994) and used as a tool for evaluating the effect of seat design (Lundell et al. 1998).

The guidelines were broken down into the following engineering requirements:

- Reduce occupant acceleration
  - ◊ The guideline can be verified by measuring the dummy acceleration in sled tests. The positions in the dummy most relevant to evaluate are in the thoracic and pelvic regions, since they are closest to the area of seat interaction and not affected much by the dummy design (e.g. standard chest or pelvis accelerometer or accelerometer at the lower neck).
- Minimize relative movements between adjacent vertebrae. For this guideline, there are no dummies existing today that would give an appropriate response in a crash test. Therefore, the WHIPS seat was developed mainly by using a mathematical model with the segmented spine together with sub-system tests, as well as geometry requirements combined with engineering judgement in order to address different occupant sizes and postures.
  - ◊ The seat backrest and head restraint should geometrically support the curvature of the back and neck as precisely as possible, i.e. by positioning them as close as possible to the occupant. This applies in particular to the head restraint. Thus a requirement for closeness was included, together with a requirement for the height of the head restraint.
  - ◊ No local hard or soft structure in the seat backrest should force the spine into localized bending. An impactor subsystem test, to determine the local distribution of force-deflection characteristics throughout the seat backrest as well as the head restraint, was used to simulate a human spine's interaction with the seat. At this stage, the goal was to make the force vs. deflection characteristics of the seat backrest and head restraint as uniform as possible throughout their combined height. If the seat follows the shape of the occupant well (in accordance with the above requirement), uniform characteristics will tend to restrain the body evenly and thus exert minimal relative movements to the head and spine.
- Minimize the forward rebound into the seat belt.
  - ◊ This guideline can be satisfied by having good energy absorption of the seat backrest during an impact, i.e. a high hysteresis. In other words, designing the seat towards lower elastic energy build-up during impact will reduce the forward rebound into the belt. A quasi-static sub-system test of the backrest was added during the initial engineering phase. In a later stage, the effect of the rebound was also evaluated in sled tests, using Hybrid III adult dummies.

The above are the main requirements. Additional requirements were also used in order to map the behaviour of the seat and to estimate the performance of a human in the event of rear end impact.

Since the engineering requirements are broken down from guidelines describing a requested behaviour, rather than defined injury mechanisms, it is not possible to establish biomechanical thresholds for the different requirements. The goal is the largest possible reduction for all the requirements. A very important rule is never to increase any response related to the biomechanical guidelines, since it may then follow that reductions in the other responses will be countered and no real positive effect achieved.

The focus has been to reduce the risk of neck injuries in low to medium severity rear end impacts. These impacts are at speeds well below those of existing regulatory rear end impact testing. This means typically in the interval of 15 - 30 km/h (approx. 10 - 20 mph), car to car, impact speed.

THE WHIPS SEAT SYSTEM

In the Whiplash Protection Study, the above requirements were used to develop a new seat concept. The new concept is based on a production Volvo seat. The WHIPS system in the seat consists of two new recliners, together with a modified backrest and head restraint. These are further described below.

The WHIPS recliner is designed to give a controlled rearward motion of the backrest in a rear end impact. For this purpose, the production recliner was modified by adding the WHIPS mechanism. In a rear end impact of sufficient severity the WHIPS mechanism is activated and then controls the motion of the backrest in relation to the seat base. This motion may be divided in two phases, as shown schematically in Figure 4.

The two phases are actually, in most cases, overlapping to some extent. The degree of overlap depends upon several parameters such as occupant weight and posture, and also impact severity.

A more detailed description of the two phases follows below.

In a rear end impact, the seat is accelerated forward with the car. Due to the inertia of the occupant, the back of the occupant is then pressed into the seat. When the forces from the occupant acting upon the seat backrest exceed a certain level, the WHIPS system will be activated. Hence no external sensor system is needed to activate the WHIPS system.

The purpose of the first phase is: 1) to let the occupant sink into the seat, thereby reducing the distance between the head and the head restraint, 2) to create an initial rearward motion of the backrest which does not move the head restraint away from the head, and 3) to keep occupant acceleration levels low, by letting the backrest move rearwards in a controlled way.

This is accomplished by the first phase being a rearward motion of the seat backrest, the nature of this motion being essentially translational, i.e. without rotation. However, depending upon the pre-impact posture of the occupant, the motion characteristics of the backrest are to some extent adaptable and adjust to the occupant's position relative to the backrest. For example, if the occupant is leaning forward before impact, this may give an initial tilt-forward motion of the backrest.

The purpose of the second phase is to limit occupant acceleration to a low level. This is accomplished by a rearward reclining of the backrest, while absorbing energy in a controlled and gentle way.

When the backrest has has absorbed the occupant's energy, and thus reclined to its rearmost position, a rebound takes place. The rebound is, however, significantly reduced, compared to a conventional seat, because of the plastic energy absorption in the WHIPS recliner.

The reclining angle of the second phase is limited to approximately 15 degrees. When the maximum angle has been reached, the recliner assumes the stiffness characteristics of the existing production recliner, and the seat will perform as a seat without a WHIPS system.

The WHIPS recliner is designed to be activated, and thus give protection, at low and moderate impact speeds primarily, which is when many whiplash injuries occur. The lower activation threshold depends on several parameters. The recliner is designed to operate primarily in the range of velocity change of approximately 10 - 20

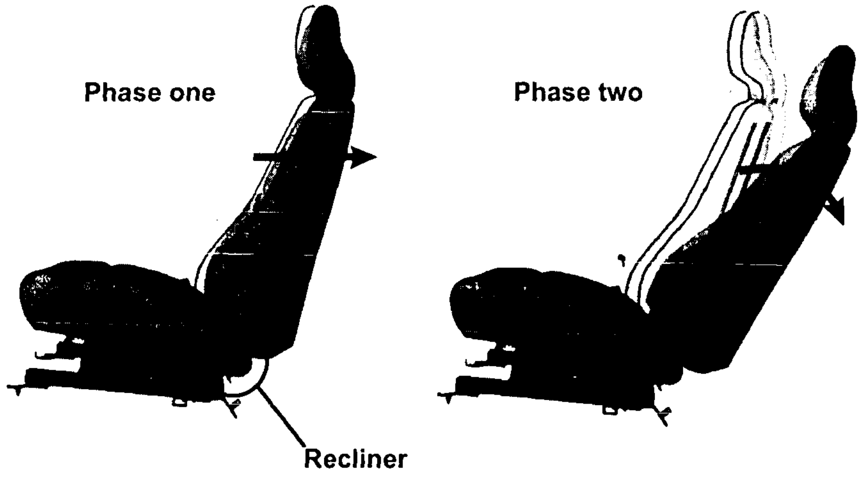

Figure 4. The WHIPS seat motion.

km/h. It will, however, give protection at higher velocities also.

Recliner Design - The WHIPS Function

The recliner is the part of the seat by which the backrest (squab) is attached to the seat base. The basic function of a recliner is to facilitate adjusting the reclining angle of the backrest. In Volvo seats, there are two recliners to each seat, one on each side. In the WHIPS recliner, an impact activated function is added.

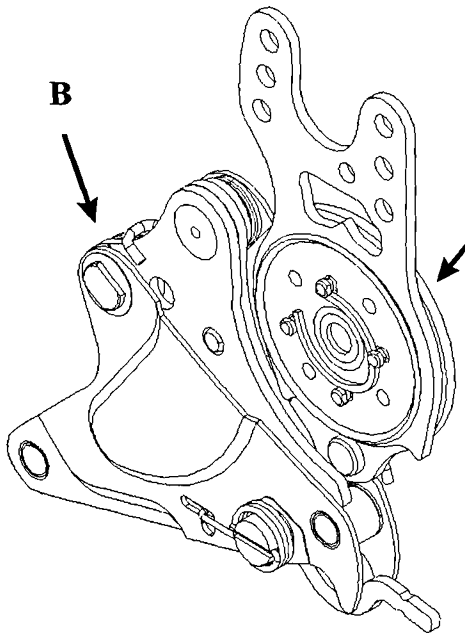

Figure 5. The WHIPS recliner.

The WHIPS recliner unit consists of two main parts (Figure 5): the mechanism for adjusting the static reclining angle (A) and the WHIPS system (B). These two parts are combined to form the complete WHIPS recliner unit.

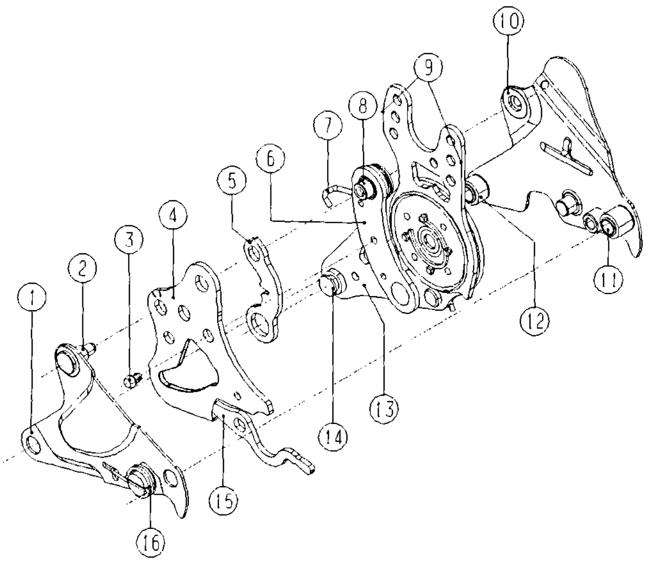

Figure 6. The WHIPS recliner, exploded view.

The details of the recliner are shown in Figure 6. The following elements are shown:

- Forward link arm; deformation element for energy absorption (5)
- Rear link arm (6)
- Return spring (7)
- Indicator (3)
- Pivot shafts for WHIPS motion (2), (8)
- Guide pin for WHIPS motion (14)
- Folding bracket (4), with WHIPS motion control window
- Side plates, outer (1) and inner (10), with attachment points to seat base (11) and (12)
- Conventional recliner mechanism (9) and bracket (13); the backrest frame is attached at (9)
- Latch (15) and spring (16) for quick folding of backrest

The complete recliner assembly is attached to the seat base by the side plates (1) and (10), at points (11) and (12). The folding bracket (4) is fixed to the side plates by the pivot point (2) and by the latch (15). The recliner mechanism (9) and bracket (13) are connected to the recliner base by the two links (5) and (6). The backrest is welded to the recliner at the upper attachment points (9).

The WHIPS recliner is secured against activation during normal use by the spring (7), by the plastic indicator (3), by a carefully chosen angle between the two links(5) and (6), and the shape of the window for the guide pin (14). When the forces from the occupant, acting upon the seat backrest in a rear end impact, exceed a certain level determined by the above design

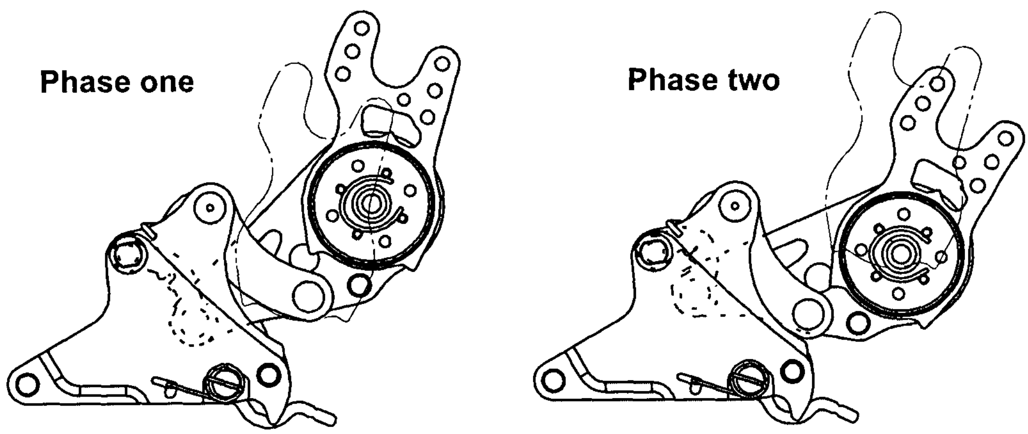

Figure 7. WHIPS recliner schematic motion.

elements, the WHIPS system is activated.

The WHIPS motion of the recliner is shown schematically in Figure 7.

During the first phase of the WHIPS motion, shown to the left in Figure 7, the upper part of the recliner moves rearwards. The motion is controlled by the two links (5) and (6), which rotate around the two pivots (2) and (8). The rear link is slightly longer than the forward link. This has the effect that the recliner, at the same time as it translates rearwards, also rotates upwards. As the backrest is attached to the recliner, this motion is also transferred to the backrest. However, because of elasticity, this rotational movement of the backrest is reduced and the resulting motion is essentially a translational rearwards motion. The exact motion depends upon several factors such as crash severity, occupant weight and occupant posture at impact.

During the second phase of the WHIPS motion, the forward WHIPS arm (5) is deformed, as shown to the right in Figure 7. The effect is that the recliner, and thus the backrest, reclines rearwards. This occurs typically when the recliner has completed the whole rearward motion of the first phase, but may also start before, so that the two phases overlap.

The force - deformation characteristics of the forward link are progressive. The shape of the link gives two distinct force levels; initially lower, higher towards the end of the deformation. The purpose to this is to accommodate the wide energy span of rear end impacts for which the recliner is designed to operate, considering both the variation in velocity change and in occupant size and weight.

As already mentioned, the two phases are actually, in most cases, overlapping to some extent. In order to control the mix of the two phases a guide pin (14) on the moving recliner bracket (9) moves in a window on the bracket (4). The window may be seen in Figure 6.

Indication and Service

When the recliner is activated in an impact, the indicator (3) is sheared and comes loose, giving a visual indication that the WHIPS system has been activated and needs service. Inspection of the indicator will be a normal service routine. Inspection will also take place when the vehicle goes to a workshop after a rear end impact. By folding the backrest forwards, as further explained below, the recliner may easily be inspected.

If the recliner has been activated in an accident, different service routines will be applied, depending upon the severity of the accident. In an impact of less severity, there will be no permanent deformation of the recliner, and only the indicator (3), the forward link (5) and the spring (7) need to be replaced. This solution will reduce service costs. In more severe impacts, which reach the recliner's upper working limit, the recliner and backrest can be replaced if the seat base is still intact.

The WHIPS recliner is equipped with a function for quickly folding the backrest forwards. By releasing the latch (15), the whole recliner assembly except the side plates, together with the backrest may be folded forwards, without using the normal recliner adjustment. This solution is primarily designed to facilitate the transport of long cargo on top of a forward folded passenger seat. With the introduction of the WHIPS recliner, this function is also included on the driver's seat, and will be used for inspection and service of the WHIPS recliner.

Backrest and Head Restraint

The backrest was locally modified to give a more even force distribution along the spine of the occupant, according to the biomechanical guidelines and engineering requirements. A sub-system test method for evenness was developed (Lundell et al. 1998). Using this method, it was found that increasing the support of the backrest foam would give more uniform characteristics. This was done by modifying the springs supporting the foam. The purpose of these springs is to give good comfort in the backrest and insulation against vibration. The springs were modified so that their characteristics during normal ride are unaffected, but for loads reached in a rear end impact their stroke is limited.

The head restraint is based on existing Volvo head restraints, having good height and being fixed in position (IIHS 1995, 1997). It was modified to be positioned somewhat closer to the head, and also somewhat higher than previously.

Other Aspects of the WHIPS Seat

In addition to what has been described above, the seat has the same strong structure as Volvo production seats. These seats are several times stronger than required by the existing legal requirements for seat backrest strength. This is accomplished partly by having recliners at both seat sides. The new recliner matches the strength of the existing backrest, meaning that the high speed crash performance has not been compromised by the new design. Thus, there is no increased risk in rear impacts, neither for the occupant of a front seat nor for adult or child occupants of a rear seat. This also applies to frontal impacts, when the seat backrest may be loaded from the rear, e.g. by luggage on the rear seat. The modified seat backrest is also equipped with the same side impact protection system (SIPS) as the standard seat.

Manufacture

The WHIPS recliner is assembled by the system supplier (Autoliv Sverige AB). The recliners are welded to the backrest by the backrest manufacturer (Autoliv Mekan AB), and the complete backrest is assembled to the seat by the seat manufacturer.

Each recliner is given its own individual number for the tracking system. The parts of the recliner are linked batch by batch to the individual number.

TESTING

During the development of the WHIPS seat, both sub-system testing and sled testing was used. Mathematical simulation was also used as an important tool.

In the sled tests, presented below, the 50th percentile Hybrid III dummy was used. One reason for using the 50th percentile dummy was that, apart from it representing a mid-size male it may also, to some extent, be assumed to represent a tall female. Tall females were shown in the accident studies to be at higher risk. Tests were also run with the 5th percentile female and the 95th percentile male dummies.

Sled Test Results

Several parameters were studied in the tests. As explained above, low acceleration was chosen as a major criterion. The lower neck horizontal acceleration was chosen to be displayed here.

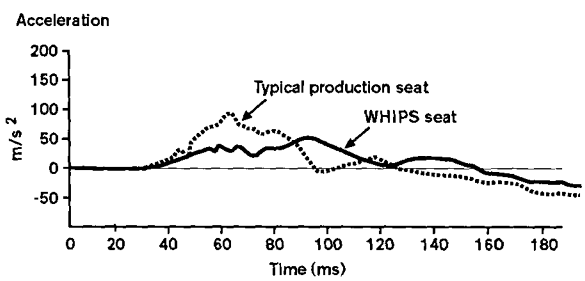

Figure 8. Sled test results, lower neck horizontal acceleration; Δv 10 km/h.

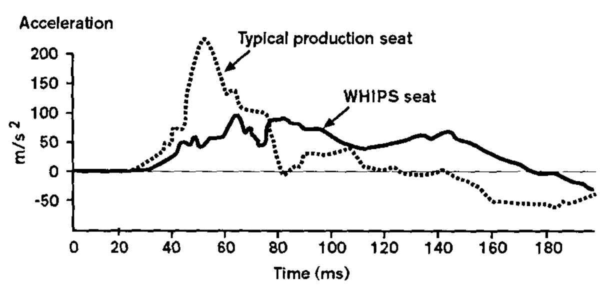

Figure 9. Sled test results, lower neck horizontal acceleration; Δv 20 km/h.

Sled test results are shown for a Δv of 10 km/h in Figure 8, and for a Δv of 20 km/h in Figure 9. The results show that the acceleration peak value decreases by approximately 40% - 60% as compared to a typical production seat, under the same test conditions. The sled testing also confirmed that forward rebound towards the end of the impact is reduced.

DISCUSSION

The procedure for the Whiplash Protection Study follow the whole chain; from the accident research and biomechanical knowledge; the interpretation of this knowledge condensed into guidelines and requirements; and finally seat development, validated by testing. We consider that this method represents a unique and holistic approach, which gives a considerable strength to this study.

The study has focused on the whole seat, and not only the head restraint. This is important, since the motion of the whole spine effects the neck, and also for the reason that the exact injury mechanism is not known.

When developing the WHIPS seat, a very important rule has been to address all aspects of the biomechanical guidelines. Increased responses of any kind should be avoided, since reductions in other responses may be countered and no real positive effect achieved.

The sled test results presented should be regarded as an indication of how much reduction may be achieved. Thresholds can not be determined due to the nature of the requirements. There are only a few test results presented in this study. More measurements, different dummy sizes and seating postures were included in the holistic approach, combined with engineering evaluation, sub system testing, mathematical modelling and geometrical requirements, in order to know that injury reduction could be achieved. The results are consistent in giving reductions in line with the guideline parameters, thus leading to a reduced risk of injury.

CONCLUSIONS

In this study the WHIPS seat for improved whiplash protection was developed. The new seat is based on a production seat, and comprises two new recliners, together with a modified backrest and head restraint.

The development of the new seat was part of Volvo's Whiplash Protection Study (WHIPS).

The seat backrest was locally modified to give a more even force distribution along the spine of the occupant. The head restraint was modified to be positioned somewhat closer to the head and also somewhat higher.

The new seat recliner was designed to be activated in case of a rear end impact, and to operate primarily in low to moderate impact speeds, where many whiplash injuries occur. The WHIPS recliner is activated by the forces from the occupant, without any external sensor system. The seat backrest will move, together with the occupant, in two phases. Phase one is essentially a translational motion, improving the closeness and support of the occupant's back and head. The second phase gives a rearward reclining of the backrest, mainly to reduce acceleration and forward rebound by plastic deformation of a metal element in the recliner.

Test results presented in this paper show that the WHIPS seat reduces peak lower neck horizontal accelerations approximately by half. Further, the WHIPS seat reduces forward rebound. The WHIPS seat also gives improved closeness as well as improved distributed load support of the back and head.

All results, including sub system testing, mathematical modelling, sled testing as well as geometrical parameters show that the WHIPS seat will have a considerable potential for offering increased protection against neck injuries in rear end impacts.

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LOWER LEG INJURIES CAUSED BY DYNAMIC AXIAL LOADING AND MUSCLE TESTING

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ABSTRACT

The effect of muscular tension on lower leg injuries was investigated in this study. Rigid body simulation was used to examine the kinematics of an occupant making a braking during a frontal crash. Muscular tension was reproduced by constant spring elements defined in the lower leg. Simulation results showed that tibial axial load was increased by the muscular tension. A series of cadaver tests was conducted to study the effect of muscular tension in detail. Dynamic axial loading was applied to human specimens with a pendulum hitting at approximately 3 m/s. The test condition represented loading to a driver's right foot stepping on a brake pedal and struck by a toe board. The metatarsal heads were placed on the brake pedal and an initial tensile force was applied on the Achilles tendon. Sixteen tests were performed on eight pairs of cadeveric lower legs. There was a significant increase in the tibial axial load in comparison with the impact load because of preloading by muscular tension. Tibial pylon fracture, which is one of the severest forms of injury of the lower leg, was frequently observed in these tests. Although the fracture load level in the tibia was almost the same as that reported in previous studies, this study shows that less external force is required to cause tibial pylon fractures with muscular tension.

INTRODUCTION

The proper use of restraint systems such as seat belts and airbags can reduce the risk of upper body injuries in frontal crashes. Although misuse of restraint system is still observed in the field and airbag aggressiveness is a problem, the consequences must be recognized and improvements need to made. As for lower leg injuries, there is no effective countermeasure which has been proven to reduce injury risk. This is due to a lack of information on the injury mechanism. What happens exactly to the lower legs during a crash and the relationship between loading condition and injury mode are not well understood.

The first approach was to review statistical data for lower leg injuries. In an analysis of NASS data from 1979-1986, Morgan (1991) reported that lower leg injury amounted to 25% of all body regions for non-belted occupants and almost the same percentage for belted occupants. The analysis also showed that ankle and foot injuries accounted for a large proportion of lower leg AIS2+ injuries. Crandall (1994) examined 1990-1992 NASS files and reported that upper and lower extrimity injuries are still frequently seen in drivers protected by airbags while head and neck injuries decreases in comparison with cases without the airbag. Otte (1992) studied the types of ankle and foot injuries based on data from 140 belted drivers between 1985-1990. The research was carried out by the traffic accident research unit of Hannover. The ankle joint was the most commonly injured area with a rate of 37.1% followed by the metatarsal bone with a rate of 36.1%. As far as brake pedals are concerned, Morgan (1991) also reported that 57% of drivers' ankles were injured while the foot was on the pedal based on his analysis of NASS data from 1979-1986. Thomas (1995) examined the CCIS database and noted that injury to the driver's right leg is increased by a brake pedal when there is 200 mm of footwell intrusion. Increased injury risk due to pedal interaction with the leg was pointed out in those studies. The brake pedal is, however, not the only cause of lower leg injury of course. External forces on the foot can be caused not only by pedal interaction but also by inertia or intrusion.

Another approach is to determine threshold of each injury by means of impact biomechanics. Currently, external forces due to inertia or intrusion are considered to be the major cause of ankle and foot injuries. Begeman investigated the impact response of human ankle in dorsiflexion and found 45 deg. to be the injury threshold (1990). He also reported that the threshold of inversion and eversion was 60 deg. (1993). As for tibial injury involving the ankle joint, a number of axial loading tests has been done. Yoganandan (1996) summarized tibial axial loading tests done at Wayne State University, CALSPAN and the Medical College of Wisconsin. He reported that the load for a 50% probability of fracture in the lower leg was estimated to be 6.8 kN. Klopp (1997) loaded fifty lower legs including the midshaft of femur. A linear logistic model revealed that 9.3 kN of contact force to the foot gave a 50% probability of injury. In terms of fracture mode, however, it has not been determined yet what loading condition is likely to cause each fracture mode. A common finding in previous studies was that calcaneal fracture was most likely to occur when the foot was impacted by a pendulum.

From the medical point of view, ankle injury is a most important subject because it is the weakest area in the lower leg and it sometimes results in long-term disability or impairment. Levine (1986) noted that tibial pylon fractures, which involve the ankle joint, require several months of medical treatment and the result tends to be poor. It is rated as one of the severest forms of lower leg injury. Pylon fractures can occur when the distal tibia is pushed very hard and upward by the talus but it has been difficult to reproduce in laboratory tests because calcaneal fracture is more likely to occur under a direct impact. Begeman (1997) conducted a series of dynamic loading tests on lower legs and found pylon fractures were generated at loads between 6 and 9 kN. He saw some pylon fractures when he removed the foot before applying the load and only one pylon fracture was observed with the foot in place. Likewise just one leg sustained a pylon fracture out of fifty specimens studied by Klopp (1977). Thus the injury mechanism causing tibial pylon fractures is not well understood.

In this study, it is hypothesized that muscular force generated in braking can increase the risk of tibial pylon fracture. When a driver's right foot is stepping on the brake pedal, the Achilles tendon pulls on the calcaneus due to muscular contraction of the calf muscles, generating preloading to the tibia. External forces could be applied to the forefoot by the pedal or the toe board coming backward after a frontal crash occurs. As mentioned in the review of analyses of accident data, there is evidence that the driver's right leg is at more risk than the left, due in part to muscular tension, intrusion and pedal interaction. A rigid body simulation using MADYMO was used to determine the kinematics of a driver's legs with muscular tension during a frontal crash. Constant spring elements were used to simulate muscular activity in the right leg. The effect of muscular tension can be examined by comparing the tibal axial load with another model without muscular tension. The simulation results could possibly reveal a mechanism for tibial pylon fracture. Then a series of cadaver tests using human specimens was conducted to confirm the hypothesis and determine the effect of muscular force combined with an external force. Because entrapment of the knee by the lower dashboard can be another factor to increase the compressive force to the tibia, this study is limited to a simple pendulum impact to a tibial/foot specimen fixed to a wall.

RIGID BODY SIMULATION

Simulation Model

Numerical simulations were performed using MADYMO Ver. 5.2. A Hybrid III Dummy Model develped by TNO was used because no humanly model was available and the dummy model would be adequate for an examination of the basic kinematics of a driver with muscular tension. The model is shown in Figure 1. Typical dimensions of a passenger car were used to the vehicular interior, such as a seat, a steering wheel and an instrumental panel. The driver's seat was equipped with a 3-point belt and an air bag system. A brake pedal was placed above the toe board. Friction factors were assigned to the toe board, floor, pedal and seat pan. Three Kelvin elements were introduced to represent the muscle forces in the calf, femur and hip. Braking was simulated by an initial contraction of these Kelvin elements. A force balance between these spring elements and the occupant was maintained to simulate this bracing motion.

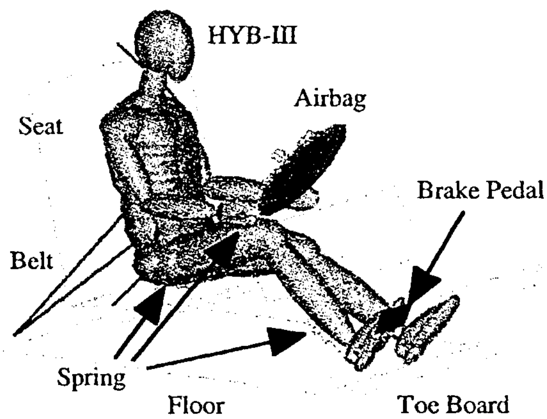


Figure 1. Rigid Body Simulation Model.

A stability analysis was conducted to obtain a quasi-static balance of the muscle forces. In the stability analysis, a linear and very stiff force-displacement curve was defined for each spring element. Then the brake pedal was moved rearwards so that it pushed against the forefoot. The contact force between the pedal and the forefoot constituted the pedal force while the tensile forces in the spring elements were the muscle forces that reacted against the applied pedal force. Figure 2 shows the relationship between the pedal force and the muscle forces from this stability analysis. For a given pedal force in this plot, the necessary force levels can be determined for each of the three muscle springs. An interesting result in this stability analysis was that both the muscle force and the joint moment were the largest at the ankle. It means that the response of the calf muscles is the most important under a set of given conditions. In this simulation, a pedal force of 1.0 kN was assumed. The corresponding forces in the calf, femur and

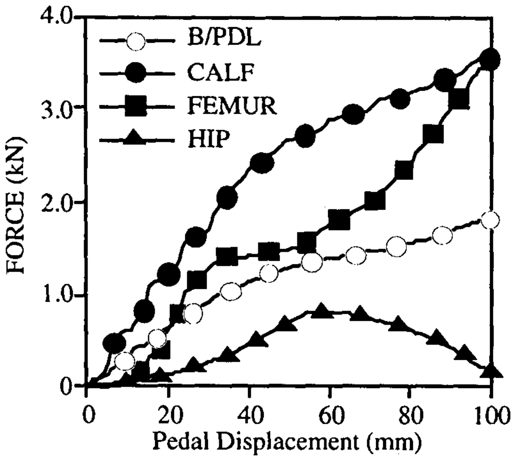


Figure 2. Force Balance of Muscle Springs.

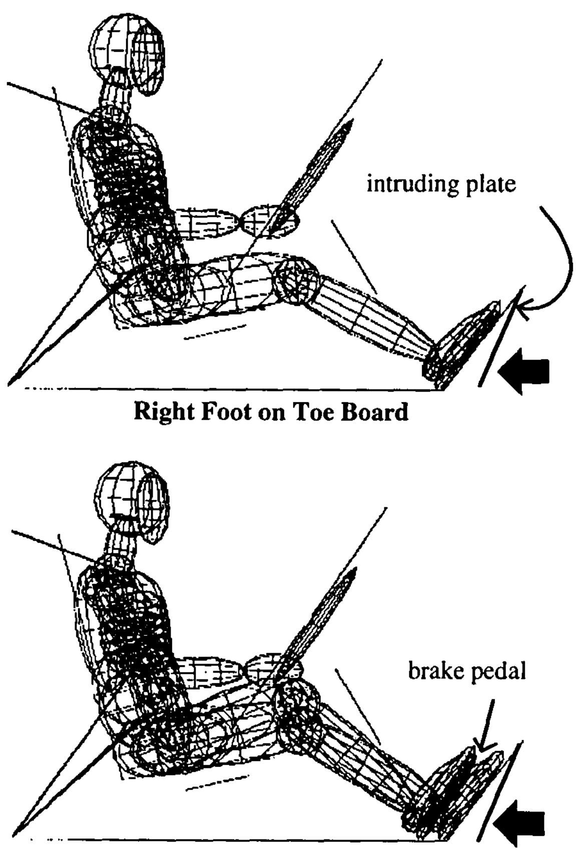


Figure 3. Models with Different Foot Position.

hip muscles were determined as 2.0 kN, 1.3 kN and 0.33 kN respectively, as shown in Figure 2. This condition only represents one possible case. Forces in a real situation can change depending on driving posture and the geometry of the vehicular interior. Thus, no attempt was made to validate this model.

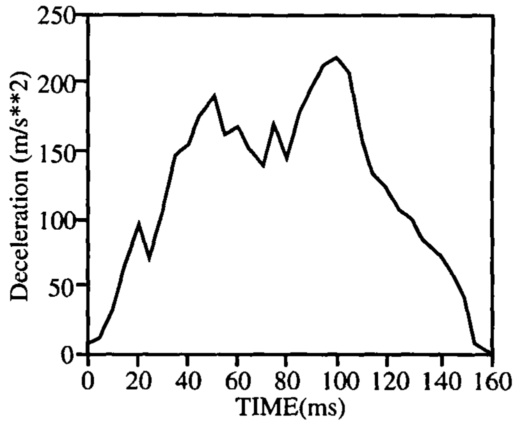


Figure 4. Vehicle Body Deceleration.

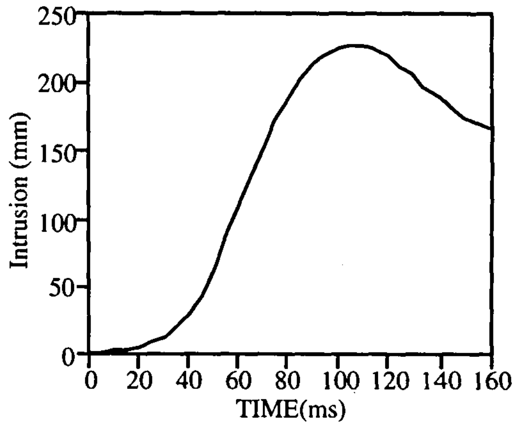


Figure 5. Intrusion of Toe Board.

Figure 3 shows two different models used in dynamic simulations. Both legs of the dummy were placed on the toe board in the first model whereas the right foot was on the brake pedal in the second model. Muscle force was not applied in the first model while the forces specified above were applied to the Kelvin elements in the second model. There is a toe board under the feet and another plate was defined to reproduce the intrusion. A steeper angle was used for this plate because the intrusion is generally larger in the upper area of the footwell. The deceleration due to a frontal crash was given to the dummy as a forward acceleration. Figure 4 shows a typical vehicular deceleration pulse for a car-to-car frontal offset crash test. The intrusion curve, as shown in Figure 5, was obtained from a numerical simulation of an offset deformable barrier crash and given to the movable toe board.The lateral component of deceleration and intrusion were neglected for simplicity. The following conditions were considered.

Case 1: No muscle force, Feet on the toe board.

Case 2: No muscle force, Right foot on the brake pedal. (same as Case 3 but no Kelvin elements)

Case 3: Muscle forces acting, Right foot on the brake pedal.

Simulation Result

Figure 6 shows dummy kinematics from 0 to 110 ms in Cases 1 and 3. Symmetric motion was observed in Case 1 because both dummy legs were placed on the toe board. With the right foot on the brake pedal in Case 3, larger dorsiflexion occurred in the right ankle as the pelvis moves forward due to inertia. Rotation of the right ankle was larger than those of the other leg joints. The contact between the dummy's right foot and the intruding toe board occurred at between 50 and 60 ms after the impact in Case 3. An external force should act on this foot after that time. Because the heel could slide forward on the floor in this simulation, the contact occurred at the heel. The timing of the contact was slightly different with and without muscles because of the difference in the rate of rotation of the right ankle. It could also change with the distance between the pedal and the toe board or with the speed of intrusion. The knees hit the bolster at around 70 ms and the maximum displacement of the pelvis was seen at about 110 ms.

Figure 7 shows the tibial axial force-time histories calculated for the right leg. The effect of braking can be seen by comparing these plots. Cases 2 and 3 have prominent peaks in the right tibial forces whereas there are only two mild peaks in Case 1. The first peak in Case 1 was probably due to the deceleration of the dummy and the second peak was due to both deceleration and the intrusion force. The maximum force occurred at 60 ms in Cases 2 and 3. This corresponds to the time of the contact between the foot and the toe board. Since the only difference between Cases 1 and 2 is the position of the right foot, that position is the major cause of the large force peak in Case 2. The effect of foot position can be also confirmed by comparing with the force curve for the left leg shown in Figure 8. Similar force curves were obtained for the left leg in all these cases. Going back to the forces on of the right leg, the maximum tibial axial force was about 2.0 kN in Case 1 at 85 ms after the impact whereas it reached 3.0 kN at about 60 ms in Case 2. The larger peak force in Case 3 indicates the effect of muscular tension on the tibial axial force. It is quite similar to that of Case 2 but the peak was increased by 1.5 kN to 4.5 kN at 60 ms. This is because of muscular tension due to braking. The additional tibial axial force increases the risk of tibial injury. However, 4.5 kN of tibial force is still smaller than the threshold values proposed in previous studies. A more severe impact may be needed to cause fracture and entrapping of the knee by the lower dashboard could be factors which can increase the tibial axial force. The plot in Figure 8 indicates that the intrusion is the dominant cause of the second force peak in the left leg. Figure 9 shows the contact force-time histories for the right foot due to the intruding toe board in Cases 2 and 3. The external force was produced by the heel contact as mentioned before. The force curves appear similar to those for the tibial axial force except

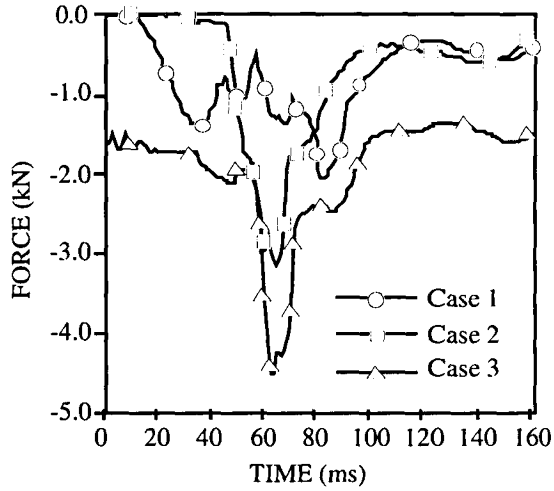


Figure 7. Axial Load on Right Tibia.

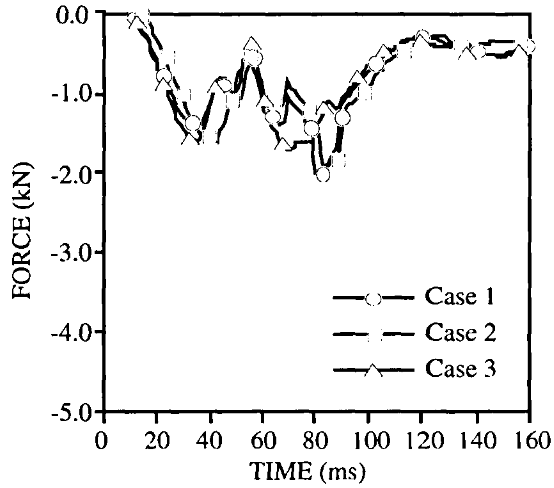


Figure 8. Axial Load on Left Tibia.

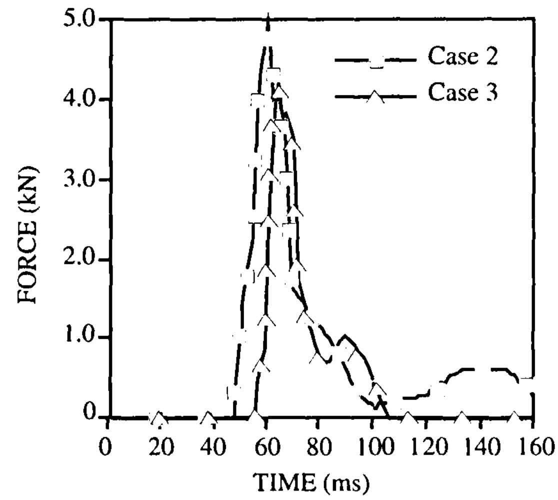
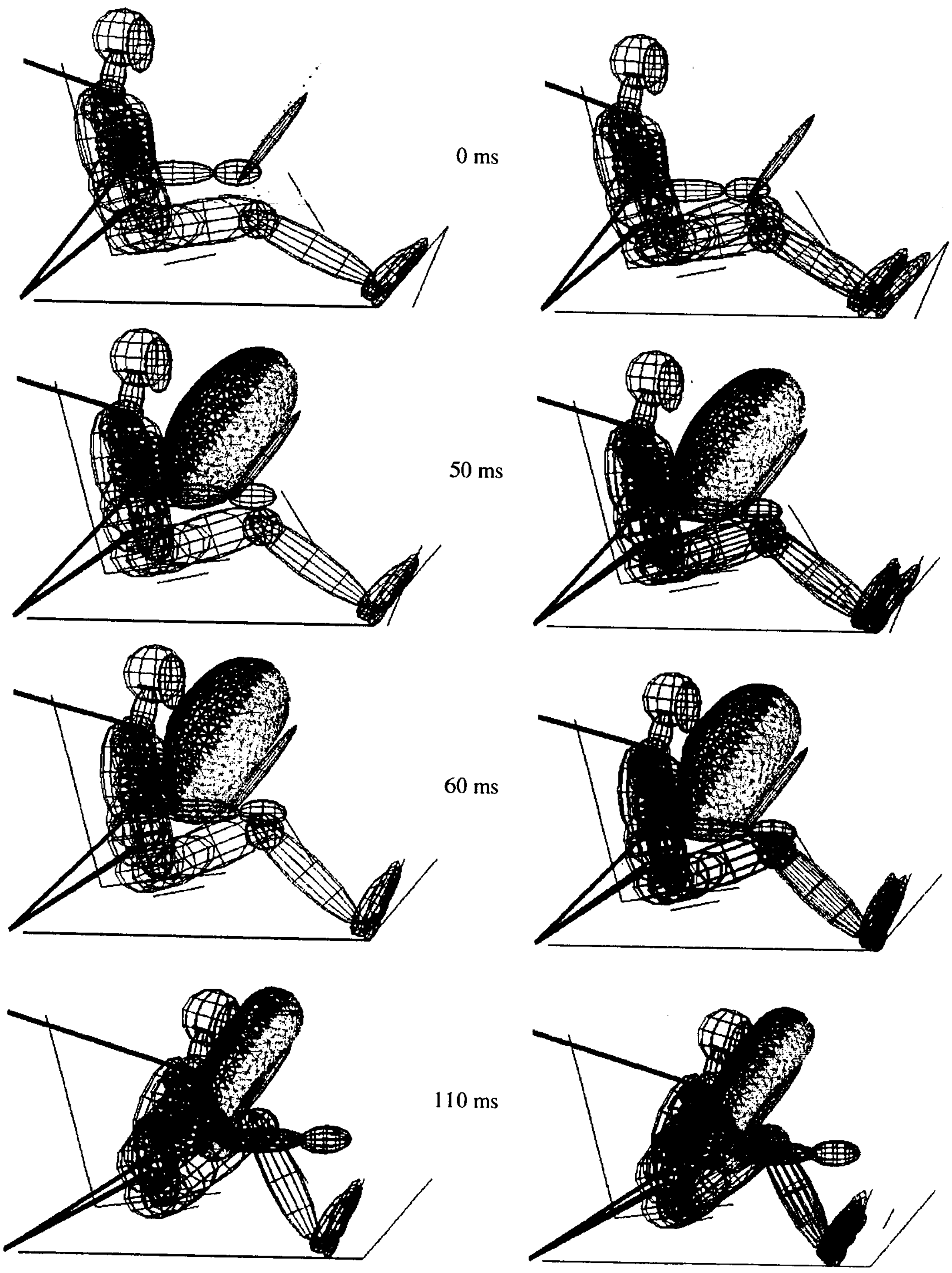


Figure 9. Contact Force on Right Foot.



Case 1: No Muscle Force, Foot on Board

Case 3: With Muscle Force, Foot on Pedal

Figure 6. Dummy Motion in Time Frames: With and Without Muscle/Intrusion.

for preloading. The large force peak in Case 2 means that the external force due to intrusion was not influenced much by the muscular tension.

Simulation results suggest that both muscular tension and external force due to intrusion can increase the axial force in the right tibia whereas the external force also determines the impact severity to the foot. As the driver steps on the brake pedal stronger, the preloading to the tibia increases. If an additional external force works on the foot, the tibia may be compressed more. The intrusion means not only its deformation but also its velocity. Since the force peaks appear at around 60 ms, the final amount of intrusion does not seem to be a major factor causing lower leg injuries. Figure 10 shows the time histories of the pedal force, the contact force and the tibial axial force of the right leg. The compressive force through the tibia in negative direction was reversed to positive for comparison. It is obvious that the tibial axial force is the sum of the muscular tension force and the external force. Figure 11 shows the velocity change in the intruding plate and the right foot in Cases 1 and 3. A positive velocity means a forward movement relative to the vehicle. The velocity of the intruding toe board was measured at the same height as that of the heel. Intrusion started at 55 ms. When the foot was on the toe board in Case 1, the heel was pushed away as the toe board moved backwards, finally reaching the same velocity as the intruding plate. The velocity change was 4.76 m/s. In Case 3, the heel had 2.75 m/s of forward velocity at 55 ms because it was sliding on the floor. This resulted in a larger velocity change of 9.3 m/s, which was almost twice of that in Case 1. But it should be still even larger without the positive motion of the heel. Although the velocity curve for Case 2 is not shown in Figure 11, a similar curve is expected based on the similarity of the contact force curves.

Some interesting issues have been raised by the simulation study. The external force due to intrusion could be the major cause of injury. The severity of the external force is determined by the foot position and intrusion speed. The calcaneus was the first contact area in this simulation. A direct impact to the heel is likely to cause a calcaneus fracture. It could be the reason why calcaneal fractures are frequently seen in real crashes. However, care must be taken as to how the external force acts on the foot. The foot was treated as a rigid body in this simulation and the toe board was defined as a flat plate. Heel contact was the most likely to occur under this condition. A real human foot can deform when the pedal pushes the forefoot back and the toe board may not be flat after a collision. The brake pedal also moves backwards and pushes on the forefoot in some cases. The external force due to intrusion, therefore, can act anywhere on the foot. Another issue is that the muscular tension generates preloading of the tibia. If the external force acts on the foot in the presence of preloading, the tibia can be under more compression and can be fractured if the impact

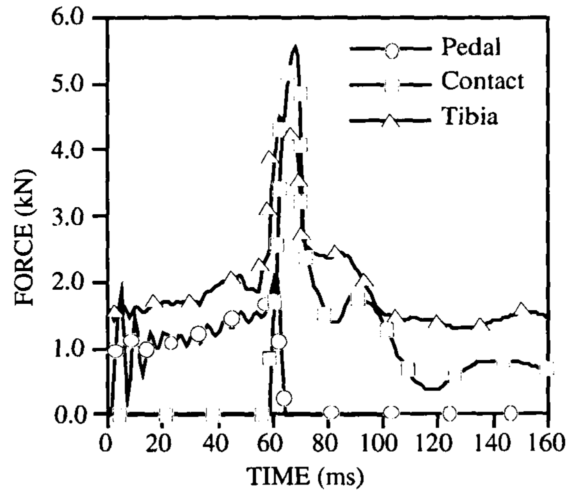


Figure 10. Force on Pedal/Heel/Tibia.

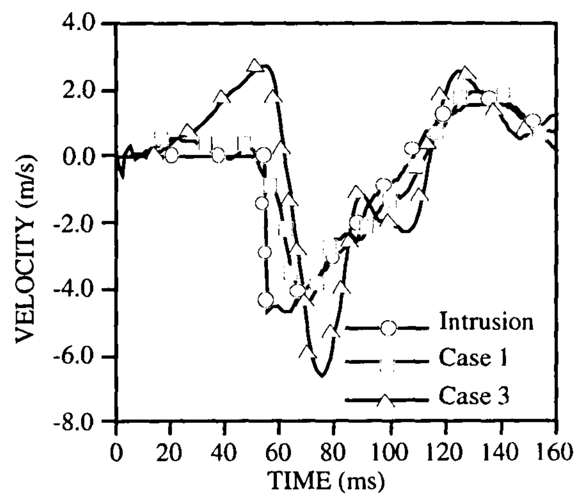


Figure 11. Velocity Change of Foot / Plate.

is severe enough. Furthermore, if the external force is applied to the forefoot, the tibia can be fractured without calcaneal fracture. This mechanism can explain why few pylon fractures are seen in laboratory tests despite the fact they are actually seen in real crashes. An in-depth analysis is necessary to understand the injury mechanism of the human foot and ankle complex under a combined loading by muscular tension and external force. Cadaver tests described below were conducted for this purpose.

CADAVER TESTS

Procedure

Eight pairs of human cadaveric lower legs were obtained for this study through the willed body programs of Wayne State University and the University of Michigan. Table 1 lists the cadavers used. Their age ranged from 59 to

83 years with an average of 71. Six of the eight cadavers were female. A total of sixteen specimens was used in the tests. All specimens were examined radiographically and physically before testing to confirm that there were no anatomic and pathologic abnormalities. Each specimen was cut distal to the knee. The length of each specimen was 300 mm and about 100 mm of soft tissue was removed from the proximal tibia for potting. The Achilles tendon was dissected free and placed into a tendon catcher made of steel mesh (finger trap). The tendon catcher tightens around the tendon as it is pulled. The maximum force it can generate depends on how slippery the tendon is. Polyester suture, Ethibond B-499, was used to increase this force. The tendon was stitched by passing the suture through the mesh of the catcher as shown in Figure 12. The suture helped increased the tendon force up to several kilo Newtons. The proximal end of the tibia was potted in a fiber reinforced epoxy block. This condition represents the entrapment of the knee by the lower dashboard. Although the condition did not allow the relative motion between the tibia and fibula, it was accepted because generally the fibula does not contribute much to the strength of the lower leg.

Figure 13 is an schematic view of the entire test apparatus. The pot was attached rigidly to the fixture. The tibial axis was adjusted to lie along a horizontal line. A rigid pendulum weighting 18 kg was used to impact the bottom of the foot. The impactor was cylindrical with a diameter of 70 mm. The height of the centerline of the pendulum was 50 mm lower than the tibial axis. This impact provided the external force to the forefoot. Half an inch of ensolite padding was used on the impactor head to damp out high frequency vibrations. An aluminum plate was fixed to the sole of the foot to prevent direct contact of the foot by the impactor. Another aluminum plate was anchored to the test fixture to keep the foot plate from rotating. When the tendon force was applied, the forefoot was resisted by this plate.

A constant tendon force was maintained by the use of an energy absorber (EA) in the form of 2 aluminum plates, which tore at a constant load as shown in Figure 14. The Y-shaped plate yielded under a constant force when the both ends were pulled. When a couple of the aluminum plates were tested, the static tearing force was 1.4 to 1.6 kN. Due to strain rate dependency, the dynamic force was expected to be 10-20% higher but almost constant. An electrically

Table 1. Cadaver Properties

CAD#	AGE	SEX	Death Date	Cause of Death
271	68	F	1995/12/19	Hepatic Coma
242	69	F	1995/10/01	Acute Myocardial Infaction
715	59	M	1992/09/05	Massive Intracranial Bleeding
28483	75	F	1997/03/11	Respiratory Failure
28443	83	F	1997/03/02	Arteriosclerotic Caroiovascular Disease
28441	69	F	1997/03/04	Advanced Cervical Carcinoma
900	75	M	1993/08/15	Pneumonitis
480	70	F	1997/02/02	Cardiac Arrythmia

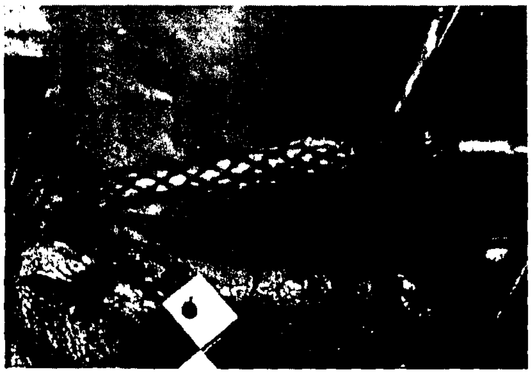


Figure 12. Tendon Catcher.

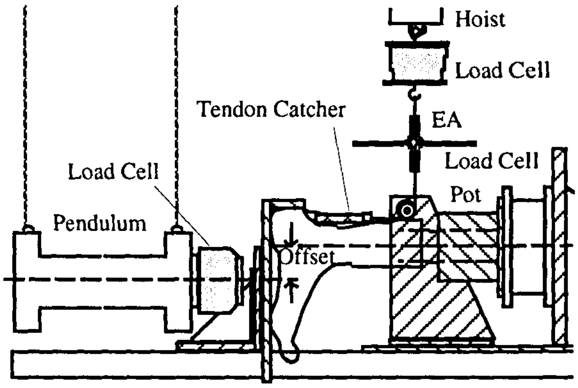


Figure 13. Dynamic Loading Apparatus.

powered hoist was used to apply a tensile force to the Achilles tendon through a cable. The tensile force, checked by a load cell placed between the EA and the hoist, was increased until the EA started tearing. The foot plate was kept perpendicular to the tibia during preloading. Then the pendulum was accelerated by a pneumatic cylinder and impacted the foot plate at approximately 3 m/s. A load cell and an accelerometer were mounted on the pendulum to provide a mass corrected impacting force. The tibial force and moment were measured by a 6-axis load cell behind the pot. The analog data were filtered and digitized at 10000 samples per second and were processed as channel class 1000 data. A 16 mm high-speed camera running at 500 fps was used to analyze the motion of foot to which photo targets had been applied. The time of impact was recorded by an electrical signal on the data acquisition system and by a synchronized flash for the high-speed camera. Each specimen was x-rayed and autopsied after the test.

Test Results

The results of the sixteen impact tests are summarized in Table 2, where *Fimp* is the impactor force, *Ftib* is the tibial axial force when fracture occurred. Some dorsiflexion and a slight eversion were observed in every test. The dorsiflexion angle of the foot at failure is denoted by θ. The first peak in the tibial force was regarded as the failure load, as shown in the Figure 15.

Five tibial pylon fractures and ten calcaneal fractures were found while Cadaver #271L sustained no injury. The average values of the impactor force and the tibial axial force with fracture were 5132 N and 7645 N respectively. Figure 15 through 17 show the time histories of force and moment obtained in the case of Cadaver #28483L, showing a typical result in this series of tests. The impactor force and the tibial axial force, shown in Figure 15, were similar to each other except for an almost constant difference between them. The tibial axial force was higher than the impactor force because of the muscular preloading. The maximum tibial axial force appeared about 5 ms after the contact. The tensile force in the Achilles tendon, shown in Figure 16, was almost constant during the test. Figure 17 shows the tibial moment around X and Y axes, where a positive *Mx* implies lateral bending on the right leg and a positive *My* indicates plantarflexion. *My* ranged from 70 to 130 Nm in dorsiflexion whereas *Mx* was always acting in a single lateral direction. *Mx* was around 150 Nm in most of the tests.

One of the specimens with pylon fracture also had a lateral malleolar fracture and two of the ten calcaneal fractures were accompanied by a small crack in the talus. The lateral malleolar fracture suggests that the distal tibia was not necessarily compressed axially because of the slight eversion. Figure 18 shows an X-ray and an autopsy picture of Cadaver #715R which sustained a tibial pylon fracture. The calcaneus bones were uninjured in all of the five cases

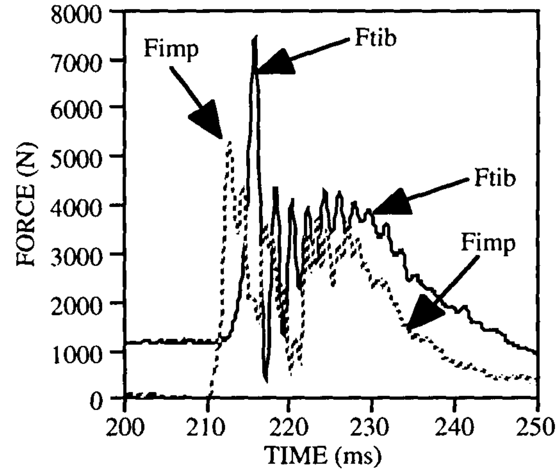


Figure 15. Impactor and Tibial Forces.

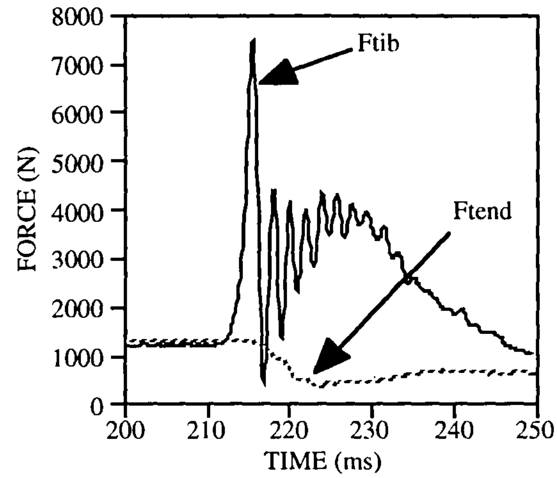


Figure 16. Tibial and Tendon Forces.

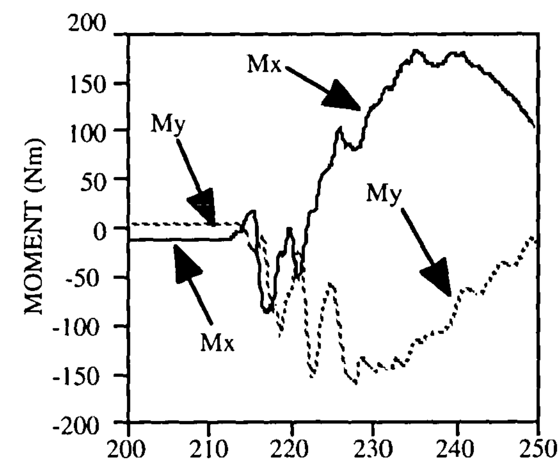
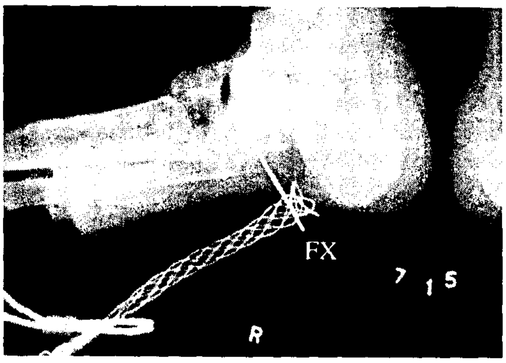
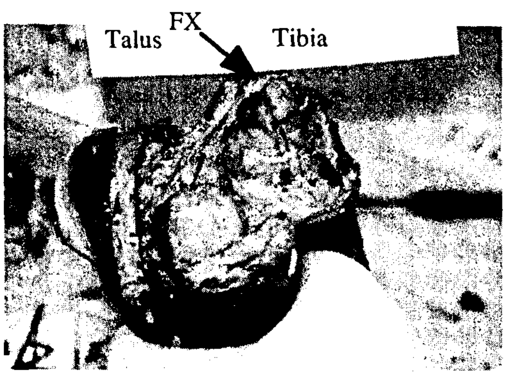


Figure 17. Tibial Moments.

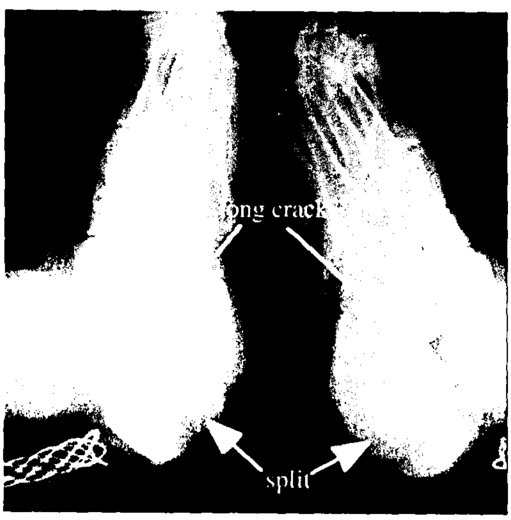


(a) X-ray Photograph



(b) Autopsy Photograph

Figure 18. CAD#715R (Pylon Fracture).



Right Left

Figure 19. CAD#28443 (Calcaneal FX).

with pylon fractures. The small values of θ for ankle dorsiflexion means that the distal tibia was compressed very hard by the talus without causing a large dorsiflexion. The consequence is either a tibial pylon fracture or a calcaneal

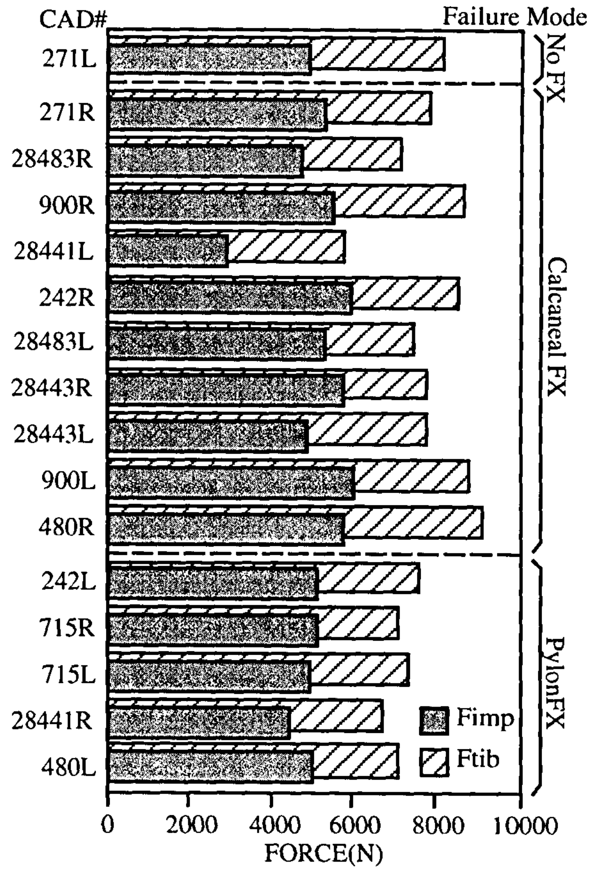


Figure 20. Failure Loads at Impactor and Tibia.

fracture. An X-ray of a typical calcaneal fracture is shown in Figure 19.

The common failure pattern in the calcaneus was a long crack from the bottom through the sinus tarsi (subtalar tunnel). There was another split-type fracture in the posterior side just under the tendon attachment point, which was found in some cases simultaneously with the first pattern. Both of them are primarily tension-type injuries. Failure forces are plotted in Figure 20 for the two types of fractures observed in this study. Cadaver #28441 was found to have advanced cervical carcinoma, which might be why its failure loads were lower than those of the other specimens despite the fact there was no indication of osteoporosis. The average impactor and tibial loads, excluding Cadaver #28441, for calcaneal fracture were 5483 N and 8115 N respectively while they were 5066 N and 7293 N respectively for pylon fracture. It is an unexpected result in that the failure load causing pylon fracture was lower than that of calcaneal fracture, as pylon fracture was supposed to occur at higher load, and bones are generally weaker under tensile loading. One reason is that the strength of bones is different between individuals. If the strength of these bones are close, two different fracture modes can occur under the same loading condition. Another possible explanation for occurrence of calcaneal fracture is that the tendon force was raised due to some reason such as the strain rate dependency of the material or the friction on the wire. The difference between the maximum impactor force and the maximum tibial axial force was approximately 2.6 kN in calcaneal fracture cases whereas it was about 2.2 kN in pylon fracture cases.

Looking back at previous work, an average tibial fracture load of 7830 N was proposed by Yoganandan (1996) and 7848 N by Begeman (1997). The impact velocity causing these fractures ranged from 4 to 6 m/s. Although the tibial fracture load in this study was almost the same as that reported previously, it was discovered that less impact force or lower impact velocity can cause tibial pylon fracture when muscular force is acting. Although muscular force is not always necessary to cause pylon fracture, it increases the injury risk compared to the relaxed case. The result is not inconsistent with the fact that there are cases where the driver's left leg or the passenger's legs sustained pylon fractures.

Future studies will focus on the threshold of tibial pylon fracture. It was not determined exactly because of the small number of specimens used and the majority of the specimens were female. The failure load is presently estimated at around 7 kN according to these test results. The impact point on the forefoot can be another dominant factor determining the fracture mode. Various impact conditions should be taken into account for a better understanding of the mechanism. In terms of methodology, numerical simulation using finite element models will be able to explain the mechanism of pylon fracture. Deformable elements are required to calculate stress and strain distribution in the bones of the foot. This will be the next effort in this research study.

CONCLUSION

1. Both muscular tension and external force due to intrusion can increase the axial force on the right tibia whereas the external force also determines the impact severity to the foot. The right tibia is subjected to preloading when the muscular force acts during braking.
2. Since the peaks in these forces appear at around 60 ms, the final extent of intrusion does not seem to be a major factor causing ankle/foot injuries.
3. The severity of external forces may be also affected by intrusion speed.
4. The calcaneus was the first contact area in the

Table 2. Test Results and Autopsy Report of Specimens

No.	CAD#	V(m/s)	Fimp(N)	Ftib(N)	θ(deg)	Autopsy
1	271R	3.62	5344	7801	2.8	Calcaneal FX(crack*)
2	271L	3.17	4932	8152	3.5	No Fracture
3	242R	3.99	5969	8549	1.8	Calcaneal FX(crack&split**)
4	242L	3.74	5179	7620	0.0	Pylon FX
5	715R	3.73	5116	7110	3.0	Pylon & Med. Malleolar FX
6	715L	3.31	4971	7349	1.5	Pylon FX
7	28483R	3.31	4791	7145	0.0	Calcaneal FX(crack)
8	28483L	3.59	5306	7437	0.0	Calcaneal FX(crack&split)
9	28443R	3.54	5786	7779	1.5	Calcaneal FX(crack&split)
10	28443L	3.17	4890	7759	3.0	Calcaneal(crack&split) & Talus FX
11	28441R	2.91	4462	6738	0.0	Pylon FX
12	28441L	2.37	2917	5737	0.0	Calcaneal(crack) & Talus FX
13	900R	3.60	5483	8654	0.0	Calcaneal FX(crack)
14	900L	3.73	6012	8803	2.0	Calcaneal FX(crack&split)
15	480R	3.76	5765	9108	0.0	Calcaneal FX(crack&split)
16	480L	3.68	4996	7091	0.0	Pylon FX

* a long crack from the bottom of the calcaneus through the sinus tarsi.
** split-type fracture in posterior side of the calcaneus just under the tendon attachment point.

MADYMNO simulation. It could be the reason why calcaneal fracture is frequently seen in real crashes.

5. The tibial axial force was always higher than the impactor force in this study because of the muscular preloading by the Achilles tendon.
6. Five tibial pylon fractures and ten calcaneal fractures were found out of sixteen specimens tested.
7. The calcaneus was intact in the five cases in which pylon fractures occurred.
8. A long crack from the bottom of the calcaneus through the sinus tarsi and a split in the posterior side were observed in calcaneal fractures.
9. The average failure loads measured at the tibial end were 8115 N for calcaneal fractures and 7293 N for pylon fractures (excluding Cadaver# 28441).
10. A high impact force or high impact velocity is not necessary to cause tibial pylon fracture when a muscular force is active.

ACKNOWLEDGMENT

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AXIAL IMPACT CHARACTERISTICS OF DUMMY AND CADAVER LOWER LIMBS

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ABSTRACT

Axial impact tests conducted at the Medical College of Wisconsin on isolated cadaver lower limbs and the original version of the 50th percentile Hybrid III dummy lower limb were examined to characterize their dynamic response. Unlike the more recent version of the Hybrid III dummy lower limb, the original Hybrid III dummy lower limb allows only 30 degrees of foot rotation in dorsiflexion and lacks biofidelic heel pad compression characteristics. This original version of the Hybrid III dummy lower limb will henceforth be referred to as HIII-o dummy lower limb. Results of the tests suggested that the axial force measured in the HIII-o lower limb was higher than that measured in the cadaver lower limb for similar impacts applied to the plantar surface of the foot.

The dynamic properties of the cadaver and HIII-o dummy lower limb were characterized by representing the lower limb in the axial impact tests as a single degree of freedom system with a Kelvin element having linear stiffness and damping properties. The stiffness and damping coefficients of the cadaver and HIII-o dummy lower limbs were obtained from linear regression using the measured accelerations on the pendulum and the leg as input and output of the system, respectively. The average stiffness and damping coefficients were estimated to be 963 kN/m and 0.21 for the cadaver and 3256 kN/m and 0.26 for the HIII-o dummy lower limbs, respectively.

The axial force response ratio between the HIII-o dummy and cadaver lower limbs under similar impact conditions was obtained using Runge-Kutta simulations of the equation of motion for the single degree of freedom system. The axial force response ratio was represented as a function of the rise time of the axial force (the time to maximum force) in the HIII-o dummy lower limb. The axial force ratio between HIII-o dummy and cadaver is greater than one for HIII-o dummy axial force rise times below 55 msec (short duration tibia force pulse). The axial force in the HIII-o dummy and cadaver are approximately the same for long duration HIII-o dummy axial force pulse.

INTRODUCTION

Recent research efforts have attributed lower limb injuries to axial loading through the plantar surface of the foot. In an epidemiological study using data from a Level I Trauma Center, Dischinger et al. (1994) and Crandall et al. (1996) noted that axial load through the plantar surface of the foot contributed to 47% of the ankle fractures sustained in frontal automobile crashes. In another study, Ziedler et al. (1981) noted that distal tibia and fibula fractures were caused by axial compression alone or by a combination of compression, torsion, bending, and tension. Injury criteria for the foot and ankle complex have recently been developed based on the contact axial force at the plantar surface of the foot (Klopp et al., 1997) and axial force in the proximal tibia (Yoganandan et al., 1996). These criteria were developed using human cadaver lower limbs.

In order to evaluate countermeasures, these injury criteria must be incorporated into testing with anthropomorphic test devices and computational models.

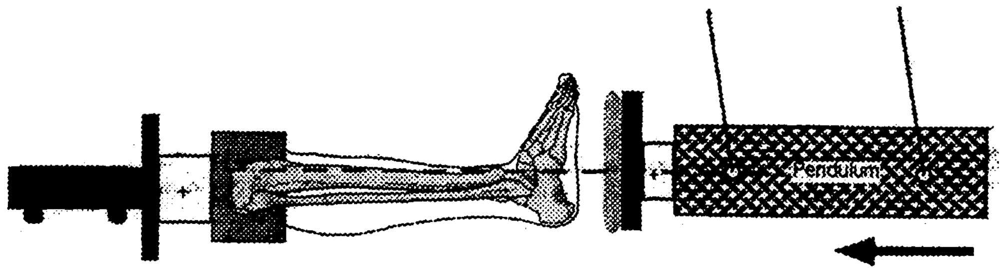

Figure 1. Setup for the axial impact tests at the Medical College of Wisconsin.

However, before applying any lower limb injury criteria to the test device, physical properties and response differences between the test device and human cadaver lower limbs need to be addressed. In particular, the mass, stiffness, and damping properties of the test device should be similar to that of the human lower limb such that the forces measured in the test device and human leg are similar under similar impact conditions.

This paper presents the research efforts concerned with the application of a lower limb injury criteria based on axial force, to the original 50th percentile Hybrid III dummy lower limb. Unlike the more recent version of the Hybrid III dummy lower limb, the original Hybrid III dummy lower limb allows only 30 degrees of foot rotation in dorsiflexion and lacks biofidelic heel pad compression characteristics. This original version of the Hybrid III dummy lower limb will be referred to in this paper as HIII-o dummy lower limb. The differences in the dynamic properties and the physical responses between the HIII-o and human cadaver lower limbs were examined. The first objective in this research effort was to determine the dynamic stiffness and damping properties of the human cadaver and HIII-o dummy lower limb. The second objective was to characterize the axial force response ratio between HIII-o dummy and cadaver lower limbs.

In order to achieve these objectives, the axial impact tests to the lower limbs of cadavers and HIII-o dummy, conducted at the Medical College of Wisconsin (MCW) were examined (Yoganandan et al., 1996).

TEST SETUP AT THE MEDICAL COLLEGE OF WISCONSIN

The test apparatus (Figure 1) consisted of a pendulum and leg specimen, attached to a mini-sled. The mini-sled was free to move on linear ball bearings over precision ground stainless steel rails after the impact. The pendulum, mass of 25 kg, impacted the plantar surface of the foot with velocities ranging from 2.2 m/s to 5.6 m/s. The human cadaver leg specimens and the HIII-o dummy leg were disarticulated at the knee and attached to the mini-sled. The mini-sled and leg assembly was ballasted to 16.8 kg in order to simulate the mass of the whole lower limb. Load cells and accelerometers were attached to the pendulum and the mini-sled system in order to measure accelerations and forces at the plantar surface of the foot and the proximal leg. The contact surface of the pendulum was padded with a one inch thick synthetic rubber (E.A.R. Composites Isodamp C-1000). Details of the test setup are provided in (Yoganandan et al., 1996).

PHYSICAL PROPERTIES AND RESPONSE DIFFERENCES BETWEEN THE HIII-o DUMMY AND HUMAN CADAVER LOWER LIMBS

The average mass of the human lower limb was obtained from a summary of cadaver segment mass data (Crandall, 1996 and NASA, 1978). The average mass of the HIII-o dummy lower limb was obtained from dummy specifications. The mass of various segments of the lower extremity are presented in Table 1. The total mass of the HIII-o dummy lower extremity (11.2 kg) is similar to the mass of the human cadaver lower extremity (11.5 kg).

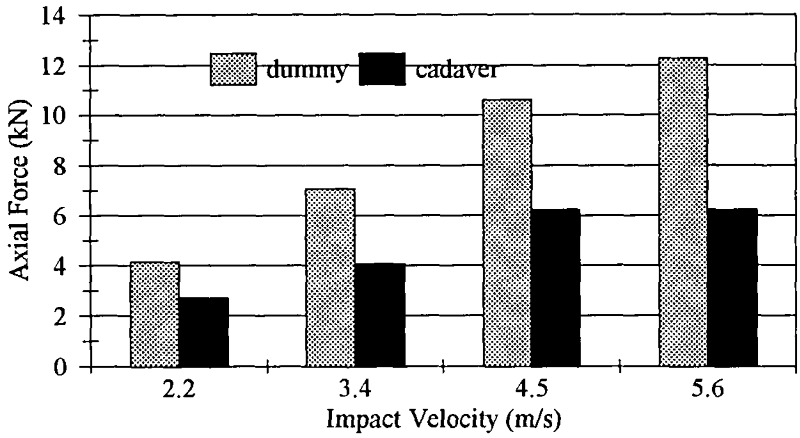

Figure 2. Cadaver and HIII-o dummy responses under similar impact conditions.

Table 1.
Mass of Segments of the Lower Extremity.

Segment	50% HIII-o Dummy (kg)	50% Human Cadaver (kg)
Thigh	6.0	7.3
Leg	3.7	3.2
Foot	1.5	1.0
Total	11.2	11.5

In order to examine response differences, the HIII-o dummy and approximately 50 percentile male cadaver lower limbs were impacted under identical conditions in the MCW test setup. Only those cadaver tests with no injury were considered. In each paired test, using HIII-o and human cadaver lower limbs, the pendulum impact velocity and impact energy was maintained the same. For these tests, the HIII-o dummy leg consistently experienced higher force (one and a half to two times higher) at the proximal end than the cadaver leg (Figure 2).

Since the mass of the HIII-o dummy and cadaver lower limbs are similar, the results in Figure 2 imply that the dynamic stiffness and damping properties of the dummy and cadaver lower limbs differ. Due to the large response differences between cadaver and dummy lower limbs, the injury criteria, developed using human cadaver lower limbs, would be conservative when applied to the HIII-o dummy in this impact condition. In order to determine the conditions under which the axial force injury criteria would be conservative when applied to the HIII-o dummy lower limb, the first step was to characterize the dynamic properties of the HIII-o dummy and cadaver lower limbs

CHARACTERIZING THE DYNAMIC PROPERTIES OF THE CADAVER AND HIII-o DUMMY LOWER LIMB

The stiffness and damping coefficients of the human cadaver and the HIII-o dummy lower limbs were obtained by analyzing the MCW test data. The dummy and human cadaver lower limbs were represented by a single degree of freedom system with a Kelvin element (Figure 3). The acceleration measured at the impactor surface of the pendulum was taken as input into the system. The acceleration measured at the proximal end of the leg was taken as the output of the system.

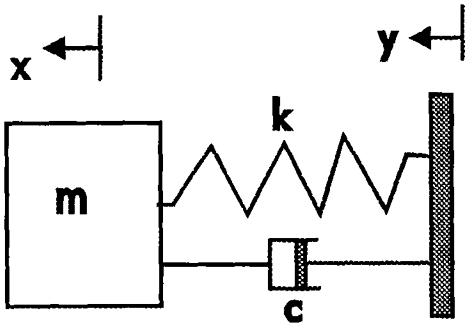

Figure 3. Single degree of freedom representation of the lower limb.

The development of a single degree of freedom linear model required several simplifying assumption which are listed below:

1. The first assumption is that the stiffness and damping coefficient are linear. During the initial phase of impact, the foot penetrates the padding material producing a growing contact area. This produces a nonlinear force versus deformation response. In order to ensure a linear stiffness and damping coefficient, analysis of the data was considered only in the range between 5% of the peak value on the leading edge of the input pulse and 10% of the peak value on the trailing edge of the input acceleration pulse. Analysis of the MCW data suggested that within this range of data, linear approximation was reasonable.
2. The second assumption is that there is no significant foot rotation during the impact. Foot rotation would also produce a nonlinear response for axial measures. Hence, only those tests were considered from the Medical College of Wisconsin where the impact was along the distal one-third of the tibia to minimize foot rotation. Film analysis of these MCW tests showed little foot rotation.
3. The third assumption is that there is no loss of contact between the foot and the impacting surface during the impact event. This is a critical assumption of linearity since any loss of contact would be expected to produce a strongly nonlinear response. This means, that the data analysis is restricted to the duration of the compression pulse measured by the pendulum load cell. This assumption can also be satisfied by considering the signals only between the range of 5% of the peak value on the leading edge and 10% of the peak value on the trailing edge.
4. The fourth and last assumption is that the stiffness and damping properties of the system are constant during the compression phase. Any injury or fracture in a cadaver specimen during the impact, would change its stiffness and damping properties. Hence, only those cadaver tests were considered in the analysis which did not sustain any injury.

For the single degree of freedom system in Figure 3, m represents the mass of the leg and mini-sled assembly (16.8 kg). The equivalent stiffness of the lower limb and padding on the pendulum impact surface is represented by k. Damping of the system is represented by c.

If $\ddot{y}$, $\dot{y}$, and y are the acceleration, velocity and displacement of the impacting surface, respectively, and $\ddot{x}$, $\dot{x}$, and x are the acceleration, velocity, and displacement at the proximal end of the leg, then the equation of motion for the system in Figure 3 is obtained from dynamic equilibrium for the lumped mass where

$$m\ddot{x} + c(\dot{x} - \dot{y}) + k(x - y) = 0 \qquad (1)$$

$$Let \quad z = x - y$$

$$\rightarrow \quad m\ddot{z} + c\dot{z} + kz = -m\ddot{y} \qquad (2)$$

$$or \quad \ddot{z} + 2\xi\omega\dot{z} + \omega^2 z = -\ddot{y} \qquad (3)$$

rearranging,

$$-\ddot{x} = 2\xi\omega\dot{z} + \omega^2 z \qquad (4)$$

The natural frequency of the system, ω, is √(k/m) and the damping coefficient, ξ, is c/2mω.

The Equation 4 is a linear relation in z and $\dot{z}$ where these values are known for all corresponding $\ddot{x}$. This relation can be generalized for the measured data

$$-\ddot{x}_i = b_o + b_1\dot{z}_i + b_2 z_i + \varepsilon_i \qquad (5)$$

$$where \quad b_1 = 2\xi\omega \quad and \quad b_2 = \omega^2$$

where $\ddot{x}_i, \dot{z}_i, z_i$ are the acceleration, relative velocity, and relative displacement of the system at the ith instant, b_o is a bias or offset value, and ε_i is a perturbation. The bias can be attributed to systematic errors in the measures. The perturbation is due in part to the precision of the instruments and to the fact that the true system response is not completely described by a single degree of freedom linear model. If one assumes that the perturbation is a random variable that is normally distributed, then an optimal line or line of best fit to the test data under consideration can be obtained by using multivariate linear regression. This method produces least squares estimates for the parameters b_0, b_1, b_2. The estimates of ω and ξ are then obtained from Equation 5. The stiffness and damping values are obtained from $k=\omega^2 m$ and $c=2\omega m\xi$. The mass considered is the mass of the leg and sled assembly (16.8 kg) which represents the total mass of the lower limb.

RESULTS

This method of linear regression was applied to each cadaver and dummy test. The errors in the estimates of b_1 and b_2 for each test were small (within 10%) and the R^2 value of the analysis was high (cadaver average R^2=0.9 and dummy average R^2=0.98) suggesting that the values of ω and ξ are reasonably constant during the compression phase of the impact. This implies that the assumptions of linearity and constant dynamic properties during the compression phase were reasonable. The details of the tests and the results of the regression analysis are presented in Table 2.

Since the dynamic properties of the cadaver lower limb are to be compared to the 50th percentile HIII-o dummy lower limb, approximately 50 percentile male cadaver specimens were used in the study. The average estimated stiffness and damping coefficient for the cadaver lower limb is 963 kN/m and 0.21, respectively. The average stiffness and damping coefficient for the HIII-o dummy lower limb is 3256 kN/m and 0.26, respectively.

The results obtained are consistent with previous studies showing the HIII-o dummy leg to be stiffer than the comparable size human leg (Crandall, et al., 1996). Mizrahi and Susak (1982) investigated the in-vitro transmission of impact forces from the foot through the entire straight leg in human volunteers. A two degree of freedom linear mathematical model was employed to describe the mechanical behavior of the leg and the rest of the body during free fall from a height of 5 cm above ground. The volunteer legs were straight and vertical when the plantar surface of the foot impacted the floor causing axial loading of the lower limb. Assuming linear stiffness and damping properties for the leg, Mizrahi and Susak estimated the stiffness for the human leg to be 340 kN/m. The value of stiffness is lower than 963 kN/m obtained in the present study. The difference could be attributed to differences in the testing protocol and the considerably lower impact force levels (maximum impact force = 1700N and maximum acceleration =5 g's) in the Mizrahi and Susak study. Mizrahi and Susak did not control for the assumption of linearity in their model. The stiffness obtained from the Mizrahi model is lower than that in the present study since the Mirzrahi-Susak model includes the compression of the heel pad which is highly nonlinear and of lower stiffness than the rest of the leg.

Having completed the characterization of the dynamic properties of the lower limbs of the human cadaver and dummy, the next step was to characterize the response ratio between the forces measured in the dummy leg to that measured in the cadaver leg.

CHARACTERIZING THE AXIAL FORCE RESPONSE RATIO BETWEEN HIII-o DUMMY AND CADAVER LOWER LIMBS

The single degree of freedom representation of the lower limb (Figure 3) with the estimated average stiffness and damping properties for the HIII-o dummy and cadaver lower limbs was utilized to investigate the axial force response ratio between the cadaver and dummy lower limb. The input acceleration to the system was represented as a half sine wave, $A \sin \varpi t$. This representation of the input acceleration is similar to the characterization of floor pan acceleration in vehicle-to-vehicle crashes by Kuppa et al. (1995).

In order to illustrate the influence of the various dynamic parameters on the force in the lower limb, consider the motion of the system to be represented by Equation 1. For simplicity, ignore the effect of damping. The stiffness of the system is given by k. The axial force in the lower limb is given by F=k(x-y)=kz, which is

$$F = \frac{mA}{(1-\beta^2)}(\sin \varpi t - \beta \sin \omega t) \qquad (6)$$

$$where \qquad \beta = \frac{\varpi}{\omega}$$

where ω is the natural frequency of the system ($=\sqrt{(k/m)}$), m is the mass of the dummy lower limb, and ϖ is the frequency of the input acceleration (Clough, R.W. and Penzien, J.,1975).

The force in the lower limb is not only a function of the dynamic properties of the lower limb but also a function of the frequency of the input acceleration. The force F_c and F_d in the human cadaver and HIII-o dummy lower limb can be determined using Equation 6. Since the mass of the dummy lower limb (m_d) and cadaver lower limb (m_c) are similar, the ratio of the axial force in the HIII-o dummy to the axial force in the human cadaver lower limb, for the same input acceleration of $A \sin \varpi t$, is given by Equation 7.

$$\frac{F_d}{F_c} = \frac{(\sin \varpi t - \beta_d \sin \omega_d t)(1-\beta_c^2)}{(\sin \varpi t - \beta_c \sin \omega_c t)(1-\beta_d^2)} \qquad (7)$$

$$\text{where} \quad \beta_c = \frac{\varpi}{\omega_c} \qquad \omega_c^2 = \frac{k_c}{m_c}$$

$$\text{and} \quad \beta_d = \frac{\varpi}{\omega_d} \qquad \omega_d^2 = \frac{k_d}{m_d}$$

k_c and k_d are the stiffness of the cadaver and HIII-o dummy lower limbs, respectively. Equation 7 suggests that the ratio of the force in the HIII-o dummy lower limb to that in the cadaver lower limb is a function of the stiffness of the dummy and cadaver lower limbs and the frequency of the input acceleration.

In order to solve the complete equation of motion which includes the effect of damping (Equation 3), a Runge Kutta simulation was conducted. using the dynamic properties of the human cadaver and the HIII-o dummy. Simulations were conducted with different input acceleration frequencies (ϖ). The input acceleration frequency was computed as $\varpi=\pi/(\text{pulse width})$. The force in the dummy and cadaver lower limbs were computed as $F = cz + kz$. The ratio of the force in the dummy to that in the cadaver for different impact frequencies is shown in Figure 4.

The axial force response ratio between dummy and cadaver is greater than one for input acceleration frequency higher than 40 rad/s (short duration pulse). The maximum response ratio is approximately 1.86 for input acceleration frequencies greater than 200 rad/s. For input acceleration frequency between 7.85 and 40 rad/s, the response ratio dips below 1 to as low as 0.77 at an input acceleration frequency of 15.7 rad/s. The force ratio is approximately 1 for input acceleration frequencies below 7.85 rad/s (very long duration input acceleration pulse).

The frequency of the input acceleration is not always easy to estimate and so may not be the best parameter to determine the axial force response ratio (F_d/F_c) for a given impact condition. However, the time at which maximum axial force occurs (rise time) in the HIII-o dummy leg is unique for a given floor pan acceleration frequency as shown in Figure 5.

Recognizing this relationship between the floor pan acceleration frequency, ϖ, and rise time (T_{rise}) of axial force in the HIII-o dummy leg, the ratio, F_d/F_c for a given impact condition can be determined by the rise time for axial force in the dummy leg (Figure 6). The ratio, F_d/F_c, is greater than one for T_{rise} smaller than 55 msec. This ratio dips below one for rise times between 55 and 200 msec. The force response ratio is approximately one for T_{rise} greater than 200 msec.

The conservative approach to the lower extremity injury criteria using axial force assumes the ratio F_d/F_c =1. This implies that the axial force measured in the HIII-o dummy leg with small rise time (less than 55 msec) and a peak level greater than the critical force may not be injurious since the force response ratio is greater than one. On the other hand, the axial force in the HIII-o dummy leg with rise time between 55 and 200 msec, may be injurious for measured peak forces slightly below the critical force level.

This complex relationship between measured axial force and injury threshold level suggests the need for an improved design of the dummy lower extremity which has similar dynamic properties as the human lower limb.

CONCLUSIONS

Axial impacts to the plantar surface of the foot of isolated cadaver and HIII-o dummy lower limbs suggested that the forces measured in the HIII-o dummy lower limb is consistently higher than that measured in the cadaver lower limb, under similar impact conditions. These axial impact tests were further examined to characterize the dynamic properties of the HIII-o dummy and cadaver lower limbs and to determine the axial force response ratio between the dummy and cadaver.

The cadaver and HIII-o lower limbs were represented by a single degree of freedom system with a Kelvin element having linear stiffness and damping properties. The stiffness and damping properties were estimated from multivariate linear regression analysis using measured accelerations on the pendulum and the leg as input and output to the system. The average stiffness and damping coefficients were estimated to be 960 kN/m and 0.21 for the cadaver and 3256 kN/m and 0.26 for the HIII-o dummy lower limbs, respectively.

The ratio of the axial force measured in the dummy leg to that in the cadaver leg (F_d/F_c) was estimated using Runge-Kutta simulation of the motion of the single degree of freedom representation of the cadaver and dummy lower limbs. The estimated average stiffness and damping values of the cadaver and dummy lower limbs were used in these simulations. The force response ratio (F_d/F_c) was characterized as a function of the rise time (time to maximum value) (T_{rise}) of the measured axial force in the HIII-o dummy leg.

The force response ratio, F_d/F_c, is greater than one and as high as 1.8 for T_{rise} less than 55 msec. This implies that for small T_{rise} values, the measured axial force in the dummy leg which is above the critical threshold value may not be injurious. On the other hand for T_{rise} between 55 and 200 msec, $F_d/F_c < 1$. Therefore the measured axial force in the dummy leg which has a T_{rise} between 55 and 200 msec may be injurious though the maximum force is slightly below the critical force value.

The presence of padding has the effect of increasing the rise time of the measured force. Therefore, the axial force response ratio (F_d/F_c) decreases when padding is added to the system. This would change the relationship between the measured force in the HIII-o dummy and the injury threshold level.

This complex relationship between the force measured in the HIII-o dummy leg and the critical force suggests that there is a need for a lower extremity device which demonstrates comparable axial compliance with the human leg.

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Table 2.
Test Data and Results of the Analysis

Test No.	Age	Sex	Test Velocity (m/s)	freq. ω Rad/s	damp. ratio ξ	stiffness kN/m	max. impactor force (N)	max. tibia force (N)
CADAVER TESTS								
PCLE110-1	27	M	2.2	235	0.19	928	3662	2666
PCLE114-1	46	M	2.2	242	0.15	984	3756	2719
PCLE116-1	27	M	3.4	282	0.22	1336	5919	4490
PCLE117-1	55	M	4.5	277	0.21	1289	7819	6226
PCLE129	66	M	3.4	230	0.22	889	5900	4607
PCLE131	64	M	2.2	206	0.18	713	3564	2776
PCLE132	50	M	3.4	209	0.3	734	4236	3093
PCLE133	50	M	5.6	223	0.24	835	7983	6239
AVERAGE				238	0.21	963		
HIII-o DUMMY TESTS								
PDLE119-1			2.2	356	0.2	2129	5447	4125
PDLE119-2			3.4	440	0.25	3252	9434	7058
PDLE119-3			4.5	498	0.27	4166	13960	10604
PDLE119-4			5.6	455	0.32	3478	17840	12278
AVERAGE				437	0.26	3256		

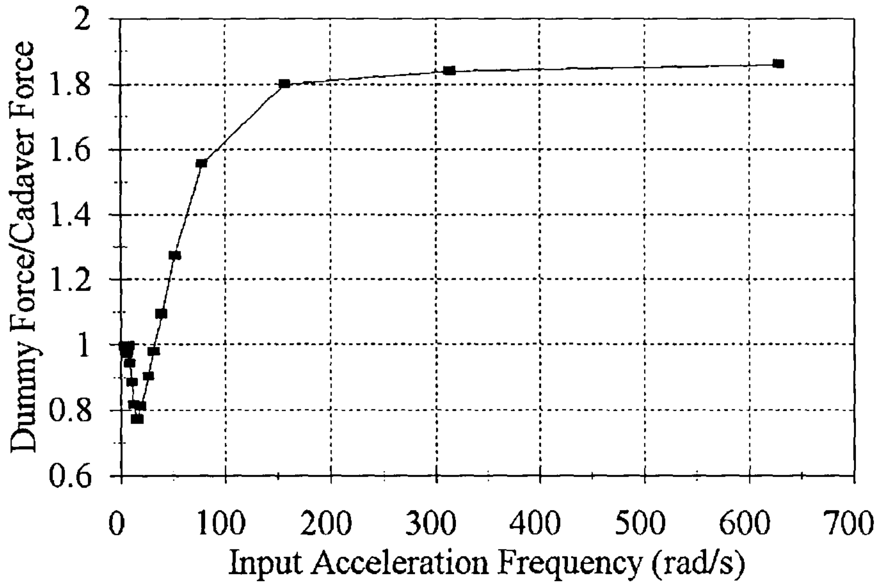

Figure 4. Ratio of HIII-o dummy / cadaver axial force for different input acceleration frequency.

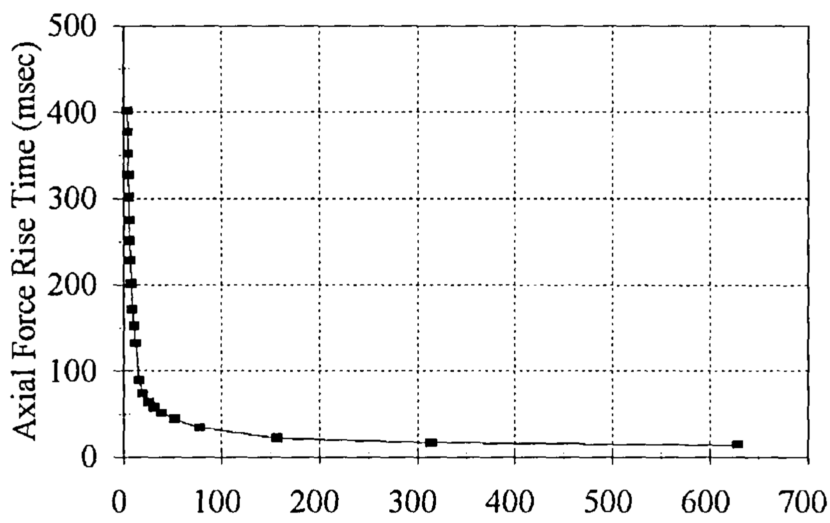

Figure 5. Axial force rise time in HIII-o dummy leg versus input acceleration frequency.

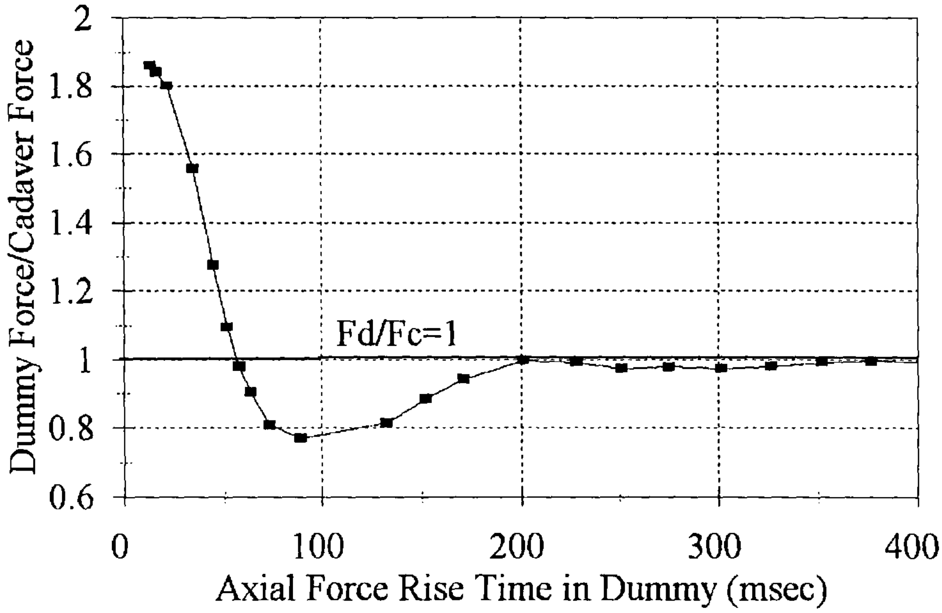

Figure 6. Ratio of HIII-o dummy/cadaver axial force versus axial force rise time in HIII-o dummy.

IMPROVED MEASURES OF FOOT AND ANKLE INJURY RISK FROM THE HYBRID III TIBIA

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ABSTRACT

From a regulatory viewpoint, the design, construction and instrumentation of the Hybrid III tibia, and the related measures of injury risk, specified in Directive 96/79/EC, present some difficulties. The paper briefly describes limitations associated with the design of the tibia, the standard instrumentation, and the currently regulated measures of injury risk. Given the anticipated delay before more advanced legs become available, interim means of increasing the utility of current data are suggested. Improvements to the instrumentation and further modification of the ankle characteristics are briefly discussed.

INTRODUCTION

Vehicle performance measures predictive of occupant injury risk, and their associated regulated limits, should provide practicable levels of protection at reasonable cost. The present paper suggests that the regulated performance requirements of Directive 96/79/EC, intended to reduce injuries to the lower leg, ankle and foot, are of limited relevance and effectiveness.

Research on the biomechanics of motor vehicle injuries necessarily precedes the improvement of ATDs. The Hybrid III was originally developed more than 20 years ago, when injuries to the lower extremities attracted much less attention than they do to-day. Not surprisingly, the design and instrumentation of the Hybrid III tibia do not reflect the understanding of lower extremity injuries that now exists. The geometry of the Hybrid III tibia also incorporates features which are absent (or at best, very much less pronounced) in human anatomy, yet significantly affect the data the tibia provides. Moreover, only one of the regulated measures of injury risk has a clear and direct association with the types of lower extremity injury observed in real collisions.

Concern for the effectiveness of the regulation extends beyond the shores of Europe; Australia has already adopted it and work is in progress in the United States to produce a regulation harmonised with the European requirement. Canada is also proposing use of the test procedure, as a complement to the CMVSS 208 test. Pre-production versions of an improved frontal impact ATD are currently being evaluated by various organisations but it is likely to be some time before a new device is certified for regulatory use. New and modified feet, intended to address some of the limitations of the existing Hybrid III hardware, are available, but they are not without significant problems.

This paper therefore has two major purposes. The first is simply to document specific limitations, inherent to the existing regulation, that result from the geometry of the current Hybrid III tibia, from the formulation of the Tibia Index and in the application of the limiting value of the Index. The second purpose is to suggest ways in which the data currently available from the Hybrid III tibia could be used to provide more informative measures of the risk of injury to the lower leg, ankle and foot.

INJURIES TO THE LOWER LEG, ANKLE AND FOOT

Overview of Data from Motor Vehicle Collisions

Morgan *et al.*, (1991) reviewed 480 cases of occupant foot and ankle injury, of AIS 2 or greater severity in frontal impacts. The data were obtained from the hard-copy files of the National Accident Sampling System for the period 1979-1987. Of those cases, 28 percent had only foot injuries, 65 percent had only ankle injuries and 7 percent had both. The authors identified six injury mechanisms, each defined in terms of a specific interaction between the ankle or foot and the vehicle interior.

Of the occupants with ankle injuries, the mechanism could not be determined in 12 percent of cases. In 43 percent of cases, the mechanism was identified as contact with foot controls (drivers only), in 24 percent it was contact with the floor (half drivers and half passengers) and in 12 percent, entrapment of the lower leg between floor and instrument panel (7:5 drivers:

passengers). In slightly more than half of the cases, the specific injury was described. Fracture of the lateral or medial malleolus was the most common, followed by fracture of the talus and then of the distal tibia or fibula.

Corresponding figures for occupants with foot injuries were 8 percent undetermined, 47 percent (drivers only), foot controls, 24 percent, contact with floor (half drivers and half passengers) and 8 percent wheel well intrusion (7:1, drivers:passengers). In three-quarters of the cases, the nature of the injury was described. Fractures of the metatarsals accounted for half of all cases, with fractures of the calcaneus accounting for 15 percent and a further 7-8 percent comprising fractures of the cuboid or cuneiforms.

Lestina *et al.*, (1992) analysed data from a clinical sample of 23 drivers who suffered a total of 25 foot or ankle injuries in frontal crashes. They classified each case according to the scheme proposed by Morgan *et al.* (1991) for defining injury mechanisms. However, in terms of the biomechanical injury mechanism, Lestina *et al.* concluded that 12 of the 13 cases that resulted in malleolar fractures were attributable to inversion or eversion of the foot, not dorsiflexion.

In a more recent paper, Parenteau *et al.*, (1996) presented an analysis of 805 cases of AIS 2 or 3 injuries to the foot or ankle, resulting predominantly from frontal collisions of passenger cars. The objective of the study was to determine the influence of impact location, occupant seating position and occupant age on the frequency, incidence and rate of foot-ankle injury. Frontal impacts accounted for 76.3 per cent of the foot-ankle injuries analysed.

An interesting conclusion, relevant to the test procedure of Directive 96/79/EC, was that near-side oblique collisions, i.e., frontal impacts from the 11 o'clock direction for the driver or the 1 o'clock direction for the front passenger, were about 50 percent more likely to result in AIS 2-3 injuries to foot or ankle than simple frontal impacts. The most commonly occurring injuries were fractures of the ankle, (including the distal tibia), ankle sprains and mid-tarsal fractures. The conclusion should however be viewed with some caution, since the analysis did not account independently for the effects of impact direction and impact location.

From their own work, and from a review of prior research, Parenteau and collaborators concluded that both intrusion and vehicle deceleration contribute to foot and ankle injuries but that the exact mechanism of injury in any particular case is usually unclear.

Biomechanical Tolerance Data

Axial force in the tibia

Using data reported by Yamada (1970), Mertz (1984) proposed a value of 8 kN for the maximum tolerable axial compressive load in the 50^{th}-percentile male tibia.

Yogandan *et al.*, (1996) tested 26 lower legs, separated at the knee joint, under impacts to the plantar surface of the foot. The proximal tibia was fixed in polymethyl-methacrylate and mounted on a small sled ballasted to 16 kg. The pendulum impactor was faced with synthetic rubber and aligned to achieve as nearly axial loading of the specimens as possible. The results of those tests were combined with those of 26 others, using somewhat different procedures, at two other laboratories. Some specimens that did not initially fracture on impact were subjected to one or more subsequent impacts.

The combined data were represented by a 2-parameter Weibull distribution with a function of age and impact force as the variate. However, disregarding age and gender, an axial force of 6.8 kN was associated with a 50 percent probability of fracture for the combined sample of 52 specimens. It should be noted that the subjects were predominantly middle-aged and elderly males. The extremes of the range of tolerance were defined by a specimen from a 27 year-old male which experienced 10.2 kN without fracture and the specimen from a 67 year-old female that fractured at 4.6 kN. Several types of fracture of the distal tibia-calcaneus complex were observed but their frequencies were not reported.

Bending of the tibia

Mertz (1984), again citing data from Yamada (1970), and Nyquist (1985) have reported estimates of the average strength of the tibia in symmetrical, three-point bending ranging from 225 to 320 Nm. The strength of the tibia at mid-shaft was reported by Nyquist to be essentially the same in anteroposterior and lateromedial directions.

Combined compression and bending of the tibia

The Tibia Index (Mertz, 1984) cited in Directive 96/79/EC appears to follow conventional engineering practice in estimating the failing strength of a column under combined compression and bending. However, as several others, including Tarrière and Viano (1995), have noted, the Index does not properly consider the combined effects of the two types of loading. It is a straightforward matter to improve the formulation of the Index, by taking account of the difference between the tensile and compressive strengths of tibial bone (though without considering either the non-linearity or the strain-rate dependence of the strength of bone). For completeness, Appendix A provides such a formulation.

In practice, however, the improved formulation is of limited significance, since the 8 kN limit on axial force severely restricts the range of loading conditions over which the difference in the tensile and compressive strengths of bone might otherwise be significant. Appendix A also shows the effects of the arbitrary increase in the maximum permitted value of the Tibia Index from 1 to 1.3.

A more fundamental issue is the relevance of the upper and lower Tibia Indices to the types of injury commonly observed in motor vehicle collisions. While moderate upper tibia x-axis moments do occur, typically if the lower leg is trapped, the predominant reason for the occurrence of large y-axis moments (and excessive values of the Tibia Index) is the unusual geometry of the tibia in the x-z plane, as explained in Appendix B. Real y-axis bending moments are necessarily difficult to generate in the vicinity of the pin joint at the knee clevis.

At the lower transducer, the Tibia Index is only slightly affected by the unusual geometry of the tibia, the effect of which can readily be discounted, as discussed in Appendix B. However, the regulated level of 225 Nm greatly exceeds tolerable moments in either flexion or inversion/eversion. While in the longer term, some form of index might evolve to cover combinations of flexion with inversion/eversion, the current Tibia Index is, for the present, more appropriately replaced by individual limits on each of the four modes of displacement of the foot at the ankle.

In summary, it is clear from the foregoing that the Tibia Index and its associated limits are of limited relevance to the types of lower leg, ankle and foot injuries observed in motor vehicle collisions.

Displacements of the foot

As indicated above, significant injuries to the ankle and foot are associated with inversion, eversion, dorsiflexion and, less commonly, plantar flexion of the foot. Inversion is often associated with fracture of the medial malleolus, while eversion may result in fracture of the lateral malleolus. The same mechanisms may cause injury to the musculature and ligaments of the foot and ankle, whether or not fracture of either of the malleoli occurs. Dorsiflexion of the foot, induced by dynamic loading at the distal ends of the metatarsals, may result in fractures of those bones, as well as damage to the ligaments.

Parenteau and collaborators (1995) have provided some biomechanical data on which tentative tolerance levels for these modes of injury might be based. The data were obtained from quasi-static loading induced by rotation of the calcaneus in the appropriate plane and sense. Crandall et al. (1996) provided similar but rather more detailed data from volunteer subjects and cadaver specimens, though plantar flexion data were not included. The ranges of tolerable moments for inversion were generally quite similar. However, Parenteau's data were appreciably higher than Crandall's for eversion, while for dorsiflexion, Parenteau's cadaver data fell appreciably below the levels tolerated by Crandall's volunteer subjects.

The following table gives tentative tolerance levels, derived from these two sources, for the four independent modes of angular displacement of the ankle. Except in the case of plantar flexion, the values are based on Crandall's data for volunteer subjects. The angular displacement corresponding with the specified maximum moment is also given. In the particular case of dorsiflexion, the tolerable levels depend on the angle of flexion of the knee. The tolerable levels in the table therefore represent the average of results reported by Crandall (1996) for volunteers at zero and 90° of knee flexion. In the absence of actual data from volunteer subjects, the values shown for plantar flexion are estimates, based on the cadaver data, of the moment and associated displacement that might be tolerated by an average volunteer subject.

Table 1.

Tentative Tolerance Levels for Ankle Injuries

Mode	Tolerable moment (Nm)	Angular displacement (°)
Inversion	16	50
Eversion	40	40
Dorsiflexion	60	35
Plantar flexion	30	40

The subjects were young males with average weight and height approximating those of the current 50^{th}-percentile Hybrid III ATD. For purposes of comparisons between the tolerance levels and crash test data, the data in Table 1 are therefore assumed to represent 50th-percentile male occupant responses. For comparisons with the inversion-eversion responses of 5th-percentile female dummies, the tolerable moments are scaled by the appropriate factor of 0.51.

COMPARISON OF ATD RESPONSES WITH BIOMECHANICAL DATA

Axial Force in the Tibia

The work of several investigators suggests that for dynamic loading of the heel, nominally aligned with the axis of the tibia-fibula complex, limiting the maximum force to 8 kN may be expected to limit the incidence of fractures of the calcaneus and fractures of the distal tibia, with or without extensions into the anatomic joints.

In pendulum impact tests of this type, attributed to Crandall by Tarrière and Viano (1995), the maximum forces measured on Hybrid III lower legs were of the order of twice the corresponding maxima observed in equivalent tests on cadaver legs. The ranges of peak force were 5500-7700 N for the Hybrid III and 1800-2500 N for the cadavers. In tests using the Renault test device to accelerate the heel directly from an initially zero velocity, the average peak force seen by the Hybrid III was 2678 N, while the corresponding figure for the cadavers was 1398 N. Depending to some extent on how the lower leg is accelerated, it thus appears that the axial force measured on the Hybrid III tibia is 2 to 3 times greater than the value observed on a cadaveric specimen. Limiting the axial force on the ATD tibia to 8 kN should thus ensure significantly smaller axial forces in the human tibia.

Flexion and Inversion/Eversion of the Foot

Interpretation of lower tibia moments

In principle, the two moments measured at the tibia transducers, may include the effects of external forces acting directly on the tibia shaft between them. However, as Saul and Zuby (1992) have pointed out, it is not possible to determine the contribution of such forces to the forces and moments observed at the transducers. A necessary assumption in interpreting the data from the Hybrid III legs is, therefore, that no contact occurred between the tibia shaft and the vehicle structure or any other external object, during the test. (Paint transfer or other simple means can be used to detect any such contacts.) Under the assumption of no external contact with the tibia shaft, it is then reasonable to attribute the moments observed at the lower tibia transducer to the forced displacements of the foot.

As noted in Appendix B, however, both tibia transducers are displaced from the axis of the lower leg, extending from the centre of the knee clevis to that of the ankle joint. The lower tranducer is not, therefore, located at the ankle joint, but some distance above and behind it. A calculation is required to determine the moments acting at the nominal location of the ankle, assuming that the forces and moments acting at the transducer are entirely attributable to the forced displacements of the foot. In the absence of the requisite data, inertial effects are neglected.

For the dorsiflexion and plantar flexion data, the only calculation made here is to subtract the portion of the y-axis moment attributable to the axial force F_z in the tibia, as described in Appendix B. The calculation is approximate, since it ignores the inertia of that part of the leg between the transducer reference point and the centre of the ankle joint. The moment associated with the force F_x should also be considered, but F_x was measured in only two of the tests reported below.

In the case of the inversion/eversion data, from 5th-percentile female ATDs, it is required to determine the value of the x-axis moment at the ankle joint with respect to the axis between knee clevis and ankle joint. The angle between that axis and the axis of the tibia shaft, for the 5th-percentile female ATD, was 8.2°. The x-axis moment observed at the lower tibia transducer may therefore be resolved into two components, one parallel with the axis of the lower leg and one normal to that axis. The normal component of the observed moment is $M_x' = M_x \cos 8.2°$, which differs very little from M_x. Also relevant to the x-axis moment at the ankle is the lateral force F_y, measured at the lower tibia transducer. Following similar logic to that described above in estimating the flexion moments at the ankle, the effect of the lateral force F_y on the observed x-axis moment is also taken into account.

The interpretation of measurements obtained from the lower tibia transducer should be significantly improved by the recently announced additions to the standard sensor complement for the 50th-percentile Hybrid III tibia. Simultaneous measurements of the axial force at both upper and lower transducers provide information on the instantaneous axial acceleration of the tibia. The provision of both x- and y-axis bending moments at the lower transducer allows the consideration of flexion and inversion/eversion of the foot. However, the presumably unavoidable omission of F_y from the lower tibia transducer limits, to some extent, the interpretation of inversion/eversion moments.

Experimental data on flexion and inversion/eversion moments

The data of Parenteau *et al.*,(1995) and Crandall *et al.*, (1996), summarised in Section 2.2.4, provide a reasonable basis for estimating the displacements and associated moments tolerable by human subjects in these modes. However, the most recent Hybrid III foot, with 45- and 35-degree limits on flexion displacements at the ankle and a stiff rubber washer to prevent metal-to-metal contact, still provides no simulation of the resistive moments induced in the lower extremities over the range of such angular displacements. As Crandall *et al.*,(1996) show, for the Hybrid III, the moment resisting dorsiflexion is essentially zero until the displacement reaches 35°, at which point it begins to rise rapidly, tending to infinitely stiff at 45° dorsiflexion. An essentially similar response is to be expected in plantar flexion, with the limit at 35°. The same concerns are associated with the responses in inversion/eversion

Direct comparisons between the flexion moments observed in crash tests and the tentative injury levels given in Table 1 remain problematical as a result of the dynamic characteristics of the current Hybrid III foot and ankle. Notwithstanding the "soft-stop" rubber washer now embodied in the foot/ankle assembly, it is to be expected that many of the more severe exceedances of the tolerable dorsiflexion moments will continue to be associated with the abrupt change in angular velocity of the foot as it hits the rubber stop. In consequence, the observed injury measures are likely to exceed the values that would be observed if the ATD ankle provided a more progressive increase in resistive moment as angular displacement increased. Essentially similar concerns relate to the other modes of displacement of the foot.

While the comparisons that follow may, with some justification, be regarded as simplistic, they are arguably more informative as to the real risk of foot and ankle injuries than the continued use of the lower Tibia Index. As earlier noted, the current limit of 225 Nm on the value of the Index substantially overstates the moments that are tolerable without injury of the lower tibia, ankle and foot. Moreover, the Index obscures the differences among the differing moments tolerable in the four modes of displacement of the foot.

Figure 1 shows the dorsiflexion and plantar flexion moments for left and right leg pairs in 56 km/h offset frontal crashes into an EEVC deformable barrier (Welbourne, 1996). The broken lines indicate the tentative tolerance levels of 60 and 30 Nm respectively, for 50th-percentile male occupants. In these tests, it should be noted that the ankle joints were not equipped with the rubber washer at the ankle.

It can be seen that five of the ten legs exceeded the suggested dorsiflexion limit and nine exceeded the corresponding limit for plantar flexion. However, only one leg exceeded the current 225 Nm limit on tibia bending moment. Basically similar results, albeit with higher maximum moments, were observed in similar tests at 60 km/h. Referring the forces and moments to the nominal location of the ankle joint generally has the effect of reducing dorsiflexion moments and increasing plantar flexion moments, because of the predominantly negative observed values of F_x and F_z.

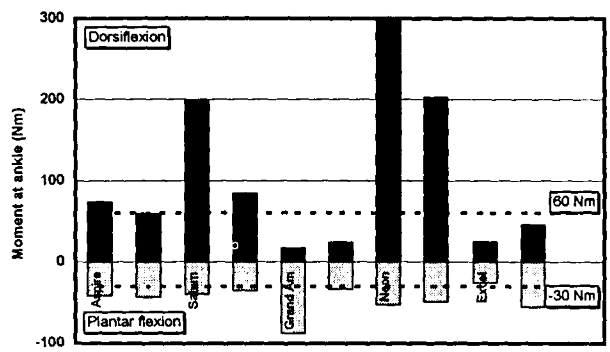

Figure 1. Dorsiflexion and plantar flexion moments in offset frontal crashes at 56 km/h into EEVC barrier.

Figures 2 and 3 show, respectively, left and right leg inversion and eversion responses of 5th-percentile female drivers in 40 km/h offset frontal crashes into EEVC deformable barriers. In considering the results, it should be noted that that speed is considerably lower than the 56 km/h specified in Directive 96/79/EC.

Eversion moments were within the tentative limits, for both feet, for all nine vehicles. For the right foot, all inversion moments were also less than the suggested 8 Nm. For the left feet, tolerable inversion moments were exceeded in four of the nine cases.

The effect of referring the moments to the nominal location of the ankle was essentially neutral for inversion of the left feet and eversion of the right. For eversion of the left feet and inversion of the right, the reference tended slightly to increase the magnitude of the moments.

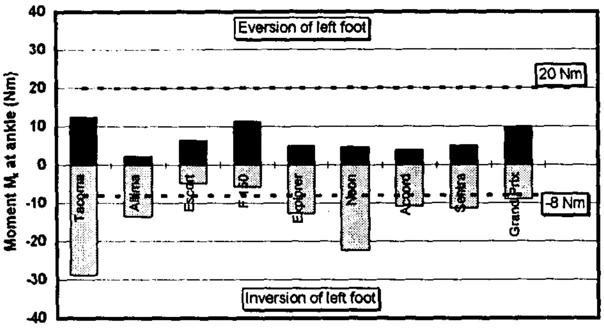

Figure 2. Inversion/eversion moments for 5th-percentile female drivers in offset frontal crashes at 40 km/h into EEVC barrier.

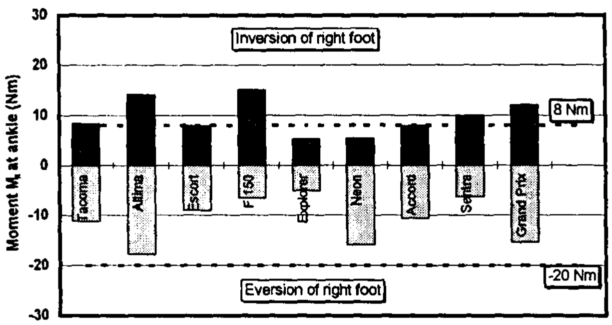

Figure 3. Inversion/eversion moments for 5th-percentile female drivers in offset frontal crashes at 40 km/h into EEVC barrier.

CONCLUSIONS

The Tibia Index is largely ineffective as a measure of the risk of injury to the lower extremities and in particular, to the foot, ankle and distal tibia-fibula complex.

The value of the Index at the upper transducer location is often inflated by the unusual geometry of the tibia, which induces a y-axis moment proportional to the axial force in the tibia. Owing to the proximity of the pin-jointed knee clevis, real y-axis moments of any significance are, however, unlikely to occur at the upper end of the tibia.

At the lower transducer location, the Tibia Index limit of 225 Nm permits moments greatly in excess of the tolerable levels for the flexion and inversion/eversion of the foot. It also serves to obscure the differences among the tolerable moments in the four modes of displacement of the foot.

Interpretation of the data obtained from the tibia transducers will be facilitated by recently announced improvements to the instrumentation of the 50th-percentile tibia. Pending the availability of more advanced ATDs for frontal impact, a modified Hybrid III ankle design providing a progressive increase in resistive moments with angular displacement of the foot would further improve the validity of flexion and inversion/eversion moments measured in regulatory tests.

ACKNOWLEDGMENTS

The crash test data presented in this paper were obtained from tests undertaken by Transport Canada personnel and, most recently, by the staff of contractor PMG Technologies. Howard Pritz of NHTSA kindly provided certain dimensional data for the 5th-percentile female tibia that could not be found elsewhere. The opinions expressed in the paper are those of the authors and do not necessarily reflect the official views of Transport Canada.

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APPENDIX A: THE TIBIA INDEX

A1 Introduction

The Tibia Index, defined by Mertz (1984) as in Equation (A1) below, appears at first sight to follow standard engineering practice in estimating the failure load of a column under combined bending and compression. It does not, however, follow that practice in accounting for the generally different strengths of materials in tension and compression. Some confusion as to the significance of the Index has therefore resulted.

It should be noted that the quantitative results given here derive directly from an assumed (though plausible) ratio of the quasi-static tensile and compressive strengths of tibial bone. Those results are, however, used purely to illustrate the consequences of considering the difference between tensile and compressive strengths. In the interests of simplicity, the analysis also preserves the convenient assumption of linear, elastic material behaviour. It is not the purpose of this Appendix to propose an alternative formulation of the Tibia Index, in view of the doubtful utility of the concept in controlling injuries of the distal tibia, ankle and foot.

A2 Tibia Failure under Combined 3-point Bending and Compression

Mertz (1984) defined the Tibia Index as:

$$TI = (F_z/35\,900 + M_r/225), \qquad (A1)$$

where F_z is the axial (compressive) force and the resultant bending moment, M_r, is given by:

$$M_r = (M_x^2 + M_y^2)^{1/2}\,. \qquad (A2)$$

In order to derive an index of the basic form of Equation (A1), it is usual to consider both the maximum stresses acting at the critical section and the strengths of the material in tension and compression. To illustrate the effect of accounting for a difference in tensile and compressive strengths, it is sufficient here to assume an arbitrary value of the ratio of compressive to tensile strengths in bending, say 1.25 to 1.

Since the tensile strength is less than the compressive strength, we conclude that the basic failure mode of the tibia in pure three-point bending is tensile. Similarly, we associate the maximum crushing force of 35.9 kN, with a compressive stress of 1.25 times the maximum tensile stress.

With the assumed ratio of the tensile strength of the tibial bone to its compressive strength of 1/1.25 or 0.8, failure of the tibia under a purely tensile force would therefore be expected to occur when that force attained a value of 0.8(35900) or 28720 N.

With the assumed linear relationship between the maximum stresses in the critical section and the bending moment at that section, tensile failure of the tibia will occur when:

$$M_r/225 - F_z/28720 = 1, \quad \text{(A3)}$$

since the compressive load F_z reduces the tensile stress at the critical section.

Failure of the tibia in compression will however, occur when:

$$M_r/225 + F_z/35900 = 1 \quad \text{(A4)}$$

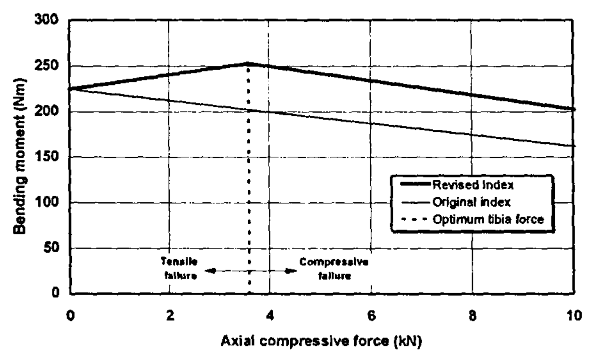

Figure A1. Revised Tibia Index.

Figure A1 shows the revised and original tibia indices in graphical form. The horizontal axis has been truncated, since the maximum axial compressive force may not exceed 8 kN.

The vertical dotted line separates the two primary failure modes, tension to the left and compression to the right. It is evident that considering the tensile and compressive failure modes separately makes a relatively modest difference to the value of the index, at least with the ratio of tensile to compressive strength assumed here. The difference is greatest at the boundary between the two failure modes, where the tolerable bending moment is 25 percent or about 50 Nm greater than if the tensile and compressive strengths of the tibia are assumed equal.

A3 Effect of Increasing the Tibia Index to 1.3

The final version of ECE R 94/01 limits the value of the Tibia Index to 1.3 rather than the conventional 1.0. The increase in the limit effectively eliminates the index as such, so that the optimum combination of axial force and bending moment consists simply of the two individual maxima. Under such loading, the value of the Index is 1.223: the value of 1.3 is not attainable without exceeding one or other of 8 kN or 225 Nm, the individual axial force and moment limits. The effect of the change is shown in Figure A2.

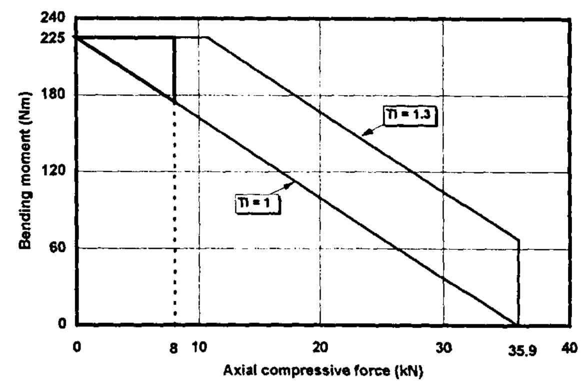

Figure A2. Maximum Tibia Index of 1.3.

The heavily outlined triangle indicates the actual extent of the increase in combined loading permitted in practice by a nominal Tibia Index limit of 1.3.

APPENDIX B: BENDING OF THE HYBRID III TIBIA INDUCED BY COMPRESSIVE FORCES

B1 Introduction

In any currently practicable ATD, gross simplifications of the human prototype are unavoidable. It is nonetheless essential that the quantities measured on the ATD and compared with proposed critical values be consistent with the injury mechanisms they are intended to control in human subjects. It is not clear that that is the case in the regulatory application of the Tibia Index currently proposed by WP29 and EEVC WG11.

In this Appendix, the primary issue of concern is the alignment, in the sagittal plane, of the compressive load paths in human and Hybrid III tibia. The consequences of the unusual geometry of the Hybrid III tibia for the observed bending moments and for the application of the injury measures discussed in Section 3 of the paper are outlined in the following sections.

B2 Geometry of Human and Hybrid III Tibiae

B2.1 Human tibia

A recent edition of Gray's Anatomy [B2] provides comprehensive descriptions of the form and function of femur, knee and tibia.

The femoral and tibial condyles, which provide the bearing surfaces for compressive forces transmitted between the two largest bones in the body, extend medially, laterally and in the posterior direction with respect to the long axes of both bones. (The small anterior extensions of the condyles are negligible in the present context.) Viewed from the side, i.e., in the sagittal or x-z plane of the leg, the posterior extension of the condyles is apparently associated with a rearward offset of the load path with respect to the long axis of the tibia, of about one quarter of the width of the tibia in that plane (op. cit., Fig. 5-70). Flexion of the knee does not appear to change the compressive load path significantly (op. cit., Fig. 4-210, Fig 5-60).

For one adult male subject of nominally 50^{th}-percentile height but lesser mass, the posterior displacement of the load path was estimated to be about 13 mm. However, given the variable cross-sections of the tibia and fibula and their irregular shape, it is not possible estimate the position of the neutral axis of the tibia-fibula complex with any confidence, from two-dimensional images. Whatever the true magnitude of the local displacement of the load path, it is almost certainly much less than the offset of the 50^{th}-percentile Hybrid III knee clevis from the long axis of the tibia. In the absence of any obvious alternative, a straight line between the knee clevis and the ankle joint is therefore used as the reference axis for the forces and moments that act on the tibia-fibula complex.

B2.2 Hybrid III tibia

Figure B1 shows the essential geometry of the Hybrid III tibia, viewed in the sagittal or x-z plane. [Anon.(1994)] It can be seen that the posterior displacement of the knee clevis with respect to the shaft of the tibia is 1.67 inches (42.4 mm). A similar, though lesser anterior displacement of the ankle joint is also apparent. The reasons for the discontinuities in the load path between the knee and ankle joints are not apparent. Their consequences with respect to the forces and moments observed at the upper and lower tibia transducers are readily demonstrated, however.

B3 Effect of Hybrid III Tibia Geometry on Injury Measures

B3.1 Static compression

In the lateral view of the tibia geometry in Figure B1 below, unit compressive forces (1 Newton) are assumed to act at the knee and ankle pivots, such that the tibia is in static equilibrium. The adjacent free-body diagram of the shaft of the tibia, shows the values of the bending moments, axial and shear forces, acting at the transducer reference points, which are required for equilibrium of the shaft under the unit forces applied at the pivots. In particular, it can be seen that a moment M_y equal to 0.02802 Nm is induced at the upper tibia transducer, a corresponding moment equal to 0.00633Nm is induced at the lower tibia transducer and that the force in the tibia shaft is 0.98944 of the force acting between the two pivots.

That part of the observed value of M_y which is attributable to an external moment may be calculated for the upper tibia as:

$$M_y' = M_y + 0.02832\ F_z. \qquad \text{(B1)}$$

where M_y is the measured moment at the upper tibia transducer and F_z is the (constant) axial force in the tibia shaft. Similarly, at the lower tibia transducer:

$$M_y' = M_y + 0.006402\ F_z. \qquad \text{(B2)}$$

The signs of the observed moments and forces are significant in the foregoing equations.

An interesting consequence of the upper tibia geometry is that the (original) maximum Tibia Index value of 1 is reached before either of the independent limits on axial force or bending moment is attained. Under a static compressive force acting between the knee and ankle joints, the index reaches unity when:

$$F_z = -6505\ \text{N};\ M_y = 184.2\ \text{Nm}. \qquad \text{(B3)}$$

Under such loading it is therefore impossible to attain the critical axial load of 8 kN in the Hybrid III tibia, without having previously exceeded the combined bending and compression limits.

Regardless of the particular loading conditions, it is desirable to refer the observed forces and moments to the knee-ankle axis and, more importantly, to the ankle joint.

B3.2 Dynamic equilibrium

Provided that no external contacts with the shaft tibia are observed during a test, an informative analysis of the dynamic equilibrium of the tibia appears feasible, given adequate instrumentation. However the subject is not considered further in this paper.

B4 References

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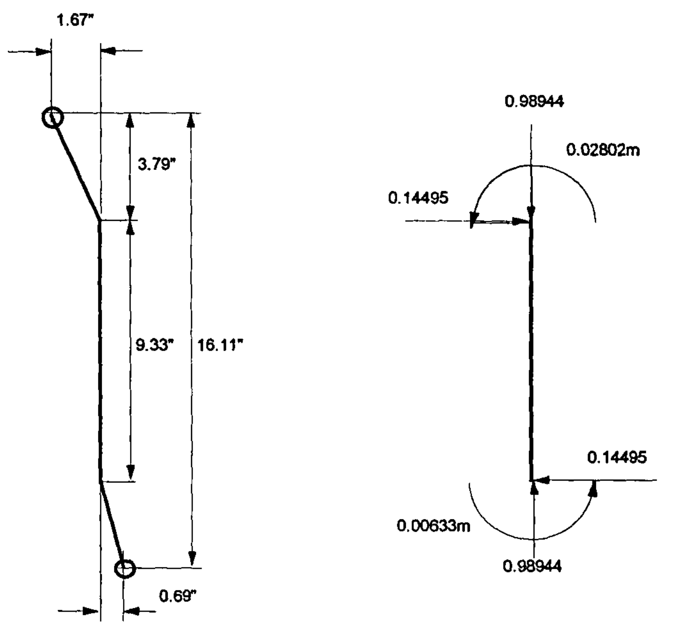

Geometry of Hybrid III tibia in sagittal plane

Free body diagram of tibia shaft with influence coefficients for unit (1N) compressive force between pivots

Figure B1. Geometry and influence coefficients for 50th-percentile Hybrid III tibia in static compression.

THE INTERACTION OF AIR BAGS WITH UPPER EXTREMITY TEST DEVICES

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ABSTRACT

This study examines and compares the response of two upper extremity test devices under driver-side air bag deployment to contribute to the development of dummy surrogates for the investigation of primary contact forearm injuries during air bag deployments. The first of these test devices, the SAE 5th Percentile Female Arm (SAE Arm), is an anthropomorphic representation of a small female forearm and upper arm that is instrumented with load cells, accelerometers and potentiometers to enable the determination of upper extremity kinematics and dynamics. The second, the Research Arm Injury Device (RAID), is a simple beam test device designed for detailed investigation of moments and accelerations resulting from close contact in the initial stages of air bag deployment. The RAID includes strain gauges distributed along its length to measure the distribution of moment applied by the air bag deployment.

The study used four air bags representing a wide range of aggressivities in the current automobile fleet. The upper extremity position was a 'natural' driving posture when turning left with one hand across the steering wheel. The forearm was positioned directly on the air bag module with the forearm oriented perpendicular to the air bag module tear seam. For the SAE Arm, the humerus was oriented normal to the steering wheel. Tests with the SAE Arm were performed both with the arm attached to a 5th Percentile Female Hybrid III dummy and with the arm mounted to a universal joint test fixture. The RAID was mounted to an articulated test fixture. In addition to the dynamic tests, a detailed comparison of the inertial properties of each of the test devices with the inertial properties of a typical small female was performed.

Forearm response from both test devices confirmed the levels of air bag aggressivity determined using previous cadaveric injury results. In addition, logistic risk functions for forearm fracture were developed using existing cadaver studies and the moment response of each test device. These risk functions indicate that for 50% risk of ulna or ulna/radius fractures, the SAE arm peak forearm moment is 61 N-m (+/- 13 N-m standard deviation) while the RAID peak forearm moment is 373 N-m (+/- 83 N-m standard deviation). For 50% risk of fracture of both the ulna and the radius, the SAE arm peak dummy forearm moment is 91 N-m (+/- 14 N-m standard deviation) while the RAID peak forearm moment is 473 N-m (+/- 60 N-m standard deviation).

INTRODUCTION

Although the use of air bag systems as supplemental restraints has significantly decreased the risk of fatality in automobile collisions, there is evidence of increased risk of non-fatal injuries including burns, abrasions, and eye injuries owing to air bag deployment. In addition, case studies suggest that upper extremity injuries, including severe fractures, may be caused by air bag deployment [c.f. **Marco 1996**, **Freedman 1995**, **Huelke 1995**, **Kirchoff 1995**, and **Roth 1993**]. Kuppa *et. al.* analyzed several accident databases to determine the incidence of upper extremity injury for accidents with and without a driver-side air bag deployment [**Kuppa 1997**]. They found that 1.1% of drivers who were restrained only by a seatbelt experienced an upper extremity injury. In contrast, 4.4% of drivers experienced upper extremity injuries in the presence of a deploying air bag.

Two modes of injury have been suggested to explain this increased incidence of upper extremity injuries with air bag deployment. The first type is a flinging type of injury in which the air bag propels the arm into an object in the vehicle (e.g. b-pillar, roof, and occupant's head). The second type is primary contact with the air bag or air bag flap; this injury may occur, for example, while executing a left turn with a continuous motion of the right hand, placing the forearm directly over the module. It is the latter group, primary contact injuries, that is the subject of the current study.

Case studies and NASS data suggest that these severe upper extremity injuries occur predominantly in women. It may be hypothesized that this represents the effects of three factors: 1) as women are generally shorter in stature than men, they drive closer to the steering wheel/air bag module, 2) women experience an age-related loss of bone mineral density, and 3) women have generally smaller bones and, hence, lower ultimate bone strength.

To investigate the upper extremity/air bag interactions causing these injuries, Saul *et al* used an instrumented 50[th] Percentile Male Hybrid III upper extremity to examine injury from direct contact **[Saul 1996]**. Using strain gauges and accelerometers, they found that bending moments and accelerations of the forearm could be accurately recorded. Moreover, a correlation was found between these values and the air bag's inflator properties, flap, and steering wheel orientation. In addition, the forearm bending moment response of the instrumented SAE 5[th] Percentile Female Arm (SAE arm) under primary air bag contact has been correlated with cadaveric injury to produce an injury risk function for small females **[Bass 1997]**.

In addition, the Research Arm Injury Device (RAID) was developed by Conrad Technologies Inc. and NHTSA to investigate the interaction between a deploying air bag and an upper extremity in close proximity to the air bag **[Kuppa 1997]**. They found that the two most significant determinants of peak measured bending moment were the orientation of the arm with respect to the air bag module and the separation distance between the two. Maximum moments were recorded when the forearm was positioned perpendicular to the air bag module. This situation occurs, for example, when making a left turn with the right hand. In this situation, the right and left sides of the air bag are at the 1 and 7 o'clock positions respectively, while the hand and elbow are at the 10 and 4 o'clock positions respectively. The maximum moments also decreased as the distance between the air bag and the forearm was increased from 1.3 cm to 7.6 cm.

It is likely that a specific air bag design is developed with a view toward total restraint system effectiveness. As different passenger automobiles have different physical sizes and stiffness, this results in installed air bags of different deployment properties (e.g. pressure-time histories, module design, and deployment characteristics) among vehicle models. Four OEM air bag types were used in this study; these air bags were identified using RAID testing as representing a wide range of aggressivities in the current passenger car fleet. Using a previously created coding scheme **[Bass 1997]**, these systems are termed System H, System K, System J, and System L air bags. The System H and System K air bags produce relatively more aggressive air bag deployments, the System J air bag produces a moderately aggressive deployment, and the System L air bag produces a relatively less aggressive deployment. In addition, the System H air bag has been identified in case studies as producing primary contact upper extremity injuries under certain circumstances.

The principal goal of this study is to examine the suitability of both the SAE arm and the RAID in characterizing the forearm forcing during air bag primary contact using OEM air bag systems. In addition, this study quantifies the dynamic response of dummy upper extremities under air bag deployment in a 'worst-case' position. Also, the study investigates factors that affect injuries in cadaveric upper extremities and develops a correlation of these injuries with dummy response using the SAE Arm and the RAID. As there are a number of design factors that may influence the upper extremity injury potential of a given air bag, including inflator properties, air bag properties and module properties, we have chosen to focus on dummy and cadaveric response criteria as the most effective measure of injury risk.

The testing was performed in two major parts. The first includes tests of the RAID test device under air bag deployment in a representative 'worst-case' position for air bag deployment. The second is a study of the same set of deploying air bags into the SAE arm mounted on a Hybrid III dummy and tests with the SAE arm attached to a universal joint arm fixture developed for cadaveric studies **[Bass 1997]**. This second series of tests involves forearm positioning similar to that prescribed for the RAID testing.

TEST DEVICES

Several instrumented dummy arms exist that are appropriate for use in arm/air bag interaction studies; these include the 50% Male Hybrid III Instrumented Arm **[Saul 1996, Johnston 1997]**, the Research Arm Injury Device (RAID) **[Kuppa 1997]**, and the SAE 5[th] Percentile Female Instrumented Arm (SAE arm) **[Bass 1997]**. As the epidemiogical analysis of air bag-induced upper extremity injuries suggests that small females suffer injuries at a much greater rate than males, this study investigates the use the SAE arm and the RAID as suitable dummy surrogates for the development of risk functions using previously reported small female cadaveric injury studies **[Bass 1997]**.

A diagram of the SAE arm is shown in *Figure 1*. Pronation/supination of the forearm is provided by a single degree-of-freedom axial 360^0 rotation in the wrist. The forearm is a single shaft incorporating a six-axis load cell located approximately mid-shaft. The elbow is a single degree-of-freedom clevis joint allowing elbow flexion/extension with a soft joint stop in each direction. This elbow motion may be measured using a potentiometer incorporated into the elbow. In addition, strain gauges to measure two bending axes are located in the distal humerus. The humerus is a single shaft with a six-axis load cell approximately midshaft. At the proximal end of the humerus, two degree-of-freedom rotations are allowed by a 360^0 axial rotation at the top of the humerus shaft and a clevis joint at the shoulder. In addition to the existing instrumentation on the SAE arm, the current study added a distal triaxial accelerometer and a single-axis MHD angular rate sensor mount located one third of the distance from the wrist to the elbow. Additional accelerometer mounting locations in the elbow were not used.

Motions allowed by the SAE arm listed in *Figure 2* are approximately anthropomorphic with the exception of pronation/supination and shoulder motions. For pronation/supination, the existence of a single shaft forearm limits both the availability and the utility of forearm rotations located outside the wrist. Though the predominant flexion/extension motions and upper humerus rotations are represented in the SAE dummy shoulder, the human shoulder has three degrees-of-freedom in rotation and limited translation that is not seen in the dummy.

In contrast, the RAID, shown in *Figure 3*, has a more limited range of motions. Developed as an investigative tool to study primary contact arm/air bag interactions, the RAID is constructed of a 3.2 mm thick aluminum tube of 51 mm diameter with a two degree-of-freedom clevis joint to allow rotational motion along two axes. The mass of the tube (1.6 kg) was chosen to approximate a 50^{th} percentile male human forearm. To simulate the effects of a hand, a small additional mass (0.5 kg) is attached to the free end of the RAID. The length of the RAID was selected as 460 mm to protect the pivot attachments from the deploying air bag. The RAID instrumentation includes five stations of diametrically opposed strain gages to measure moments along two axes. In addition, rotations are measured by two angular potentiometers, and triaxial accelerations are measured at the approximate mid-length of the RAID. The RAID is covered with 20 mm of foam and rubber skin similar to that on the Hybrid III mid-forearm.

As the RAID incorporates simple two-dimensional rotation, the RAID simulates only the forearm degrees of freedom associated with elbow flexion/extension and shoulder abduction/adduction. So, while the RAID may be appropriate for primary contact with a deploying air bag, it is likely not appropriate for later interactions involving additional upper extremity degrees of freedom.

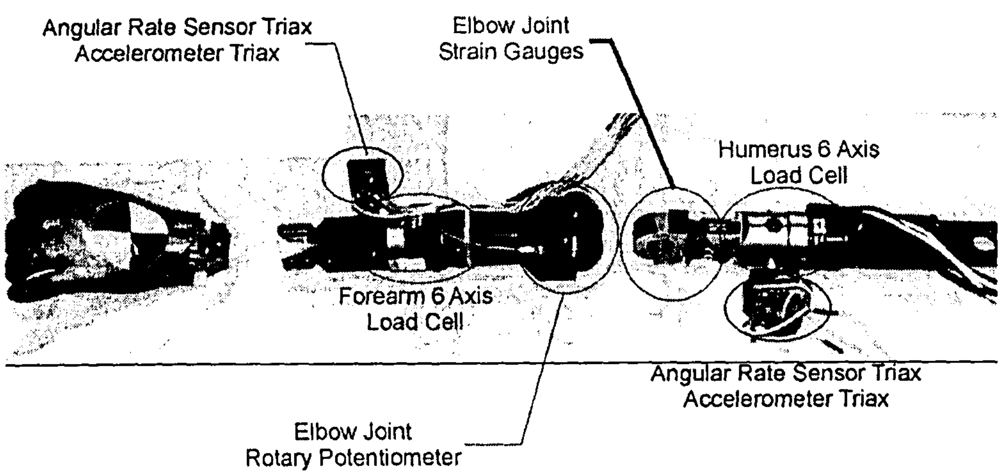


***Figure 1.** Picture of the SAE 5th Percentile Female Instrumented Arm (SAE Arm).*

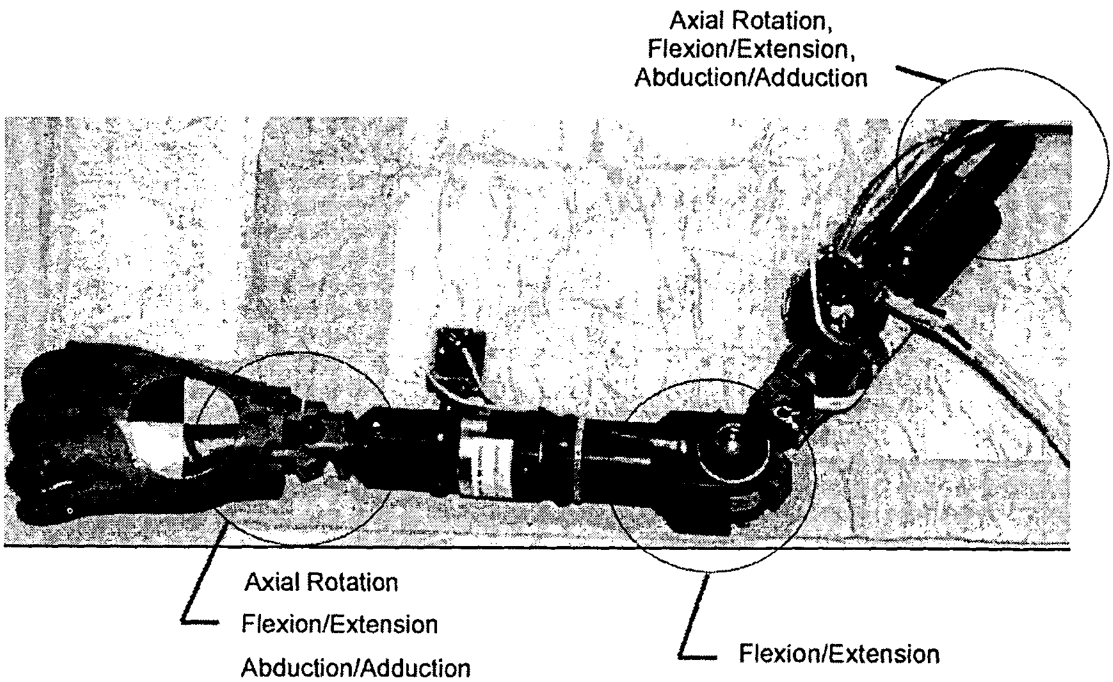


Figure 2. *Motions of the SAE 5th Percentile Female Arm.*

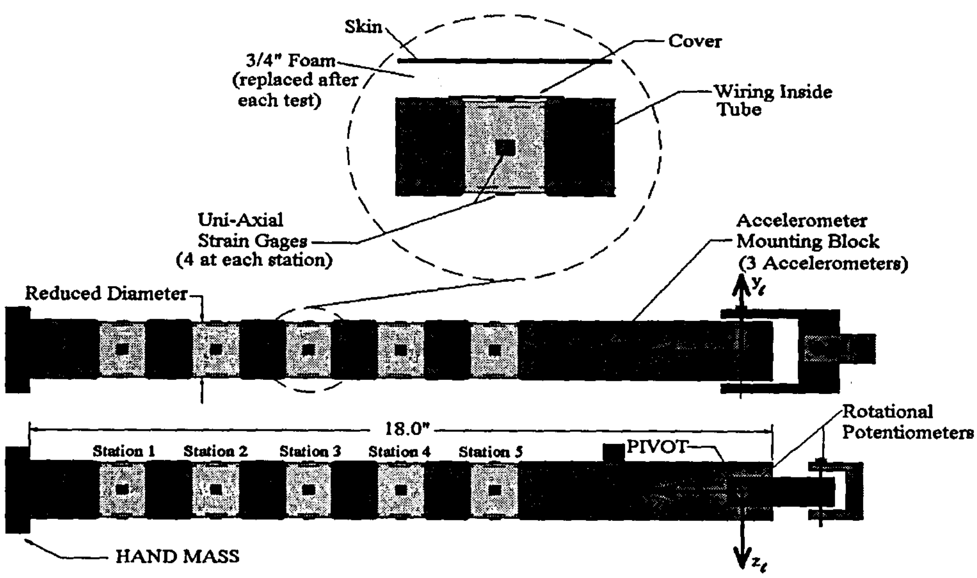


Figure 3. *Research Arm Injury Device (RAID).*

A comparison of the segment masses of the SAE arm and the RAID with the 5th and 50th percentile female population are shown in **Error! Reference source not found.**. The SAE arm is substantially heavier than the reference 5th percentile female population but is similar to the reference 50th percentile female population. The RAID, however, was designed to simulate a 50th percentile male. So the RAID is substantially heavier than the forearms of the reference female populations.

Reference forearm and hand lengths shown in **Error! Reference source not found.** were derived from an anthropometric study on 1905 USAF women **[McConville 1979]**. For the human population, the forearm length is taken to be the distance from the tip of the olecranon to the tip of the ulna styloid process, and the hand length is the distance from the ulna styloid process to the middle finger of the outstretched hand. The dummy arm measurements are taken from the rotation centers.

The total forearm/hand length of the SAE arm of 405 mm is comparable to the 5th percentile female length of 397 mm but over 20 mm less than the forearm/hand length of the reference 50th percentile female. In contrast, the total length of the RAID (460 mm) is much larger than the forearm/hand length of the reference female population and is comparable to the forearm/hand length of a 50th percentile male population (491 mm) but significantly larger than the forearm length of a 50th percentile male population (299 mm). So, the SAE dummy forearm is similar to a 5th percentile female population in length but a 50th percentile female population in mass ,while the RAID is, by design, similar to the 50th percentile male in mass and forearm/hand length.

Table 1. *Comparison of Reference and Dummy Arm Anthropometry*

Arm	Mass (kg)			Length (mm)		
	Forearm	Hand	Total	Forearm	Hand	Total
Reference 5th % Female[1]	0.71	0.28	0.99	227	170	397
Reference 50th % Female[1]	0.90	0.36	1.26	244	184	428
Reference 50th % Male[1]	1.3	0.5	1.80	299	192	491
SAE Instrumented 5th % Female Arm	1.08	0.41	1.49	240	165	405
RAID[2]	1.6	0.5	2.1	460		460

Three-wire torsional pendulum studies were performed on the segments of the SAE arm to determine inertial properties in the principal axes. Axes of rotation passing through the segment center of gravity define all moments, and the reference female forearms are oriented in the neutral position. The x and y principle axes of the dummy and reference female forearms are approximately normal to the anatomical axis running along the forearm. The z principle axis is approximately tangential to this axial axis. Moments of inertia were calculated for the RAID assuming a uniform aluminum cylinder.

For primary contact injury under air bag deployment, kinematics observed in previous dummy and cadaver studies [c.f. **Bass 1997**] indicates that there is no significant motion of the humerus prior to peak moments or cadaveric injury. So, the inertial properties of the upper arm are negligible in the investigation of surrogate response under primary contact air bag deployment. Also, the dynamic significance of pronation/supination (axial rotation of the forearm) motions is minimal in primary contact studies, so the principle moment of inertia about the axial axis is of limited significance in this study.

For the SAE arm, the influence of the mass of the centrally located load cell on the x and y principle moments of inertia is clear. Though significantly heavier than the reference 5th percentile female reference population, the SAE arm has x and y moments of inertia that are comparable to the reference 5th percentile female population. A significant portion of the mass of the SAE forearm is included in this load cell. The z (axial) moment of inertia of the SAE arm, however, is larger than the 5th percentile female owing to the size of the SAE arm. In addition, owing to the substantial mass of the SAE hand, principle moments of inertia in the x and y axes are much larger than those of the reference 5th percentile female population, and are more comparable to those of the 50th percentile female.

For the RAID, the length is significantly greater than the forearm of either female reference population or that of a 50th percentile male. So, the moment of inertia of the RAID forearm segment is substantially larger than that of either reference female population. In air bag tests, this

[1] **[McConville 1979]**

[2] RAID is single segment.

will likely result in lower peak velocities and possibly much larger moments. This imposes an additional limitation on the use of the RAID in the investigation of 'flinging' injuries in which maximum velocity plays an important role in injury mechanics. The RAID axial moment of inertia (z axis) of 1040 kg-mm^2 is commensurate with a 50th percentile male value of 1180 kg-mm^2 **[McConville 1979]**. The 'hand' mass of the RAID can be considered to be concentrated at the end of the RAID for the purpose of this study as the test device allows only rotations about the other end.

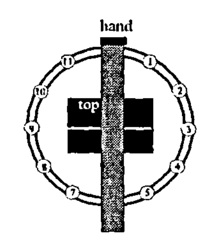
Table 2. *Principle Moments of Inertia*

	Forearm Principle Moment of Inertia (kg mm^2)			**Hand Principle Moment of Inertia (kg mm^2)**		
Arm	**x**	**y**	**z**	**x**	**y**	**z**
Reference 5th % Female[3]	3100	2900	410	340	280	94
Reference 50th % Female[1]	4700	4600	630	530	430	150
Reference 50th % Male[1]	8850	8610	1180	1040	850	290
SAE Instrumented 5th % Female Arm	2800	2300	550	970	450	55
RAID	28200	28200	1040	NA	NA	NA

EXPERIMENTAL SETUP

Both the RAID and the SAE arm attempted to attain a 'worst-case' test condition and hence a 'worst-case' response under air bag deployment. The test position selected is roughly a 'natural' driving position in a one-armed left turn maneuver modified for enhanced repeatability and 'worst-case' behavior. The SAE forearm was placed directly on the air bag module with the forearm oriented perpendicular to the air bag tear seam as shown in *Figure 4*. The distal third of the SAE forearm was placed over the module tear seam, and the humerus was oriented normal with respect to the plane of the steering wheel. In this configuration, the dummy fingers do not reach the steering wheel for any of the OEM air bags tested. Positioning was maintained using frangible tape.

This position represents the 'worst case' or most vulnerable position for four reasons. First, previous RAID testing indicated that bending moments were maximized when the test device was oriented perpendicular to the air bag tear seam **[Kuppa 1997]**. Second, RAID bending moments under air bag deployment were found to decrease as the test device was moved away from the module. Though the RAID was placed at distances 13 mm and greater from the air bag module, out-of-position thoracic testing **[Melvin 1993, Bass 1998]** suggests that positioning directly on the air bag module may constitute a worst case for certain occupant/air bag interactions. Third, the distal third of the human forearm is the weakest location in bending with the lowest combined polar moment of inertia of both the radius and ulna, providing the greatest risk of fracture. Fourth, the humerus oriented normal to the steering wheel provides a support for the forearm under air bag deployment forcing the initial center of forearm rotation to be about the elbow with a relatively long moment arm.



Config. V

Figure 4. *Test Configuration - Arm Relative to Steering Wheel.*

Eight of ten SAE arm tests were performed on a universal joint test fixture diagrammed in *Figure 5*. The fixture is comprised of two components. The first supports the steering wheel/air bag module on a five-axis load cell. The second mounts the arm to a four degree-of-

[3] **[McConville 1979]**

freedom universal joint. A five-axis humerus load cell was mounted at the interface between the SAE arm and the universal joint at the shoulder. For the fixture tests, the center of rotation of the universal joint was located at a position equivalent to the center of rotation of the Hybrid III shoulder joint relative to the humerus. The remaining two tests were performed with the SAE arm attached to the Hybrid III 5th percentile female dummy.

One possible objection to the use of the test fixture is that, for experimental convenience, the location of the point about which the shoulder rotates is fixed in space. In a natural driving condition, the shoulder is relatively free to translate in response to forcing. This translationally fixed shoulder was examined using the Articulated Total Body (ATB) lumped-mass simulation program as shown in *Figure 6*. The figure shows a comparison of the humerus axial force for a subject with a shoulder fixed in translation versus a shoulder free to translate under the action of a deploying air bag. There is little difference in humerus response between the two cases, especially in the crucial initial deployment period. This result justifies using a shoulder that is fixed in translation for the experimental setup.

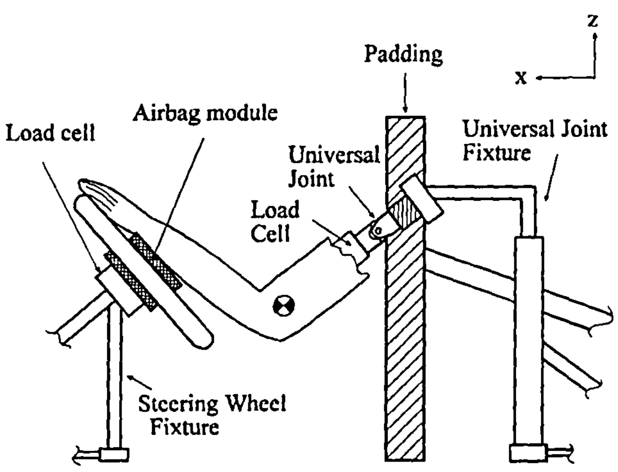


Figure 5. *Arm/Air Bag Test Fixture.*

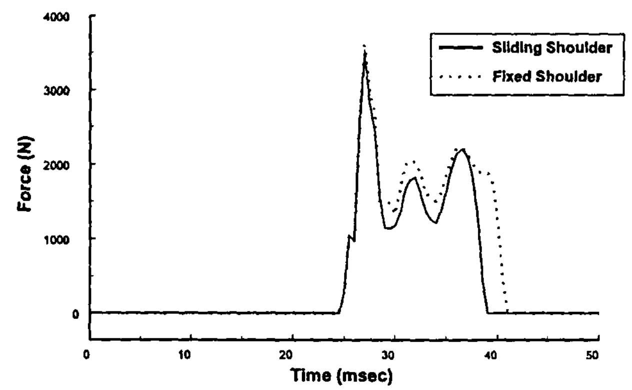


Figure 6. *ATB Simulation of Fixed vs. Sliding Shoulder.*

A side view of the test setup with the RAID is shown in *Figure 7*. The RAID hangs vertically in front of the steering wheel and rotates at the mounting pivots. The test device may be translated in three dimensions to achieve desired positioning with respect to the air bag module. For this study, the distance from the surface of the RAID to the plane of the steering wheel rim was set to 13 mm to achieve 'worst case' response. Positions closer to the steering wheel were not investigated. The steering wheel was oriented as shown in *Figure 4* with the RAID perpendicular to the air bag tear seam. As with the SAE arm tests, a five-axis load cell was located behind the steering wheel to measure reaction forces. The time of air bag cover opening was determined using break wires over the tear seam. In addition, a backstop with foam padding was used to stop the RAID after the test.

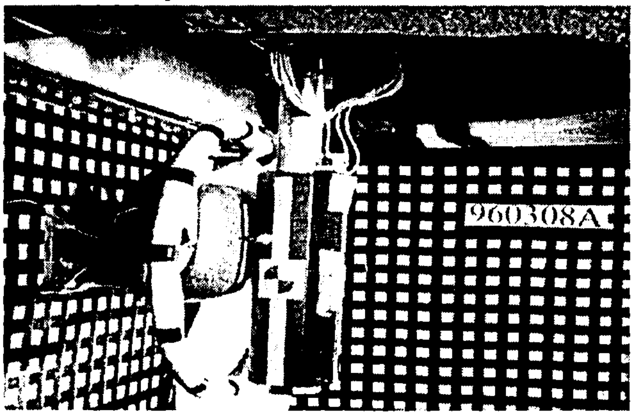


Figure 7. *Side View of RAID.*

EXPERIMENTAL RESULTS

Four OEM air bags that are representative of a wide range of air bag aggressivities in the current automobile fleet were used in the testing. These air bag systems, in order of decreasing aggressivity identified in previous RAID testing **[Kuppa 1997]**, are denoted System K, System H, System J, and System L. The air bags were mounted in original equipment steering wheels appropriate for the air bag tested. Inflator performance of each air bag system from tank testing (60 L tank) is shown in *Figure 8*. Tank tests for System J are not available. Tests on the remaining inflators confirm the ordering of aggressivity suggested in the RAID testing. The System K inflator is very aggressive with a high peak pressure and a high pressure onset rate. During this study, several System K air bags burst around the vent holes during deployment. System H inflators are also very aggressive with peak pressures slightly lower than those seen in System K inflators but with a high pressure onset rate. The System L inflator is relatively non-aggressive with a very low peak pressure and onset rate.

There are significant differences in the air bag modules, especially the location of the module tear seam as shown in *Figure 9*. The tear seams for the System K and System L modules are approximately mid-way between the top and the bottom of the module. In contrast, the System H module has a very large and heavy flap with a low tear seam. This large flap has been found to provide some protection during the initial air bag deployment to cadaveric arms under air bag deployment **[Bass 1997]**. System J has a relatively small vertically oriented tear seam with wide side flaps. The air bags are all similar in height and width, and the steering wheels are similar in dimension. Only the System J air bag is untethered.

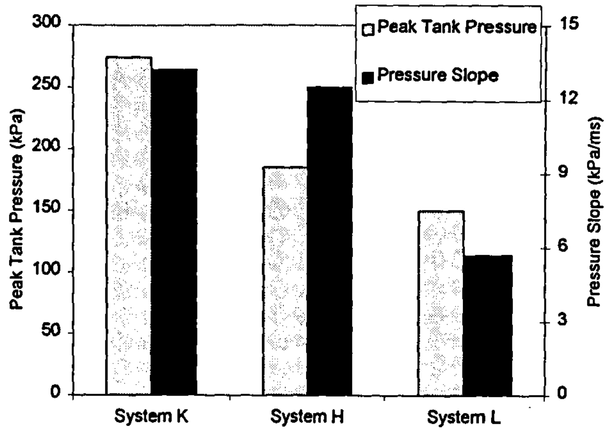


Figure 8. *Static Tank Pressure and Pressure Slope Curves – Values Based on a 60 L Tank, Pressure Slopes Derived from Maximum 10 ms Values.*

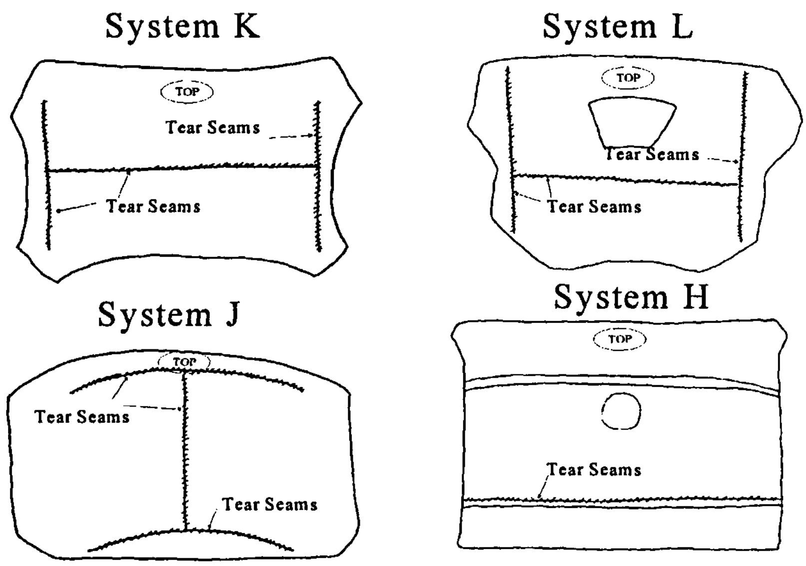


Figure 9. *Sketches of Air Bag Module Covers Indicating the Tear Patterns.*

Table 3. *Characteristics of Air Bag Modules (All Measurements in mm)*

Air Bag System	System H	System L	System K	System J
Diameter of steering wheel	380	380	387	397
Location of module plane wrt. wheel	3.2 above	9.5 above	6.4 above	6.4 above
Distance from top of rim to tear line	259	238	222	200
Vertical height of module	178	152	152	152
Horizontal width of module at seam	203	171	191	216
Distance from top of module to seam	138	91	78	108
Thickness of flaps	3.2	4.4	5.1	3.2
Vertical height of air bag	686	699	635	660
Horizontal width of air bag	686	635	660	635
Number of tethers	4	2	3	none
Length of tethers	267	279	318	--

System K, System H, System J, and System L air bags were each tested twice with the SAE arm mounted on the test fixture used in previous cadaveric tests. In addition to the fixture tests, one System H air bag and one System L air bag were deployed into the SAE arm mounted on a 5th Percentile Hybrid III dummy. For the RAID, one test was performed using each of the air bag systems in this study. In addition to these tests, several repeatability tests were performed with the System K and System J air bags.

A typical deployment for both test series begins with a bulge in the air bag module following air bag initiation. Then, the air bag deploys through a scored tear seam oriented perpendicular to the forearm. In the initial stages of air bag inflation with the SAE arm, there is no significant humerus motion, and the forearm begins to rotate about the elbow until it reaches the joint stop. After the elbow reaches the joint stop, the humerus begins rotating toward the center of the steering wheel. This continues until the SAE arm hits the dummy in the Hybrid III tests or the backstop in the fixture tests. For the RAID, the deployment rotates the arm until the arm contacts the padded backstop. For the SAE arm mounted to the Hybrid III, there is no substantial shoulder movement until the air bag deploys into the dummy chest. Moment time histories from both test devices suggest that the greatest forces on the forearm occur during the air bag punch-out and shortly thereafter.

All air bags deployed normally except for one of the System K air bags in the SAE arm testing. As seen in a previous cadaveric test series [**Bass 1997**], the System K air bag suffered large tears during the deployment originating at the reinforced seam around the peripheral vent holes. In spite of these holes, the air bag appeared to inflate fully.

Peak resultant forearm bending moments for both the SAE arm and the RAID are presented in ***Error! Reference source not found.***. For repeated tests within each air bag system using the SAE arm, these moments are consistent, showing a maximum difference of approximately 10%. Peak humerus axial loads for the SAE arm are not as consistent since they are associated with the details of the air bag/elbow joint stop interaction at times greater than injury times identified in cadaveric tests. So, these peak humerus axial loads are not generally relevant to primary contact injuries.

Peak moment values for the RAID are much larger than those measured using the SAE arm. This is likely the result of the RAID having greater mass and moments of inertia than the SAE arm. In addition, the ordering of aggressivity quantified using peak moments of the System K and System H air bags is reversed in the RAID from that found using the SAE arm. This is likely the result of a heavier air bag module cover with a lower air bag seam than the rest of the test devices. As the SAE arm testing placed the distal third of the forearm on the air bag tear seam while the RAID maintained uniform radial placement with respect to the steering wheel, the larger, lower flap of the System H air bag tends to increase peak moments for the RAID relative to the SAE arm. However, the peak moments derived from testing using the SAE arm and testing using the RAID, compared in *Figure 10*, show a correlation coefficient of 0.90 indicating similar peak moment response.

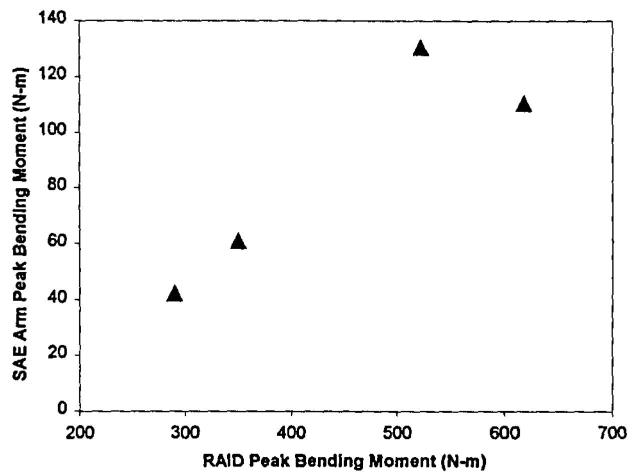


Figure 10. Peak Forearm Moments of the SAE Arm and RAID.

Forearm moment time histories for each of the systems tested are plotted in *Figure 11* for the SAE arm and in *Figure 12* for the RAID. As expected, the peak SAE arm forearm bending response of System K and System H is significantly greater than that seen in System J or System L. Large peak moments after 15 ms are associated with the SAE arm elbow reaching the joint stops. Interestingly, the peak forearm moments from the System K tests are much earlier than those seen in the System H tests. High-speed video analysis indicates that while peak bending moments occur during module cover/arm interactions for System K, the peak moments for System H occur after the time that the arm interacts with the module cover. This indicates that while the module cover may play a role in injuries, module cover interaction may not be necessary for such primary contact injuries.

For the RAID, the timing of forearm moment peaks is similar to those found with the SAE arm. The System K air bag has the earliest peak, and the System H air bag has the latest peak moments. Though the order of peak forearm moment was switched between System L and System J air bags for the RAID and SAE arm, the timing of these peak moments was similar. Both the SAE arm and the RAID show peak moments for System H after the time of arm/module cover interaction.

In contrast, with the System K air bag, the second moment peak appears later for the SAE arm than for the RAID. Because the acceleration of the SAE arm is much greater than that of the RAID, the RAID is closer to the inflator when the air bag emerges from the module cover, producing earlier peak moments. The kinematics of the SAE arm appear to be more consistent with cadaveric test results. In addition, the SAE arm moment peaks generally maintain the order of aggressivity found in previous cadaveric testing.

As expected from the inertial properties, the peak accelerations shown in **Error! Reference source not found.** using the SAE arm are substantially larger than the peak accelerations found using the RAID even though the accelerometers were placed in similar locations. The RAID has a 40% greater forearm/hand mass and nearly ten times the forearm lateral moment of inertia. For the SAE arm, the accelerations generally maintain the order of aggressivity found in previous cadaver tests. The relatively aggressive System K air bag demonstrated over twice the peak forearm acceleration than the other three air bag systems tested. The System H and System J air bags showed comparable peak accelerations; however, the more aggressive System H air bag delivered approximately 10% more peak impulse to the distal forearm than the System J air bag during the first 15 ms of deployment. The similarity of peak accelerations with dramatically different peak moments may be accounted for by differences in air bag deployments between System H and System J. From high-speed video, the System J air bag appears to deploy in a smaller forearm area than do the System H air bags. One likely source of this difference is the lack of tethers in the System J air bag. This concentration of air bag deployment may lead to increased risk of fracture relative to a tethered bag. In addition, the System H air bag deploys generally more distally than the System J air bag when accounting for the difference in SAE forearm position with respect to the steering wheel. This effect is not present in the RAID tests as the test device was not adjusted radially to account for the differences in air bag tear seam location. The less aggressive System L air bag demonstrated peak accelerations and impulses that were substantially lower than the other air bag systems.

Table 4. *SAE Arm and RAID Peak Response Data*

Value	Test Device	System K	System H	System J	System L
Peak Forearm	SAE arm	131	111	61.0	42.5
Moment (N-m)	RAID	522	617	350	280
Peak Distal	SAE arm	450	187	208	137
Accel. (g's)	RAID	137	183	65	57
Peak Humerus	SAE Arm	2110	1660	1680	940
Axial Load (N)	RAID	NA	NA	NA	NA

Measured shear loads in the SAE dummy forearm were relatively low, under 800 N for all tests. Such shear loads are unavailable in RAID instrumentation. These low forearm shear loads are likely the result of the center of pressure of the air bag deployment being close to the center of the load cell.

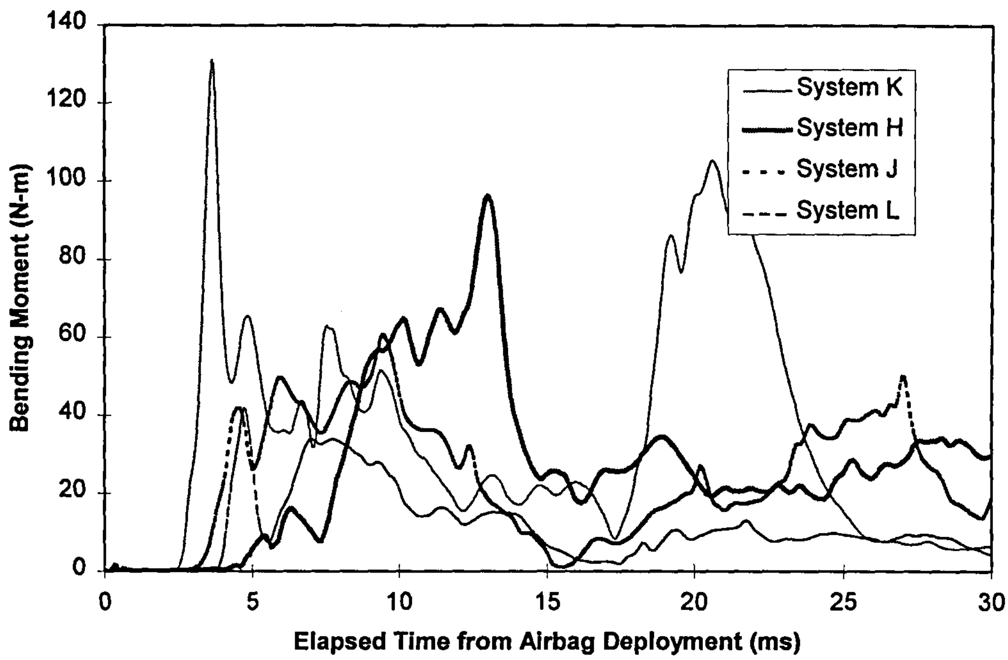


Figure 11. SAE Arm Midshaft Forearm Resultant Bending Moment (All Signals Filtered to SAE CFC-600).

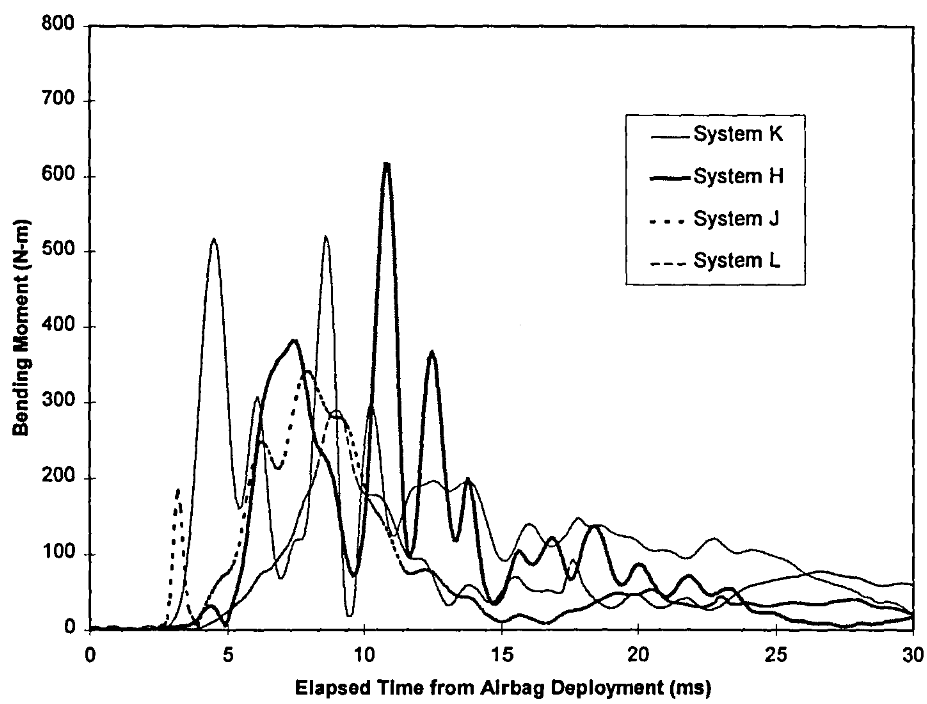


Figure 12. RAID Midshaft Forearm Resultant Bending Moment (All Signals Filtered to SAE CFC-600).

SAE elbow flexion is shown in *Figure 13* under System H air bag deployment for typical dummy and cadaver tests. The two tests see peak flexion angles of approximately 50° with similar timing. The minimal effect of the soft joint stop is seen in the System H tests. The SAE arm enters the joint stop region of 40° flexion at approximately 18 ms and reaches the limits of travel at approximately 23 ms. In contrast, the effect of the joint stop on the SAE arm is seen clearly in the System K air bag deployment. The slope of the flexion is substantially larger than that seen in the System H dummy tests, so the arm attains larger velocities and hence larger forearm bending moments entering the joint stop. On the other hand, all dummy tests see the elbow reach the joint stop later than 20 ms from the time of air bag deployment. As this time is much later than the time of primary contact injury as determined in the cadaveric tests, the behavior in the joint stop is not relevant for research into primary contact injuries. So, although flexion to simulate a human elbow is not expected to be biofidelic with the RAID, these results suggest that the lack of a biofidelic humerus may not detract from use of the RAID as a diagnostic device for investigation of primary contact air bag injuries.

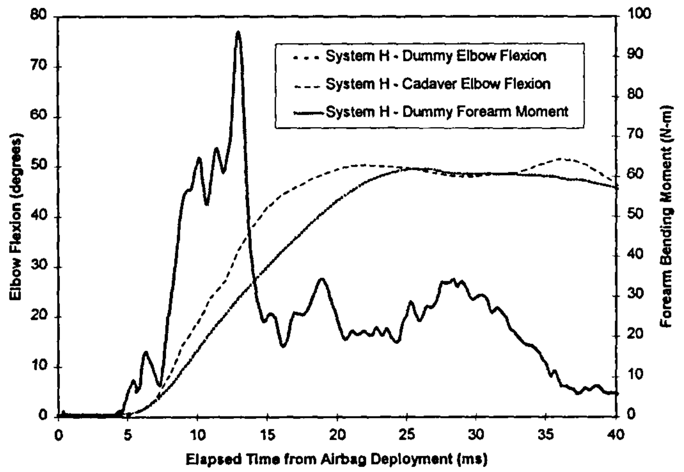


Figure 13. *SAE Arm - System H - Dummy vs. Cadaver Elbow Flexion and Dummy Forearm Moment (Moment Filtered to SAE CFC-600, Flexion Angles Filtered to SAE CFC-1000).*

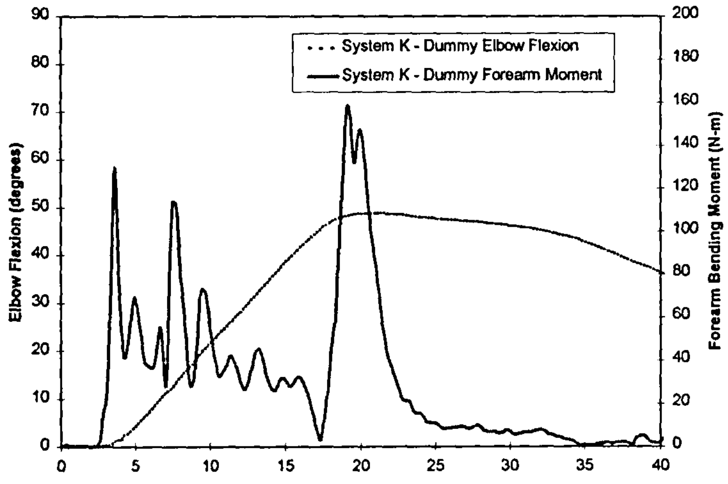


Figure 14. *SAE Arm - System K - Dummy Elbow Flexion and Dummy Forearm Moment (Moment Filtered to SAE CFC-600, Flexion Angles Filtered to SAE CFC-1000).*

Figure 15 shows the similarity of the responses of System L air bag deployments into the SAE arm with the arm on the dummy compared to the arm mounted to the universal joint fixture. This suggests that such fixture tests are appropriate for simulation of primary contact arm/air bag interactions. The three tests show resultant forearm peak moments that are within 14%, and the timings of the initial peaks are within 2 ms. Similar repeatability in the resultant forearm moments is seen in the System H tests. These results provide additional evidence that the use of the fixed test fixture with the SAE arm is appropriate for investigation of primary contact arm/air bag interactions.

In addition, with the System L air bag, we can separate the effects of arm/flap and arm/air bag interaction. The first peaks in bending moment are the result of flap deployment into the arm, ending at approximately 7 ms as identified from high-speed video analysis. The second peaks, however, are solely the result of arm/air bag interaction. These second peaks rival the first in magnitude for each of the tests and have substantially greater impulse.

For the RAID, the results of two repeated tests using System K air bags are shown in *Figure 16*. The initial peak in resultant moment in repeated tests using the System K air bag shows only 3% difference in value and 0.1 ms difference in peak timing. In addition, the second peak shows less than 10% difference in value with a 0.5 ms difference in peak timing. Additional repeated tests with the System J air bag showed good repeatability in both peak values and timing. So, both the RAID and the SAE arm showed good overall repeatibility.

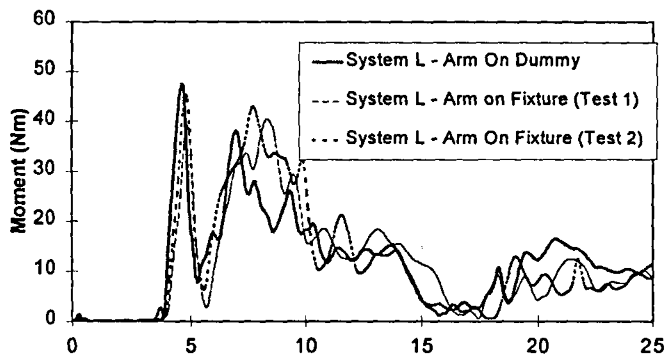


Figure 15. SAE Arm - Forearm Resultant Moment - Arm on Dummy vs. Arm on Fixture (Signals Filtered to SAE CFC-600).

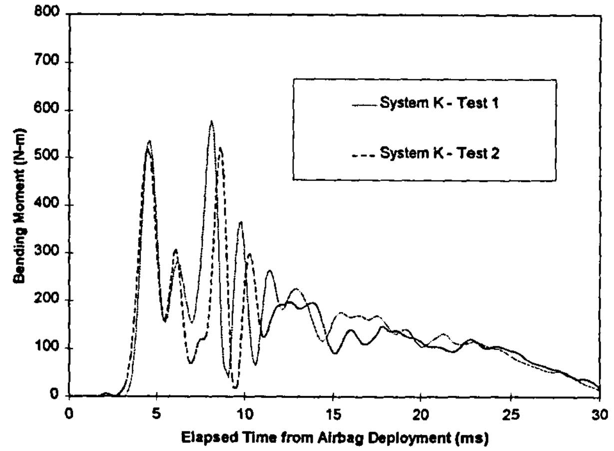


Figure 16. RAID Repeatability – Forearm Moment Response for System J Air Bag Deployment.

INJURY RISK FUNCTIONS

Since the currently reported arm/air bag tests were performed in nominally the same condition as previous cadaveric tests **[Bass 1997]**, we can correlate the injury results from the cadaveric testing with the average peak forearm bending moments resulting from air bag deployment into the SAE arm and the RAID. This is further justified by the strong correlation between the peak forearm moment response of the SAE arm and the RAID. For the forearm bending moments, we use all the tests with the System K, System H, System J, and System L air bags as seen in ***Error! Reference source not found.***. For the cadaveric forearms, we limit the injury sample to the 11 small female cadaveric subjects tested with the same air bags on the SAE arm test fixture. For a model of fracture/no fracture, the cadaveric response shows complete separation at an average SAE arm peak forearm moment value of 61 N-m. If, however, we assume a polytomous process where the level of fracture in the cadaveric tests is associated with the average bending moment for the repeated tests with a given air bag, we obtain the logistic regression for the probability of either an ulna or an ulna/radius fracture for the SAE arm as shown in *Figure 17*. The result is statistically significant to $p=0.02$. The regression suggests a 50% risk of at least one fracture at 67 N-m (+/- 13 N-m Standard Deviation) forearm moment in the SAE arm under the same test conditions. The risk of both radius and ulna fracture using the same model for the SAE arm is shown in *Figure 18*. This curve suggests that there is a 50% risk of both radius and ulna fracture at 91 N-m (+/- 14 N-m Standard Deviation) peak forearm bending moment in the SAE arm. For both logistic risk curves, the one standard deviation confidence intervals are plotted.

Injury risk functions for the RAID using peak moment values correlated with cadaver injury data are shown in *Figure 19* and *Figure 20*. These risk functions indicate that for 50% risk of ulna or ulna/radius fractures, the RAID peak forearm moment is 373 N-m (+/- 83 N-m standard deviation). For 50% risk of fracture of both the ulna and the radius, the RAID peak forearm moment is 473 N-m (+/- 60 N-m standard deviation). The results are statistically significant to $p = 0.06$, and the one standard deviation confidence intervals are plotted.

Table 5. *Test Device Peak Bending Moments vs. Cadaveric Injuries [Bass 1997].*

Air Bag	Average Peak Forearm Bending Moment (N-m) SAE Arm	RAID	Cadaver Tests	Ulna/Radius Fractures
System K	131	522	2	2/2
System H	111	617	3	3/2
System J	61.0	350	4	2/1
System L	42.5	290	2	0/0

These risk functions for forearm fracture can be analyzed using the available quasistatic ultimate bending moments for isolated arm bones reported above. Grouping all the available tests, we obtain a weighted average value of 39 N-m for ulna ultimate strength. Carter and Hayes **[Carter 1976]** suggest dynamic dependence on strain rate of the form $F \propto \varepsilon^{0.06}$ where F is a compressive ultimate load and ε is the dynamic strain rate. For our typical dynamic strain rates of 5 per second, the Carter and Hayes strain rate dependence results in 53% increase in ultimate strength for dynamic bending as compared with UVa quasistatic ultimate strength for the ulna. This is consistent with the suggestion of Melvin and Evans **[Melvin 1985]** who suggest an increase of 50% for dynamic ultimate strength over quasistatic ultimate strength. Further, Schreiber *et al* **[Schreiber 1997]** report a 68% increase in the dynamic bending strength of the tibia over quasistatic tests at strain rates of 5 per second.

So, if we assume 50% increase in the ultimate strength of the isolated ulna, the dynamic bending strength of the isolated ulna is approximately 59 N-m. If we assume that the radius provides some support under dynamic bending in the region of the distal third of the forearm, the 50% risk of fracture at SAE dummy forearm moments of 67 N-m seems quite consistent with the quasistatic data. In addition, for a pronated subject arm, we expect a forearm ultimate strength to be less than the sum of the ultimate strengths of the radius and the ulna. Dynamic drop tests presented above suggest that there may be a 30% decrease in dynamic ultimate strength from impact into a pronated arm as compared with a supinated arm. If we assume that the ultimate strength of a supinated forearm is approximately the sum of the ultimate strength of the radius and ulna, we obtain a weighted average ultimate forearm bending moment of 73 N-m under quasistatic conditions. Further, if we compensate this value as above for the increase in dynamic ultimate strength and for the decrease in ultimate strength owing to arm pronation, we obtain an ultimate dynamic bending strength of approximately 76 N-m for the forearm in a pronated position. This compares well with the 50% risk SAE arm moment value of 91 N-m for forearm ulna and radius fractures. Given the nature of the approximations above, there is a rough correspondence between quasistatic bending results and the derived risk functions for the SAE forearm.

Using this simple order of magnitude analysis, it is clear that the moments measured in the RAID are far larger than expected in small female human forearms under primary contact from a deploying air bag. However, the RAID was designed as a research tool to investigate air bag aggressivity and primary contact air bag injuries. As shown above, measurements taken using the RAID under air bag deployment can be successfully correlated with both cadaver injury and more biofidelic test devices.

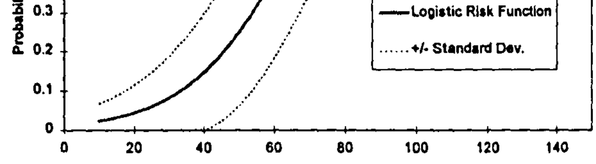


Figure 17. SAE Arm - Risk of Ulna or Radius/Ulna Fracture.

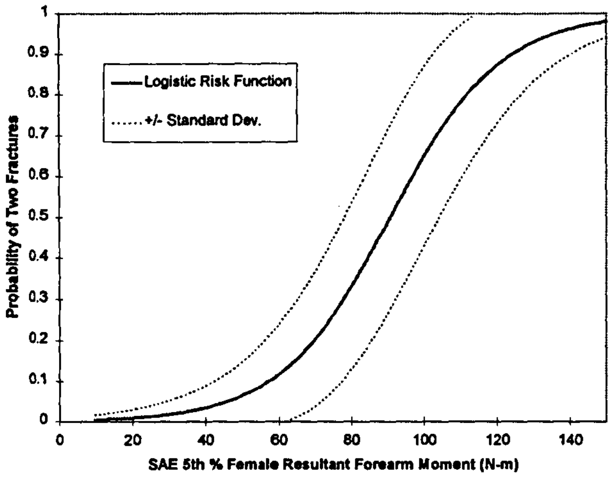


Figure 18. SAE Arm - Risk of Radius and Ulna Fracture.

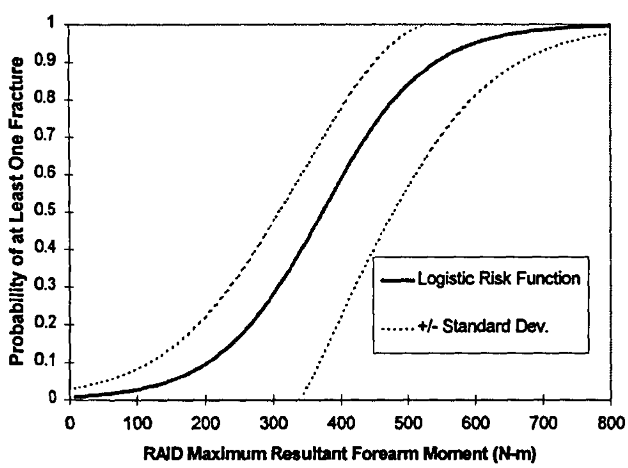


Figure 19. RAID - Risk of Ulna or Radius/Ulna Fracture.

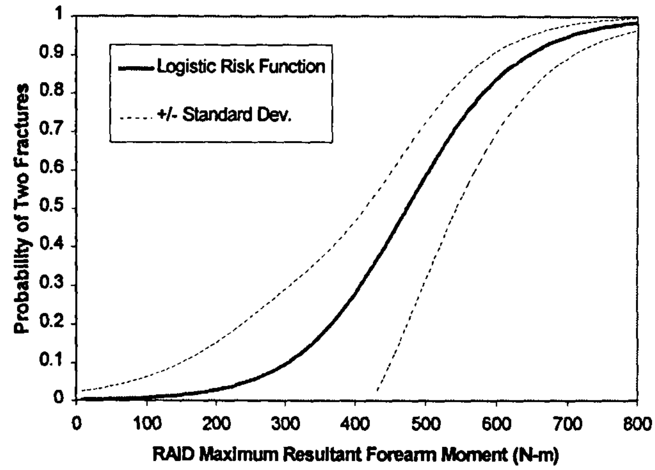


Figure 20. RAID - Risk of Radius and Ulna Fracture.

CONCLUSIONS

This study investigated the primary contact phase of air bag deployment into dummy upper extremities using four OEM air bags representative of a range of air bag aggressivities in the current automobile fleet. This aggressivity may be quantified using forearm moment response of a dummy surrogate in an appropriate worst-case position. Using this measure for primary contact injuries, this study found the System K air bag and the System H air bag to be relatively more aggressive, the System J air bag to be moderately aggressive, and the System L air bag to be less aggressive.

Maximum moments and accelerations for both test devices under air bag primary contact occur early during air bag deployment. However, peak forearm moments obtained using a System H air bag with the SAE arm occurred after the time of significant module cover/arm interaction. So, module cover interaction may not be necessary for injury with current OEM air bags.

Both the RAID and the SAE arm were found to be appropriate for examination of air bag aggressivity under primary air bag contact. Results from previous cadaveric tests suggest that primary contact injuries occur very early, before significant elbow flexion occurs. This is confirmed with moment and acceleration results from both the SAE arm and the RAID. This suggests that both devices can be successfully correlated with cadaver primary contact injury data.

There is, however, one significant potential caveat with the use of the RAID for primary contact injuries into small female occupants. As the result of a large mass and lateral moment of inertia, the kinematic response of the RAID is dramatically different from both a human forearm and the more biofidelic SAE arm. This is seen clearly in the distal acceleration response of the RAID. For all air bag systems, the acceleration was substantially smaller than that seen with either the human forearm or the SAE arm. So, the RAID will not generally be suitable for the investigation of forearm moment response of primary contact phenomena that depend on details in timing of the arm/module cover/air bag interaction. In addition, for the investigation of later phases of air bag deployment, flinging, or occupant contact, the SAE arm is more appropriate since its allowed motions are approximately anthropomorphic.

A comparison of tests using the SAE arm mounted to a Hybrid III dummy and the SAE arm mounted to a universal joint test fixture show that the use of a translationally fixed fixture has minimal effect on forearm response. So, either the SAE arm or the RAID may be used in a fixed test fixture for experimental convenience without significant effect on primary contact response.

The dummy forearm moment obtained under air bag deployment into the SAE arm and RAID correlates well with injury levels observed in cadaveric testing with the same upper extremity orientation. A logistic injury risk function was developed for small females in the 'worst-case' position using the cadaveric injuries and the dummy forearm moments. This risk function predicts a 50% risk of ulna fracture at a SAE forearm moment of 67 N-m (+/- 13 N-m standard deviation) or a RAID moment of 373 N-m (+/- 83 N-m standard deviation). The SAE arm value is consistent with an extrapolation of quasistatic ultimate bending strength of the ulna to dynamic conditions. As the result of differences in mass and moments of inertia, the moment value in the RAID is not expected to be similar to those found using a more biofidelic small female arm. In addition, we find a 50% risk of radius and ulna fracture at a SAE forearm moment value of 91 N-m (+/- 14 N-m standard deviation) that is consistent with the combined bending strength of the radius and ulna in a pronated position. A similar risk of two forearm fractures is seen with a RAID peak forearm moment of 473 N-m (+/- 60 N-m standard deviation).

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INVESTIGATION OF INERTIAL FACTORS INVOLVED IN AIRBAG-INDUCED FOREARM FRACTURES

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ABSTRACT

Unembalmed, human cadavers were used in direct-contact, airbag-interaction deployments to assess the influence of upper-extremity inertia during vehicle deceleration on the likelihood and severity of airbag-induced forearm fractures. Comparisons were made for static and dynamic test configurations. Dynamic conditions were simulated by accelerating the steering-wheel/airbag module assembly toward the cadaver at the time of airbag deployment, with the cadaver forearm in contact with the airbag module. The results of the dynamic simulations suggest that the increased inertia of the upper extremity due to crash deceleration does not influence the incidence or severity of forearm fractures resulting from direct forearm airbag interaction. Also, the inertial loading of the airbag by the forearm did not significantly change the deployment characteristics of the airbag. The results of this study reinforce the efficacy of conducting static airbag deployments to assess airbag aggressivity and the potential for forearm fractures. The results also support the use of a simple kinematic measure, such as peak distal forearm speed (PDFS) or average distal forearm speed (ADFS), for the prediction of airbag-induced upper-extremity fractures.

INTRODUCTION

A number of recent research efforts have focused on airbag aggressivity assessment as well as upper-extremity fracture mechanisms and prediction. Saul et al. (1996) designed an instrumented Hybrid III arm for the assessment of direct-loading airbag-induced forearm fractures. The instrumented arm was used in six static deployments with three different airbag systems in two configurations to illustrate its ability to measure forearm bending moment, acceleration, and wrist velocity. The Research Arm Injury Device (RAID), a stylized surrogate upper extremity, was introduced and tested by Kuppa et al. (1997). Accident investigation data, inflator tank tests, and module characteristics were used to identify a set of driver airbags thought to be less or more injurious. The accelerations and bending moments measured by the RAID in a series of thirty-four static deployments using four different airbags were compared to the hypothesized relative aggressivity of the airbags. The performance of the RAID was compared to the performance of the instrumented Hybrid III by Johnston et al. (1997). Although the kinematics associated with each device were dramatically different, both the RAID and the instrumented dummy arm ranked the airbag systems similarly according to relative aggressivity.

Bass et al. (1997) examined a set of five driver airbags considered to range from less to more aggressive in a series of sixteen tests using human cadaver upper extremities excised at the proximal humerus. A load cell was fixed to the humerus with a universal joint simulating the shoulder. Two strain gage rosettes were applied to both the radius and ulna. Four additional tests were conducted using whole bodies. Four of the five airbags were also tested using the SAE fifth percentile female instrumented arm. The bending moments measured with the SAE arm were correlated with the observed fracture responses in the cadaver upper extremities. This indirect comparison suggested that 67 N-m represents a fifty-percent risk of ulna fracture and that 91 N-m represents a fifty-percent risk of both radius and ulna fracture.

Hardy et al. (1997) used seven unembalmed human cadavers to investigate upper-extremity injuries resulting from direct interaction with driver airbags. Seventeen static deployments were conducted using a steering-wheel-and-airbag assembly mounted to a fixed platform. Varying forearm-module proximity was investigated. Triaxial accelerometer mounts and crack detection gages were fixed to the bones of the forearm to measure general kinematics and fracture timing. The concept of using peak or average distal forearm speed (PDFS or ADFS) was introduced as a simple approach to the problem of predicting the potential for an airbag system to produce forearm fractures. Fracture is difficult to predict based upon the tolerance of bone to a given input because the tolerance of forearm bones varies along the length of the bones, and with the direction of the applied load relative to the cross section of the bones. However, fracture tolerance as indicated by bone mineral content, was found to be highly correlated with body and upper extremity mass. Distal forearm speed was also found to be related to upper extremity mass. The inter-relationship between tolerance, mass, and speed produced a PDFS fracture threshold of 15.2 m/s, and an ADFS fracture threshold of 11.7 m/s. Proximity of the forearm to the airbag was found to greatly influence the incidence of fracture. It was stated that a simple airbag-aggressivity assessment tool could be based on measurement of distal forearm speed using static airbag deployments into a biofidelic, surrogate arm of appropriate mass.

Hardy et al. (1998) used four unembalmed human cadavers in eight direct-forearm airbag-interaction static deployments to assess the relative aggressivity of two different airbag modules. Instrumentation of the forearm bones included triaxial accelerometry, crack detection gages, and film targets. The forearm-fracture predictors, PDFS and ADFS, were evaluated and compared to the incidence of transverse, oblique, and wedge fractures of the radius and ulna. Internal-airbag pressure and axial column loads were also measured. The less-aggressive airbag system (LAS) produced half the number of forearm fracture as the more-aggressive system (MAS), yet exhibited a more aggressive internal-pressure performance. However, no direct relationship between internal-airbag pressure and forearm fracture was found. Both the peak internal pressure and the initial-inflation rate of the LAS were higher than for the MAS, but the PDFS, ADFS, and axial column loads of the LAS were lower. This inverse relationship between internal airbag pressure and airbag aggressivity prompted an investigation of the LAS and MAS design characteristics. It was hypothesized that the closed-module design of the LAS, coupled with longer, thicker tear seams, resulted in higher peak-internal pressures and greater rates of pressure increase when compared to the MAS. Therefore, more inflator energy was used to achieve bag egress from the LAS module, making less energy available to be imparted to a forearm. The smaller and more distributed mass and size of the LAS doors may have assisted in the reduction of focused energy transfer to forearms, as would have the less-aggressive inflator of the LAS, as measured in tank tests. The results of this study supported the use of PDFS or ADFS for the prediction of airbag-induced upper-extremity fractures, and their application to airbag-aggressivity analysis.

Although preliminary methods for predicting forearm fractures and assessing relative airbag aggressivity have been developed, the influence of upper-extremity inertia on airbag deployment has not been previously investigated. Prior research has been limited to static airbag deployment scenarios. This study attempts to determine the effect that dynamic loading on the airbag by the upper extremity might have on fracture incidence and severity.

METHODS

Unembalmed, previously frozen human cadavers were used in direct-contact, airbag-interaction deployments to assess the influence of upper-extremity inertia on the likelihood and severity of forearm fracture and airbag aggressivity. Comparisons were made with each cadaver using static-column and dynamic-column test configurations. Instead of accelerating the cadavers toward the airbag, the airbag was accelerated toward the cadavers in the dynamic-column tests. One arm of each cadaver was subjected to a static-column deployment, while the other arm was tested using a stroking column. The static and dynamic configurations were alternated between left and right forearms from one cadaver to the next. In all tests, the middle of the pronated forearm was initially resting lightly on the center of the airbag module. The lower portion of the steering rim was modified to accommodate this configuration, while retaining the integrity of the rim. The airbag characteristics were consistent throughout the test series.

Static Tests

Static deployments were conducted with a steering-wheel-and-airbag assembly mounted to a fixed platform. Figure 1a and Figure 1b show a representative test configuration. The cadavers were placed in a supine position on the platform with the forearm positioned in the path of the deploying airbag. The cadaver was offset laterally from the center of the steering wheel, allowing free motion of the entire upper extremity. The upper extremity was positioned such that the forearm was perpendicular to the module tear seam with the middle of the pronated forearm near the center of the module. The hand was held loosely in place on the steering-wheel rim with perforated tape. The anterior forearm lightly contacted the airbag module in all tests. The angle of the elbow ranged between 170 and 180 degrees, and the steering wheel was inclined 30 degrees to vertical. After installation of the triaxial-accelerometer cluster and crack-detection-gage connections, the instrumentation cables were sutured to the shoulder and the forearm was wrapped lightly with utility tape. Thick padding was placed on the platform surface to eliminate the possibility of airbag-induced fling injuries.

Dynamic Tests

A Madymo model of a belt-restrained driver was used to determine the relative forearm-airbag module acceleration and velocity profiles necessary to conduct the dynamic-simulation cadaver tests in the laboratory. A 54-kph crash was simulated using a 30-G, 100-ms

Figure 1a. A Lateral perspective of a typical static-deployment configuration.

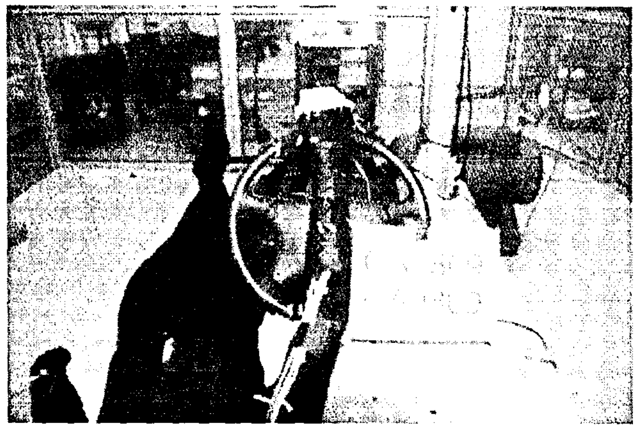

Figure 1b. A front view of the test shown in Figure 1a.

deceleration pulse. With the wrist positioned at the top of the steering rim and the middle of the forearm approximately 15.2 cm away from the center of the airbag module door, it was found that the peak relative speed between the forearm and airbag module was approximately 3 m/s after 30 ms, without the airbag firing but with the occupant belted. This suggested a 10-G acceleration of the forearm relative to (toward) the airbag just prior to deployment of the airbag.

Figure 2 shows the dynamic-simulation test fixture, which consists of a 25-cm stroke pneumatic cylinder, a guided square-tube ram, a load cell, and a steering-wheel/airbag-module assembly that is fixed to the ram. An adjustable support interfaces this fixture to the fixed platform. The stroke of the cylinder is snubbed by urethane padding placed between plates attached to the ram and the ram guide. The firing mechanism consists of a regulator, a 100-liter accumulator, a manual ball valve (safety valve), and a solenoid operated gate valve (fire valve). The cylinder inlet and outlets were enlarged to a 2.5-cm cross section and all associated piping is 2.5-cm inner diameter, to accommodate a 6-m/s stoke speed with and a 14-kg moving mass. The system operates using approximately 1.7 MPa (250 psi) nitrogen. Measured parameters include column forces and moments, column acceleration, column speed (inductive transducer), column displacement (laser transducer), triaxial distal forearm accelerations, and crack detection gage outputs (five forearm locations).

The cadaver and upper-extremity positions used for the dynamic simulations were the same as those used for the static deployments. The airbag was deployed approximately 30 ms into the stroke of the column, at which time the column had stroked between 5.0 and 7.5 cm, and the column speed was generally between 3 and 4 m/s. The total column stroke was limited to 15.2 cm with a peak speed of approximately 6 m/s after 50 ms. Thus, the column continued stroking throughout the airbag deployment. The ram, and therefore column, acceleration was essentially constant and the speed increased linearly prior to the deployment of the airbag. This was accomplished by controlling the motion of the cylinder up to the time of airbag deployment by ripping a metal plate, as shown in Figure 3. The ram was attached to this plate by a cable, and the opposite end of the plate was attached to a winch via a second cable. The winch was used to remove the slack from the cables prior to the test, and to adjust the length of the rip in the plate. This plate system provided approximately 5500 N (1250 lb) of constant resistance to the action of the cylinder, up to the time of airbag deployment. The pressure in the

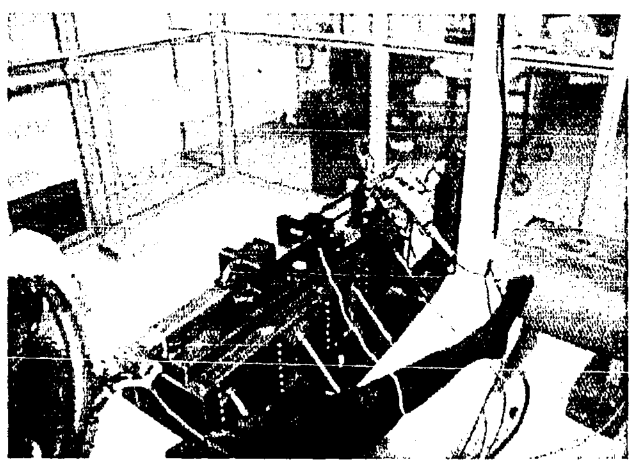

Figure 2. The dynamic-simulation test fixture for accelerating the steering-wheel/airbag-module assembly toward the cadaver forearm.

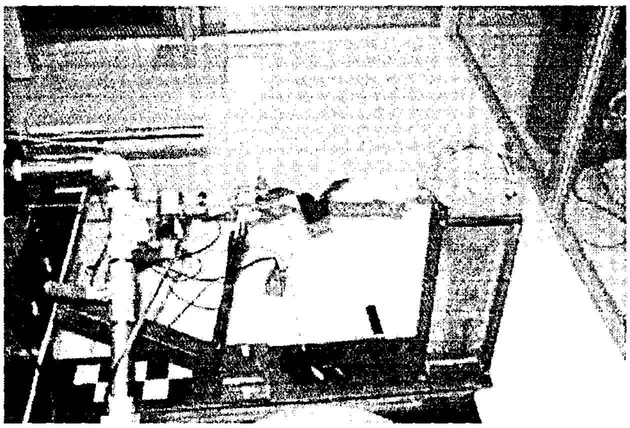

Figure 3. The ripping-plate mechanism used in the dynamic simulations to control the motion of the ram, prior to airbag deployment.

accumulator was set so that the cylinder was able to rip the plate and still provide roughly 10-G acceleration to the ram and column assemblies. The airbag was fired just as the plate ripped completely through, so that the extra force provided by the pneumatic cylinder upon ripping through the plate offset the reaction force of the airbag deployment and forearm interaction. This was done to minimize the effects of the forces developed during airbag deployment on the ram motion.

Figure 4a shows a ram acceleration trace, generated by averaging the ram accelerations obtained from five dynamic simulations. Five basic phases to the ram acceleration profile can be noted. The first phase of the trace corresponds to the start, overshoot, and settling of the ram. The second phase of the trace corresponds to ripping of the metal plate, which provides a nearly constant acceleration of approximately 10 G. Near the end of this phase the airbag is triggered, beginning the third phase at T=0 ms on the acceleration trace. During this phase there is a short period of deceleration, lasting about 1.5 ms. The fourth phase occurs after the deployment of the airbag. The column then accelerates at a higher rate, since its motion is no longer impeded by the deploying airbag or ripping plate. During the final phase, the motion of the column is arrested by urethane foam.

Figure 4b shows an averaged ram-velocity trace. The essentially constant nature of the column acceleration is evident here as the velocity ramps at nearly constant slope from -20 ms to +12 ms. There is only a slight disturbance during deployment of the airbag. Figure 4c shows an averaged ram-displacement trace.

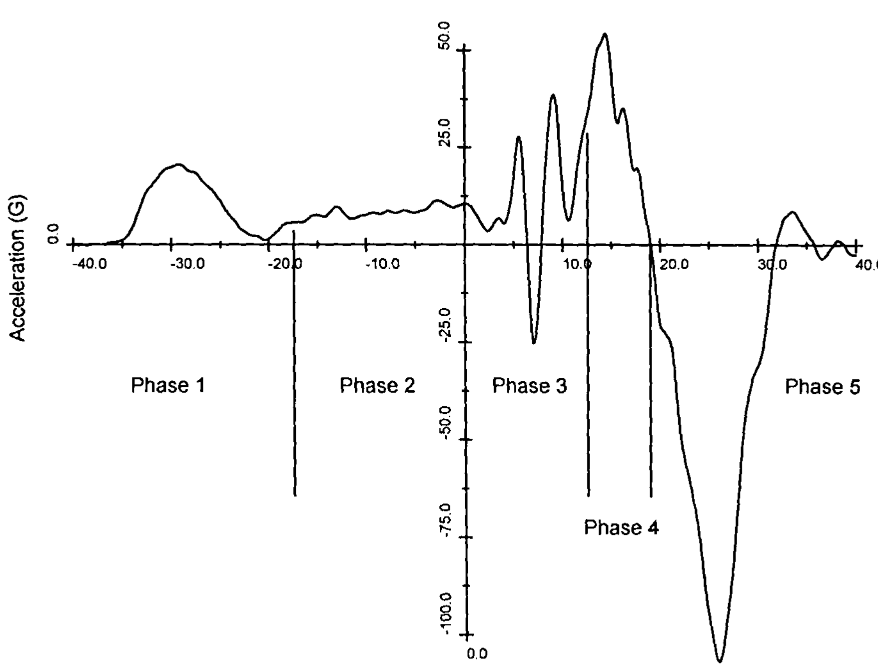

Figure 4a. Averaged dynamic-ram acceleration-time history (airbag triggered at T=0 ms).

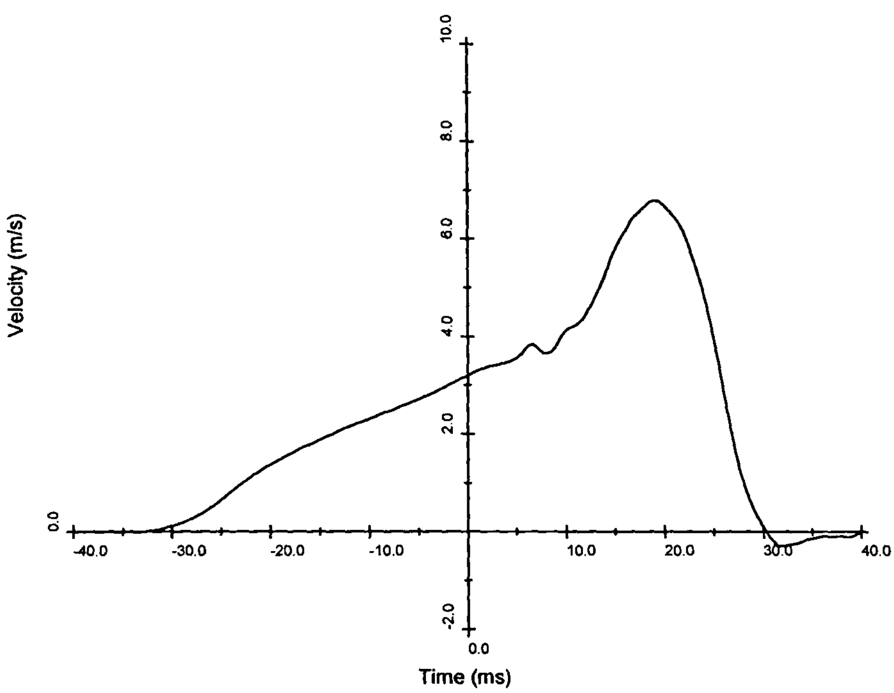

Figure 4b. Averaged dynamic-ram velocity-time history (airbag triggered at T=0 ms).

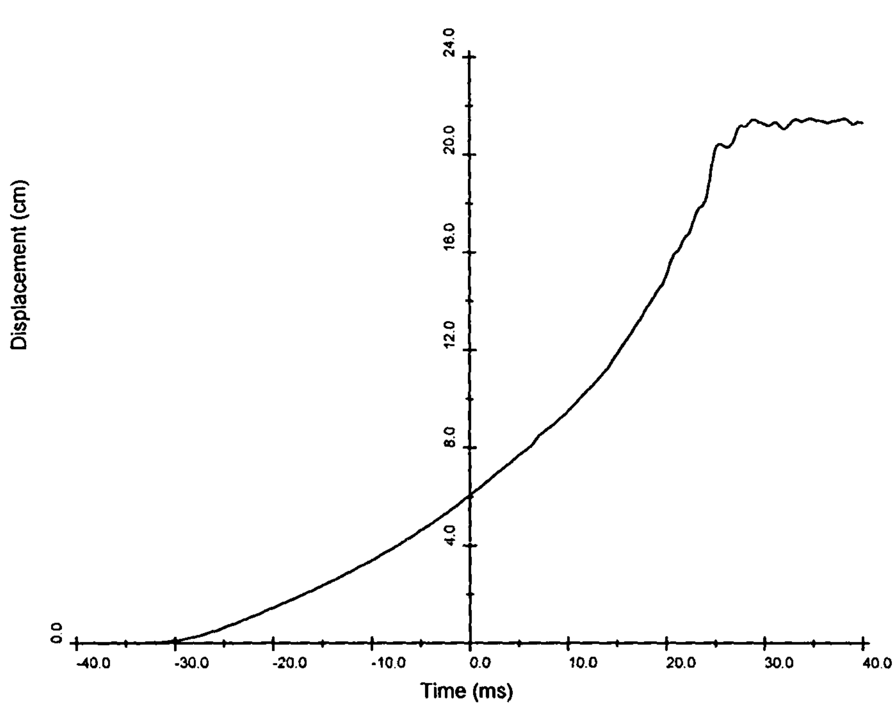

Figure 4c. Averaged dynamic-ram displacement-time history (airbag triggered at T=0 ms).

All signals were filtered using SAE Channel Class 300 Hz. These curves suggest that there was nearly constant loading of the airbag module by the forearm prior to and during the deployment. Any amount of energy transfer from the airbag to the driving mechanism was minor, and the overall energy of the system was greater than the static-deployment case.

Specimen Preparation

Figure 5 shows a typical forearm preparation prior to suturing of the wounds. Accelerometer mounting blocks made of Delrin were attached to the distal one-third region of the radius via plastic cable ties. Unlike previous tests, a target-mast block was not attached to the middiaphysis of the radius. Three crack detection gages were fixed to the radius in proximal, middiaphysis, and distal locations using cyanoacrylate. Two gages were also fixed to the middiaphysis and distal portions of the ulna. After instrumentation, pretest x-rays were taken of the forearms in pronation and supination.

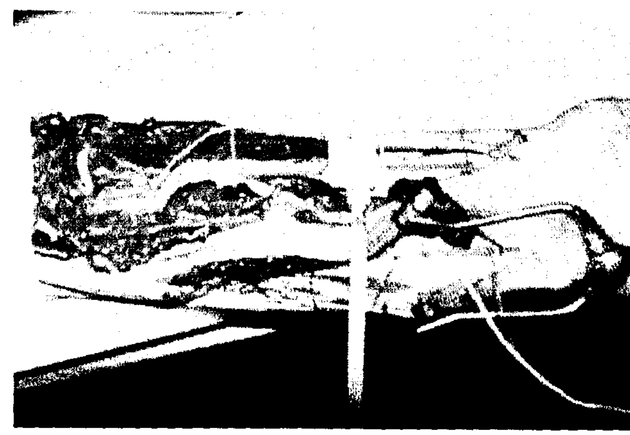

Figure 5. A typical forearm preparation after installation of the crack detection gages, prior to suturing.

Test Matrix

Ten deployments (G09 - G18) were conducted using five cadavers, three male and two female, as summarized in Table 1. Cadavers ranged in age from 65 to 85 years, with an average age of 76 years. The average stature and mass were 169 cm and 69 kg, respectively. One prototype airbag system was used for all tests. As previously noted, one static and one dynamic simulation deployment were conducted using each cadaver, so that direct comparisons could be made. The static and dynamic simulations were alternated between forearms, resulting in three dynamic and two static simulations on the right upper extremities, and two dynamic and three static simulations on the left upper extremities. The forearms and airbag modules were initially in direct contact and the steering column angle was 30 degrees to horizontal for all tests.

Table 1.
Matrix of Test Subjects and Conditions

Test	Gender	Age	Stature (cm)	Mass (kg)	Arm	Test Condition	Initial Spacing (cm)	Column Angle (deg)
G09	male	71	182	64	right	static	0.0	30
G10					left	dynamic	0.0	30
G11	male	74	181	77	left	static	0.0	30
G12					right	dynamic	0.0	30
G13	male	85	165	91	left	static	0.0	30
G14					right	dynamic	0.0	30
G15	female	65	164	61	right	static	0.0	30
G16					left	dynamic	0.0	30
G17	female	85	155	51	left	static	0.0	30
G18					right	dynamic	0.0	30
Avg.	-	76	169	69	-	-	0.0	30

After testing, posttest x-rays were taken, and the arms were disarticulated at the glenohumeral joint. At autopsy, forearm anthropometry was taken and the injuries were documented. The rate of mineralization and mineral content were determined by ashing 2 cm of the distal one-third of the radius and ulna. Peak and average distal forearm speeds were calculated and compared to fracture incidence and severity.

RESULTS

The test conditions and results are fully tabulated in Table A.1 of Appendix A. The observed injuries are cataloged in Appendix B.

Forearm-fracture timing was determined from the output of five crack detection gages that were installed on the bones of the forearms. Fractures of either the radius or ulna were found in nine of the ten tests, but one of these fractures was very minor. Missing fracture timing data resulted from gages not spanning a fracture or wires breaking during the test. All fractures captured by the crack detection gages occurred at the midulna position. However, this was not the only region that experienced fracture, nor were all of the fractures that occurred in this region captured by a crack detection gage. As discussed by Hardy et al. (1997), fractures coincide with local reductions in acceleration, and local speed plateaus, as shown in Figure 6 (Test G18). Figure 6 shows time histories of distal speed and resultant distal acceleration plotted with crack detection gage output. Time zero is defined as the point at which the airbag was triggered. The crack detection gage output, which indicates fracture, is the sharp vertical transition. This transition is associated with a commensurate drop in resultant distal acceleration, and a distal speed plateau.

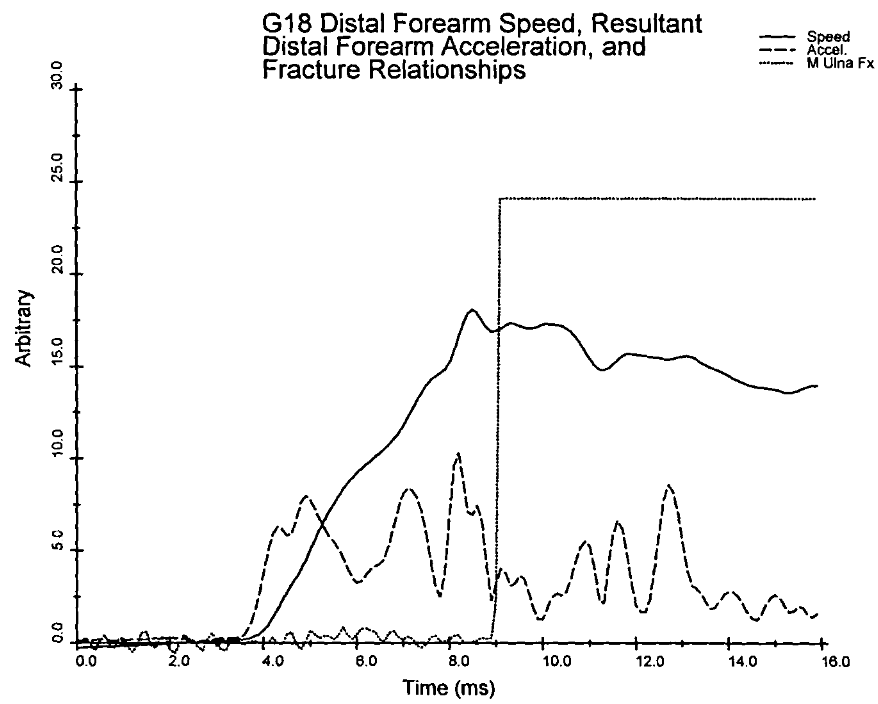

Figure 6. The relationship between distal forearm acceleration, speed, and fracture timing for G18.

The key results of the ten static/dynamic comparison tests are summarized in Table 2. Upper-extremity mass was measured after excising tissue in a circumferential fashion around the head of the humerus. Mineral content is expressed in grams of ash per centimeter of dry bone length. This is generally considered to be a more important parameter than rate of mineralization, since the quantity of bone available is as important as the quality of the bone, and mineral content reflects both quantity and quality of bone. The airbag-induced forearm-fracture predictors, peak distal forearm speed (PDFS) and average distal forearm speed (ADFS), were calculated over a 12-ms interval as described by Hardy et al. (1997), using the resultant magnitude of integrated triaxial accelerations. The 12-ms limit was selected to reduce the influence of integration errors and to minimize the effects of forearm rotations. The available crack-detection-gage information indicates that fractures occurred between 6 and 9 ms after triggering the airbag, supporting the use of a 12-ms interval. This information also shows that none of the measured fractures occurred within the short period of negative acceleration experienced by the stroking column. Each of the measured fractures occurred at a point during the column stroke when there was a substantial loading of the airbag by the forearm.

Table 2.
Summary of Test Results

Test	Gender	Arm	Extremity Mass (kg)	Mineral Content (g/cm)		Test Condition	Combined Distal Forearm Speed (m/s)	Peak Distal Forearm Speed (m/s)	Average Distal Forearm Speed (m/s)	Forearm Fractures	Midulna Fx Time (ms)
				Ulna	Radius						
G09	m	r	3.22	0.61	0.78	static	-	-	-	2 ulna, 2 radius	-
G10		l	3.36	0.60	0.83	dynamic	19.5	14.0	11.7	2 ulna	-
G11	m	l	3.89	1.01	1.48	static	-	17.8	13.9	1 ulna (minor)	-
G12		r	3.94	1.25	1.43	dynamic	25.4	20.7	14.7	none	-
G13	m	l	4.40	0.87	1.04	static	-	18.2	14.8	2 ulna	6.9
G14		r	4.38	0.94	1.13	dynamic	22.0	18.4	12.4	2 ulna	8.6
G15	f	r	2.90	0.50	0.81	static	-	20.8	18.4	2 ulna	6.3
G16		l	2.77	0.69	0.80	dynamic	21.6	17.8	13.8	1 ulna	-
G17	f	l	1.95	0.43	0.55	static	-	-	-	1 ulna, 2 radius	6.2
G18		r	1.95	0.52	0.55	dynamic	20.6	17.7	14.4	1 ulna, 1 radius	9.0

In the dynamic-simulation tests, the distal forearm speed values result not only from the deploying airbag, but also from the velocity imparted by the stroking column. The combined distal forearm speed (CDFS) values include the contribution of the column. The PDFS values are obtained by subtracting the measured velocity time history of the column from the CDFS time history. The distal forearm speed curve shown in Figure 6 resulted from this procedure. Even though the forearm was in motion at the time the airbag was triggered at T=0 ms, the distal forearm speed does not increase from zero until T=4 ms. This method essentially removes the velocity contribution of the stroking column from the speed calculations, thereby isolating the effects of the airbag deployment from the stroking of the column. The ADFS values are calculated using this adjustment procedure as well.

Table 2 also summarizes the number of distinct ulna and radius fractures observed for each test. As indicated, both male and female specimens sustained fractures. These fractures can be divided into three general categories: simple, wedge, and complex, as suggested by Mueller et al. (1991). The observed injuries were largely transverse, oblique, and wedge fractures of the ulna or radius, or both, similar to those reported in field investigations. Tears of the elbow joint capsule were also found in some cases.

The most pronounced observation is the similarity between the static and dynamic-simulation results. The dynamic-simulation PDFS and ADFS values differ little from those obtained in the static tests. In one pair of tests, G13 and G14, the PDFS values differ by only 1 percent. The average PDFS and ADFS values for the dynamic simulations are 17.7 and 13.4 m/s, respectively, while the average PDFS and ADFS values for the static tests are 18.9 and 15.7 m/s, respectively. These slightly lower values obtained from the dynamic tests are reasonable because the accelerating forearm will appear heavier to the deploying airbag. The dynamic simulations produced essentially the same number and severity of forearm fractures as did the static tests. Examples of forearm fractures generated by static (right arm in Test G15) and dynamic (left arm, in Test G16) testing using a representative cadaver specimen are shown in Figure 7a and Figure 7b, respectively. Figure 7a (static) shows a transverse and a wedge fracture of the ulna, and Figure 7b (dynamic) shows a wedge fracture of the ulna. Both x-rays are of the supinated forearm.

The fracture thresholds for direct-contact conditions previously reported by Hardy et al. (1997) are summarized in Table 3. These values represent a fifty-percent probability of forearm fracture. All of the PDFS and ADFS values obtained from both the static and dynamic tests were above the threshold values, and forearm fractures were obtained in all tests except Test G12. While previous airbag/upper-extremity interaction tests have shown that some forearm bones are so weak that they would likely fracture under virtually any conditions, the forearm bones of the cadaver used for Test G12 represent the opposite extreme, having mineral contents of 1.25 and 1.43 g/cm for the ulna and radius, respectively. It is unlikely that these bones would fracture under even the most severe airbag-deployment conditions. The bones of the other forearm from this cadaver had similarly high mineral contents of 1.01 and 1.48 g/cm for the ulna and radius, respectively. The ulna from this forearm experienced a minor intra-articular fracture (chip) of the proximal ulna. In three tests, G10, G15, and G16, the mineral content of the radius was below the previously determined mineral-content threshold of 1.03 g/cm, yet the bones did not fracture. This suggests that a lower mineral-content threshold slightly lower than 1.03 g/cm may be more appropriate. All other fractures occurred in bones having mineral contents below 1.03 g/cm.

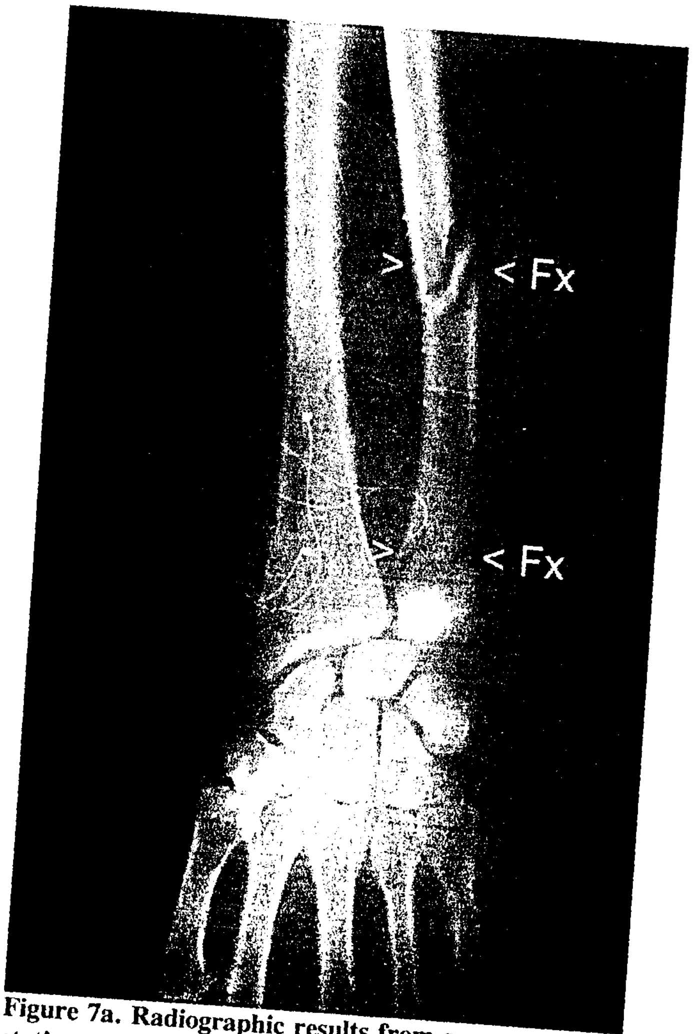

Figure 7a. Radiographic results from a representative static test (right arm, in supination).

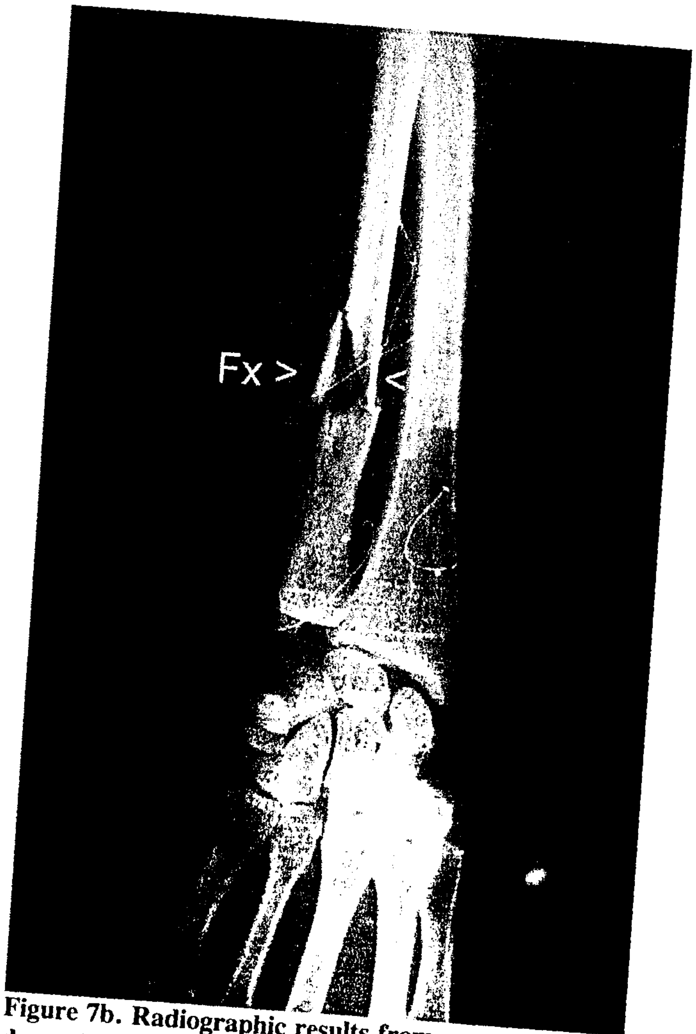

Figure 7b. Radiographic results from a representative dynamic simulation (left arm of the cadaver shown in Figure 7a, in supination).

Table 3
Prior Fracture Thresholds for Contact Conditions

Peak distal forearm speed (PDFS)	m/s	15.2
Average distal forearm speed (ADFS)	m/s	11.7
Upper extremity mass (UEM)	kg	2.9
Mineral content (MC)	g/cm	1.03

DISCUSSION

The results of these dynamic simulations suggest that increased inertia of the upper extremity, due to crash deceleration, does not influence the incidence or severity of forearm fractures resulting from direct forearm/airbag interaction. The results also support the use of a simple kinematic measure, such as PDFS or ADFS, for the prediction of airbag-induced upper-extremity fractures.

Within these tests, the inertial loading of the airbag by the forearm did not significantly change the deployment characteristics of the airbag. Although there was a 10-G preload applied to the airbag module by the forearm at the time of airbag deployment, and the airbag module was accelerated toward the forearm at approximately 50 G toward the end of the deployment (Phase 4 of Figure 4a), the deployment of the airbag was the overwhelmingly dominant effect on the response of the upper extremity. The peak distal forearm acceleration magnitudes ranged from approximately 700 to 1300 G in these tests. Given the large contribution of the deploying airbag and the low mass and small size of the typical upper extremity, the relatively small contribution of the simulated crash deceleration is apparently insignificant. Even with the forearm pressed against the airbag module prior to and during deployment, the forearm did not noticeably influence the egress of the airbag from the module. These results suggest that the inertial effects of crash deceleration are of little concern to upper-extremity/airbag-interaction testing. This result differs from that encountered in other types of direct-interaction testing, such as out-of-position thorax/airbag-interaction tests, where the mass and size of the body significantly inhibit the egress of the airbag from the module. The dynamic simulation used in these tests differs from a real-world crash in that the entire cadaver was not subjected to the crash dynamics. However, given the flexible coupling of the forearm to the rest of the body through the elbow and shoulder, it is felt that this would have been a negligible effect.

While the accelerating airbag module had little effect on forearm fracture outcome, it had a dramatic effect on the distal forearm speed values. This is essentially due to the additive nature of the airbag module speed and the distal forearm speed for the initial phases of the airbag deployment. The airbag module speed curves, obtained using an inductive transducer, were subtracted from the distal forearm speed curves when calculating the PDFS values. This technique provides nearly the same result as simply subtracting the speed the airbag module had attained at the time the airbag was triggered. If the CDFS curves are tared using this approach, the resulting values differ from the PDFS values by an average 1.1 m/s. The combined distal forearm speed approximates the magnitude of the total change in velocity that would be experienced by a forearm during a dynamic crash event. During a dynamic crash event, the forearm first approaches the airbag prior to deployment, and then rapidly changes direction as the airbag deploys. In these dynamic simulations, the airbag module is first accelerated against the forearm, and then the airbag deploys. In this case, the motion of the forearm is in one direction, relative to the airbag module

As in previous static airbag deployment tests, the PDFS values were able to accurately predict forearm fracture except in one instance of an extremely high-tolerance forearm, indicating that there may be individuals whose forearm fracture tolerance is so great that these kinematic predictors are irrelevant.

The results of this study are significant because they reinforce the efficacy of conducting static airbag deployments in biomechanical investigations of airbag aggressivity with respect to forearm fractures. The majority of previous airbag/upper-extremity interaction testing has been performed using static deployments. The kinematics of static deployments are more repeatable and more easily defined. Also, static deployments are easier to conduct, and are far less costly than dynamic tests. This study provides additional support for the use of PDFS and ADFS in static deployment testing, and shows that static deployments are a meaningful method of evaluating upper-extremity/airbag-interaction parameters and fracture outcome.

In summary, these tests showed no appreciable difference in forearm fracture outcome between static deployments and dynamic simulations. Although the dynamic simulation method was not fully representative of the dynamics of a real-world crash, it is believed to have provided appropriate accelerations and energy to the cadaver upper extremity during crucial phases of the airbag deployment to substantiate this observation. In addition, the fracture predictors PDFS and ADFS performed well in this study.

CONCLUSIONS

The simple airbag-aggressivity and forearm-fracture predictors, PDFS and ADFS, have been used in a comparison of static airbag deployments and dynamic simulations. The results:

- support the use of PDFS or ADFS as predictors of airbag-induced forearm fractures;
- indicate that there is essentially no difference in fracture incidence or severity between static and dynamic conditions; and
- suggest static testing may be used to assess airbag aggressivity with respect to forearm fractures instead of more complicated and costly dynamic testing.

ACKNOWLEDGMENTS

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APPENDIX A Summary of Results

Table A.1
Summary of Specimen Attributes, Test Conditions, and Test Results

CADAVER	#	28889		28879		28838		28800		28942	
Gender	m/f	male		male		male		female		female	
Age	years	71		74		85		65		85	
Stature	cm	182		181		165		164		155	
Mass	kg	64		77		91		61		51	
Upper Extremity	r/l	r	l	l	r	l	r	r	l	l	r
Upper Extremity Mass	kg	3.22	3.36	3.89	3.94	4.40	4.38	2.90	2.77	1.95	1.95
Elbow to Finger Tip	cm	-	46	43	-	48	-	-	44	39	-
Elbow Circumference	cm	-	28	25	-	30	-	-	24	20	-
Mid-Forearm Circumference	cm	-	26	22	-	25	-	-	19	17	-
Wrist Circumference	cm	-	19	16	-	18	-	-	15	14	-
Biceps Circumference	cm	-	27	26	-	35	-	-	26	20	-
Humerus Circumference	cm	7.0	7.1	7.9	8.1	7.4	8.0	6.6	6.3	5.6	5.6
Length of Ulna	cm	29.0	29.0	27.3	28.0	26.5	27.6	25.5	25.3	24.0	26.0
AP Ulna Depth	cm	1.30	1.41	1.81	1.76	1.24	1.51	1.07	1.36	1.12	1.35
ML Ulna Width	cm	1.40	1.47	1.33	1.34	1.39	1.34	1.10	1.30	0.94	0.97
Ulna Rate of Mineralization	%	65.2	65.6	63.9	68.0	65.9	66.0	66.3	66.1	57.4	63.8
Ulna Mineral Content	g/cm	0.61	0.60	1.01	1.25	0.87	0.94	0.50	0.69	0.43	0.52
Length of Radius	cm	27.0	27.0	25.4	26.0	25.0	25.2	23.3	23.1	23.5	22.0
AP Radius Depth	cm	1.19	1.18	1.32	1.29	1.30	1.28	1.11	1.08	0.97	0.96
ML Radius Width	cm	1.76	1.61	1.95	2.01	1.55	1.57	1.25	1.26	1.18	1.16
Radius Rate of Mineralization	%	65.0	65.7	65.9	66.5	63.5	64.0	65.3	65.0	56.8	59.5
Radius Mineral Content	g/cm	0.78	0.83	1.48	1.43	1.04	1.13	0.81	0.80	0.55	0.55
TEST	#	G09	G10	G11	G12	G13	G14	G15	G16	G17	G18
Condition	sta/dyn	sta	dyn	sta	dyn	sta	dyn	sta	dyn	sta	dyn
Spacing	cm	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Column Angle	deg	30	30	30	30	30	30	30	30	30	30
Fractures	#u,#r	2u,2r	2u	1u*	-	2u	2u	2u	1u	1u,2r	1u,1r
Capsular Tears	y/n	y	n	n	n	y	y	y	y	y	y
Combined Distal Forearm Speed	m/s	-	19.5	-	25.4	-	22.0	-	21.6	-	20.6
Peak Distal Forearm Speed	m/s	-	14.0	17.8	20.7	18.2	18.4	20.8	17.8	-	17.7
Average Distal Forearm Speed	m/s	-	11.7	13.9	14.7	14.8	12.4	18.4	13.8	-	14.4
Column Speed at Deployment	m/s	0.0	3.8	0.0	3.5	0.0	2.8	0.0	3.5	0.0	3.1
Peak Distal Acceleration Mag.	G	-	850	951	1032	709	779	899	1300	-	822
Time of Midulna Fx After Trigger	ms	-	-	-	-	6.9	8.6	6.3	-	6.2	9.0

* Very minor fracture

APPENDIX B Necropsy Results

The cadaver numbers are presented in the order of testing. The left and right arm information appears in the left and right columns respectively, regardless of the order of testing. Fracture locations are specified as the distance in mm from the distal end of the bone (styloid). Mineral contents (MC) are specified for both bones of the forearm.

Necropsy Results for Cadaver 28889

Male, 71, 64 kg, 182 cm

Left arm: G10
- Condition: dynamic
- Mass: 3.36 kg
- Ulna MC: 0.60 g/cm
- Radius MC: 0.83 g/cm

- Simple, oblique, distal fracture of the ulna starting anteriorly @ 20 mm, ending posterolaterally @ 42 mm
- Simple, oblique, diaphyseal fracture of the ulna starting anteriorly @ 41 mm, ending posterolaterally @ 68 mm, accompanied by a 27-mm chip

Right arm: G09
- Condition: static
- Mass: 3.22 kg
- Ulna MC: 0.61 g/cm
- Radius MC: 0.78 g/cm

- Single tear of the elbow joint capsule @ medial aspect of the ulna head (@ 7 mm)
- Simple, oblique, distal fracture of the ulna starting medially @ 23 mm, ending anterolaterally @ 41 mm
- Diaphyseal volar wedge fracture of the ulna starting anterolaterally @ 135 mm, centered medially @ 124 mm, ending laterally @ 185 mm
- Simple, transverse diaphyseal fracture of the radius @ 73 mm, accompanied by a 22-mm chip
- Simple, oblique, diaphyseal fracture of the radius starting laterally @ 185 mm, ending medially @ 194 mm

Necropsy Results for Cadaver 28879

Male, 74, 77 kg, 181 cm

Left arm: G11
- Condition: static
- Mass: 3.89 kg
- Ulna MC: 1.01 g/cm
- Radius MC: 1.48 g/cm

- Dislocation of the distal ulna
- Intra-articular 20-mm x 6-mm chip of the proximal ulna

Right arm: G12
- Condition: dynamic
- Mass: 3.94 kg
- Ulna MC: 1.25 g/cm
- Radius MC: 1.43 g/cm

- Negative

Necropsy Results for Cadaver 28838

Male, 85, 91 kg, 165 cm

Left arm: G13
- Condition: static
- Mass: 4.40 kg
- Ulna MC: 0.87 gm/cm
- Radius MC: 1.04 gm/cm

- Single tear of the elbow joint capsule @ anterior aspect of the radius head (@ 30 mm)
- Simple, oblique, diaphyseal fracture of the ulna starting anteriorly @ 62 mm, ending posterolaterally @ 48 mm
- Simple, oblique, diaphyseal fracture of the ulna starting anteriorly @ 165 mm, ending posterolaterally @ 184 mm

Right arm: G14
- Condition: dynamic
- Mass: 4.38 kg
- Ulna MC: 0.94 g/cm
- Radius MC: 1.13 g/cm

- Single tear of the elbow joint capsule @ anterior aspect of the radius head (@ 20 mm)
- Single tearing of the elbow joint capsule @ posterior aspect of the ulna head (@ 18 mm)
- Simple, transverse, diaphyseal fracture of the ulna @ 70 mm
- Simple, oblique, intra-articular fracture of the proximal ulna starting posteriorly @ 225 mm, ending anteromedially @ 242 mm

Necropsy Results for Cadaver 28800

Female, 65, 61 kg, 164 cm

Left arm: G16
- Condition: dynamic
- Mass: 2.77 kg
- Ulna MC: 0.69 g/cm
- Radius MC: 0.80 g/cm

- Single tear of the elbow joint capsule @ lateral aspect of the radius head (@ 25 mm)
- Diaphyseal anteromedial wedge fracture of the ulna starting anteriorly @ 44 mm, centered laterally @ 52 mm, ending anteromedially @ 65 mm

Right arm: G15
- Condition: static
- Mass: 2.90 kg
- Ulna MC: 0.50 g/cm
- Radius MC: 0.81 g/cm

- Single lateral tear of the elbow joint capsule @ lateral aspect of the radius head (@ 23 mm)
- Single vertical tear of the elbow joint capsule @ lateral aspect of the ulna head (@ 25 mm)
- Simple, transverse, distal fracture of the ulna @ 17 mm
- Diaphyseal anteromedial wedge fracture of the ulna starting anteriorly @ 64 mm, centered laterally @ 71 mm, ending anteromedially @ 84 mm

Necropsy Results for Cadaver 28942

Female, 85, 51 kg, 155 cm

Left arm: G17
- Condition: static
- Mass: 1.95 kg
- Ulna MC: 0.43 g/cm
- Radius MC: 0.55 g/cm

- Single oblique tear of the elbow joint capsule @ anterior aspect of the radius head (@ 27 mm)
- Single transverse tear of the elbow joint capsule @ lateral aspect of the radius head (@ 31 mm)
- Dual wedge fracture of the ulna starting anteromedially @ 61 mm, centered laterally @ 73 mm, ending anterolaterally @ 87 mm
- Simple, oblique, diaphyseal fracture of the radius starting laterally @ 134 mm, ending anteromedially @ 145 mm
- Dual wedge fracture of the radius starting anteromedially @ 67 mm, centered laterally @ 80 mm, ending anteriorly @ 87 mm

Right arm: G18
- Condition: dynamic
- Mass: 1.95 kg
- Ulna MC: 0.52 g/cm
- Radius MC: 0.55 g/cm

- Single transverse tear of the elbow joint capsule from the medial aspect of the ulna head to the lateral aspect of the radius head (@ 75 mm)
- Simple, transverse, diaphyseal fracture of the ulna @ 52 mm, accompanied by a 8-mm chip
- Simple, oblique, distal fracture of the radius starting medially @ 25 mm, progressing along the anterior surface to 38 mm, ending laterally @ 32 mm

CHILD SAFETY IN SMALL AND MICRO CARS

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ABSTRACT

The recent past shows enormous efforts of some CRS-manufacturers to improve the protective properties of Child Restraint Systems (CRS). Several tests performed by different associations forced these manufacturers to improve the safety qualities of their products. In addition, activities, like the ISOFIX working group, help to increase the child safety in the future.

Examining the car manufacturer activities in passive safety, the development is only partially considering the child safety. At least two trends of upcoming small and micro cars may cause negative effects:

- Lack of space in the rear compartment
- Higher deceleration pulse due to increasing car stiffness

These trends seem to be contradictory to the general requirements given in Figure 1.

Regarding the actual ECE-regulation, it is obvious that commonly certified and used CRS are not designed for those changed requirements. This paper contains the analysis of these both effects on the child and the investigation of three different, actually discussed, CRS attachments.

INTRODUCTION

Modern small and future micro cars are characterized by short front end designs with increasingly dense arrangements of engine units, nevertheless high quality passive safety standards are demanded. They lead to a stiffer design of the front structure resulting in increasing acceleration of the compartment.

The latest development of the automotive industry and other institutes working on micro cars are proofing this trend. Maximum dynamic car deformation of around 300mm lead to a peak deceleration of 60g and more. Only the design and use of sophisticated restraint systems can guarantee the high level standard of passive safety in these small cars.

At the same time it can be observed that actual small cars rear compartments seem to be more and more optimized. European cars are on average used by 1.2 persons. Due to this real-world observation the car industry tends to reduce the space in the rear compartment in order to improve the comfort for the front passengers.

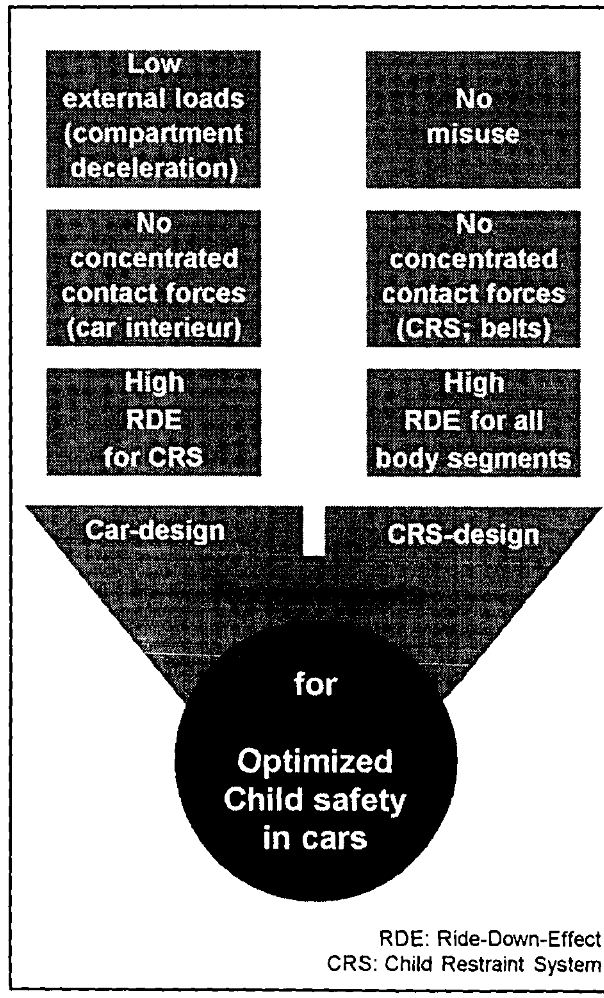

Figure 1. General theoretical requirements for child safety in cars.

Seventeen small cars, commonly used in Europe, were investigated on this matter, measuring the horizontal distance between the seat bight of the rear bench and the front seat. The front seats were adjusted 40mm ahead the rear position according to the seated position of a 50-percentile male. Figure 2 makes clear that most small cars provide less headroom for the child than demanded in the actual ECE regulation. The measured values are astonishing low, although they do not represent the worst case of taller front seat passengers.

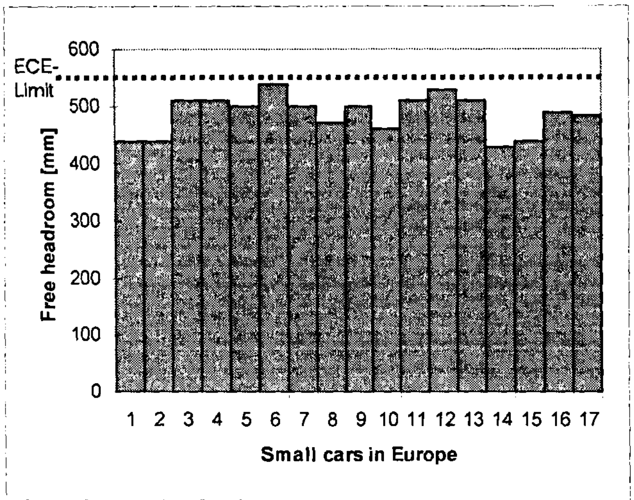

Figure 2. Horizontal distance in the rear compartment between seat bight of bench and front seats.

ACTIONS

Based on those trends following tests were carried out:

Table 1.
All performed tests

		ECE-pulse	30g-pulse	40g-pulse
Exp. Simulation	Standard 3pt Retr.	•		
	2pt-ISOFIX	•		
	ISOFIX+ Top Tether	•		
Num. Simulation	Standard 3pt Retr.	•	•	•
	2pt-ISOFIX	•	•	•
	ISOFIX+ Top Tether	•	•	•

A standard forward facing seat (Figure 3.) with 5pt harness was tested with three different types of anchor fittings:

- 3pt-retractor belt:
  This type of CRS fixation represents the actual situation in Germany.
- 2pt-ISOFIX:
  2pt-ISOFIX is proposed for regulation in Europe. The ISOFIX-prototype contains the possibility of pretensioning the CRS versus the seat/bench geometry. Functions like that are prescribed for 2pt-ISOFIX systems.
- 2pt-ISOFIX + Top Tether:
  The Top Tether use is specified in the Australian and Canadian regulations and strongly discussed in Europe.

The experimental tests were used to:

- analyze three different anchorage principles,
- validate the numerical MADYMO-models.

The head- and CRS-displacement curves were transferred to the numerical model. This technique allows a validation process with high quality results which correspond to the experimental tests. The validated numerical models were then used to examine the behavior of those three anchorage types in case of higher external loads.

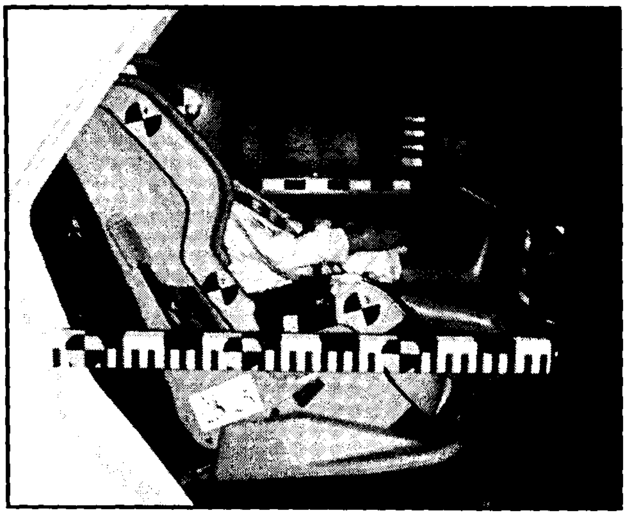

Figure 3. ISOFIX-prototype on Body-in-White device

TEST CONDITIONS

The experimental tests were performed on a body-in-white sled with a TNO P-18month dummy. A conventional, but in comparison to others, stiff rear bench was mounted.

The sled deceleration was set according to the ECE-R44-03 corridor (v_{coll} = 50km/h; s_{def} = 680mm) (Figure 4.).

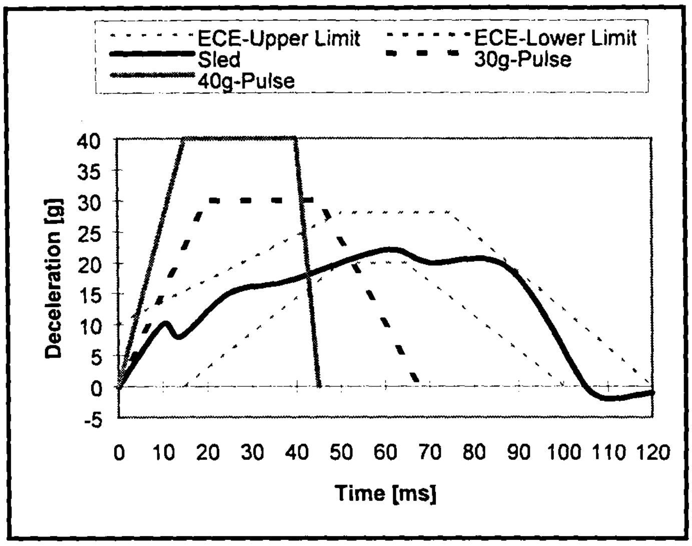

Figure 4. Variation of sled pulses (v=50km/h)

The numerical MADYMO models were build up using:

- the validated P-18month database
- the standard belt model of MADYMO.

Due to the unavailability of real car test deceleration pulses, theoretical deceleration pulses were taken (Figure 4.):

- 30g-pulse (v=50km/h, s=500mm)
- 40g-pulse (v=50km/h, s=300mm).

Equal gradation of the maximum deceleration (20g-30g-40g) and the maximum deformation (680mm-500mm-300mm) are considered. Thus, these three pulse types represent a wide range of potential small and micro car decelerations.

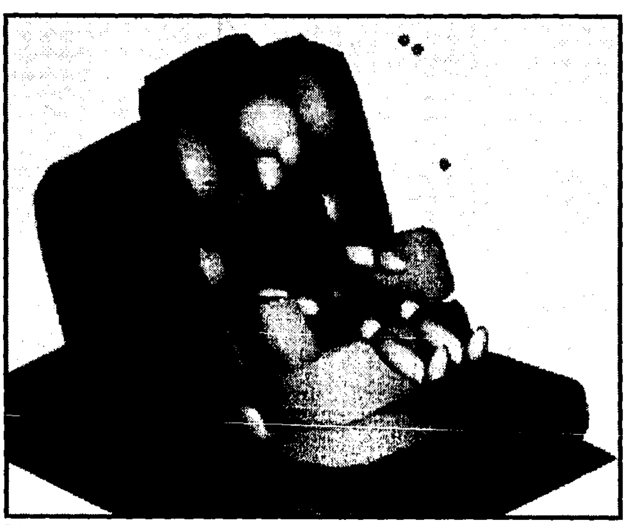

Figure 5. MADYMO model of the dummy, belted by a 5pt-harness in a forward facing CRS.

Following measurements were taken:

- Head linear acceleration (Figure 6.)
- Upper neck force & moment (Figure 7.)
- Head & CRS displacement (Figure 10.)
- Chest linear acceleration (Figure 8.)
- Pelvis linear acceleration (Figure 9.)
- Harness force

TEST RESULTS

The head acceleration is increasing for all kind of CRS attachments, but the highest values were received by 2pt-ISOFIX system. An additional Top Tether reduces the head loads by around 40% (Figure 6.).

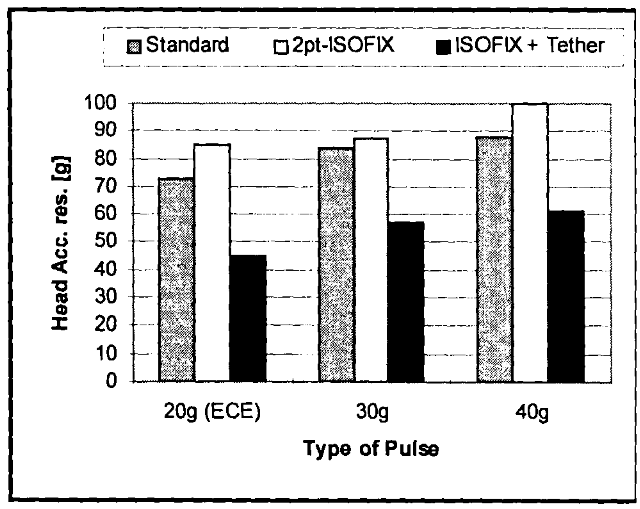

Figure 6. Head acceleration

The neck moments are showing the same effect. Only the improvements due to the Tether are less striking (Figure 7.).

The disadvantages of the 2pt compared to the standard 3pt-retractor fixation is observed only for the head/neck region. All other body segments received lower loads than the standard system (Figure 8., Figure 9.).

The head displacements in x-direction (Figure 10.) are almost identical for the standard and the 2pt-ISOFIX CRS.

Only the Top Tether again reduces the values by 30%. Considering the ECE-Limit of the head excursion, only the Top Tether system achieves conformity to this limit. Generally, it is remarkable that increasing deceleration pulses have almost no effect on both ISOFIX systems.

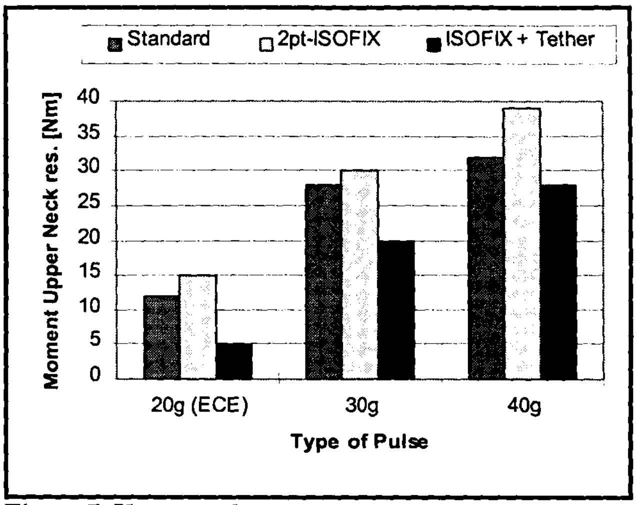

Figure 7. Upper neck moments

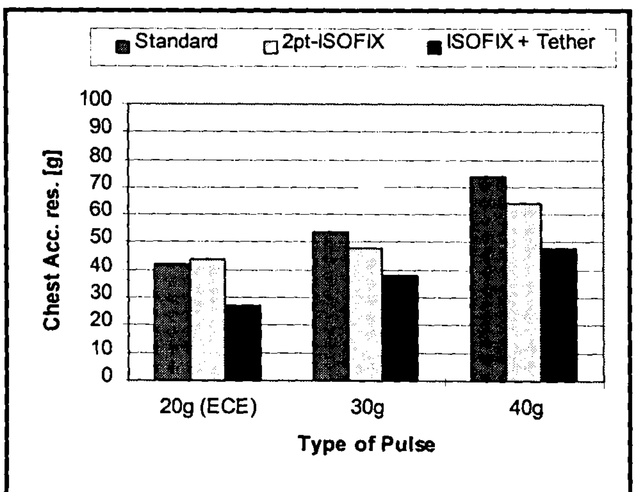

Figure 8. Chest acceleration

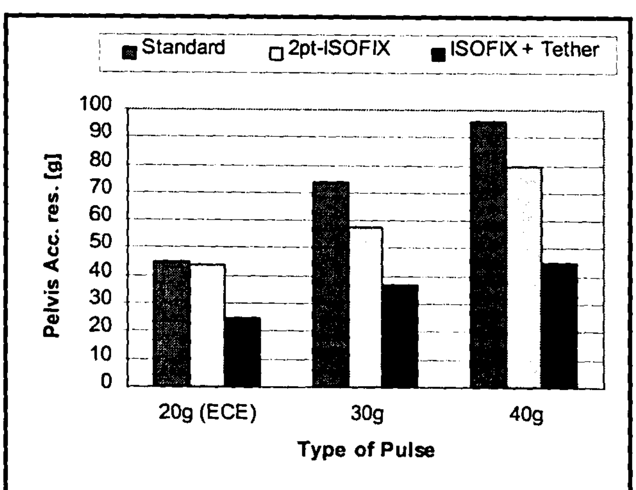

Figure 9. Pelvis acceleration

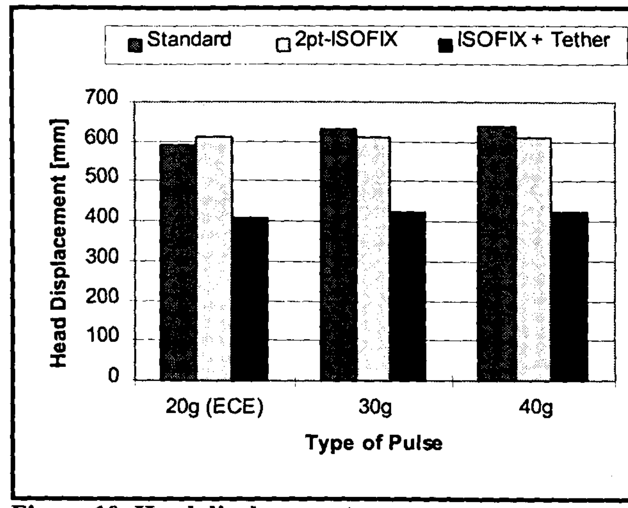

Figure 10. Head displacement

DISCUSSION

Four main effects occured:

- The increasing deceleration pulses lead to increasing loads on the dummy.
- The 2pt-ISOFIX system shows disadvantages concerning the head/neck region, but advantages on the chest & pelvis.
- The use of the Top Tether leads to enormous reductions of all loads on the dummy.
- The Top Tether allows low loads even at high deceleration pulses.

The reasons are known:

2pt-ISOFIX systems need the seat/bench stiffness to reduce the y-axis rotation. Although the CRS was installed with pretension on the bench, large rotation of the CRS and the child's upper body segments were observed. Analyzing the measurements and the high speed films, the stiffness of the rear bench equals a slack in the system. The rigid structure of the seat or bench seems to be more relevant for the CRS behavior than the stiffness of the upholstery.

Structural rigid designs used for the front seats preventing submarining can be adapted to the rear bench to reduce the rotation of 2pt-ISOFIX systems. Regarding the design of car rear benches, you find a remarkable wide range of different designs today (stiffness, thickness of the upholstery, structural support). That is why 2pt-ISOFIX CRS should not be assessed independently.

Latest tests in Germany with a forward facing shield seat proof our investigation. This seat was tested with 3pt-belt and 2pt-ISOFIX attachment. The head acceleration was only slightly higher, but the head excursion increased by 20% for the 2pt-ISOFIX system.

CONCLUSIONS

- 2-point-ISOFIX systems are neither able to reduce the loads on the child head/neck region nor to reduce the maximum head displacement. In case of higher loads and small headroom in small cars, the 2-point system may not protect the child sufficiently.
- The direct dependency of 2pt-ISOFIX systems to the seat/bench properties needs to be examined in further studies.
- The use of an additional Top Tether reduces all loads and the head displacement extremely. Even in cars with small headroom this protection device will prevent a direct head contact and high loads on the child. The renunciation of the Top Tether use seems to be unacceptable.
- The real-world trends on small car designs show increasing acceleration for the compartments and small headroom for the rear passengers. The ECE-R44 regulation in Europe does not consider this development. A revision of the ECE regulation for frontal testing should be discussed. Future CRS should be certified considering these essential changes in car design.

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PELVIS HUMAN RESPONSE TO LATERAL IMPACT

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ABSTRACT

This paper gives a further approach to provide information on the human pelvis tolerance against lateral impacts with unembalmed cadavers. The aim of this work was to verify the influence of impactor parameters as velocity and weight on the criteria measured on pelvis as force, acceleration and deflection.

A previous study, presented in 1994 at the ESV Conference, concerned the establishment of behaviour laws for the pelvis response by a 23.4 kg impactor. The analysis of crash tests showed that the impacting masses are lower and the impact velocities are higher. It was essential to know the pelvis behaviour in new impact conditions.

A series of 11 new tests were conducted with a guided horizontal impactor at several speeds. The impactor was flat and rigid. It weight was 12 kg or 16 kg.

From the 31 tests it is possible to propose a deflection limit value of 46 mm at a 50% AIS ≥ 2 probability

We propose 2 'force / deflection' corridors for impacts energies of 800 and 1100 joules.

From these study results we propose :

A EUROSID-1 pelvis performance criteria of 3.93 kN with a 50% AIS ≥ 2 probability.

A EUROSID-1 pelvis performance criteria of 6.16 kN for a 50% AIS ≥ 3 probability.

1. INTRODUCTION

An experimental programme was set-up to determine the influence of the impactor's mass and velocity on the pelvis response to lateral impact. The experimental phase evaluation concerned 11 tests on human pelvis (1 impact per pelvis) and 20 tests on the same EUROSID-1 pelvis.

The impacting device used is a linear impactor guided and propulsed by a 6 or 9 Sandow series depending on the velocity to be reached. Its mass is about 12 or 16 kg and the impact surface used for all the pelvis impacts is a 200 x 200 mm square. This surface comprises two trapezoids in such a way as to be able to dissociate the bearing on the hip (iliac) crest from that on the trochanter : this is achieved by using three accelerometers fixed on the back of each of the 2 plates.

The cadavers used are unembalmed, kept in a sitting position and impacted laterally on the right side of the pelvis.

The triaxis accelerometer are attached to T1, T8, and T12 thoracic vertebrae and one on the sacrum.
Double targets were attached to the occipital, T1, T4, T8, T12 vertebrae and similar targets were attached to third lumber vertebrae and to the sacrum.
High speed camera (1000 frames/second) were used to analyze movements and deformations.
The same tests were carried out on the EUROSID pelvis.

For the human pelvis study, anthropometric measurements were made before each test on PMHS. The main data on the 11 cadavers are shown table 1 below.

Table 1 : Characteristics of PMHS solicited at the pelvis

Test N°	Sex	Age	Height (m)	Weight (Kg)	Pelvis Width (mm)
LCB 01	M	65	1.76	54.5	311
LCB 02	F	53	1.64	78.0	341
LCB 03	F	80	1.57	30.0	286
LCB 04	F	93	1.57	43.0	280
LCB 05	M	84	1.60	42.0	315
LCB 06	M	77	1.75	67.5	350
LCB 07	M	72	1.81	82.0	325
LCB 08	M	66	1.73	59.0	320
LCB 09	M	65	1.65	66.0	245
LCB 10	M	69	1.80	56.0	265
LCB 11	M	71	1.69	71.0	315

An autopsy is carried out after each test to assess the extent of injuries observed (see table 2).

Test conditions on the EUROSID-1 pelvis are given in table 3 below.

Various measurements made during the tests will be analyzed according to the following plan.

Analysis of sacrum acceleration caused by the impactor (chapter 2).

Analysis of the sacrum's angular velocity caused by the impactor (chapter 3).

Analysis of the impact force applied at the pelvis by the impactor (chapter 4).

Analysis of the impact force measured on the impactor (chapter 5).

Analysis of the load measured at the pubis of the EUROSID-1 dummy (chapter 6).

Pelvis deflection analysis during impact (chapter (7).

Load / deflection behaviour of the pelvis (chapter 8).

Human tolerance and performance criteria (chapter9)

Table 2 : Test conditions on PMHS pelvis and autopsy results.

Test N°	Mass (Kg) Impactor	Velocity (M/S) Impactor	Energy (J)	AIS	Autopsy Results
LCB 01	12.0	11.4	774	2	Ilio pubic branch fracture
LCB 02	16.0	9.91	786	3	Ilio + ischio pubic branch fract + sacro-illiac art.
LCB 03	16.0	10.0	803	3	Ilio + ischio pubic branch fract + illiac wing + femur.
LCB 04	12.0	10.0	600	3	Ilio/ischio pub branch fract + sacro-illiac art. + femur
LCB 05	12.0	13.4	1077	3	Illiac wing fracture + femur. Ilio/ischio pub branch fract
LCB 06	12.0	13.7	1120	3	+ illiac wing + cotyle Ischio pubic branch fracture
LCB 07	16.2	11.5	1073	3	+ femur Ilio/ischio pub branch fract
LCB 08	16.2	11.8	1118	3	+ sacro-iliac + femur Ischio pubic branch fracture
LCB 09	16.2	9.47	725	2	No injury
LCB 10	12.0	10.4	645	0	Ilio + ischio pubic branch fract. + cotyle
LCB 11	12.0	11.8	834	3	

Table 3 : Test conditions on the EUROSID-1 pelvis

Test N°	Mass (kg) Impactor	Velocity (M/S) Impactor	Energy (J)
LMB 01	12.0	6.00	216
LMB 02	12.0	11.4	778
LMB 03	12.0	11.4	778
LMB 04	12.0	13.4	1077
LMB 05	12.0	13.7	1120
LMB 06	12.0	13.1	1025
LMB 07	16.1	10.0	803
LMB 08	16.1	9.95	794
LMB 09	16.1	13.4	1430
LMB 10	16.1	13.2	1396
LMB 11	12.0	8.67	451
LMB 12	12.0	8.62	446
LMB 13	12.0	12.7	962
LMB 14	12.0	12.5	935
LMB 15	12.0	13.4	1081
LMB 16	11.4	10.3	600
LMB 17	11.4	9.56	521
LMB 18	11.4	10.4	611
LMB 19	16.2	11.4	1028
LMB 20	16.2	12.2	1201

Table 4 : Correspondence between tests carried out at constant energy

Objective selected for pelvic impact energy (joules)	Name of tests on dummy	Energy measured (joules)	Name of tests on PMHS	Energy measured (joules)
12 kg Impactor				
600 J	LMB 16	600	LCB 04	600
	LMB 17	520	LCB 10	645
	LMB 18	611		
1094 J	LMB 06	1025	LCB 05	1077
	LMB 04	1077	LCB 06	1120
	LMB 15	1081		
800 J	LMB 02	786	LCB 01	774
	LMB 03	803	LCB 11	834
16 kg Impactor				
800 J	LMB 08	794	LCB 02	786
	LMB 07	803	LCB 03	803
			LCB 09	725
1094 J	LMB 19	1028	LCB 07	1073
	LMB 20	1201	LCB 08	1118

2. Analysis of sacrum acceleration caused by the impactor

2.1 Analysis of resultant accelerations during impacts.

Four situations are selected to superpose curves recorded under the same tests conditions :

a) 12 kg impactor with a kinetic energy of about 800 j
b) 12 kg impactor with a kinetic energy of about 1100 j
c) 16 kg impactor with a kinetic energy of about 800 j
d) 16 kg impactor with a kinetic energy of about 1100 j.

The four figures (fig. 1 a, b, c, d) are shown using the same scale and on a single page in order to have an overall view for a qualitative analysis.

The curves representing resultant accelerations of the sacrum for both the PMHS and the EUROSID-1 dummy, have the same general form. However the maximum values obtained with EUROSID-1 are always higher than those obtained with PMHS.

The tests with EUROSID-1 show good reproducibility no matter what the configuration is. This is not always the case with PMHS.

At identical energy levels, the 16 kg impactor (fig. 1 c and d) gives resultant pelvic accelerations (for both EUROSID-1 and PMHS) slightly lower than those given by the 12 kg impactor (fig. 1 a and b) except for one 16 kg test on PMHS. This observation on the few curves selected to produce figure 1 cannot be generalized. Specifics are formulated in chapter 3 by analyzing the total data obtained from all the tests.

PMHS pelvic deflection and statistical Analysis
Pelvic deflection of the EUROSID-1 dummy.

The impactor's kinetic energy at the moment of impact, is an important parameter in several analysis foreseen and mentioned previously. In table 1 we have also established correspondences between the tests carried out on EUROSID-1 and PMHS for each impact zone and each energy level selected in the test programme.

These test references can be found in the various graphical representations of the results.

2.2. Analysis of the maximum resultant acceleration values of the sacrum as a function of impact energy.

These values are shown together in tables 5 & 6 in the annex.

All the tests (LCB and LMB) made during the last two years were used to analyze the maximum acceleration values of the sacrum under various loading conditions.

Graph (fig. 3) was produced by taking the following four groups into account :

a) Tests on PMHS with 16 kg impactor
b) Tests on PMHS with 12 kg impactor
c) Tests on EUROSID-1 with 16 kg impactor
d) Tests on EUROSID-1 with 12 kg impactor.

Straight regression lines are plotted for each group. In addition, two straight regression lines representing all the results for all the tests made on EUROSID-1 and on PMHS were superposed on the same graph with the equations and correlation values (R^2).

It is not possible from the tests made on the PMHS to differentiate between the results obtained with the 12 kg impactor from those with the 16 kg one. The straight regression lines are virtually superposed. Test results obtained with EUROSID-1 however indicate that sacrum accelerations obtained with the 12 kg impactor are slightly higher than those with the 16 kg one. At identical energy levels therefore, velocity does have a slight influence : An increase in impactor velocity results in an increase in sacrum acceleration.

The comparison of EUROSID-1 and PMHS in figure 3 **shows that the slope of the line representing the mean response of all the dummy tests is double that of the PMHS tests.** On the contrary, if we extrapolate this PMHS curve, it would seem that the dummy could be biofailthful between 200 to 400 j. but that above 500 j. the dummy's pelvis no longer absorbs the impact sufficiently to have a behaviour identical to PMHS.

3. Analysis of the sacrum's angular velocity caused by an impactor.

A sensor for measuring angular velocity around the X axis was attached to the sacrum in order to assess the rotational velocity and rotational angle of the pelvis during a lateral impact. The main aim was to confirm the values obtained during the film analysis. This analysis should make it possible to reconstitute the kinetic of the vertebral column during impacts on both the thorax and pelvis. This information is vital for validating the digital models of the human body.

a) 12 kg impactor with a kinetic energy of about 800 j
b) 12 kg impactor with a kinetic energy of about 1100 j

c) 16 kg impactor with a kinetic energy of about 800 j

d) 16 kg impactor with a kinetic energy of about 1100 j.

The four figures (fig. 4 a, b, c, d) are shown using the same scale and on a single page in order to have an overall view for a qualitative analysis

The same sensor for measuring angular velocity was also used on EUROSID-1 and on PMHS.

The EUROSID-1 tests show very good reproducibility, no matter what the configuration used. Looking at all the curves in figure 4 we observe that in all cases both on the dummy and on PMHS and no matter what impact energy was used, two very similar amplitude peaks with a time lag of about 12 milliseconds. After a very brief (about 10 ms) and positive rotation, the pelvis stops rotating and even oscillates in the opposite direction before rotating again in a positive direction. The behaviour of the dummy and the PMHS are very similar in the first phase; but in the second phase EUROSID-1 is much shorter.

What are the factors which could explain this behaviour ?

The first phase corresponds to a very small rotation, it is thus a question of a slight adjustment of the various bony or metallic elements making up the pelvic girdle. The second phase enables the complete pelvis to be rotated which is confirmed by the analysis of the movement using the films. Apart from this qualitative aspect of the movements, it would be difficult to analyze the values obtained due to the small number of tests available.

In the current database availability situation, the angular velocity measurement at the sacrum cannot be accepted as a usable parameter.

4. Analysis of the impact force applied on the pelvis by the impactor.

4.1 Comparison of maximum load values

We have consolidated on the same graph (figure 5) the maximum load values applied to the pelvis of either the EUROSID-1 dummy or the PMHS by the impactor, as a function of the kinetic energy levels available on the impactor at the moment of impact.

For the impacts on EUROSID-1 the tests were carried out with 2 impacting masses of 12 and 16 kg, whereas for the PMHS, we have the results obtained with the 12 and 16 kg impactors as well as results obtained with a 23.4 kg impactor used for a previous test programme carried out between 1992 and 1994. The characteristics of the PMHS tested in this previous programme are given in table 7. All the load values of the impactor tests (12, 16, and 23.4 kg impactors) have been consolidated in table 8. The straight regression lines were calculated by consolidating all the test results on the dummy and on the PMHS.

At low energy levels, the dummy gives the same impact load values as PMHS, but as soon as the impact energy increases, the loads recorded on the dummy are clearly higher than those measured on the PMHS. At 1100 j, the loads transmitted to the dummy are on average twice those transmitted to the PMHS.

In the graphical representation, we have used a different sign to mark the different impactor masses. Thus, we can see that the points are well distributed around the straight regression lines, from which we can conclude **that the impactor's mass is a parameter which relative to the applied load, has an unaccessible influence with these results. The dispersion of measurements due to the subjects characteristics makes this differentiation unusable.**

4.2 Comparison of curves representing loads on the PMHS pelvis.

The PMHS response curves were superposed on figures (6 a, b, c) by on the one hand separating them by taking account of the impact energy and on the other hand by marking the type of impactor used.

At 800 joules, the two tests made with a light impactor (12 kg) give higher force values than those obtained with a slightly heavier impactor (16 kg) : this result however was not confirmed during tests at 1100 joules. With such a small number of tests, no orientation can be considered for the conclusion. Other tests will be necessary to better understand this divergence in behaviour.

4.3 Comparison of load curves on the EUROSID-1 pelvis

PMHS response curves were superposed on figures (figure 7, a, b, c, d, e, f, g), by on the one hand, by separating them, by taking account of the impactor energy and on the other hand marking the type of impactor used. At 800 and 1100 j, the tests were made with two impactor devices (12 and 16 kg). At 800 joules the two tests made with a light impactor (12 kg), gave higher force values than those obtained with a slightly heavier impactor

(16 kg) : this result however was not so clear when the tests carried out between 1000 and 1100 joules were superposed. These results confirm the conclusion of paragraph 1 above.

5. Analysis of the impact force measured on the impactor.

In previous studies, load measurements taken in the contact zone were always a global measurement. When the zone is large, it takes into account all the forces transmitted by both the support on the trochanter and the support on the iliac wing. When the zone is small it only takes the impacted element into account (e.g. the trochanter) : however in this case we are distancing ourselves from the reality of automobile type impacts. An originality of this study is having envisaged dividing the support face into two in order to differentiate the loads passing through the iliac crest from those passing through the trochanter.

The support face of the impactor was split into two parts, each one resting on three load cells : because of this, there is a lower plate in correspondence with the trochanter and an upper plate in correspondence with the iliac wing.

From tables 5 and 6 showing the maximum values recorded by each load cell, the following figures have been plotted :

a) Distribution of loads during PMHS pelvis impacts (fig. 10).

b) Distribution of loads during EUROSID-1 pelvis impacts (fig. 9).

c) Superposing load distributions during PMHS and EUROSID-1 impacts (fig. 10).

In these three figures, the distributions were made as a function of the summation of loads measured and the same representation scales were kept.

5.1 Analysis of load distributions during PMHS pelvis impacts (fig. 10).

In the graph, the results obtained on each plate and impactor type used were marked differently. On the contrary, each straight regression line corresponds to all the results obtained on each of the support plates. When examining these straight regression lines it seems that the force measured on the upper plate corresponds to the support on the iliac wing, levelling out between 350 and 400 daN whereas the total load develops from 900 to 1500 daN.

The iliac wing is more flexible than the zone of the pelvis behind the trochanter. Under these conditions, the main load automatically passes via the most rigid point and the pelvis deflection thus corresponds to that of the trochanter. The iliac wing is involved in the transmission of the loads, but its deflection is primarily imposed by the capacities of the trochanter.

The differentiation between tests on different impactor masses was not shown on figure 10 because the straight regression lines are almost superposed.

The results of the 11 PMHS tests were too close to permit any conclusions to be drawn on the effect of the impactor's mass in relation to the load transmitted to the pelvis.

5.2 Analysis of load distributions during EUROSID-1 pelvis impacts (fig. 9).

The results obtained with the EUROSID-1 dummy show that, the load distribution between the lower and upper plates is about 75% (trochanter) and 25% (iliac crest) when all the results are taken into account (table 6) :

However, when we separate the results concerning the impactor masses, the distribution seems to develop differently. **A heavier impactor mass tends to increase the load supported by the trochanter.**

We have no explanation for this phenomena, all the more so since it does not appear on the PMHS figure (fig. 10).

5.3 Superposing load distributions during PMHS and EUROSID-1 impacts (fig. 10).

On this figure, only straight regression lines relative to the two plates have been represented for a global analysis. The lines representing the dummy results pass very close to zero, which is quite logical. On the contrary, the lines representing the PMHS results pass quite a long way from the origin of the coordinates, which tends to indicate that the line does not correctly represent the PMHS behaviour. This is especially valid for the load transmitted at the iliac crest.

In summary, we see that on the dummy (table 6), 75% of the loads pass by the trochanter and 25% by the iliac crest; whereas on the human body (table 5), although the average distribution is 68% by the trochanter and 32% by the iliac crest, we see a levelling off at 400 daN of the loads supported by the iliac wing.

6. Analysis of the load measured at the pubis of the EUROSID-1 dummy.

We have superposed on the same graph (fig. 11) the maximum total load values applied to the pelvis by the impactor (F app. MAX.), and the maximum values measured at the pubis of the dummy (F pubis MAX.). This latter measurement cannot be obtained on human bodies. On the contrary the load at the pubis is a value measured and recorded on the lateral impacted dummy; it makes it possible to evaluate the orthogonal load applied to the whole EUROSID-1 pelvis during the impact and of which we could not know the characteristics as in a vehicle environment.

To complete table 9, we have used the values obtained during the previous test series made at LBSU in 1992 and 1993. These tests were chosen because the impactor mass is different. All the values are consolidated in table 9 in annex.

The ratio (F pubis Max./ F app. Max.) of values obtained on each test enables us to pinpoint the load passing through the pubis at about 21 to 30% of the total load applied externally to the pelvis.

It nevertheless seems that the impactor's mass has an influence because when its mass increases, the ratio (F pubis Max. / F app. Max.), corresponding to the load transfer at the pubis reduces : The ratio of 29.8% for the 12 kg impactor falls to 21.7% for the 23.4 kg impactor. The use of a transfer coefficient of about 25% can be envisaged providing it is specified that a significant difference is implied.

7. Analysis of pelvis deflection during impact

Pelvis deflection can only be obtained by analyzing films made during the impact.

The camera is set to provide about 1000 frames / second.

With the help of "Photospot" follow-up sights, the coordinates of several points, attached to rigid elements of the body or dummy were recorded to be able to calculate the displacement of these points and the deflection of the demi-pelvis. To eliminate the effect of camera vibrations, the information is smoothed out compared to a fixed point of the picture (sight attached to the wall).

The deflection is obtained by studying the variation of distance between a fixed target on the impactor and one of the sights fixed on the sacrum.

To evaluate the basic difference, the starting image is tagged the moment the flash occurs. A check with a known distance is made to confirm the value of the enlargement scale used.

An initial deflection curve as a function of time can be established and the maximum value selected and shown in table 10.

The viscosity criteria 'V*C' makes it possible to take account of the compression and deflection velocity of a material or a set when this element is likely to have a more or less fluid plastic behaviour in accordance with the penetration velocity. This type of criteria is currently used a lot for evaluating the behaviour of the thorax.

Although the pelvis girdle is stiffer than the thoracic cage, it can nevertheless be subjected to significant deflections (in the order of 90 mm maximum in this experiment). It was thus worthwhile evaluating the effect of penetration speed and checking that the 'V*C' calculation can give a usable criteria value.

To estimate the influence of velocity on pelvic behaviour we have therefore calculated 'V*C' which represents the product of the demi pelvis compression that multiplies the compression velocity of this pelvis. The following steps are necessary to calculate the maximum 'V*C' value :

The demi-pelvis compression calculation $C = D/L$

D = deflection (mm); this is a 6 order polynomial of the measured deflection (study over about 60 ms with one point per ms)

L is the demi-width (mm) of the pelvis measured at the trochanter

The instantaneous velocity calculation (m/s) $V = dD/dt$; it is the derivative of the polynomial curve corresponding to the deflection.

Calculation of the 'V*C' product and extraction of the maximum value (given in table 10).

7.1 Deflection of PMHS pelvis and associated viscosity criteria ('V*C')

To complete the database, the results of the previous tests (1992 to 1994) at LBSU were incorporated with the results of the 11 tests of this experimental programme. All the data associating energy, deflection and viscosity criteria were consolidated in table 9 with the level of injuries obtained for each PMHS test.

We chose to represent maximum deflection as a function of the impactor's kinetic energy (fig. 12a) and also the injuries expressed in AIS severity (fig. 12b).

At identical energy levels, the impactor's velocity does not appear to be a determining factor. The points obtained overlap too much to evaluate any behavioural differences.

It seems ***that above 600 j, the available energy only* serves to accelerate the body and not to crush it because the *deflection no longer increases.***

The representation of the injury severity measured by AIS as a function of deflection, clearly shows that there is a relationship between penetration and the severity of pelvic injury.

Below 50 mm of penetration very few fractures occur, from 40 to 60 mm penetration a few simple fractures are seen and it is as of 60 mm penetration that serious injuries occur (AIS = 3).

We decided to represent the maximum viscosity criteria value as a function of both the impactor's kinetic energy (fig. 12c) and the AIS injury severity, (fig. 12d). The figures obtained are very close to the previously treated 12a and 12b figures.

Due to the overlapping of the points representing the results with the 12 kg and 16 kg impactors no behavioural differences could be established.

However, we can see that the dispersion is a little greater and thus that this complementary 'V*C' calculation does not provide any additional information in relation to the deflection.

7.2 Statistical analysis

A statistical analysis was carried out on all the results expressed in terms of AIS injury severity, as a function of either maximum deflection or 'V*C', in order to determine the critical values acceptable for the human pelvis.

For this, we calculated the injury probability using logistic regression and giving the value 0 for non fractured pelvis (AIS = 0) and the value 1 for all other pelvis (AIS $\geq$ 2). Each logistic regression is shown graphically in figures (13 a and b).

The limit values proposed for protecting the human pelvis, corresponding to a 50% AIS $\geq$ 2 probability, are 46 mm for pelvis deflection and 0.62 m/s for the 'V*C' criteria.

7.3 Pelvis deflection of the EUROSID-1 dummy

We selected 5 tests made under different impact conditions on the EUROSID-1 pelvis. the films taken during the impacts were analyzed to obtain deflections as a function of time. The results are given in table 10 and show that for **impact energies between 600 and 1100 joules, the deflection level is about 50 mm,** which corresponds to the maximum penetration of the foam covering of the pelvis.

The maximum deflection is thus reached at a very low impact energy and is therefore not a very representative indicator of the severity of the impact.

8. Pelvis « Load/Deflection » behaviour

8.1 *Conception of corridors representing human bodies*

The graphic presentation of the pelvic behaviour of the human body is made by using the measurement of the total force applied to the pelvis as a function of the deflection of this pelvis.

The deflection is a parameter obtained from the film analysis (see § VII above). The data was obtained at 1000 hz because of the camera speed. The force applied to the pelvis is calculated (see § IV) from values measure on 6 load sensors. This data was obtained at 10 Khz. To obtain the correspondence between load and deflection, we can only keep 1 point in 10 for the curve representing the load. As a function of available data enabling several results to be superposed, it was possible to give two graphs (figures 14 a and b), one for 800 joules impact energy and the other for 1100 joules. the corridors surrounding these curves are consolidated in figures (fig. 14 a and b) with the values of the coordinates.

8.2 EUROSID-1 Behaviour

The results obtained with the EUROSID-1 dummy, under the same test conditions were superposed in the corridors representing the human bodies (figures 16 a & b)

The EUROSID-1 response curves do not correspond at all to the human body corridor. Even though using the same conditions, EUROSID-1 has loads which are too high.

9 Human tolerance and performance criteria in terms of applied force.

9.1 History of the "pelvis" criteria in lateral impact

In 1982, D. Césari showed, with a test series made with a 17.3 kg hemispherical impactor, that there was a correlation between the impact force and the mass of the human subject (correlation R = 0.75). From the straight correlation line, he proposed an impact force limit of

10 kN for the tolerance of a human body weighing 75 kg (26th STAPP 82 1159). In this analysis, the impact force value selected corresponded to a duration equal to 3 ms and the injury severity corresponded to AIS ≥ 3.

The first EUROSID dummy, for which a performance criteria was envisaged, had a pelvis made of cast aluminium iliac wings. In March 1987 the Ad-Hoc CEVE group proposed performance criteria to use with this lateral impact dummy. The value of 10 kN was suggested for the maximum force measured at the pubic symphysis. ISO groups 5 and 6 (tc 22 / sc 12 / wg 6 N° 268 and wg 5 N° 312) have taken up the values proposed by CEVE.

The dummy has an impact response which revealed much higher loads than on the human body; on the contrary the measurement at the pubis is about one third of the external force. It was accepted that the one compensated the other, and an acceptable force at the pubis could be 10 kN.

From 1990, the EUROSID-1 dummy was commercialized. A few improvements were made, especially to the pelvis by making the iliac wings in plastic material. This made the complete unit more flexible and enabled an impact response to be obtained closer to that of the human body. Since then a redefinition of the measurable criteria value on the dummy proved to be essential. In 1991, CEVE duplicated some tests with EUROSID-1 and concluded that the pelvis performance criteria should be 6 kN measured at the pubiic symphysis.

The European parliamentary directive dated 20/05/96, concerning the protection of occupants in vehicles in lateral shock specifies a pelvic performance criteria which is : the maximum force recorded on the pubic symphysis must be less than or equal to 6 kN.

9.2 Establishing human tolerance as a function of applied force

In figure (fig. 13c) we have plotted the results in terms of AIS ≥ 2 as a function of the applied force and calculated and plotted the logistic regression curves for both AIS ≥ 2 and AIS ≥ 3. This analysis was based on 30 tests carried out with the same impactor using different masses and energies. AIS ≥ 2 was reached 8 times and AIS ≥ 3. was also reached 8 times with these tests.

For a 50% AIS ≥ 2 probability we have a 7.6 kN tolerance limit for the applied force. For a 50% AIS ≥ 3 probability, we have a 11.4 kN tolerance limit of the applied force. These results are of the same order as those published by D. Césari. A slight correction of the performance criteria will nevertheless be required no matter what protection level is wanted : AIS ≥ 2, AIS ≥ 3.

9.3 Performance criteria for the EUROSID-1 dummy pelvis

The performance criteria of the EUROSID-1 dummy pelvis can be defined as the value of the measurable load at the pubic symphysis, which corresponds to the human tolerance value for an acceptable injury severity. In the scope of this study, two situations can be considered, because by consolidating the data corresponding to the last two test series, (Test LCB and MRB) we have 8 tests causing AIS = 2 injuries and 8 tests causing AIS = 3 injuries. As a function of the new results available we are going to define two criteria, one associated to AIS = 2 and the other to AIS = 3.

We saw previously that :

EUROSID-1 was not completely biofaithful; at a given energy level, the applied force is higher for the dummy than for PMHS.

The load measured at the pubis moved with the test conditions.

Further, in order to pass from the impact force corresponding to the human tolerance to the force limit acceptable at the EUROSID-1 pubis, a double correction is necessary.

In table 11, we have consolidated the PMHS data corresponding to the tests of the two selected categories (AIS = 2 and AIS = 3). We recorded the impact energies corresponding to those tests in order to select out of the EUROSID-1 test series all the tests carried out under the same load conditions.

In the energy zone concerned, we took the middle point, (we obtained 629 joules for zone AIS = 2 and 860 joules for zone AIS = 3) and we plotted these values in figure 5; Using straight regression line equations of the PMHS and dummy responses, we obtained average theoretical values of the forces corresponding to AIS = 2 and AIS = 3 injury severities.

To reach AIS = 2, the ratio of forces gives :

F (EUROSID-1) = 1.82 F (PMHS)

To reach AIS = 3, the ratio of forces gives :

F (EUROSID-1 = 2.04 F (PMHS).

For the tests made with EUROSID-1, the ratio of the load measured at the pubis compared to the force applied at the pelvis, develops as a function of impact energy (see figure 17). As we did before, we used the straight regression line equation to calculate the theoretical ratio of forces at the middle points of the zones likely to result in an injury.

For the energy zone giving an AIS = 2,
the ratio is : **F (pubis) / F (applied) = 28.4%**
For the energy zone giving an AIS = 3,
the ratio is : **F (pubis) / F (applied) = 26.5%.**

The new performance criteria can be evaluated from the human tolerance values defined in the previous paragraph :

The 50% AIS ≥ 2 probability : the tolerance limit of the applied force is **7.6 kN.**

The 50% AIS ≥ 3 probability : the tolerance limit of the applied force is **11.4 kN.**

Performance criteria for the EUROSID-1 dummy pelvis : Performance criteria proposal for an
AIS ≥ 2 : 7.6 x 1.82 x 28.4% = 3.93 kN.
Performance criteria proposal for an
AIS ≥ 3 : 11.4 x 2.04 x 26.5% = 6.16 kN.

10 Conclusions

11 human pelvis were impacted laterally using an horizontal impactor fitted with a 200 x 200 mm impacting plate. The test programme had been developed to try to reveal a dominant parameter by varying the mass and velocity of the impactor. It emerges from the analysis of the various measurements taken during the impacts that, for a given impactor energy neither its mass nor velocity seemed to be dominant.

The impact force is transfered via the two support points namely the trochanter and iliac wing. As far as the load transfers are concerned, we see that for the dummy, 75% of the load passes via the trochanter and 25% via the iliac wing, whereas on the human body we note that even though the average load distribution is 68% via the trochanter and 32% via the iliac wing, there is a levelling out of the loads supported by the iliac wing at 400 daN.

Concerning the transfer of loads inside the dummy pelvis, the load sensor attached at the pubis enables us to locate the load passing via the pubis to about 21 to 30% of the total applied load. A transfer coefficient of about 25% can be considered.

The 20 impact tests previously carried out on the 10 human pelvis enabled the data base to be completed in order to obtain a human tolerance value. The analysis carried out using logistic regressions gave the following results. The limit values suggested for the protection of the human body corresponding to a 50% AIS ≥ 2 probability are 46 mm for maximum pelvis deflection and 0.62 m/s for the V*C viscosity criteria.

Two 'Force / Deflection' corridors are published, corresponding to impact energies of 800 and 1100 joules. The EUROSID-1 response curves do not correspond at all to the human body corridor. Although carried out under similar conditions to those applied to human bodies, the EUROSID-1 pelvis gives loads which are too high.

In terms of applied force, the human pelvis tolerance is based on the analysis of 30 tests made with the same impactor but with different impact masses and energies.

In these tests, AIS = 2 was reached 8 times and AIS = 3 was also reached 8 times. The analysis carried out using logistic regressions gave the following results : for a 50% AIS ≥ 2 probability, we have a 7.6 kN applied force tolerance limit and for a 50% AIS ≥ 3 probability we have an 11.4 kN applied tolerance limit.

The latter result is near the same force as that published by D. Césari.

By taking into account : the ratio of the forces sustained by the dummy and the PMHS impacted to the same load conditions, and the ratio between the force recorded at the pubis and the force applied to the EUROSID-1 pelvis, it was possible to calculate the value of new pelvis performance criteria.

With the results obtained in this study, we are able to propose : With a 50% AIS ≥ 2 probability that the pelvis performance criteria of EUROSID-1 is 3.93 kN. With a 50% AIS ≥ 3 probability, the pelvic performance criteria of EUROSID-1 is 6.16 kN.

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Table 5 : PMHS Pelvis impacts : Maximal measurements

Test N°	Impactor mass (kg)	Impactor speed (m/s)	Impact Energy (joule)	Max Result. accelerat (g)	Fs (N)	Fi (N)	Σ F (N)	Ratio Fs/ Σ F %	Ratio Fi/ Σ F %	(1) Measured Result. Force (N)	(2) Applied Force (N)
LCB 01	12.0	11.4	774		3 920	8 170	12 090	68	32	11 850	13 940
LCB 02	16.0	9.91	786	84	2 910	5 210	8 120	64	36	7 920	8 930
LCB 03	16.0	10.0	803	105	2 770	4 090	6 870	60	40	6 850	7 720
LCB 04	12.0	10.0	600	82	1 630	5 310	6 940	77	23	7 060	8 300
LCB 05	12.0	13.4	1077	107	3 560	6 170	9 730	63	37	10 020	11 790
LCB 06	12.0	13.7	1120	115	3 510	10 090	13 600	74	26	12 820	15 090
LCB 07	16.2	11.5	1073	86	3 290	11 660	14 950	78	22	14 310	16 120
LCB 08	16.2	11.8	1118	136	3 890	7 600	11 500	66	34	11 500	13 520
LCB 09	16.2	9.47	725	79	3 670	5 690	9 360	61	39	9 400	10 590
LCB 10	12.0	10.4	645	72	-	-	-	-	-	-	-
LCB 11	12.0	11.8	834	97	3 670	8 950	12 620	71	29	10 230	12 040
							Mean	68%	32%		

'Fs' = Maximum value of the summation of the three loads measured on the upper plate
'Fi' = Maximum value of the summation of the three loads measured on the lower plate
Σ 'F' = Summation of 'Fs' and Fi'
'(1) Measured Resultant Force = Maximum from the 6 filtered load measurements.
'(2) Applied Resultant Force = 'Measured Resultant Force totale (1)' x (Impacteur Mass) / (Impacteur Mass - Plates Masses)

Table 6 : EUROSID-1 Pelvis impacts : Maximal measurements -

Test N°	Impactor mass (kg)	Impactor speed (m/s)	Impact Energy (joule)	max résult. accelerat (g)	Fs (N)	Fi (N)	Σ F (N)	Ratio Fs/ Σ F %	Ratio Fi/ Σ F %	Applied Force (N)
LMB 01	12.0	6.00	216	55.	1 390	4 160	5 550	75	25	6 530
LMB 02	12.0	11.4	778	115	5 630	14 530	20 160	72	28	23 720
LMB 03	12.0	11.4	778	141	6 230	14 960	21 190	71	29	24 930
LMB 04	12.0	13.4	1077	186	10 750	18 760	29 510	64	36	34 720
LMB 05	12.0	13.7	1120	192	10 210	18 760	28 970	65	35	34 080
LMB 06	12.0	13.1	1025	184	10 450	18 500	28 940	64	36	34 050
LMB 07	16.1	10.0	803	114	3 820	14 370	18 190	79	21	20 500
LMB 08	16.1	9.95	794	115	3 100	15 050	18 150	83	17	20 450
LMB 09	16.1	13.4	1430	199	5 460	25 360	30 830	82	18	34 730
LMB 10	16.1	13.2	1396	202	6 990	29 720	36 710	81	19	41 360
LMB 11	12.0	8.67	451	68	2 410	5 580	7 990	70	30	9 400
LMB 12	12.0	8.62	446	73	1 990	8 110	10 090	80	20	11 870
LMB 13	12.0	12.7	962	162	5 270	15 390	20 660	74	26	24 310
LMB 14	12.0	12.5	935	164	5 180	16 120	21 300	76	24	25 060
LMB 15	12.0	13.4	1081	190	6 320	20 540	26 860	76	24	31 600
LMB 16	11.4	10.3	600	106		10 390				
LMB 17	11.4	9.56	521	89	2 190	8 160	10 350	79	21	12 180
LMB 18	11.4	10.4	611	114	2 980	10 420	13 400	78	22	15 770
LMB 19	16.2	11.4	1028	178	5 990	23 460	29 440	80	20	33 170
LMB 20	16.2	12.2	1201	190	5 100	24 600	29 700	83	17	33 470
							Mean	75 %	25%	

'Applied Resultant Force' = Measured Resultant Force totale x (Impacteur Mass) / (Impacteur Mass - Plates Masses)

Table 7 : Corps qualities and tests conditions (INRETS 1992/94)

Impactor mass = 23.4 kg
Each PMHS is impacted 2 times. First at lower speed (no injury), second at higher speed (juxta injury)

Tests N°	Sex	Age	Height (m)	Weight (Kg)	1/2 pelvis width (mm)	Speed (m/s)	Energy (joule)	Applied force (N)
MRB 01	M	76	1.73	82.0	165	3.50	143	5 640
MRB 03	M	57	1.74	76.0	165	3.40	135	6 220
MRB 05	M	66	1.72	69.0	170	3.41	136	3 670
MRB 07	M	69	1.64	52.0	155	3.43	138	4 160
MRB 09	M	78	1.62	54.0	160	3.29	127	4 010
MRB 11	M	38	1.81	86.0	155	3.34	131	4 270
MRB 13	M	63	1.70	60.0	150	3.35	131	3 000
MRB 15	F	69	1.69	59.5	165	3.26	124	3 210
MRB 17	M	81	1.67	82.0	170	3.22	121	4 310
MRB 19	M	70	1.90	70.0	165	3.26	124	4 920
Mean		**66.7**	**1.72**	**69.1**	**162**	**3.35**	**131**	
MRB 02	M	76	1.73	82.0	165	6.74	532	8 400
MRB 04	M	57	1.74	76.0	165	6.50	494	10 550
MRB 06	M	66	1.72	69.0	170	6.77	536	9 120
MRB 08	M	69	1.64	52.0	155	6.46	488	6 520
MRB 10	M	78	1.62	54.0	160	6.50	494	8 150
MRB 12	M	38	1.81	86.0	155	6.64	516	9 840
MRB 14	M	63	1.70	60.0	150	6.44	485	5 840
MRB 16	F	69	1.69	59.5	165	6.57	505	6 540
MRB 18	M	81	1.67	82.0	170	6.57	505	10 040
MRB 20	M	70	1.90	70.0	165	6.43	484	10 180
Mean		**66.7**	**1.72**	**69.1**	**162**	**6.56**	**504**	

Table 9 : EUROSID-1 Pelvic impact tests, maximal values of applied forces on pelvis and pubic symphysis.

Test N°	Impact energy (joule)	Applied Force (N)	Mesured Pubic Force (daN)	Fmes / F app %
Impactor	**200x200**	**12 kg**		
LMB 11	451	9 400	3 280	34.9
LMB 12	446	11 870	3 530	29.7
LMB 13	962	24 310	6 870	28.3
LMB 14	935	25 060	7 180	28.6
LMB 15	1081	31 600	8 120	25.7
LMB 16	600		4 310	
LMB 17	521	12 180	3 790	31.2
LMB 18	611	15 770	4 760	30.2
Mean				**29.8**
Impactor	**200x200**	**16 kg**		
LMB 07	803	20 500	5 880	28.7
LMB 08	794	20 450	5 680	27.8
LMB 09	1430	34 730	7 900	22.7
LMB 10	1396	41 360	8 450	20.4
LMB 19	1028	33 170	7 980	24.0
LMB 20	1201	33 470	7 890	23.6
Mean				**26.35**

Test N°	Impact energy (joule)	Applied Force (N)	Mesured Pubic Force (N)	Fmes / F app %
Impactor	**Φ 120mm**	**17.3 kg**		
IBE 27	294	7 260	2 000	27.5
IBE 28	662	13 040	3 580	27.5
IBE 29	300	7 550	2 190	29.0
IBE 30	671	13 320	4 050	30.4
Mean				**28.6**
Impactor	**100x200**	**23.4 kg**		
MRE 01	139	3 160	700	22.1
MRE 02	134	3 170	720	22.9
MRE 03	137	3 110	650	20.9
MRE 04	505	10 230	2 170	21.2
MRE 05	521	10 120	2 240	22.2
MRE 06	525	10 640	2 250	21.2
Mean				**21.7**

Impactors (12 and 16 kg) are squared plates (200x200mm); Impactor (23.4kg) is rectangular (100x200mm); Impactor 17.3kg) is an hemispherical plate (Φ 120 mm)

Table 10 : PMHS and EUROSID-1 pelvics impact tests : Maximum values of deflection and V*C.

PMHS Tests					EUROSID-1 Tests				PMHS Tests				
Test N°	Impact Energy (joule)	Deflection Max. (mm)	V*C Max (m/s)	AIS	Test N°	Impact Energy (joule)	Deflection Max. (mm)	V*C Max (m/s)	Test N°	Impact Energy (joule)	Deflection Max. (mm)	V*C Max (m/s)	AIS
LCB 01	774	50	1.12	2	LMB 01	216	-	-	MRB 01	143	31.8	0.26	0
LCB 02	786	89	1.78	3	LMB 02	778	63.0	226	MRB 03	135	28.0	0.23	0
LCB 03	803	67	1.54	3	LMB 03	778	66.9	2.38	MRB 05	136	32.7	0.20	0
LCB 04	600	75	1.55	3	LMB 04	1077			MRB 07	138	21.2	0.18	0
LCB 05	1077	61	1.53	3	LMB 05	1120	-	-	MRB 09	127	28.8	0.21	0
LCB 06	1120	71	1.80	3	LMB 06	1025	62.9	2.45	MRB 11	131			0
LCB 07	1073	66	1.04	3	LMB 07	803	67.9	2.23	MRB 13	131	24.5	0.16	0
LCB 08	1118	68	1.22	3	LMB 08	794	70.0	2.34	MRB 15	124	32.4	0.27	0
LCB 09	725	56	1.64	2	LMB 09	1430	63.4	2.64	MRB 17	121	36.4	0.26	0
LCB 10	645	67		0	LMB 10	1396	58.7	2.30	MRB 19	124	28.3	0.23	0
LCB 11	834	65	1.77	3	LMB 11	451	48.6	1.23	MRB 02	532	60.6	0.75	2
					LMB 12	446	44.9	1.12	MRB 04	494	38.8	0.65	2
					LMB 13	962	-	-	MRB 06	536	54.6	0.56	2
					LMB 14	935	49.6	1.73	MRB 08	488	56.7	0.95	2
					LMB 15	1081	62.1	2.50	MRB 10	494	56.9	0.86	2
					LMB 16	600	65.6	2.09	MRB 12	516			0
					LMB 17	521	45.3	1.21	MRB 14	485	54.0	0.66	2
					LMB 18	611	-	-	MRB 16	505	50.8	0.80	0
					LMB 19	1028	62.5	2.29	MRB 18	505	46.7	0.63	0
					LMB 20	1201	57.3	2.00	MRB 20	484	38.2	0.52	0

Table 11 : Impact tests used on EUROSID-1 and PMHS for evaluate a pelvic force criterion

a) Impact tests on EUROSID-1 used at a level of impact energy corresponding to AIS = 2 on PMHS.

EUROSID-1 Tests	Impact Energy (joule)	Applied Force (N)	Fpubic/Fapp %
LMB 12	446	11 870	29.7
LMB 11	451	9 400	34.9
LMB 17	521	12 180	31.2
LMB 16	600		
LMB 18	611	15 770	30.2
LMB 02	778	23 720	27.3
LMB 03	778	24 930	24.5
LMB 08	794	20 450	27.8
LMB 07	803	20 500	28.7

PMHS Tests	Impact Energy (joule)	Appied Force (N)	Injury AIS
LCB 01	774	13 940	2
LCB 09	725	10 590	2
MRB 02	532	8 400	2
MRB 04	494	10 550	2
MRB 06	536	9 120	2
MRB 08	488	6 520	2
MRB 10	494	8 150	2
MRB 14	485	5 840	2
Middle point	**629**		

(485 + 774) / 2 = 629

b) Impact tests on EUROSID-1 used at a level of impact energy corresponding to AIS = 3 on PMHS.

EUROSID-1 Tests	Impact Energy (joule)	Applied Force (N)	Fpubic/Fapp %
LMB 02	778	23 720	27.3
LMB 03	778	24 930	24.5
LMB 08	794	20 450	27.8
LMB 07	803	20 500	28.7
LMB 14	935	25 060	28.6
LMB 13	962	24 310	28.3
LMB 06	1025	34 050	22.2
LMB 19	1028	33 170	24.0
LMB 04	1077	34 720	23.0
LMB 15	1081	31 600	25.7
LMB 05	1120	34 080	22.7

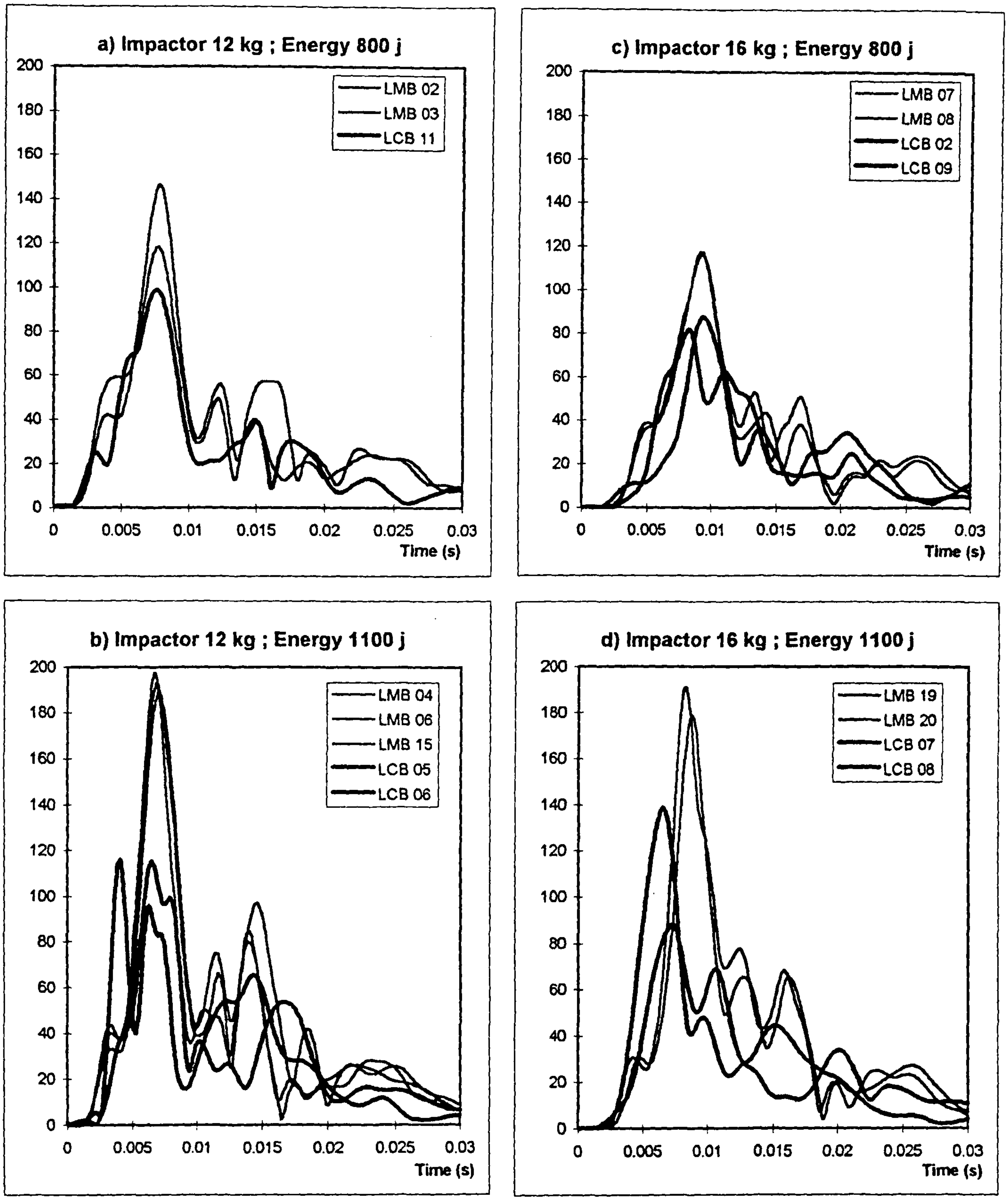
PMHS Tests	Impact Energy (joule)	Appied Force (N)	Injury AIS
LCB 02	786	8 930	3
LCB 03	803	7 720	3
LCB 04	600	8 300	3
LCB 05	1077	11 790	3
LCB 06	1120	15 090	3
LCB 07	1073	16 120	3
LCB 08	1118	13 520	3
LCB 11	834	12 040	3
Middle point	**860**		

(600+ 1120) / 2 = 860

In the energy zone concerned, we took the middle point, (we obtained 629 joules for zone AIS = 2 and 860 joules for zone AIS = 3) and we plotted these values in figure 5 and 17. Using straight regression line equations of the PMHS and dummy responses, we obtained

1) average theoretical values of the forces corresponding to AIS = 2 and AIS = 3 injury severities.
   To reach AIS = 2, the ratio of forces gives : **F (EUROSID-1) = 1.82 F (PMHS)**
   To reach AIS = 3, the ratio of forces gives : **F (EUROSID-1 = 2.04 F (PMHS).**
2) theoretical ratio of forces.
   For the energy zone giving an AIS = 2,,the ratio is : **F (pubis) / F (applied) = 28.4%**
   For the energy zone giving an AIS = 3, the ratio is : **F (pubis) / F (applied) = 26.5%.**

Figure 1 : Pubic resultant acceleration versus history



LMB tests = EUROSID-1 tests
LCB tests = PMHS tests

Figure 3 : **Peak of pelvic resultant acceleration versus impact energy**

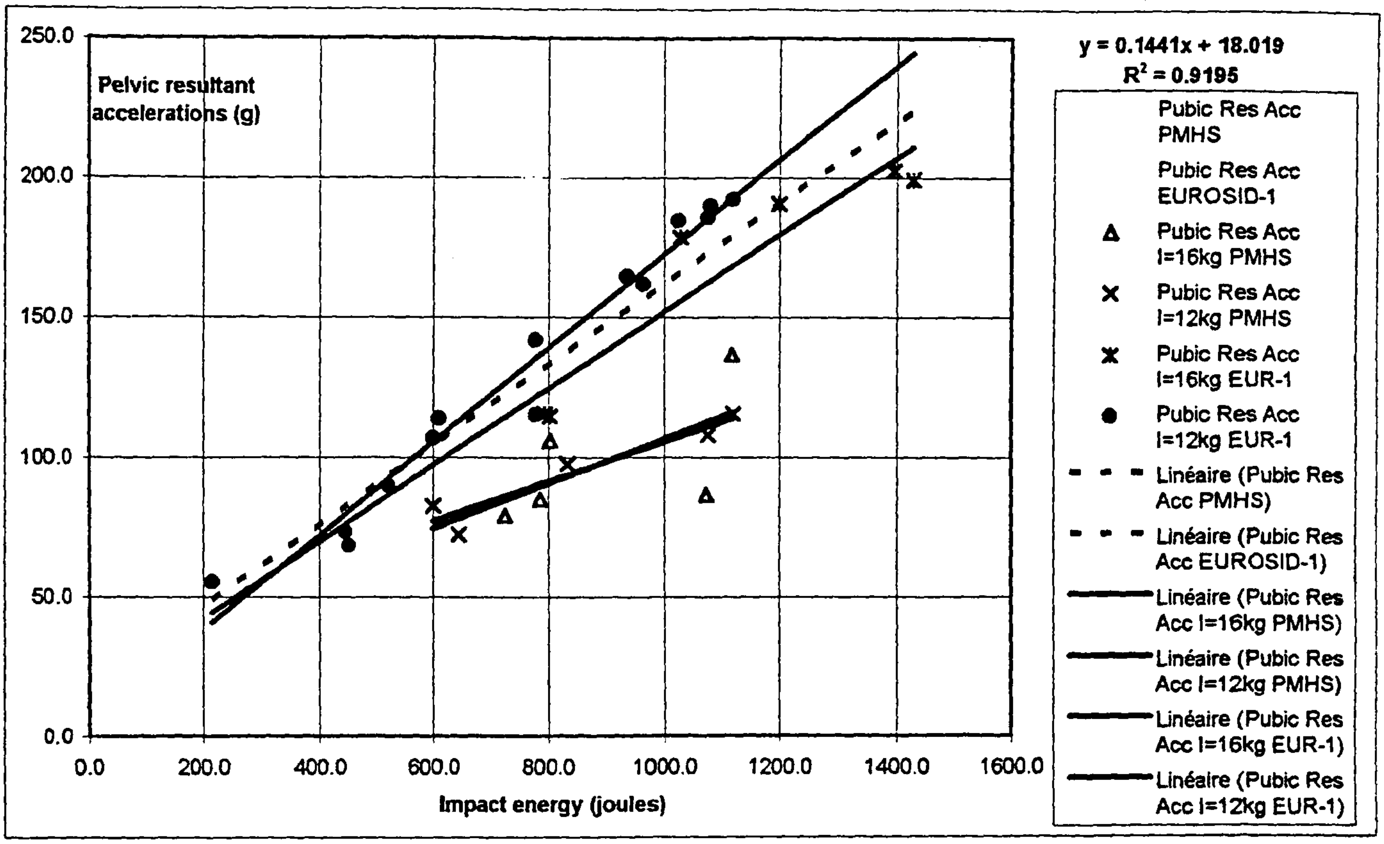


Figure 5 : **Total applied force on pelvis versus impact energy. Comparison between EUROSID-1 and PMHS.**

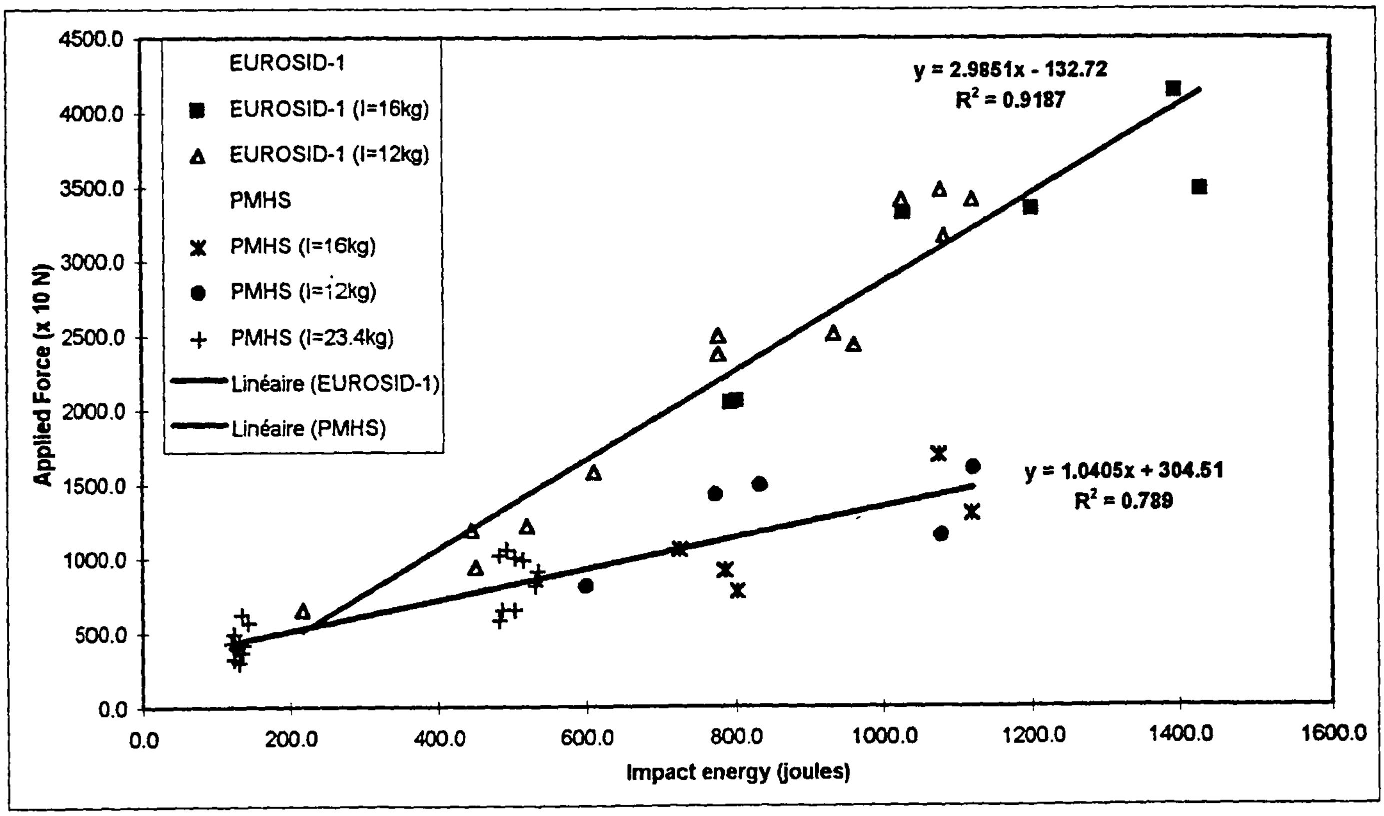
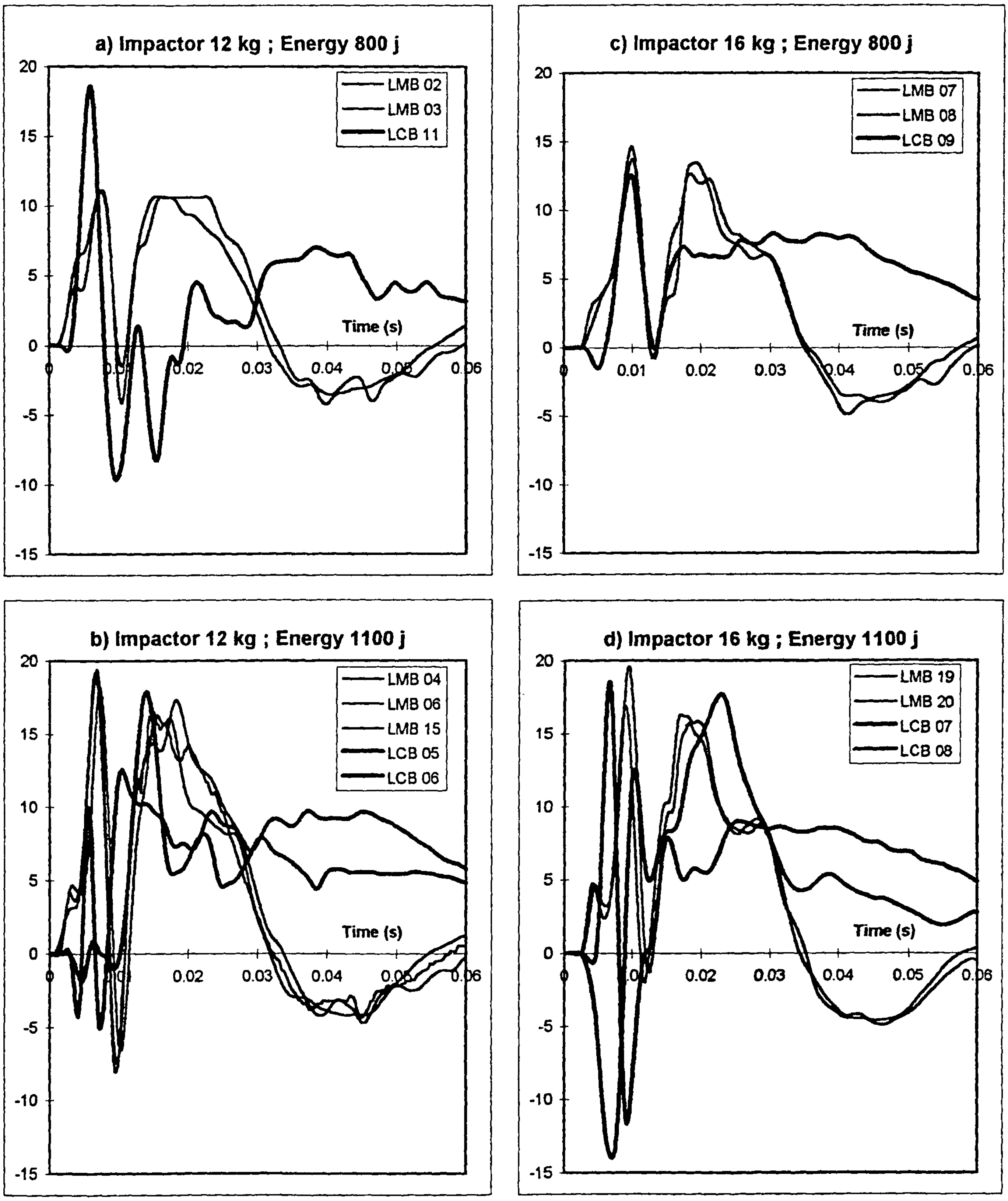
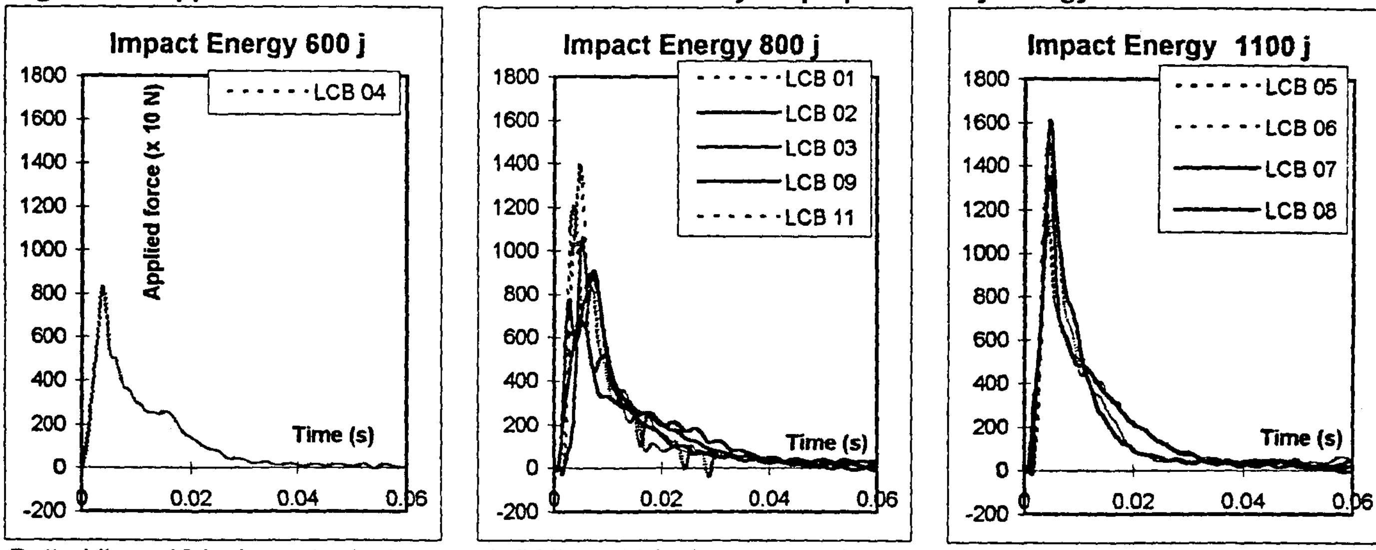


Figure 4 : **Pubic angular speed versus history**



LMB tests = EUROSID-1 tests
LCB tests = PMHS tests

Figure 6 : Applied Force on PMHS Pelvis versus History. Superposition by Energy



Dotted line : 12 kg impactor tests Solid line : 16 kg impactor tests

Figure 7 : Applied Force on EUROSID-1 pelvis

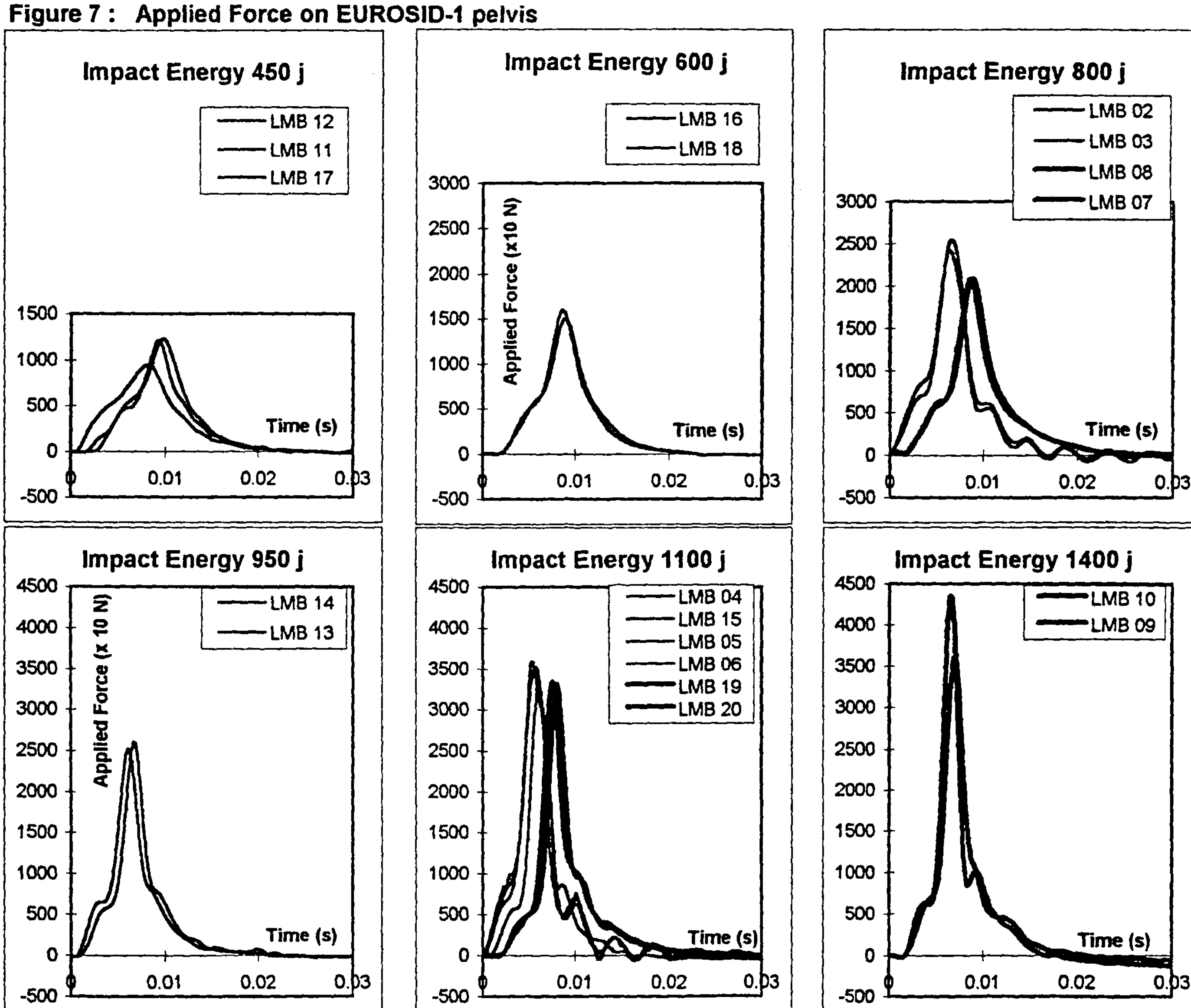


Figure 9 : EUROSID-1 pelvis tests. Forces distribution on 'Trochanter' plate (Troc pl) and iliac plate (Iliac pl).

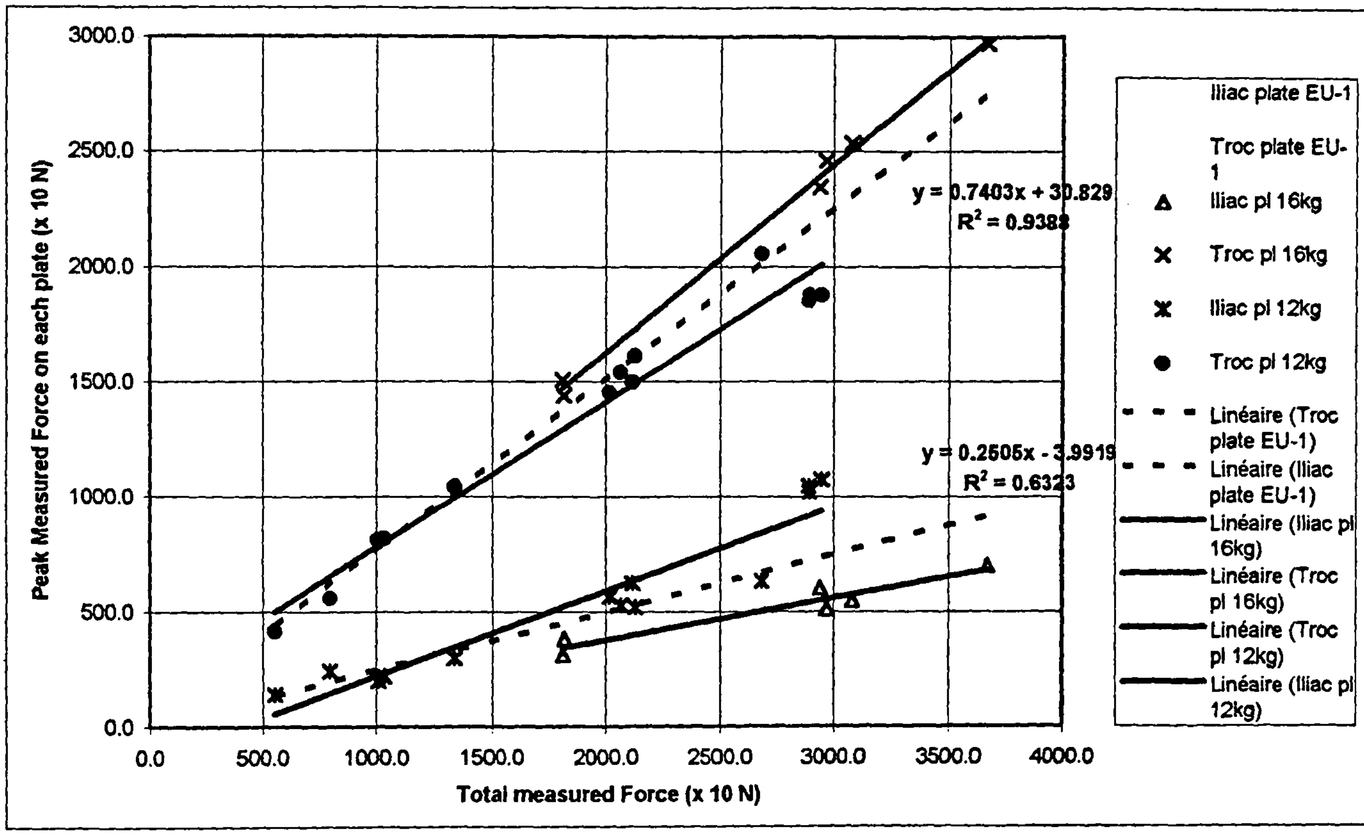


Figure 10 : PMHS and EUROSID-1 pelvis tests. Force distribution on trochanter plate (Troc pl) and iliac plate (Iliac pl)

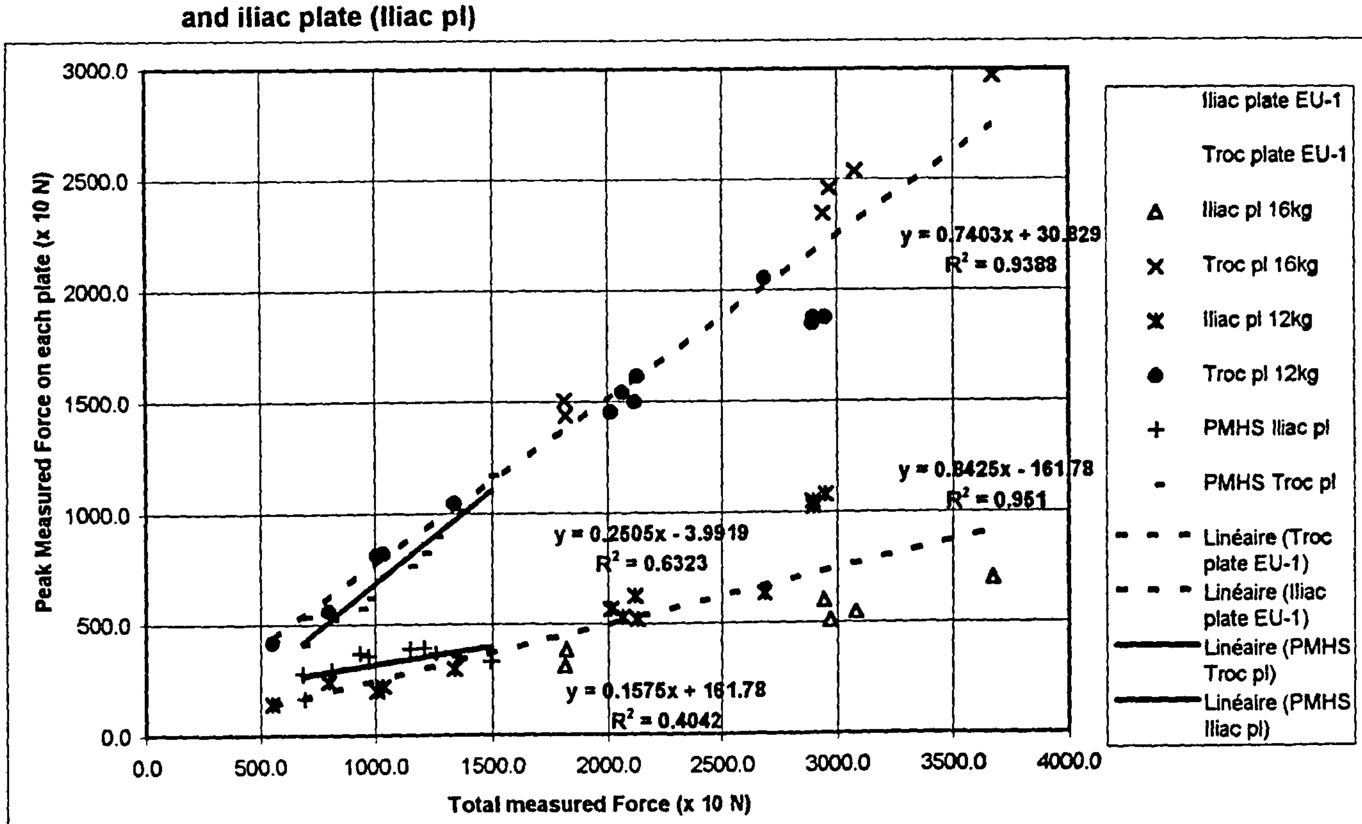


Figure 11 : Measured force on pubic symphysis and total applied force on EUROSID-1 pelvis

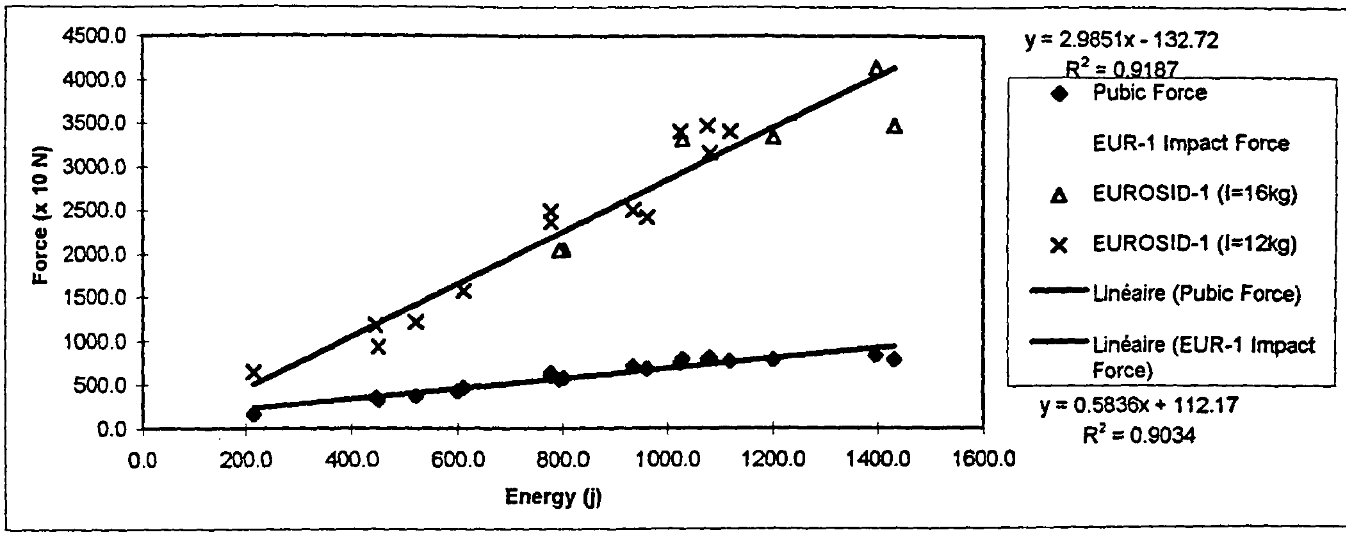


Figure 12 a & b : Maximum deflection analysis of each PMHS pelvis

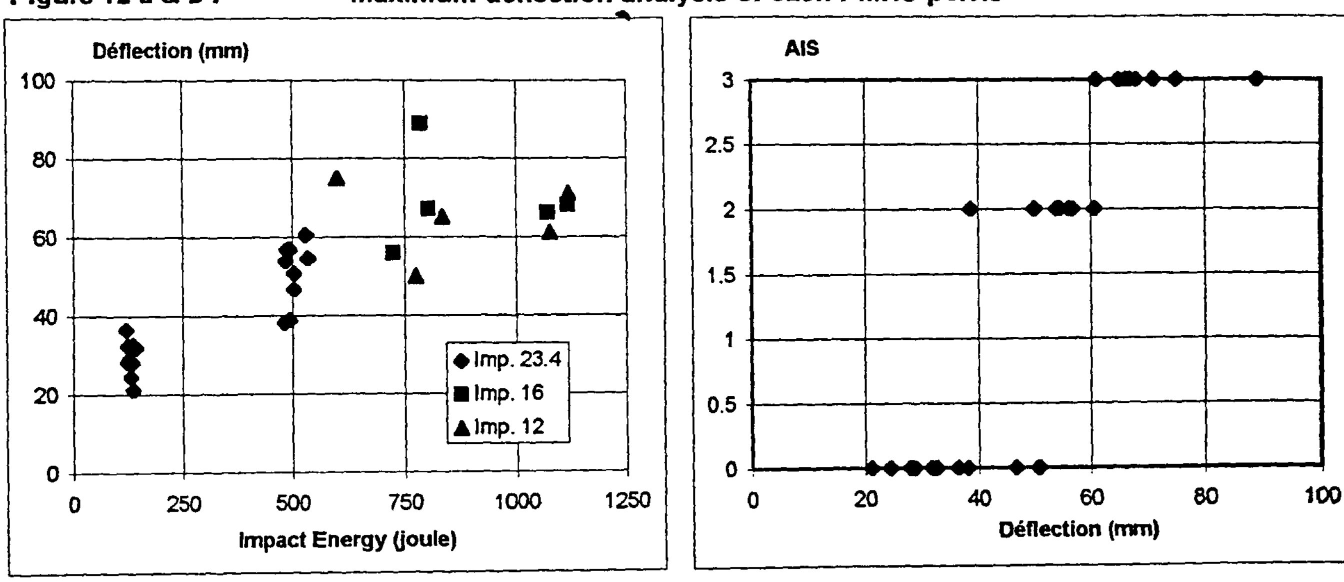


Figure 12 c & d : V*C analysis of each PMHS pelvis

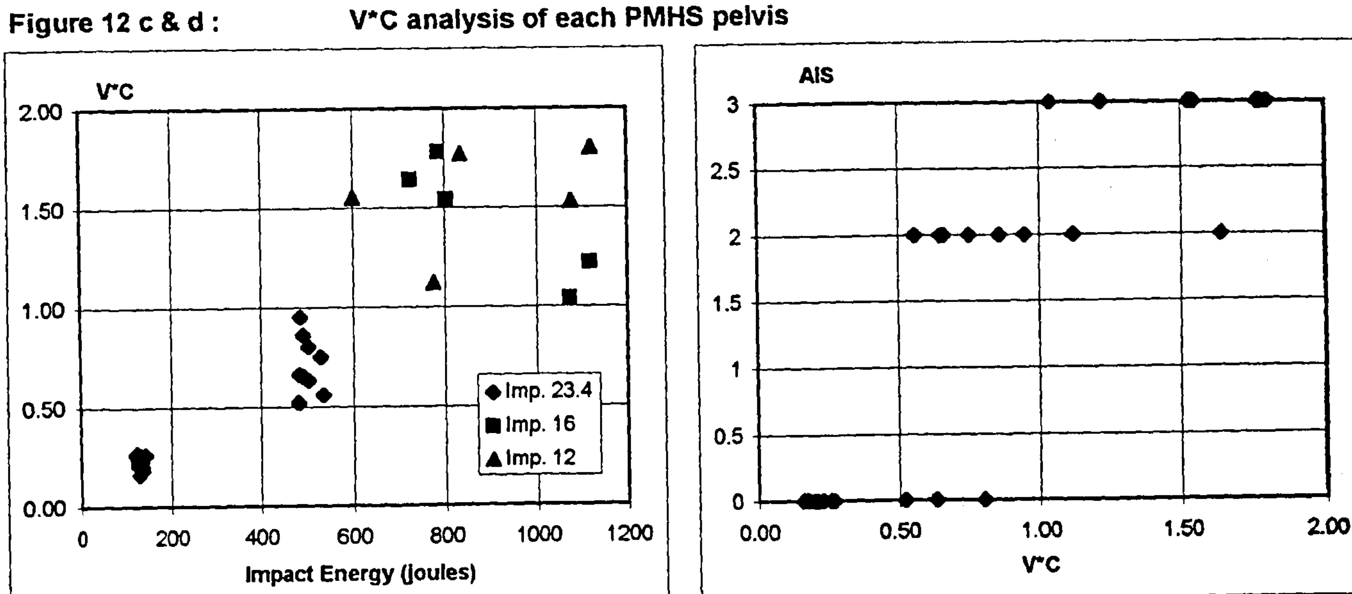
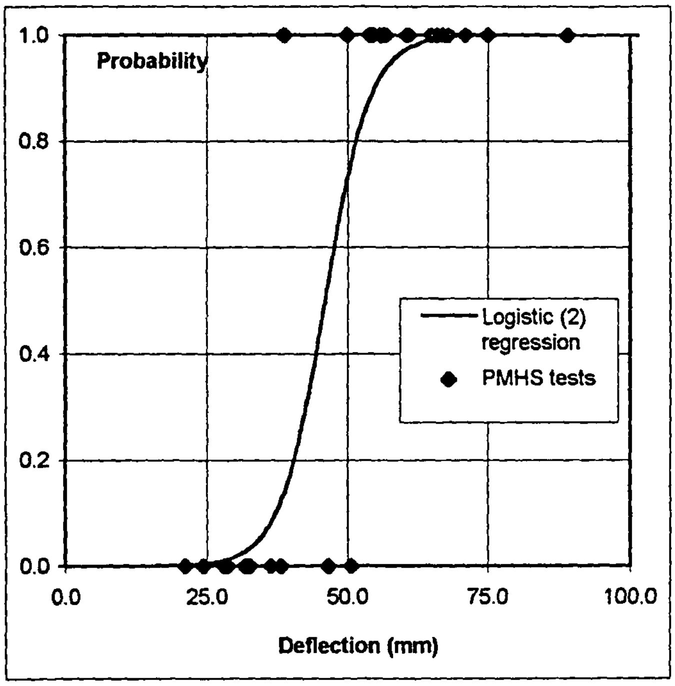
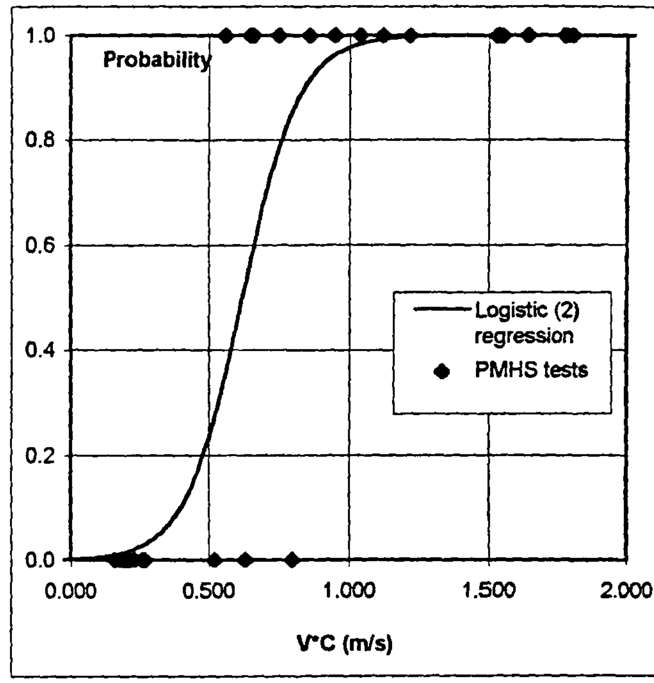


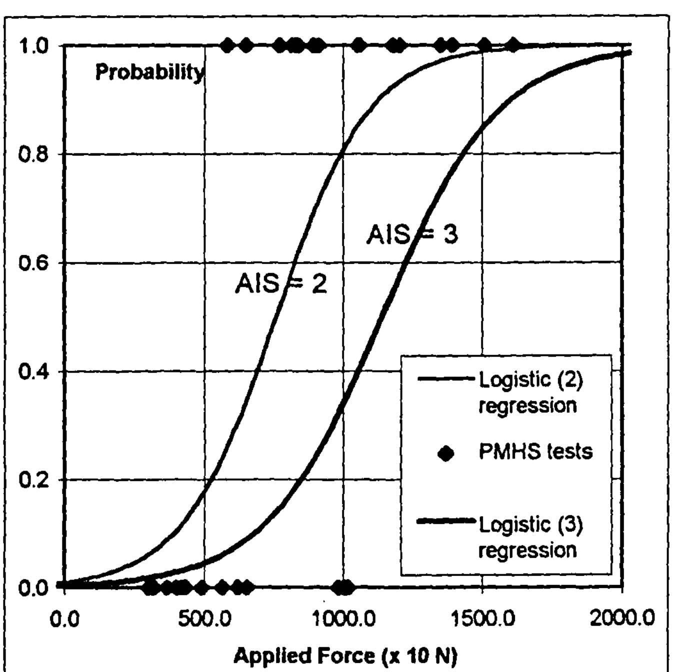
Figure 13 : Criterion assessment with logistic regressions



a) Deflection criterion of the human pelvis



b) Viscous criterion of the human pelvis



c) Human Pelvic Force Criterion

Criterion values of Human pelvis

Probability = 50% AIS ≥ 2

Deflection criterion= 46 mm

Viscous criterion (V*C) = 0.62

Applied Force criterion = 7600 N

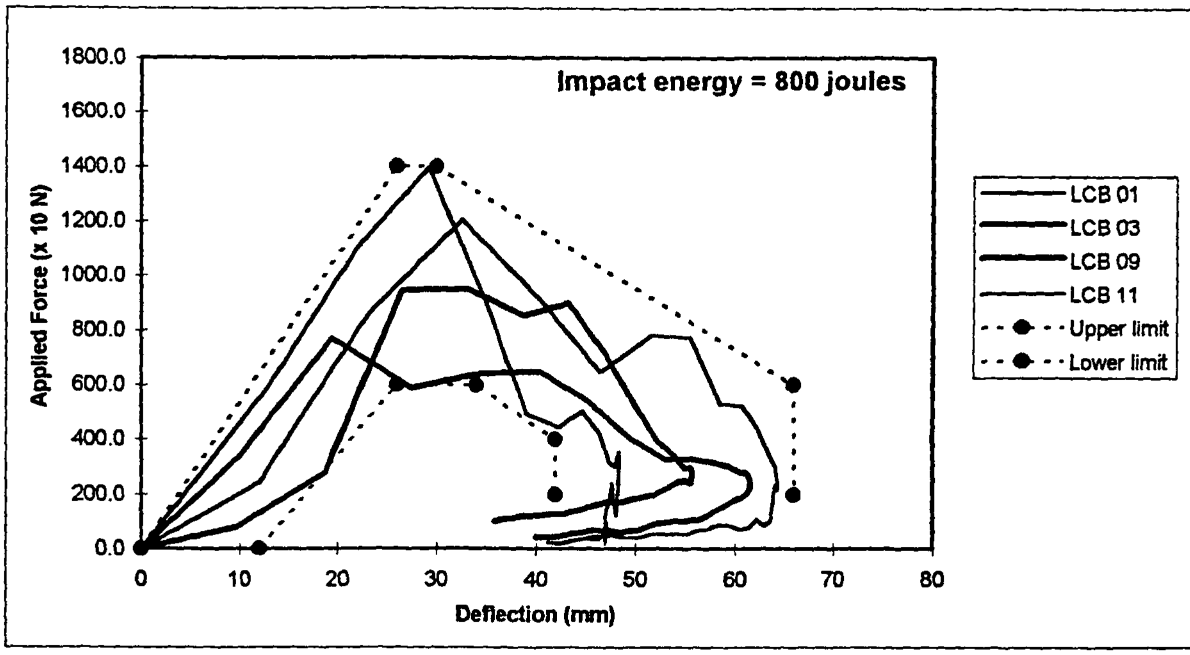
Probability = 50% AIS ≥ 3

Applied Force criterion = 11400 N

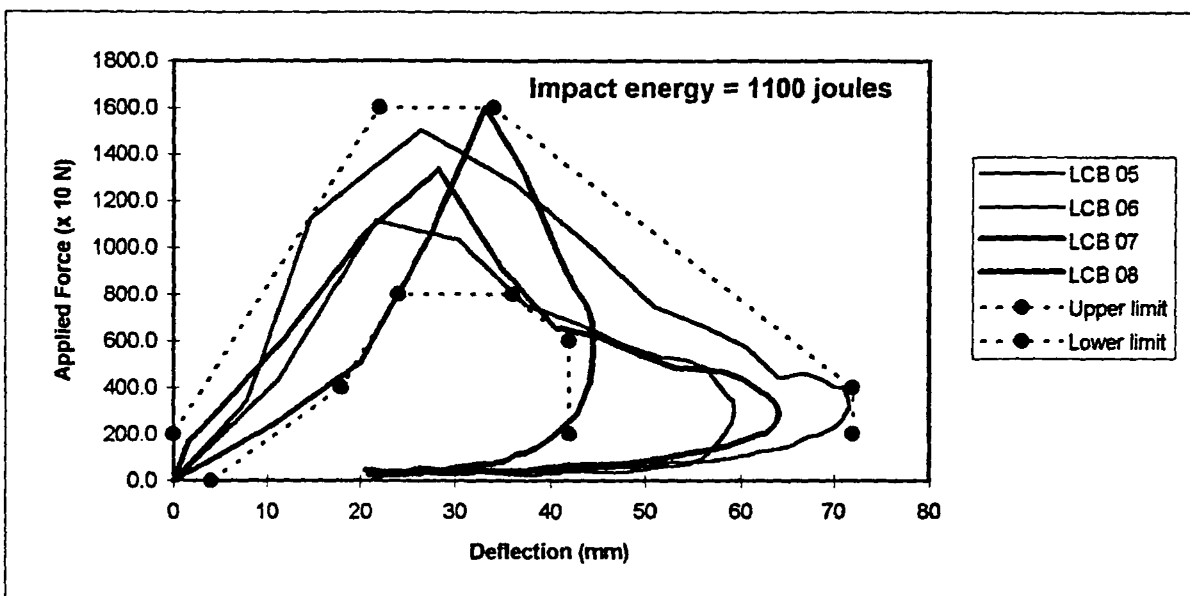
On the 3 graphs (a, b, c) the tests distribution is made with :

when AIS = 0 the probability is 0
when AIS =2 or 3 the propability is 1

Figure 14 : Corridors of human pelvis 'Force/Deflection' curves



Dotted line = Impactor mass : 12 kg Solid line = Impactor mass : 16 kg



a) Corridor = 800 joules **b) Corridor = 1100 joules**

Deflection mm	Force N	Deflection mm	Force N	Deflection mm	Force N	Deflection mm	Force N
	Upper limit		Lower limit		Upper limit		Lower limit
0	0	12	0	0	2 000	4	0
26	14 000	26	6 000	22	16 000	18	4 000
30	14 000	34	6 000	34	16 000	24	8 000
66	6 000	42	4 000	72	4 000	36	8 000
66	2 000	42	2 000	72	2 000	42	6 000
						42	2 000

Figure 16 : Corridors of human pelvis 'Force/Deflection' curves and EUROSID-1 responses

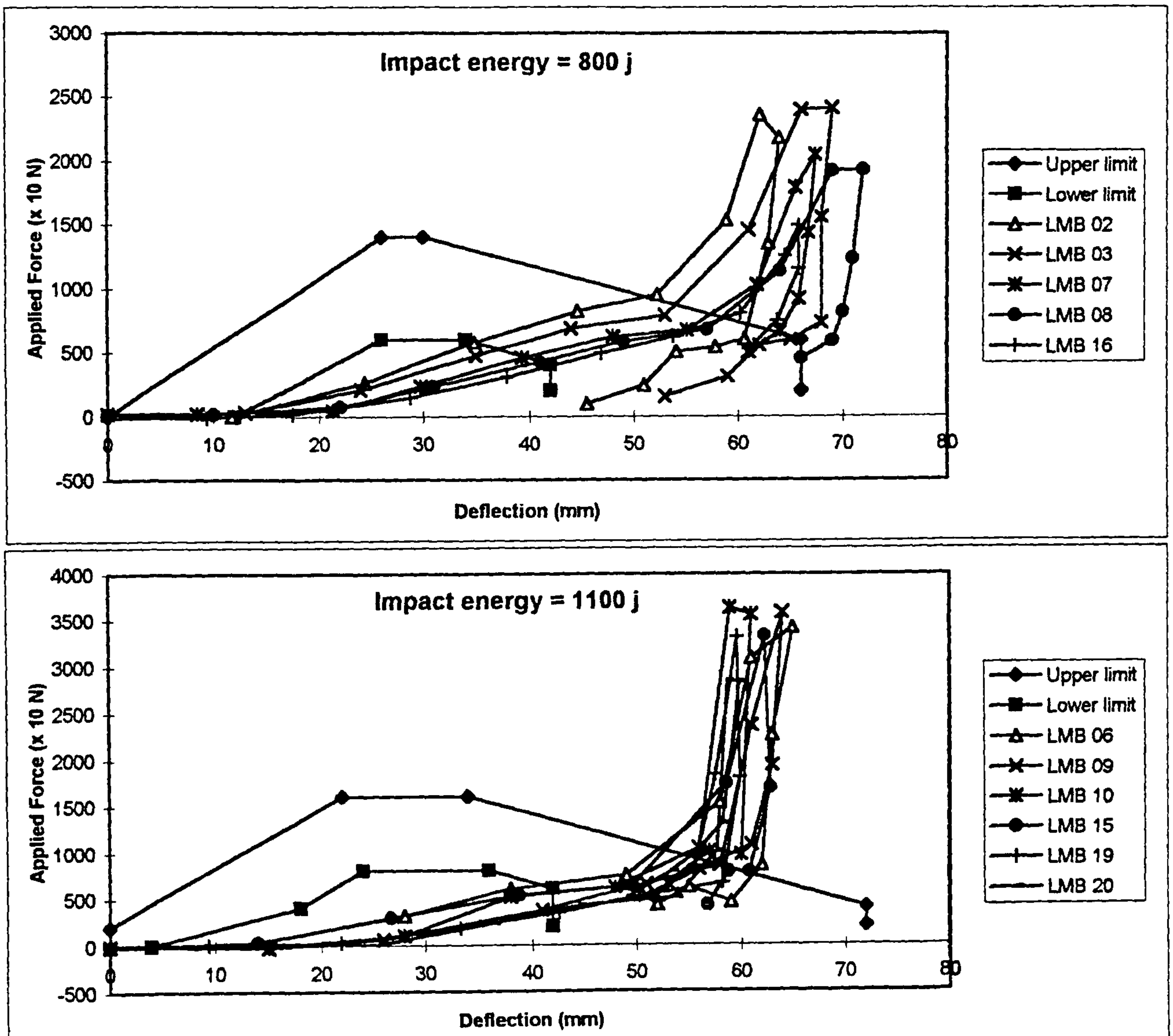
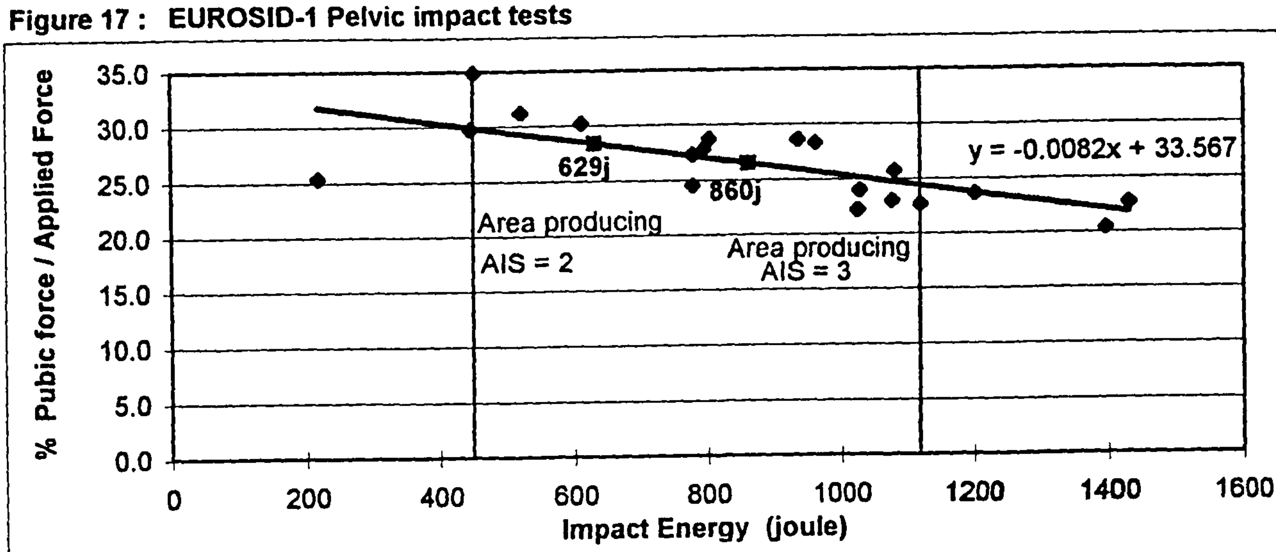


Figure 17 : EUROSID-1 Pelvic impact tests



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