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of Transportation

**National Highway
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Administration**

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Foreword

This report of the proceedings of the Fourteenth International Technical Conference on the Enhanced Safety of Vehicles was prepared by the National Highway Traffic Safety Administration, United States Department of Transportation.

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For clarity and because of some translation difficulties, a certain amount of editing was necessary. Apologies are, therefore, offered where the transcription is not exact.

Introduction

The International Experimental Safety Vehicles (ESV) Program originated under NATO's Committee on the Challenges of Modern Society (CCMS) and was implemented through bilateral agreements between the United States Government and the governments of 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 in safety engineering and to meet periodically to exchange technical information on their progress. Over time the focus of the Conferences has shifted from concentration on the development of experimental safety vehicles to broader issues of motor vehicle safety. In 1991, the name of the Conference was changed to "The International Technical Conference on the Enhanced Safety of Vehicles" (ESV) to reflect these broader issues.

To date, thirteen international conferences have been held, each hosted by one of the participating governments. These conferences have drawn participants from government, the worldwide automotive industry, and the motor vehicle safety research community. International cooperation in motor vehicle safety research continues at the highest level.

The proceedings of each Conference have been published by the United States Government and distributed worldwide. These reports, which detail the safety research efforts underway worldwide, have been recognized as the definitive work on motor vehicle research.

We are certain that this outstanding example of international cooperation seeking reductions in motor vehicle deaths and injuries will continue its past success.

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U.S. DOT/NHTSA

Alex Butt
American Suzuki Motor Corporation

Thomas Carr
American Automobile Manufact. Assoc.

Carl Clark
Safety Systems Corporation

Gregory Dana
AIAM

Robert Davis
General Motors Corporation

Kennerly H. Digges
George Washington University

William R. Edwards
Chrysler Corporation

Bruce Enderle
Yamaha Motor Corporation

Rolf Eppinger
U.S. DOT/NHTSA

Leonard Evans
General Motors Corporation

Karl-Heinz Faber
Mercedes-Benz of North America

Eugene Farber
Ford Motor Company, Ltd.

Michael Finkelstein
Finkelstein & Associates

David Finnegan
U.S. House of Representatives

Joseph G. Finnerty
Piper & Marbury

Virginia Fischbach
Chrysler Corporation

Dr. Franklin G. Fisher, Jr.
Applied System Technologies, Inc.

Lawrence Fleming
Nissan North America

Donald Friedman
Liability Research, Inc.

Thomas Fugger
Accident Research & Analysis

Thomas J. Gibson
Biokinetics & Associates, Ltd.

William H. Gillespie III
General Motors Corporation

Ed Gordon
Mayne-McKenney & PARS

Charles Griswold
C.J. Griswold, Inc.

Michinori Hachiya
Nissan North America

Chester Hale
American Honda Motor Company, Inc.

Christopher A. Hart
U.S. DOT/NHTSA

Philip Haseltine
American Coalition for Traffic Safety

Martin Heitkamp
Chrysler Corporation

Sherman Henson
Ford Motor Company, Ltd.

Kazuo Higuchi
American Honda Motor Company, Inc.

Ralph Hitchcock
U.S. DOT/NHTSA

William T. Hollowell
U.S. DOT/NHTSA

Kenneth D. Holmgren
Morton Automotive Safety Products

Toshio Horiuchi
Nissan North America

Avraham Horowitz
General Motors Corporation

Robert W. Hultmann
Ford Motor Company, Ltd.

Richard F. Humphrey
General Motors Corporation

Philip A. Hutchinson, Jr.
International Automobile Manufacturers

Steven Jonas
Volkswagen of America

Charles Kahane
U.S. DOT/NHTSA

Joseph N. Kanianthra
U.S. DOT/NHTSA

Jim Karlow
Takata Inc.

Joseph Kennebeck
Volkswagen of America

William K. King
Ford Motor Company, Ltd.

William F. Kiniry, Jr.
Piper & Marbury

Wayne J. Kippola
Ford Motor Company, Ltd.

George F. Kirchoff
Morton Automotive Safety Products

Tadao Kobayashi
American Honda Motor Company, Inc.

Tyler Kress
University of Tennessee

William Leasure
U.S. DOT/NHTSA

Christopher Lerch
Honda R&D North America

John I. Lisowski
Morgan, Melhuish & Lisowski

Francois Louis
Renauld USA

Adrian Lund
Insurance Institute for Highway Safety

Jack B. Meister
Echlin, Inc.

Charles A. Moffat
United States

Gordon B. Morgan
First Technology Safety Systems

George Mouchahoir
U.S. DOT/NHTSA

Ranganatha Mulabagula
EASi Engineering

Robert H. Munson
Ford Motor Company, Ltd.

John R. Musgrave
Coburn & Croft

Gopal Narwani
ASL

James Newman
Biokinetics & Associates, Ltd.

Toshimitsu Nose
Nissan R&D, Inc.

Guy Nusholtz
Chrysler Corporation

Soichiro Okudaira
Toyota Motor Corporation

Linda L. O'Connor
U.S. DOT/NHTSA

Brian O'Neill
Insurance Institute for Highway Safety

George L. Parker
U.S. DOT/NHTSA

Dr. Muir A. Parker
First Technology Safety Systems

Elana Perdeck
University of Miami

Helen O. Petrauskas
Ford Motor Company, Ltd.

Walter Pilkey
University of Virginia

Wes Pittman
Pittman, Manuel & Hundley P.A.

Gordon Plank
Volpe

Timothy Potok
Chrysler Corporation

Priya Prasad
Ford Motor Company

Nagarajan Rangarajan
Gesac, Inc.

David J. Romeo
Romeo Engr. Intl. Inc.

Gary Rossow
Freightliner Corporation

Greg Schmeling
Harley-Davidson, Inc.

Tarry Schmidt
Harley-Davidson, Inc.

William J. Schultz
Harley-Davidson, Inc.

Donald M. Schwentker
Automotive Regulatory Consultant

John Secrest
Kohl, Secrest, Wardle, Lynch, Clark & Hampton

Minoo Shah
General Motors Corporation

William Shapiro
Volvo Cars of North America, Inc.

Philip Sheets
Kawasaki Motors

Michael Sivak
University of Michigan

Albert J. Slechter
Chrysler Corporation

Brad Smith
Morton Automotive Safety Products

John Smreker
AM General Corporation

Mark Sochor
Chrysler Corporation

Jerome Sonosky
Mercedes-Benz of North America

Michael Stanton
American Automobile Manufact. Assoc.

James E. Stratton
University of Miami

Bob Sulouff
Analog Devices Crash Sensor Group

Masaaki Tanahashi
Honda R&D North America

Louis Tijerina
Battelle

Douglas Toms
American Honda Motor Company, Inc.

John R. Treat
John R. Treat and Associates, P.C.

Francis J. Turpin
U.S. DOT/NHTSA

James Ughetta
Wilson, Elser, Moskowitz, Edelman & Dicker

John H. Van Zant, Jr.
Dynamic Science, Inc.

David Viano
General Motors Corporation

Ronald Wasko
American Automobile Manufact. Assoc.

Emroy Watson
Yamaha Motor Corporation USA

David Weir
Dynamic Research Inc.

Greg Weisenfeld
Honda R&D North America

Prof. Walter Wierwille
Virginia Polytechnic Institute & State University

Kenneth Wiley
Dynamic Research Inc.

Albert Yamada
Takata Corporation

Gershon Yaniv
Simula Inc.

Narayan Yoganandan
Medical College of Wisconsin

James Yukevich
Lester Schwab Katz & Dwyer

John Zellner
Dynamic Research Inc.

Karl-Heinz Ziwica
BMW of North America, Inc.

David Zuby
Insurance Institute for Highway Safety

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Section 1
Opening Ceremonies

Introductory Remarks

Klaus Weinspach

President, Federal Highway Research Institute,
Federal Republic of Germany

Ladies and Gentlemen,

I have the honour today of opening the 14th International Conference on the Enhanced Safety of Vehicles here in Munich. I welcome you most warmly.

Since the last conference, Europe with the creation of the single European market has grown a little more closely together. The world as a whole appears to become constantly smaller since distances can be overcome faster, more comfortably, and also more safely. However, far more than the technical progress made on the sector of transport routes and means of transport, the political development of recent years have caused peoples and countries to draw nearer. Many of the obstacles to transfrontier traffic which caused trouble in the past no longer exist. I therefore welcome most warmly the delegates from the governments of Central and Eastern Europe.

But I am also glad to see that so many of you have taken the trouble to come such a long way in order to gather information about the progress made in safety research or to impart the latest findings on this sector to others.

Twenty-five years have passed since the ESV programme was started by the Government of the United States of America. In the intervening time this conference has become one of the most important events on the issue of vehicle safety.

Ladies and Gentlemen, the accompanying exhibition and the following lecture by Professor Braess on the development of ESV efforts in a quarter of a century will offer ample opportunity to get an overview of the tradition established by these conferences and to reminisce.

The large number of participants from administration, science and industry clearly demonstrates the importance accorded to safety research on the transport sector worldwide. But I am not about to talk about scientific or economic or transport policy issues at this point.

As you can see in the conference programme there are far more competent participants in this conference to do this. Thanks to their contributions and "technical papers" which will be presented in the course of this conference you will profit from their knowledge in their fields.

Ladies and Gentlemen, my task has been to welcome you here. But beyond that I also wish to thank all those who have contributed and are contributing to the organization and smooth running of this conference.

I wish you all pleasant days at the conference and in Munich which, after all, is known as the "metropolis with a human touch." I hope and wish that we will have days of lively and interesting discussions during the conference so that we can take home a new impetus for our work.

Ladies and Gentlemen, I hereby declare the 14th ESV conference open.

George L. Parker

Associate Administrator, Research and Development,
National Highway Traffic Safety Administration,
United States

Thank you Professor Dr. Weinspach,

I would like to express my appreciation to the German Government for hosting this 14th ESV Conference which marks the 25th anniversary of the ESV Program. I would also like to thank the State of Bavaria and the City of Munich for their hospitality to all the conference attendees. I also very much appreciate the efforts of the corporate sponsors, BMW and AUDI, in making this conference possible.

We have all moved beyond the development of ESV's into intensive exploration of possible safety improvements focusing on specific crash modes and vehicle systems. However, the legacy of the development of ESV's is a realization that safety can be improved in all areas of vehicle performance and occupant protection. This conference is also a legacy of the ESV program and, to me, the pre-eminent international safety R&D gathering of experts.

We have all made much progress in improving motor vehicle safety, but the fact that we have a record attendance at this conference and an agenda rich in the results of advanced safety research, is testimonial that much more progress is possible. In my mind we have not reached a point of diminishing returns. The research that is now being performed is allowing us to see how we can still make substantial safety improvements without large investments, especially if the improvements can be made when major vehicle designs are changed. I see the new opportunities especially in improved frontal crash protection involving an offset test and in preventing crashes through driver warning and control systems based on advanced sensing, computing, and communications technology.

On behalf of the government of the United States, I welcome you all to the 14th ESV Conference and wish you the most productive exchange of information and ideas. Thank you.

Keynote Addresses

Benno Ziegler

City Manager, Bavarian State Capital of Munich,
Federal Republic of Germany

Ladies and Gentlemen,

In the name of Mr. Christian Ude, Lord Mayor of the Bavarian State Capital of Munich, it is a great pleasure for me to welcome you here in our city.

It is a great honour for the Bavarian Capital that this important conference is hold here.

The Bavarian State Capital of Munich and the organizer of this conference, the enterprise BMW, will spare no effort to ensure that you and your company will enjoy optimal conditions during the course of the conference.

Please permit me to raise briefly some topics of this conference, seen from the point of view of the responsibilities of a big city:

- trafffic safety is the centre of your work and it is determined by the coordination of manifold activities,
- here in Munich, you will find a lot of safety-promoting factors:

- the cars produced by BMW offer an exemplary safety level, that is provided by the car itself,
- the State Capital of Munich and the Free State of Bavaria, with the support of the European Union, are presently working on the project of the "intelligent road." Collective and individual traffic guidance technologies are combined to conduct the project Munich COMFORT in the north of Munich and on the stretches of the Munich-Berlin autobahn situated in this region. This project is part of the "Cooperative Traffic Management" and is not only an example of most modern traffic infrastructure but also a contribution to a considerable traffic safety improvement, as it has been demonstrated by the results of the first ten year. The number of traffic accidents counted on this autobahn stretch, for instance, has been reduced by a third on the annual average.

A point that must be clearly pointed out here is that the BMW enterprise, under the former managing board chairmanship of Eberhard von Kuhnheim, has launched this traffic project both under the technical and the conceptual aspect - a project that contributes to solve the traffic problems on the basis of an exemplary cooperation of state and city and of industry and science.

The idea of applying new technologies to improve traffic safety in the region of Munich gains special importance when one follows the long-term development of the accident figures. This may be illustrated by the following numbers:

- in 1953, Munich counted 900,000 inhabitants and 112,000 registered cars. The number of accident fatalities was then 231;
- in 1973, 1.3 million inhabitants were living in Munich and 417,000 cars were registered. The number of accident fatalities dropped to 204;
- in 1993, the population stayed almost the same but meanwhile the number of registered cars reached 700,000. It was possible however to reduce the number of accident fatalities to 44.

As you can see, dear guests, there is a noticeable and measureable success which could only be attained by means of a continuous and constructive cooperation of all parties involved.

To sum up I would like to repeat the question as to which is the reason for the successful continuity of our work: Manifold factors have been combined to achieve this success but the essential point is - and you are working on it - the concerted further development of modern traffic technology to the advantage of the traffic safety for everybody.

Coming to the conclusion, I would like to quote a famous German traffic magazine with wide circulation: two days ago, on the 20th of May 1994, a city ranking consisting of several parts was published, saying among things:

"More mobility through less traffic...
In Munich, mobility conditions are much better than most of the other big German cities - provided that modern, future-orientated standards are applied...
Instead of enraged hunting of people parking against the law, one is concentrating in Munich on intelligent traffic guidance, cooperative traffic management and High Tec instead of Middle-Age radical cures."

I believe, dear guests, that you have made an optimal decision in choosing Munich as the place for this meeting.

In the name of the Lord Mayor of the Bavarian State Capital, I wish you every success for this conference.

Michael Schneider

Ministerialrat, Bavarian State Ministry of
Economy and Transportation,
Federal Republic of Germany

On behalf of the Bavarian Minister-President, Dr. Edmund Stoiber, and the Bavarian State Minister of Economy and Transportation, Dr. Otto Wiesheu, it is a great honour for me to greet you and extend a warm welcome to the 14th International Conference on the Enhanced Safety of Vehicles. I specially welcome the many guests who have come to Bavaria from abroad. Many thanks and appreciation also to the German and Bavarian car industry, especially the BMW company, for the efforts it invested in the organization of this conference.

Ladies and gentlemen, improving vehicle safety, reducing accidents and accident consequences are important issues well worth the trouble taken to pursue the high purpose. Bavaria as the venue for this conference is a good choice. The car industry in Bavaria and the south of Germany traditionally ranks among the first. The issues you intend to talk about are on familiar ground here.

In 1993, the Bavarian car industry offered jobs to nearly 150,000 people. On the whole, every sixth job here depends on the motor vehicle. With an export share of nearly 60% and foreign sales clearly in excess of DM 15 billion (Audi and BMW) Bavarian motor vehicles were the most important export goods of the state in 1993.

The economic success is the result of the advantageous conditions the State of Bavaria is able to offer the car industry, namely:

- an excellent infrastructure (making for faster goods transport and increase in productivity)
- the central location of Bavaria in Europe
- the outstanding quality of its products and reliable delivery terms
- the trendsetting high-tech orientation of the industry
- the close cooperation between science and industry
- an industry-friendly environment and a state government determined to remove bureaucratic obstacles and speed up approval and other authorization procedures.
- the presence of a large number of important components supplying industries, especially in the fields of electrical engineering and electronics.

On account of the success story of electronic components in the car industry to which we also owe numerous safety facilities (e.g. ALS, airbag) this is worthy of attention. The potentials of electronics, however, can also be used to help cope with the traffic streams expected in the future.

Up to the year 2010, the truck traffic using Bavaria as a transit country is likely to double compared to 1990. The increase in car transit traffic cannot yet be estimated, although a similar increase as in goods traffic is expected. The behaviour of all of us in terms of consumption, investment and recreation is responsible for this development. But the negative effects on our living conditions associated with this development cause problems of social acceptance.

The focal point of the future can no longer be accommodating and improving present mobility patterns but to achieve sustainable patterns of mobility, namely the patterns of activities and access which are needed and justifiable in economic and ecological terms. In view of the high relative importance of mobility as an expression of the way individuals feel personally responsible for shaping their lifestyle patterns today and in view of the fact that mobility is an elementary prerequisite for our social and economic order, the state government relies on the free-market instruments of supply and price policies as well as changes in attitudes to influence behaviour and choices. It rejects the instrument of dirigisme to control drivers and harassing traffic restraints.

Nothing can be gained by fundamentalist traffic policies. In view of the latest tax hikes for gasoline and diesel at the beginning of this year, we also object to using drivers as the nation's gold mine.

In order to avoid being misunderstood: it would be wrong to exclusively or primarily depend on the car in the future. The weights will have to shift to other goals, for instance,

- avoidance of unnecessary traffic
- the use of less harmful means of transport instead of those substantially polluting the environment
- the creation of resources-saving and environmentally compatible traffic patterns and means of transport
- the linking of all traffic systems to achieve more efficient traffic patterns.

In order to achieve this, we will also make use of modern communication and traffic guidance systems. Telematics will be one of them. Electronic warning and guidance systems offer a great variety of possibilities, many of them still requiring further research.

To warn in time of dangerous situations, congestion and incidents is already possible. Unnecessary trips searching for a place to park can thus be largely avoided. Information on where to transfer to public transport vehicles can also be supplied. These are just a few examples of how to better control traffic and avoid congestion. They now have to be tested in practice and then implemented as fast as possible.

The Bavarian automobile industry has taken up the challenge. The "cooperative traffic management" project currently in preparation in the northern part of Munich is a promising model in this direction. The project also forms part of the technical programme of this conference. In this manner the partnership between science and politics will contribute to enhancing the attraction of Bavaria even further for the car industry.

Ladies and gentlemen, we are well aware that where it concerns vehicle safety--and not only there--we are defending a leading position in the field. We are aware that much will depend on technology and innovative products to be successful. Based on a comparative technology ranking, Bavaria has come off as one of the leading countries in this field:

- with an 18% share in the German population the R&D expenditure of the Bavarian economy amounts to 28% of the German expenditure on this sector.
- Japan leads the international hit list of R&D expenditures with more than 3% of its gross domestic product (USA 2.9%, Germany 2.6%). In Bavaria the public and private expenditure on R&D exceeds 4%.

We want to continue this way. "Live and let live" is a Bavarian maxim. This also means linking progress with tradition.

As the rest of the world sees it, there are many factors which make Bavaria lovable and worth living in. Despite the radical change from a primarily agricultural economy to a society dominated by modern industry and the tertiary sector Bavaria has not lost its identity. The cultural riches of this country are not less worth seeing than its intact environment and the natural beauty of its landscape, mountains and lakes. This makes it so attractive for our visitors both in our towns and the countryside. One can feel at home in Bavaria provided that everyone shares and profits likewise.

Let me paraphrase Eugen Roth, a Bavarian poet, who put it succinctly:

"Vom Ernst des Lebens halb verschont,
ist der schon, der in Bayern wohnt."

I hope you will feel this a little bit while you are here and wish the conference every success.

Dieter Grupe

Ministerialdirectkor, Federal Ministry of Transport,
Federal Republic of Germany

Dear Ladies and Gentlemen,

On behalf of the Federal Minister of Transport it is a great honour for me to welcome you here in Munich. It gives me great pleasure to see that so many of you have been able to come and I welcome most warmly the delegations of the various governments and the guests from the United States of America, Japan and Australia, the West-European countries and also those from Central and Eastern Europe.

With the 14th International Conference on the Enhanced Safety of Vehicles, it is the third time that this important conference is taking place in Germany. After the 1971 Conference in Sindelfingen and that of 1980 in Wolfsburg, the selection of Munich as the venue for this conference represents another important location where the German automobile industry is based.

Since the last conference in 1980, there have been a great many radical changes here in Germany.

After the unification of both German states in 1990 and the completion of the Internal Market of the European Union in 1993, Germany now faces a great number of special and conflicting political challenges.

On the one hand, we have to cope with the unprecedented consequences of merging the very different economies of the Federal Republic and former East Germany making not only intensive efforts towards the economic development and reconstruction of the east, but seeing also to it that the people of both parts of Germany are reconciled with one another. On the other hand, there is the Maastricht Treaty which is to be implemented in the scope of the European Union and the goals of the single European Market have to be further pursued.

Against this European background, it also seems to me of great importance to make progress with harmonization worldwide in order to facilitate the exchange of motor vehicles, being the product we are dealing with at this conference, between the marketplaces all over the world. The list of the countries participating in this conference shows that the scientific prerequisites for the harmonization efforts have been established and that it is now up to the Administrations to agree on the regulations, codes and standards required.

The themes of this conference demonstrate that although much has already been accomplished to improve vehicle safety, there is still a lot that needs to be done. The exchange of knowledge and information between scientists, car manufacturers, and legislators will contribute greatly towards this end as will the personal talks between the participants in this conference.

I am glad to have the opportunity of wishing you a pleasant stay in this city and our country and the conference every success. Ladies and Gentlemen, thank you very much for your attention.

Christopher A. Hart

Acting Administrator,
National Highway Traffic Safety Administration,
United States

Thank you Herr Professor Dr. Weinspach,

I am very pleased to be here for the twenty-fifth anniversary of the International ESV Conference. I would particularly like to thank the German Government, the State of Bavaria, and the City of Munich for receiving us. In addition, I want to acknowledge the outstanding support given by BMW AG and AUDI AG. Dr. Ricardo Martinez, who has been nominated by President Clinton to be Administrator of the National Highway Traffic Safety Administration, asked me to express his regrets that he could not attend this conference.

Since so many of the advances in automobile safety over the years have come from the people in this room and their colleagues and predecessors, I have looked forward to this conference and to the exchange of ideas it produces.

Your innovations in safety designs have set the pace for the automotive industry's engineers around the world, and your accomplishments have done much to advance the technology of safer, more socially responsible cars.

For the last three years I was a member of the National Transportation Safety Board, which is the agency in the United States that investigates transportation crashes and makes recommendations in an effort to prevent future crashes. At the safety board, I gained insight into the human, vehicle, environmental, and prevention aspects of transportation crashes, including those involving motor vehicles. I also gained first-hand experience about the causes of motor vehicle crashes, the forces involved, and what happens to vehicle occupants when they are subjected to the violent forces of a crash.

Similarly, Dr. Martinez has had a long and distinguished career as an emergency room physician. His career has included the treatment of all types of injuries from motor vehicle crashes. His emergency room experience made him acutely aware of the terrible consequences that motor vehicle crashes can have on patients, their families, their friends, and the community.

As a result of our respective experiences, Dr. Martinez and I have both developed the firm conviction that prevention is the key to controlling the extent and magnitude of injury from motor vehicle crashes. And prevention, of course, is the major mission of the National Highway Traffic Safety Administration.

The overall economic impact of motor vehicle crashes is enormous. We estimate that highway crashes caused a direct economic cost to society in the U. S. of $137. 5 billion in 1990. $14.2 million of this was for health care costs. Although our agency actively pursues numerous measures to reduce the injuries that result from crashes, our most cost-effective activities are those that are directed at preventing the crashes in the first place.

We have made significant progress in traffic safety in the United States since the beginning of the ESV program in 1969, when more that 53,000 people died on our nation's highways and the fatality rate was 5.0 per 100 million vehicle miles traveled. The traffic fatality rate in 1993 was 1.7, which is the lowest since we have been keeping records. If the fatality rate had remained unchanged since 1969, the number of fatalities in the U.S. last year would have been well over 100,000.

Nevertheless, much remains to be done. This is illustrated by the fact that the total number of traffic fatalities in the U. S. for 1993 reversed its downward trend in recent years and rose to an estimated level of about 40,000 deaths, slightly more than in 1992.

Until recently, the emphasis in motor vehicle and highway safety has been on preventing death, more than on preventing or reducing injuries. Yet for every motor vehicle fatality in the United States there are about 120 non-fatal motor vehicle injuries. Motor vehicle crash injuries frequently involve long hospital stays and long-term disability.

In cold and in human dollar terms, each serious injury that is prevented saves at least $35,000 in health care costs. Moreover, unlike medical illness, prevention strategies have rapid payoff. The money saved in motor vehicle crash prevention can be generated 18 to 24 months after an intervention. To make a greater contribution to health care cost reduction in the years ahead, we all must intensify our efforts on crash and injury prevention without lessening our focus on saving lives.

As a former member of the National Transportation Safety Board, I firmly believe that the prevention model includes a strong crash investigation component for precise problem identification and program evaluation. After problem identification, it is necessary to develop and demonstrate effective intervention methods. The intervention methods include the three "E's" of prevention, -- education, enforcement, and engineering. Education increases knowledge and awareness and is the first element in getting people to change risky behavior, such as drinking and driving. Enforcement helps ensure compliance with laws regarding vehicle operation, and engineering maximizes the use of advanced technology and focuses on the vehicle, the roadway, and the human interaction with both.

Strategies for reducing motor vehicle crashes must focus both on the driver, such as by increasing safety belt usage reducing drunk driving; and on the vehicle, by advancing state-of-the-art crashworthiness and crash avoidance technologies.

This conference is evidence of the international partnership that has existed for twenty-five years to accomplish similar goals. With the internationalization of the automobile industry, we must continue to build on this partnership. The goals of producing environmentally and socially responsible vehicles that meet consumer needs at an affordable price are too universal and too important for us not to share our knowledge and expertise.

In closing, I would like to say again how pleased I am, to be at this conference, and I look forward to meeting individually with many of you and learning more about how we can move forward together in this profoundly important undertaking.

It is now my pleasure to participate in the presentation of the Department of Transportation's Awards for Safety Engineering Excellence. We use the ESV Conference to present two types of awards for motor vehicle safety accomplishments. The first award is for safety engineering excellence in recognition of and appreciation for extraordinary contributions in the field of motor vehicle safety engineering and for distinguished service to the motoring public. The second is a special award of appreciation in recognition of outstanding leadership and extraordinary contributions in the field of motor vehicle safety.

Awards Presentations

U.S. Government Awards for Safety Engineering Excellence

Head of U.S. Delegation: Christopher A. Hart

In recognition of and appreciation for extraordinary contributions in the field of motor vehicle safety engineering and for distinguished service to the motoring public.

Canada

S. Christopher Wilson
Transport Canada

Mr. Wilson has been an international leader in promoting highway safety. He is responsible for Transport Canada's programs which include the development of motor vehicle safety and emission standards, safety research, and the enforcement of standards. For the past 20 years, Mr. Wilson has been instrumental in ensuring Canada's commitment and involvement in automotive safety research. Some of his noteworthy contributions include spearheading the creation of Canada's occupant restraint policy, the development of joint Canada United States road safety research activity, and the refocusing of Transport Canada's crash investigation activity to be more responsive to airbag performance, side impact injuries, and heavy vehicle load security. Mr. Wilson is being recognized for his outstanding leadership of Canada's automotive safety regulatory efforts and his contributions to the advancement of our understanding of vehicle safety issues.

France

Hélène Fontaine
INRETS

Ms. Fontaine's pioneering research has focused on risk analysis and methodologies for accident and exposure data management systems. Ms. Fontaine is being recognized for her significant contributions in the safety evaluation of new driving aids in the Prometheus and Drive programs. Her contributions to the understanding of the risks and the safety effects that this new technology will have on driver and vehicle characteristics has significantly advanced the state of automotive safety. For these contributions to automotive safety, she is being recognized with this award.

Gerard P. Mauron
PSA Peugeot Citroën

Mr. Mauron's accomplishments have been in the field of passive occupant protection. Some of his noteworthy contributions include the concept of automatically deployed safety belts, the manufacture of stationary safety belts fitted with textile energy absorption systems, the technology for passive protection of occupant, anti-submarining structure integrated in the seat structure, installation of safety belts on the seat structure to ensure correct wearing geometry for all sizes of occupant. Mr. Mauron deserves special recognition for his contributions to child restraint protection systems. His work has made a substantial contribution to saving lives and reducing injuries.

Federal Republic of Germany

Guntram Huber
Mercedes-Benz AG

Prof. Huber has devoted his professional life to furthering the development of safer cars. In 1969, he played a leadership role in Mercedes-Benz's decision to begin intensive crash investigations and analysis. The results of these analyses formed the basis for future Mercedes passenger car development. Prof. Huber was responsible for the development of the safety body structure and advanced restraint systems for four Mercedes-Benz ESV prototype vehicles. These ESV efforts led to pedestrian "friendly" exteriors, the first safety belt pretensioners, supplemental restraint airbags, seat integrated belt systems, automatic pop-up rollover bar systems, and energy distributing structural advancements on Mercedes-Benz passenger cars. For his significant contributions in occupant and pedestrian safety, Prof. Huber is being recognized with this award.

Arnold Ensslen
Volkswagen AG

Mr. Ensslen is being recognized for his contributions to occupant protection systems and vehicle components. He coordinated the development of Volkswagen's motorized passive restraint system and its airbag supplemental restraint. Because of the lower cost of this airbag and the development of retrofit capabiltiy, a breakthrough for airbags in Europe was created. For these contributions to occupant safety, Mr. Ensslen is receiving this special award.

Hans-Joachim Kraft
BMW AG

Mr. Kraft has made significant contributions to both active and passive vehicle safety. In 1979 under his management, BMW introduced electronic four-wheel anti-lock brakes in production cars, being one of the first carmakers in the world to do so. Mr. Kraft played an important role in the development of safer vehicle chassis and new stability control systems. He was responsible for improvement of occupant protection by focusing on driver and passenger airbags. Recognizing the importance of accident analysis in car design, he initiated significant accident investigation research at BMW. Mr. Kraft is being recognized for his important work in improving vehicle safety.

Italy

Dante Bigi
Fiat Spa

Dr. Bigi's career has been dedicated to the improvement of the safety of vehicle structures and to occupant survival through passive safety. Through extensive development of computer simulation and experimental pilot programs, Dr. Bigi has made important contributions to the enhancement of the safety performance of small vehicles, influencing the design and developments of new cars from concept to production especially in the field of passive safety. Recognition is being given for his contributions to automotive safety.

Japan

Haruhiko Iizuka
Nissan Motor Company, Ltd.

Mr. Iizuka has been a pioneer in active vehicle safety research and technology in Japan. He has developed both drunken driving and drowsiness warning devices. Mr. Iizuka directed studies of visual perception characteristics in the elderly and head lamp performance in night driving. As a result of his analyses of these subjects, optimal low beam illumination patterns were developed. Mr. Iizuka conducted groundbreaking research on the impact of perception and the decisionmaking process on the causes of turning accidents. For his significant contributions to automotive safety, Mr. Iizuka is receiving special recognition.

Makoto Satō
Honda Research and Development Company, Ltd.

Mr. Satō has made major contributions to active vehicle safety technology. He developed the anti-lock brake system concept which was used on the 1983 Prelude. He contributed to the crash avoidance safety field by developing a traction control system that was introduced in 1990 and by developing an electronic four-wheel steering system introduced in 1992. For his many accomplishments in the field of vehicle safety, Mr. Satō deserves this special recognition.

Seiichi Sugiura
Toyota Motor Corporation

Mr. Sugiura is being recognized for his contributions to the study of human factors and their impact on automobile driving. He has specialized in analyzing the interrelationship of head lamp and rear-view mirror configuration and placement as a cause of traffic accidents. Mr. Sugiura's research defined the need for vehicle design that promotes a more accurate, faster driver recognition, judgement, and action cycle. His evaluation and analysis of the driver's "work space" led to interior car design that makes operating a car easier and reduces driver fatigue. Mr. Sugiura was one of the developers of the first voice navigation system using real time vehicle position. This system is aimed at enhancing driving safety by reducing the driver's burden. For the many contributions he has made to active safety technology, Mr. Sugiura is being recognized with this special award.

Sweden

Stefan Nilsson
Volvo Car Corporation

Mr. Nilsson is being recognized for his outstanding contributions to the development of the side impact protection system and the frontal effect performance for Volvo. He also played a major role in developing Volvo's deformable load sensing faceform, which is used for improving vehicle interior impact surfaces. Mr. Nilsson's interest in child protection led to the development of the rearward facing child seat. His research on head and facial injuries and rotational acceleration assisted in the development of a rotational accelerometer and the corresponding injury criteria. Mr. Nilsson is to be commended for his significant automotive safety improvements.

United Kingdom

Richard Lowne
Transport Research Laboratory

Mr. Lowne has made major contributions to the understanding and knowledge of human tolerance to injury, side- and frontal-impact protection, the design and performance of safety belts, child restraints, dummy development, impact test procedures, and pedestrian protection. Mr. Lowne chairs the European Experimental Vehicle Committee's (EEVC) Working Groups on side-impact protection and frontal-impact protection. The former group has successfully developed a practical test procedure for side-impact protection, the EUROSID side-impact dummy. Its assessment of the performance of current car models has enabled EEVC to suggest goals which are attainable and provide substantial improvements in occupant protection. For his leadership in these important developments in motor vehicle safety, Mr. Lowne deserves special recognition.

Murray Mackay
University of Birmingham

Mr. Mackay established the Accident Research Unit at the University of Birmingham in 1964. This Unit and its findings have been an important force in Britain in establishing vehicle safety research as an academic discipline. Professor Mackay has made a major contribution in advancing knowledge about the role of biomechanics of injury in vehicle design and performance, and in promoting and disseminating information about safety within and beyond the vehicle industry. He is Co-Chair and Director of the United Kingdom Parliamentary Advisory Committee on Transport Safety, which has done much to keep vehicle safety issues on the political agenda. Professor Mackay deserves special recognition for these accomplishments.

United States

Dr. David S. Breed
Automotive Technologies International, Inc.

Dr. Breed has made significant contributions to the theory of sensory equipment to detect vehicle crashes and in 1969, developed the first crash sensor. He invented the ball-in-tube sensor, which is used on more than half of the airbag vehicles worldwide and is one of the inventors of the Breed all mechanical airbag system. Dr. Breed designed velocity and crash scaling sensor tools which accurately represent most real world and barrier crashes. He developed a single crash sensor, currently being tested, which covers the entire front of a vehicle. For his contributions to occupant safety, Dr. Breed is deserving of this special award.

William H. Gillespie III
General Motors Corporation

Mr. Gillespie, along with his team, Alex Kade and Phillip Headley, had a key role in making the safety benefits of the anti-lock brake systems widely available throughout the world. Mr. Gillespie managed the systems development, the systems engineering team, and the manufacturing process of an anti-lock brake system which, because of its lower cost, is available as standard equipment on economy, as well as premium priced, vehicles. By the end of 1994 model year five million vehicles with this system will be on the road. This award is given in recognition of Mr. Gillespie's contribution to automotive safety.

George F. Kirchoff
Morton International, Automotive Safety Products

Mr. Kirchoff is being recognized for his research on airbag technology. Mr. Kirchoff's accomplishments include advanced processing concepts for volume production of airbag gas generant, improved filtering components on inflation devices, and the radial passenger inflator and module which lead to reduced weight, size, and complexity of passenger airbag modules. He designed a self-contained driver airbag system which includes sensor and module. He developed advanced inflatable belt concepts for occupant protection. All of his accomplishments have significantly simplified driver and passenger airbag modules. Mr. Kirchoff is deserving of special recognition for these occupant protection accomplishments.

Helen O. Petrauskas
Ford Motor Company

Ms. Petrauskas is recognized as an advocate of supplemental airbags and as a crusader for safety belt use in the United States. Ms. Petrauskas championed Ford's strategy to incorporate air bags as a long-run investment in customer benefits. Ms. Petrauskas rallied support among United States auto manufacturers to adopt airbags in preference to other systems and aggressively sought the support of the automotive insurance industry. She advocated that Ford Motor Company be the first American company to provide both driver and passenger-side airbags as standard equipment. For Ms. Petrauskas' leadership in passenger safety, special recognition is being given.

Special Awards of Appreciation

In recognition of and appreciation for outstanding leadership and extraordinary contributions in the field of motor vehicle safety.

France

Georges Dobias
INRETS

Mr. Dobias has demonstrated outstanding leadership in the field of automotive safety not only within France, but throughout the world. He founded and is Director General of the French National Institute for Research in Transportation and Safety (INRETS). He has been instrumental in the definition and construction of a driver simulator for use in driver safety research in France. He initiated, with car manufacturers, an important research program that included analysis of accidents and active and passive car safety features. Internationally, Mr. Dobias created the Forum of European Road Safety Research Institutes (FERSI) in which 15 countries engage in cooperative research aimed at achieving European scientific consensus. This award is being given in appreciation of his leadership in the automotive safety field.

Federal Republic of Germany

Hans-Herrmann Braess
BMW AG

Prof. Dr. Braess is being recognized for his many contributions in the course of his long and distinguished career towards the improvement of vehicle dynamics and traffic safety. He conducted groundbreaking studies on steering behavior and elastokinematic wheel suspension. Seeking to improve the standard of safety and environmental compatibility in transport, Prof. Dr. Braess and his team initiated and developed the concept of integrating transport information and guidance facilities into a cooperative traffic management system. He was the first to prove the effect of the negative steering scrub radius. In 1967, Prof. Dr. Braess proposed the "stable-steering brake system," which for years was the state-of-the-art system in many front-wheel drive vehicles. His five-arm rear axle design was a forerunner for other multi-arm axles with specific elastokinematic features. He has promoted the potential of electronics and communication technologies in road traffic safety. For these and many other contributions, Prof. Dr. Braess is being recognized.

United States

John D. Horsch
General Motors

Mr. Horsch has made many lasting and significant contributions to procedures now widely used to assess injury causation and prevention. He developed the systematic application of the Hybrid III dummy to injury assessment of airbag and belt restraint systems. Mr. Horsch was a leader in the development of improved methods for estimating the overall effectiveness of safety system improvements by assessing the risk of injury from dummy test measurements and relating that performance to real-world conditions. Mr. Horsch developed an innovative self-aligning steering wheel concept, used in many car models, for improved protection of the unrestrained driver in a non-airbag equipped environment. For his many distinguished contributions to occupant safety, Mr. Horsch is being recognized with this special award.

25 Years of ESV Development

Opportunities and Risks of Government-Induced Goals

Prof. Dr.-Ing. H.-H. Braess, BMW AG
Prof. Dr.-Ing. H. Appel, Technical University Berlin
Prof. Dr. med. B. Friedel, Federal Highway Research Institute
Germany

INTRODUCTION

The start of the motoring age was accompanied by efforts to improve the operating reliability of vehicles in such a way that it would actually be possible to reach the desired destination within a reasonable period of time (Figure 1).

Technical regulations decreed by the state, such as those introduced in Germany in 1910, had the same purpose and were gradually extended.

Increasing traffic density and traveling speeds prompted car manufacturers to pay greater attention to braking and active safety from about the start of the 1930s on.

Figure 2 shows systematic analytical testing of vehicle dynamics in 1941.

As far back as the late 1920s, serious accidents had prompted initial investigations into vehicles' crash behaviour (Figure 3).

After the second world war, the accident rate increased in all industrialized nations, despite the progress that had been made in virtually every area of traffic safety, due to the sharp rise in the level of road traffic.

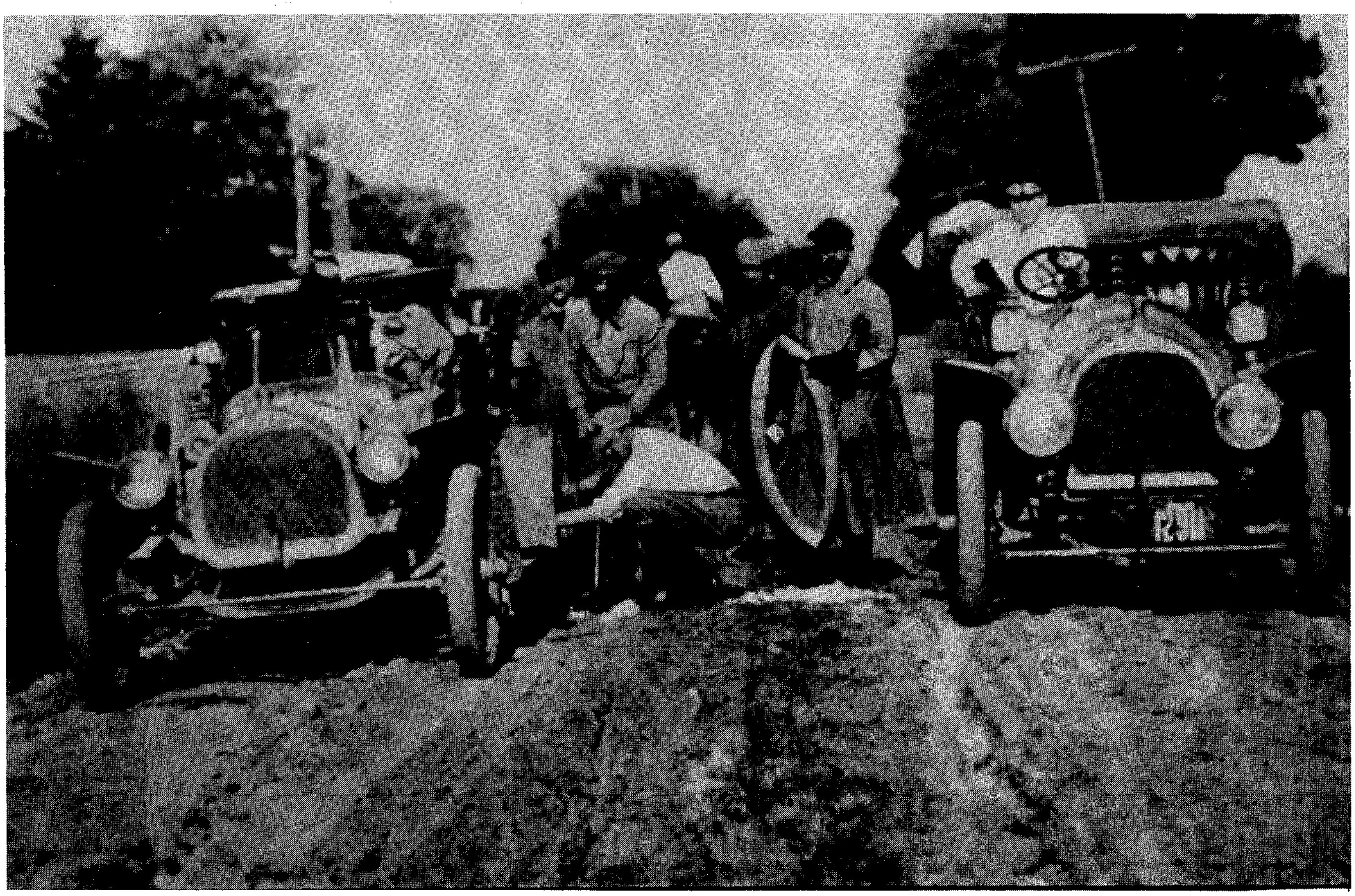


Figure 1. In the Beginning, Driving Wasn't Always Sheer Pleasure...

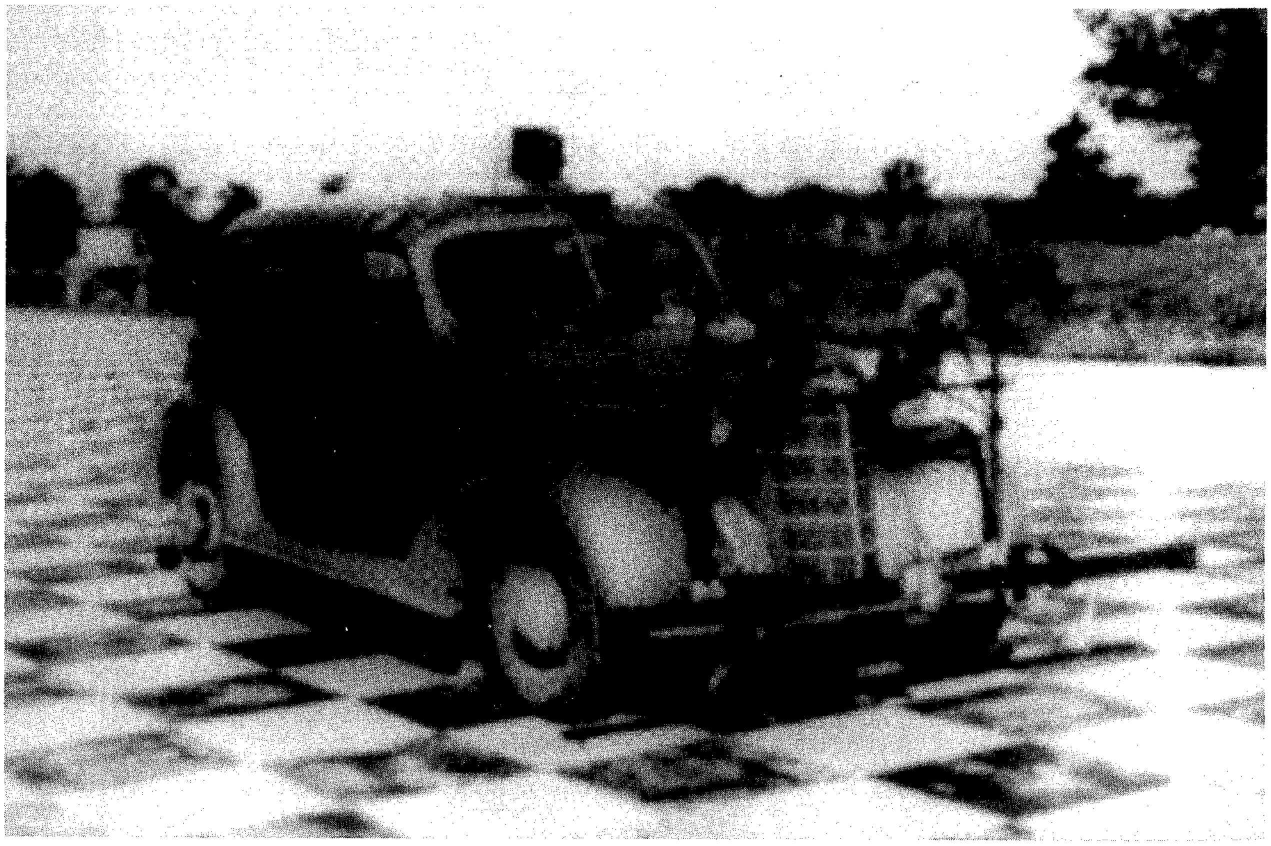


Figure 2. Measurements of Vehicle Dynamics (1941)

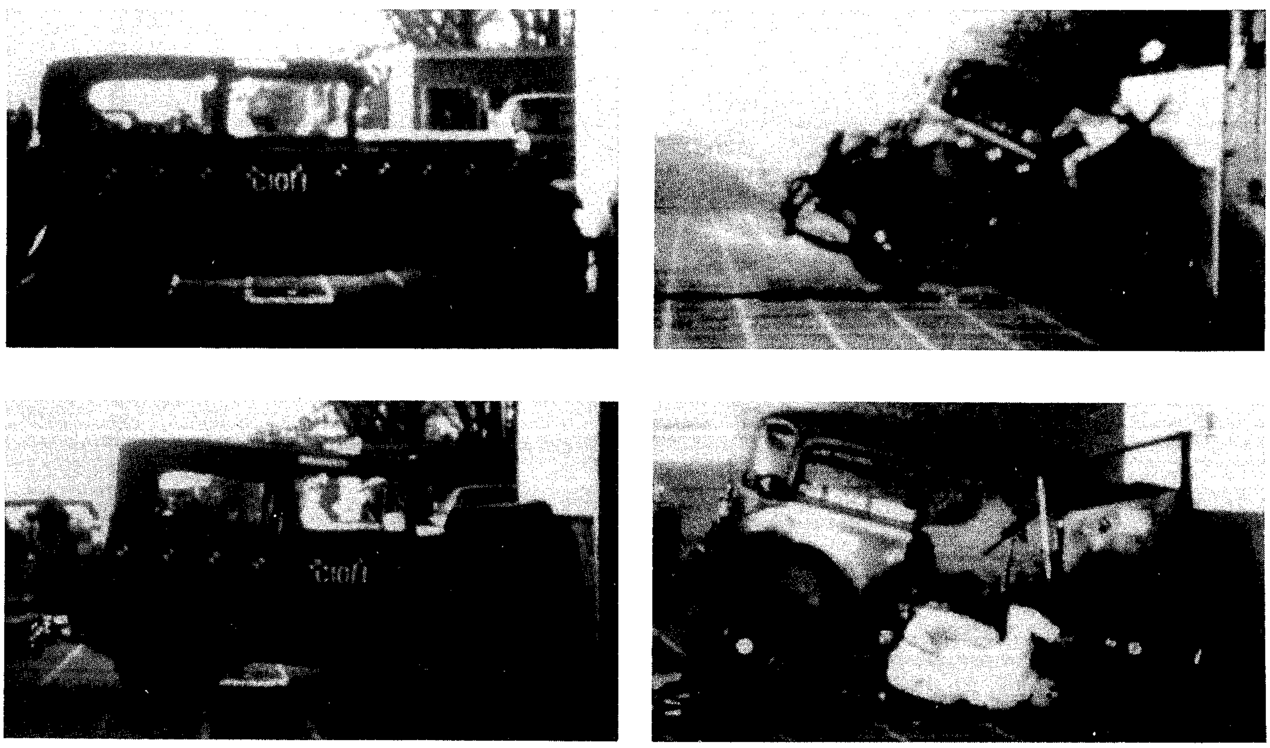


Figure 3. Front End Crash (30 mph) of a 1929 Model Year Vehicle

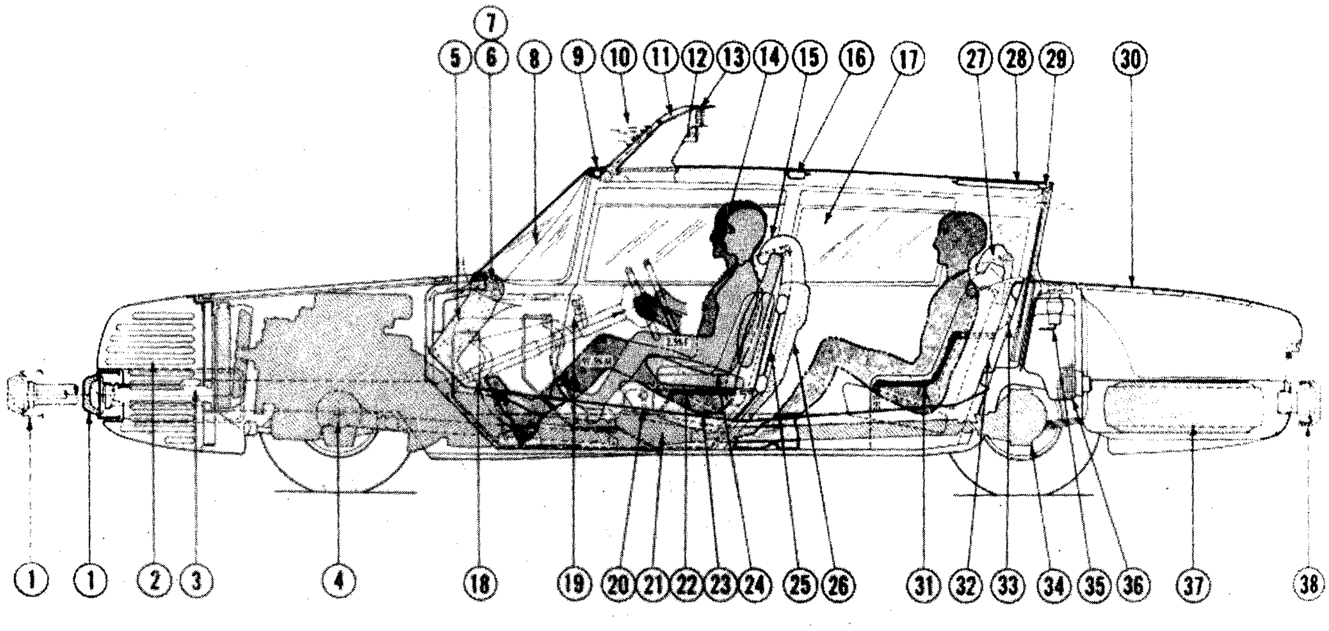


Figure 4. New York State Safety Sedan (1968)

Vehicle concepts with safety features playing a particularly prominent role had consequently begun to be considered by the end of the 1940s.

One early example of such a concept is the Cornell safety car, dating from the 1950s.

A further safety vehicle was commissioned by the State of New York (Figure 4). By the end of the 1960s, the accident figures were approaching record levels in virtually all countries, as described below. In 1968 the U.S. government responded to this situation and to the increasing number of small foreign automobiles on the roads by starting work on a worldwide campaign to develop "Experimental Safety Vehicles;" all car-producing countries in Western Europe and Japan were invited to participate.

Accident Statistics for 1970

Worldwide:	app. 200,000 killed
	> 4 million injured
Including:	
USA:	< 60,000 killed
	app. 2 million injured
FRG:	< 20,000 killed
	> 500,000 injured

The first International Technical Conference on Experimental Safety Vehicles, under the patronage of the NATO CCMS, was held in Paris in January 1971. Dr. Brenner, Chief Scientist of the NHTSA at the time, described the fundamental objectives of the program listed below as primarily to accelerate and demonstrate advancements in safety performance and to intensify international cooperation.

Experimental Safety Vehicle Program Objectives

- Demonstrate the Feasibility of Advancements in Automotive Safety Performance
- Stimulate Public Awareness of the Injury Reduction Potential and Associated Economic Advantages of Advanced Safety Design
- Encourage the Automotive Industry to Increase its Level of Efforts in Safety Research to Accelerate the Integration of Advanced Safety Systems
- Apply Data from the Testing of Experimental Vehicles to the Development of New Motor Vehicle Safety Standards

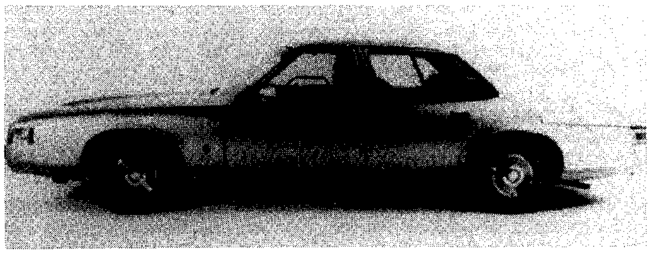
Mr. Slechter (NHTSA) presented the technical specifications for the 4000 lb vehicle. The notion of "crashworthiness" was introduced.

4000 Pound Sedan - Major Objectives

- Demonstrate Crashworthiness for Front Collision at 40-50 mph
- Minimize Injurious Forces in Side, Rear, Rollover Collisions
- Provide Handling on Par With Existing Sedans
- Demonstrate Advanced Braking, Lighting, Visibility, Controls and Display Systems

Fairchild Hiller AMF

Ford



GM

Daimler Benz

Figure 5. First-Generation ESV's

IMPORTANT RESULTS FROM THE FIRST PHASE OF THE ESV PROGRAM

The special emphasis on occupant protection at high impact speeds against walls and poles resulted in large, heavy vehicles. The U.S. ESVs shown in Figure 5 have a weight of between 5000 and 6000 lb (instead of 4000 lb) while measuring 220" (5.60 m) in length; with all the associated consequences; a further disadvantage is the high weight and rigidity imbalance compared with less substantial road users.

Europe and Japan concentrated on vehicles in the weight class below 4000 lb. Fiat unveiled the smallest vehicle, which was in the 1200 lb class; it placed the emphasis above all on preserving the survival space (Figure 6).

All the work carried out in phase 1 revealed that in addition to the technological challenges, including the problems of feasibility for volume production, numerous methodical questions of ESV development needed to be resolved. These included:

- Precise determination and assessment of various accident causes
- Safety-relevant test procedures and assessment criteria for active and passive safety
- Special design and test procedures for protecting weaker road users (compatibility)
- Biofidelity and reproducibility of anthropomorphic test dummies
- Achieving reasonable cost-benefit ratio for safety-test conditions
- Methods of solving conflicting objectives in vehicle design

By 1973 the expectations that the ESV program had aroused had only been partly satisfied:

On the one hand it had been demonstrated that thanks to the automobile industry's considerable efforts, significant improvements in vehicle safety were possible; on the other hand, it became evident that excessive requirements would lead to technical and economic disadvantages. However, there is no doubt that the ESV program has stimulated more intensive accident, biomechanics and safety research worldwide.

ESV, RSV, SYSTEMS AND METHODS

Following modification of the ESV specifications in 1973, which involved in particular reducing the head-on impact speed against a post and eliminating the rear-end pole test, NHTSA unveiled the RSV program in 1974. The RSV program includes:

- No fixed specifications
- Safety Objectives integrated into the S 3 E concept
  - Safety
  - Environment
  - Energy
  - Economy
- Determining realistic, consistent test conditions
- Taking into account resources, vehicle weight, utility, costs
- Objective: series feasibility

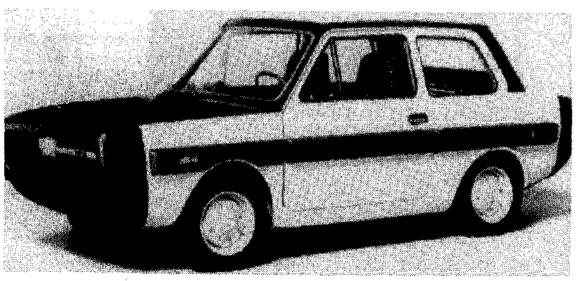
The main difference from the previous program was that no fixed specifications were dictated. Instead, the participants themselves were to indicate what requirements they considered advisable on the basis of their own general considerations and optimization work.

Over the next few years a number of research vehicles were presented (examples in Figure 7), all of which were relatively close to series versions.

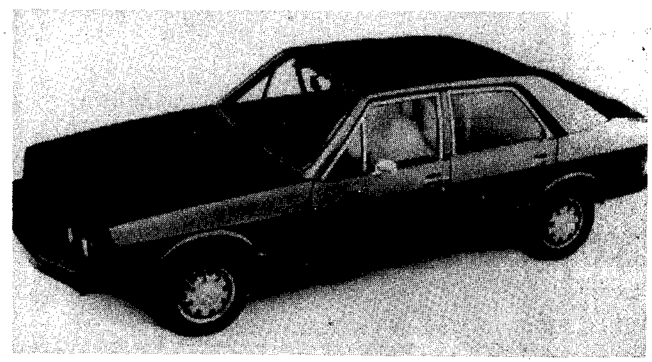
The principal results can be summarized as follows:

- 40 mph appears to be advisable as an upper limit for the head-on collision speed against a rigid barrier.
- Withstanding side-on collisions will become increasingly important.
- Significant improvements in pedestrian protection are possible.
- Test dummies, above all for investigating side-on collisions and accidents involving pedestrians, are in need of significant improvement.
- No progress over and above the European standard could be achieved for vehicle dynamics.
- Electronics play an increasingly important role in active and passive safety.
- It remains unclear whether it is possible to assist the average driver in critical road situations by providing additional safety systems.
- Despite the need for safety progress, improvements in all other areas such as fuel economy and environmental protection are also needed.

Only limited progress was achieved in harmonizing requirements on an international scale: one reason for this is the fact that it is not possible to obtain a comprehensive picture of a vehicle's safety characteristics in actual, i.e. highly complex, accident situations from a limited number of test procedures.

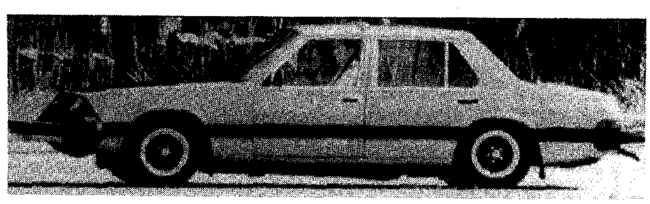


Fiat



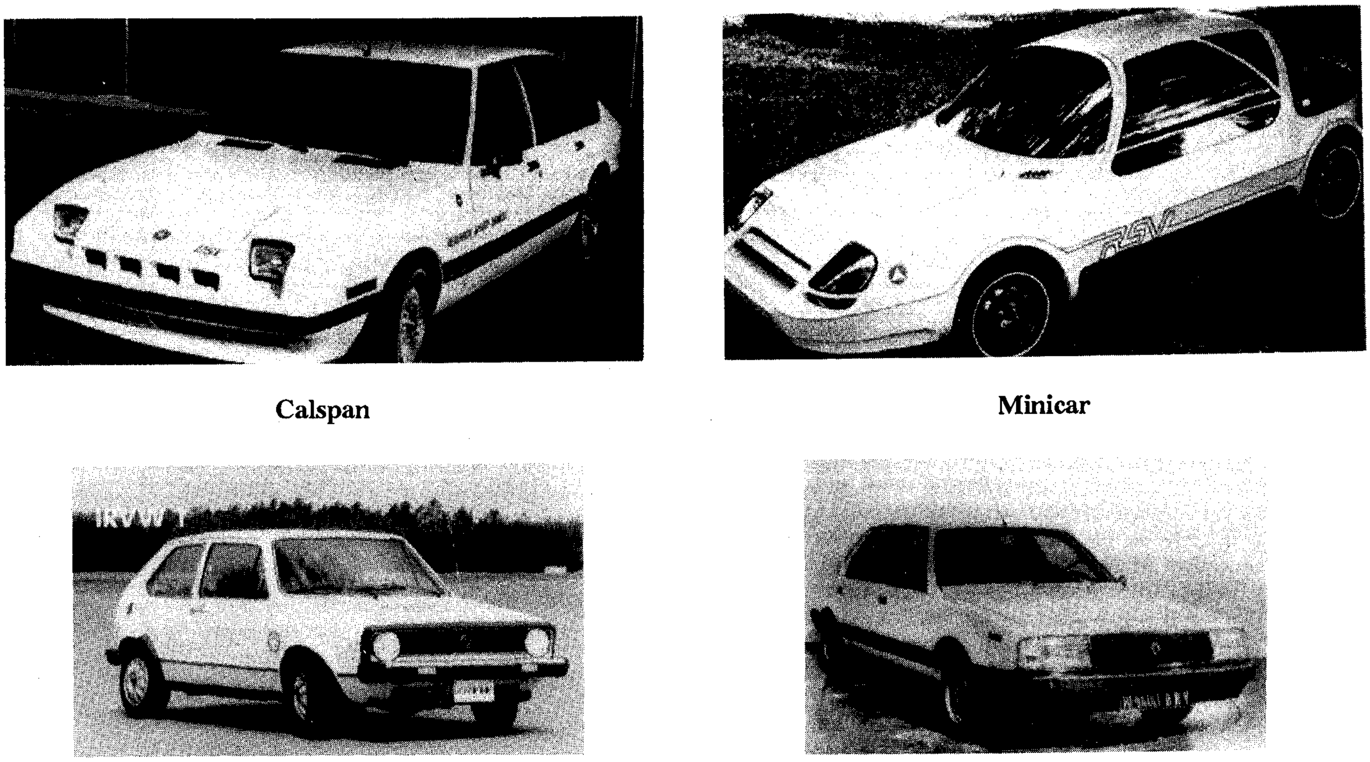
VW

Nissan



Volvo

Figure 6. Examples of ESVs in the Class Below 4000 lb



Calspan

Minicar

VW

Renault

Figure 7. Examples of RSVs

FROM RESEARCH TO SERIES PRODUCTION

Whereas considerable importance was attached to maximum active safety on European automobile markets in the 1960s, the level of interest being shown worldwide in passive safety was at that time relatively slight.

The ESV program has therefore without any doubt helped stress the importance of passive safety in the field of automotive technology (industry, research institutes) and heightened the public's interest.

In view of these very demanding requirements, all proposed solutions for improving passive safety were stated at the very start of ESV development work (Table 1).

The situation in the field of active safety is somewhat different; in the course of 25 years of development, many new systems which were not anticipated at the start of the ESV program have been launched (Table 2), including new research programs such as PROMETHEUS.

In conclusion, it can be stated that development work on the ESV has benefited series development worldwide, but that no actual experimental vehicle has served as a direct basis for a model that has ultimately gone into series production.

Since 1970, the traffic volume in the Federal Republic of Germany has more than doubled but the number of road deaths has been cut by more than half. Improved vehicle safety has certainly played an important part in this trend. In common with other areas of technology, progressive developments were first introduced at the top-price end of the model spectrum, gradually filtering down to smaller vehicles.

Further improvements are naturally necessary and possible. However, it should be borne in mind that the conflict of objectives with other requirements will become gradually more serious, both in terms of degree and quantity, and that the cost-benefit ratio for potential improvements will gradually deteriorate. Socially oriented decisions and increasing prosperity may nevertheless facilitate their acceptance.

25 years of ESV development therefore provide us with an opportunity to reflect on what lies ahead.

WHAT DOES THE FUTURE HOLD IN STORE?

Accidents usually have several causes. It has been known for some time that traffic safety can ultimately only be improved if all the work areas involved make a concerted effort.

The following disciplines have therefore been working together intensively with the developers of complete vehicles and safety systems for some time now on the sub-area of vehicle safety:

Table 1. 25 Years of Developing Passive Safety Systems

Proposed technical solutions at the start of the ESV program	Safety systems launched between 1969 and 1994 (examples)	Safety systems used on production cars (1994)
• Body structures with special crash energy management design for all types of collision • Honeycomb sandwich structures for body components • Hydraulic bumper elements, also with mechanical and lateral cross-linking for asymmetrical collisions • Safety steering columns, guaranteed to function in all types of collision • Safety glass with additional properties • Largely padded interior • Safety seats • Belt force limiter, belt tensioner • Passive restraint systems (belts, airbags - also with radar pre-triggering) • Pedestrian-friendly nose end design • Retention device for preventing further possible injury to pedestrians after an accident	• Restraint systems for children of different ages • Child's seats • Lateral airbag	• Body structures with special crash energy management design for all types of collision • Accident-safe fuel systems, generally improved fire prevention measures • Safety steering column, guaranteed to function in all types of collision • Accident-minimised interior design (cushioning, footwell, instrument panel...) • Belt systems with height adjustment, belt clamp, belt tensioner, seat-integrated belts, restraint systems for children of different ages • Driver and front-passenger airbag • Automatic extended roll-over protective hoop for Convertibles • Pedestrian-friendly exterior design

Table 2. 25 Years of Developing Active Safety Systems

Proposed technical solutions at the start of the ESV program	Safety systems launched between 1960 and 1994 (examples)	Safety systems used on production cars (1994)
• Antilock braking systems • Safety tyres • Systems for widening angle of vision	• Traction control systems • Spatial elastokinematic suspension • Permanent four-wheel drive • Tyre pressure monitoring • Driver monitoring systems • Light systems with auxiliary functions • Distance radar • Head up display • Active suspension • Additional driver information • Traffic guidance systems • Inclusion of PROMETHEUS and similar research programs	• Antilock braking systems • Traction control systems • Suspension designs with spatial elastokinematics • Four-wheel steering • Tyres with run-flat properties • New lighting techniques • Monitoring of important vehicle functions

- Accident research
- Biomechanics
- Physiology
- Ergonomics
- Psychology
- Mathematical simulation
- Test techniques

Even closer interaction is possible in certain sub-areas, in order to identify all deficits in the complex process chains of traffic safety and propose solutions without any negative side-effects.

All facts and findings must then be put into practice on the roads in as efficient a way as possible. One conceivable strategic approach is shown in Figure 8. The basic idea behind this approach is to extend the compatibility concept launched in 1973 - when its purpose was to protect weaker road users - to render all areas of road use compatible with each other in every respect. At the end of the chain, this also involves helping road traffic to interlock efficiently with other transport systems.

Figure 8 also shows that active safety, in other words avoiding accidents by human and technical intervention, is both now and in future a higher priority than in the first ESV specifications.

By presenting safety sub-areas in the form of a process chain, it is possible to identify those areas covered by safety systems which can act both independently in the vehicle and in conjunction with the infrastructure (Figure 9).

It is moreover becoming evident how various systems complement each other and how the basis for the areas they cover can be broadened. In addition, it is for instance apparent that active safety systems also have a certain passive effect and that vehicles which have been involved in an accident can warn other approaching vehicles, so as to avoid pile-ups.

CONCLUDING REMARKS

There is no doubt that 25 years of ESV development have provided clear stimuli for progress in automotive technology and road safety, and that the level of interdisciplinary, international cooperation has been significantly enhanced (Table 3).

A topical example of this is the EEVC, which has drawn up the specifications for the offset front-end crash against a deforming barrier. Its proposal has been accepted by all partners, from governments to the car industry worldwide.

We are pleased that the NHTSA and other non-European countries have been involved in drawing up this proposal. We hope that it will lead to a globally standardized offset test, in contrast to the side impact test, for which two different methods need to be used.

However, all joint efforts have also revealed that genuine progress cannot be achieved by coercion; it has to be accomplished progressively, with all those in positions of responsibility joining together in a concerted effort.

Bearing this in mind, on the basis of the objectives stated in Figure 8, a new period of ESV development should be agreed on, with the aim of once again cutting accident figures by a significant amount, e.g. by half.

A further task would be to plan the transfer of expertise and technology to third-world countries so that they can be implemented there with the support of the local traffic safety authorities.

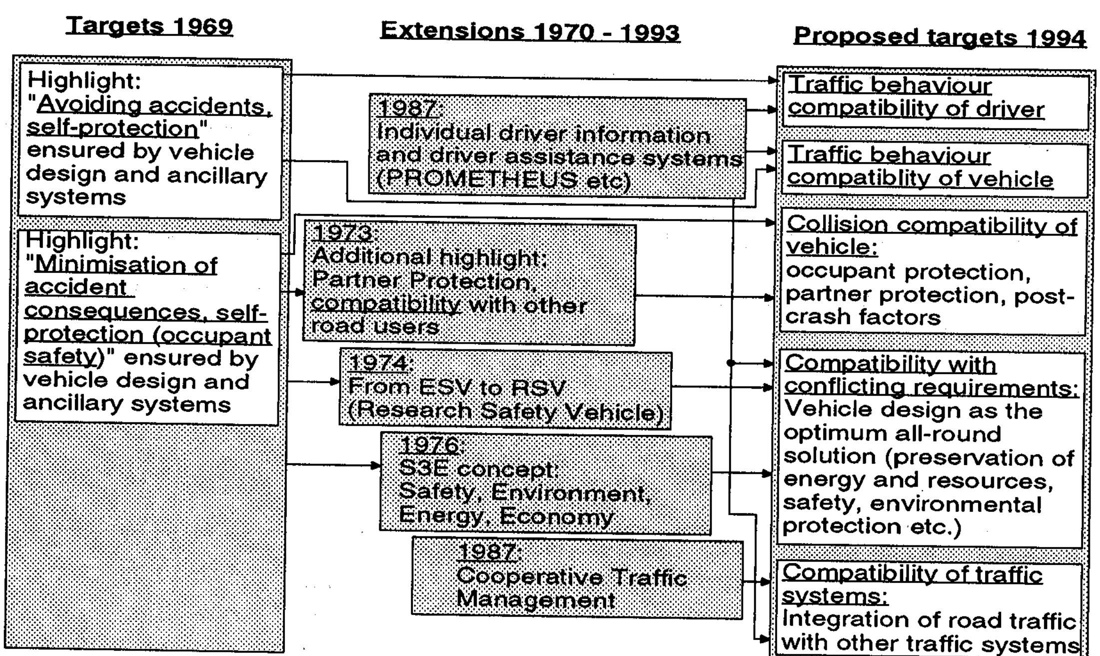


Figure 8. From the "Experimental Safety Vehicle" (1969) to the "Enhanced Safety of Vehicles" (1994)

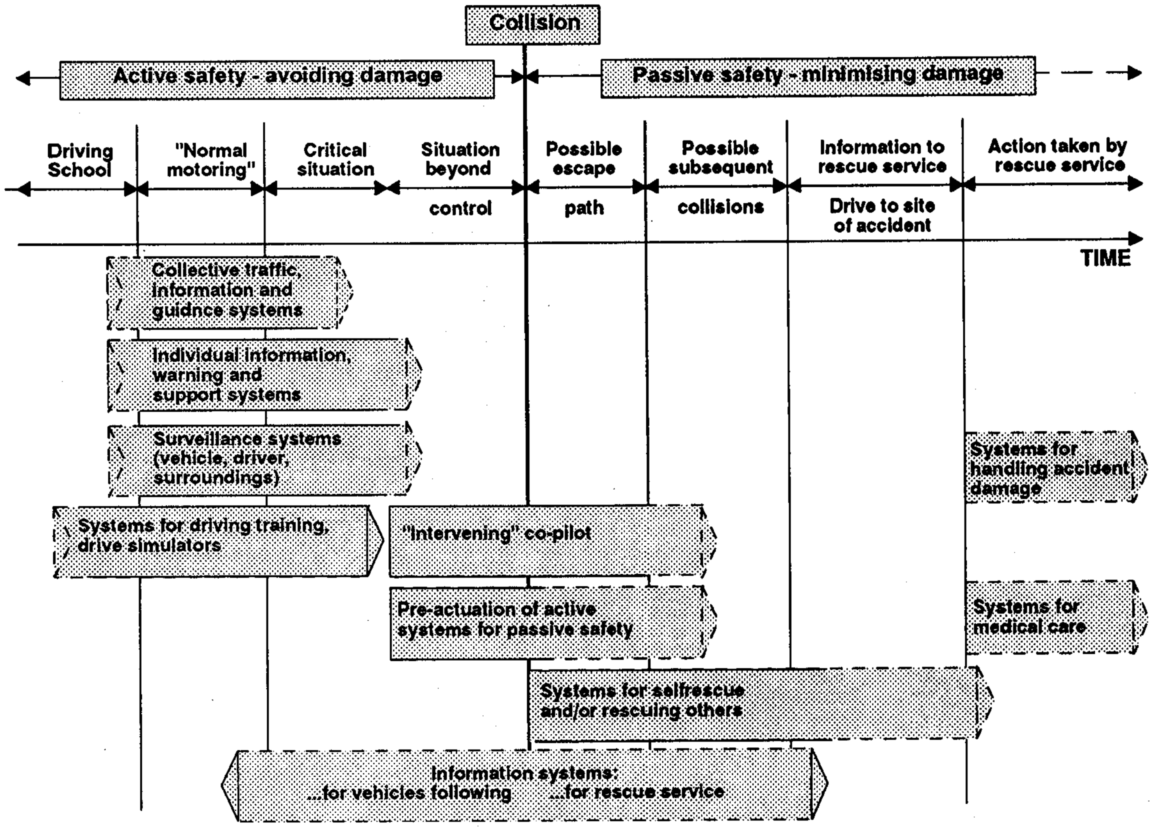


Figure 9. Active and Passive Safety as a Process Chain - Application of Safety Systems (Examples)

Table 3. Opportunities and Risks of Government-Induced Goals

<u>Opportunities</u>

- To speed up progress in areas with a relatively weak market incentive
- To intensify concerted action in basic research, the application of industrial research in the pre-competition phase, and cross-border research
- To make allowance for principles of legality and prudence, and to ensure safety in planning
- To mutually acknowledge existing regulations differing from one country to another, and to harmonise new/improved regulations worldwide

<u>Risks</u>

- Targets are primary too academic and not practical enough
- Targets are not always optimised in terms of benefits and costs
- Sometimes targets are oriented too much towards rare, exceptional cases, circumstances frequently encountered being neglected
- There is a trend towards deficits in flexibility and the willingness to run risks

Section 2
Government Status Reports

Chairperson: George L. Parker, United States

Australia

Peter Makeham
Department of Transportation and Commerce

ABSTRACT

Over the past five years from 1989 to the present we have made significant achievements in improving Australia's road safety performance. Fatalities from road trauma have fallen more than 30% from 2,801 to 1,949 in 1993. Our performance is fast approaching the equal of the best in the world in terms of vehicle ownership (1.9 deaths/10,000 vehicles) and travel (1.3 deaths/100 million kms).

We have set ourselves a target of 10 deaths/100,000 population and in recent years we have reduced this indicator to 11.1 deaths, close to our medium term goal.

Our achievements must be tempered by the knowledge that the challenge will be more difficult in future.

This paper outlines the broad road safety policy framework that developed and the range of tools that employed in Australia to achieve our recent success. It will then discuss the even greater challenges we face and the strategic platform put in place.

IMPROVED ROAD SAFETY PERFORMANCE

After a period of reduction in the 1970s and early 1980s, it became increasingly clear in the mid 1980s that this performance had in fact 'plateaued'.

In policy terms it was recognised that a major initiative had to be taken if a downward trend was to be achieved. It was clear that Australians had to become more proactive in road safety.

THE SETTING FOR AUSTRALIA'S RESPONSE

A number of factors combined in 1989 to create the appropriate climate for telling national action on road safety.

Throughout 1988 there had been growing community concern about the safety of long distance heavy vehicles. Australia then experienced a number of horrific road crashes in some of the larger States with considerable loss of life. These circumstances galvanised the political will at both the Federal and State levels of government, as well as an acceptance in the community that we could no longer rest on our laurels. It was clearly time for action.

BLUEPRINT FOR ACTION

The first thing the Federal Government did was to assume full control over the development and implementation of safety standards for new vehicles. Previously that had been a shared responsibility with the States. This gave the Federal Office of Road Safety an opportunity to develop its own policy and research programs to support this role.

The Federal Government also announced a comprehensive road safety initiative in 1989 designed to have a fundamental impact on road safety in Australia, to reverse the trend of the time and to push Australia to equal the world's best road safety performance.

The initiative sought to address road trauma through the integration of regulatory measures, the provision of financial incentives, significantly increased research and public education, fundamental structural change in the field and long term strategic planning.

I'll deal with each of these ingredients of the Australian Government's road safety initiative in turn.

Regulatory Measures

The centrepiece of the initiative was a National 10 Point Road Safety Package. A bold, innovative and as it has proven, controversial approach to reduce road trauma through the introduction of ten regulatory countermeasures by all Australia's States and Territories.

The ten measures were essentially designed to introduce a range of best national and international practice to all Australian States and Territories. Nevertheless they were still treated with great trepidation as they first saw the light of day. The countermeasures can be put into three major groupings:

Alcohol

- a national .05 blood alcohol concentration limit for all States and Territories
- a zero blood alcohol concentration limit for young drivers (learners and first three years of licensed driving)
- a zero blood alcohol concentration limit for heavy truck, bus and coach drivers
- random breath testing of at least one in four drivers every year

Speed/Licencing

- a national speed limit of 100/110kph
- the introduction of speed limiters on new heavy trucks and buses with retrofitting on vehicles up to three years old; a national license for all heavy vehicle drivers with a uniform points demerit scheme
- a graduated license scheme for young drivers

Other

- compulsory bicycle helmet wearing
- daytime running lamps for new motorcycles
- a commitment by States and Territories to re-emphasise the enforcement of seat belt and child restraint wearing rates.

The obvious question of course is did the measures work? Was the gain worth the undoubted political pain that follows the implementation of tough regulation? The answer is an unqualified "yes."

The package has now gained broad support. The Australian community has shown the capacity to accept measures provided they are perceived to be relevant to the problem, are practical, and the reasons are clearly and simply articulated.

Two particularly controversial areas are worth further discussion to illustrate the point.

Drink driving has and remains a major road safety problem in Australia. However we are making significant inroads. In the early 1980s some 44% of driver fatalities had been drinking over the legal limit (0.08 in most jurisdictions). Today that figure is below 30%, and approaching 20% in some of the more populous states while the limit is 0.05.

Social attitudes to drinking and driving have moved radically. Drink driving, once considered a minor issue, something to laugh about later, is now seen as strictly anti-social behaviour by the vast majority of the population.

The involvement of young people, particularly males in alcohol related crashes has reduced. Importantly there is the clear expectation in the community that anywhere and anytime you could be breath tested. This is made so by the fact that in some areas police have exceeded expectations and are breath testing one driver in two every year.

We haven't beaten drink driving but we have made great progress and that is a direct outcome of those measures in the 'Package' targeting alcohol.

One measure opposed by many, but solidly supported by our research at the time, was the making of bicycle helmet wearing compulsory. The statistics available since the measure was introduced provide unqualified support for the move.

Since the introduction of mandatory helmet wearing bicycle related fatalities have fallen by 50% and serious head injuries from bicycle crashes have also fallen: reductions from 55% to 70% have been recorded in different states. Success by any measure. Initially there was some reduction in bicycle usage, but with the exception of teenage males, usage has generally returned to long term rates.

Financial Incentives

An essential ingredient of the total initiative was the provision of financial incentives to the States and Territories to fund the rectification of major accident black spots throughout Australia. Access to the funding was conditional on the States and Territories implementing the ten countermeasures. The use of such an incentive was vital to the success of the program. The outlays were relatively modest.

Australia is a federation and as such the States and Territories have a wide range of responsibilities for road safety legislation and enforcement. Without the availability of the financial incentive it is a matter for conjecture whether the States and Territories would have been prepared to implement the more controversial regulatory measures. As it was, the incentive proved attractive and the 'blame' for new regulation could directed at the Federal Government.

With this aspect of the program we tried to target our investment. Our focus was specifically on those accident sites with a history of fatal and/or serious crashes.

The Black Spots program has proven very successful. As well as providing the lever to encourage the States and

Territories to introduce the 'ten point plan' the program has realised its own achievements. A pilot study has revealed that a 50% reduction in crashes has been achieved at sites treated under the program realising an average benefit-cost ratio of at least 4.3.

Research and Public Education

While Australia had been active in road safety research and public education for many years, the funds available were limited, confining the nature and scope of the work undertaken. The 1989 Federal initiative significantly increased funding available in these important areas allowing us to lift our sights on what we could accomplish.

As an agenda setter, the initiative also led to individual states making larger financial commitments to research of public education. While the extent of financial support varied markedly, there were some significant "first steps" in areas where commitment had been low.

In the research area increased and secure longer term funding has enabled us to undertake in depth research on few priority areas such as occupant protection, driver fatigue, young drivers and drink drive with the view to tackling the problems from something of a new dimension. Many of the research findings received to date have been particularly encouraging and could provide a sound basis for future initiatives.

In public education we have been able to tackle many of the key road safety problem areas through the conduct of professionally based large scale national mass media and public relations programs that have proven particularly successful. We have tried to complement and supplement State efforts in this field.

Vehicle Standards

For more than a quarter of a century Australia has recognised the importance of improving the integral safety of its car fleet. Australian vehicle safety standards have been among the most stringent in the world. We started early (with regulations for compulsory fitment and use of seat belts) and built on international experience, with the support of local industry.

The Federal Government has always had a central role in this area, but until 1989 it relied on State legislation to implement standards. Even now, the development of new standards still involves close consultation between all Australian governments, manufacturers and consumer representatives.

Like many other countries, Australia has moved away from design-specific regulations towards performance-based standards: leaving maximum room for innovative solutions to produce the best results as cheaply as possible.

We have adopted rigorous procedures for assessing the costs and benefits of all new regulations: a discipline that often requires a very significant local research effort. We have a very efficient and cost-effective certification and type approval system, based on a state-of-the-art quality assurance approach.

We are committed to international harmonisation of standards. Australia in relative terms is a small market and has a range of vehicles built there which are designed in the USA, Japan, or Europe. We also import vehicles from major centres around the World. Harmonisation is, therefore, an important aspect of our philosophy. For us, that includes:

- timely adoption of the best in international practice, once we have satisfied ourselves that there is scope for worthwhile safety gains, at a reasonable price, in the Australian context
- a flexible approach that accommodates competing standards where necessary (it seems likely that our approach to side impact protection will be an instance of this)
- a commitment to contribute to the development of truly international vehicle regulations
- a substantial local research effort to support these objectives: including detailed studies of real-world crashes, crash testing, modelling and economic analysis.

In the area of bus safety we have been at the forefront of early implementers, with standards covering rollover strength, seat mounting strength, emergency exits and lap/sash seat belts.

From July 1994 all new coaches will have lap sash seat belts and seat mountings capable of withstanding 20g.

For cars, we have introduced a performance standard for full frontal crashes, based on FMVSS 208 and are working toward standards for offset and side impacts.

Apart from the development of the standards themselves, I believe that publicity surrounding this work has played an important role in increasing public awareness of the importance of vehicle safety features, and road safety generally.

Four wheel drive vehicles and vans are an important and growing part of the Australian passenger vehicle fleet, and we have a research program including crash testing and in-field crash analysis for these vehicles.

We are also working on a number of projects relating to truck safety, ranging from spray suppression in wet weather, to the economic evaluation of anti-lock brakes.

Enforcement

Another outcome of the initiatives we took was the added emphasis given to enforcement - especially of random breath testing and speeding.

States and Territories which are responsible for enforcement increased their commitment to this most important aspect of the overall equation.

Police received more support for their activities. Investment in new technology was made. Public education programs were designed to support enforcement activities. Positive action was taken to bring traffic police from all the states and territories together regularly to plan national enforcement programs.

Structural Change

Beginning in 1989 through the Government's road safety initiative Australia has made a number of key structural changes to the way we manage our approach to and treatment of the road safety problem.

I have mentioned the transfer of responsibility for new vehicle safety standards to the Federal Government.

The Government established an expert advisory body, the National Road Trauma Advisory Council, to provide advice to all levels of Government in Australia on road trauma. The Council is made up of eminent Australians in the medical, transport and enforcement fields. An important dimension that the Council has added to road safety in Australia is the ability to link transport and public health aspects of road trauma.

Another key change, vital in a federation like Australia, was the establishment of the National Road Transport Commission which is responsible for developing and implementing uniform operational and pricing national regulations for all vehicles. The Commission reports to a council of Federal, State and Territory transport ministers.

The Commission represents a significant breakthrough and it is hoped it will provide the means for us to realise uniformity in regulations particularly for interstate trading heavy vehicles but also in basic road laws.

The Council of Ministers is required to vote on issues. They are carried by the majority unlike our previous arrangement which relied on governments to implement consensus agreements.

Strategic Approach

At the Federal level it was agreed that Australia should set itself the objective of providing a level of safety equal to the best in the World.

We recognised that many countries were actively planning to reduce their levels of road trauma.

We recognised that we had to focus on components of the problem where we would achieve most gains.

We recognised that we had to work within our own physical, political, social and financial environment.

We expressed a will to adopt best world wide practice where that was possible.

We have attempted to make road safety a major economic, as well as social issue.

We realised that strategic planning was critical if we were to achieve consistent levels of safety across the country and then achieve even gains in future.

The Federal Government was able to bring the States and Territories along with local government and other key community stakeholders to develop a National Road Safety Strategy. The Strategy seeks to ensure that Australia's road safety performance in the year 2001 would be equal to that of the leading developed countries in the world. As mentioned earlier a target of 10 deaths per 100,000 population was set. We are close to that rate now and will adjust the target as time goes by.

The Strategy has broad community ownership and wide community involvement in its implementation as a key objective.

It emphasises road safety as both a major public health and economic issue. It truly provides the framework for a coordinated national assault on road trauma in the coming years.

The States, Territories and local government have or soon will implement their own strategies and workplans complementary to the national effort.

WHERE DO WE GO FROM HERE?

As I declared at the outset, Australia in recent years has made real improvements in its road safety performance.

The key question is can we keep this performance up.

In recent years, like most of the rest of the world, Australia has experienced an economic downturn. The downturn had a major impact on most aspects of our lives and road safety was not an exception.

The Federal Office of Road Safety and others had quantitative analysis undertaken to assess the extent of that impact on road safety performance. Estimates suggested that up to a third of our improvement in road safety performance could have been attributed to economic conditions. It was not just a question of reduced travel because travel indicators (e.g. fuel sales) had not fallen significantly but probably because of a change in discretionary travel and travel among higher risk groups.

Australia is now clearly on the way out of the recession. Business and the community at large can quite rightly rejoice, but this situation poses a road safety problem.

The continuing improvements in Australia's economic conditions will pose new challenges for road safety. We are committed to managing road safety during the economic upturn.

The outstanding success in reducing our road toll we have enjoyed in recent years has heightened community expectations for continually improving road safety performance.

Were we to continue with the present mix of road safety strategies and regulatory tools without doubt the economic recovery would see the level of road trauma on the upswing. In fact in recent times our statistical collection and analysis clearly reveals the beginning of this trend.

However we are in a much better position now to answer these new challenges than we were in the mid 1980s. Through the Australian Government's road safety initiatives and those made by State and Territory Governments, we have made fundamental changes to our road safety policy settings and to the structural framework we have in place to implement that policy.

We firmly believe that these developments of the past five years will provide us with the means to cope with the problems of the future.

Arising from the National Road Safety Strategy has been the development and endorsement by Federal, State and Territory Ministers of a National Road Safety Action Plan which provides the blueprint of activities to realise the Strategy's objectives. Its completion could have not have been more timely.

The Action Plan places significant emphasis on medium to long term behavioural countermeasures. Some 40 nationally significant activities have been identified that will form the basis of road safety initiatives to be introduced nationally between now and the turn of the century. From those 13 priority items have been selected for early implementation. These key actions will have a substantial impact on Australia's road safety and will make all Australians work a little harder at being safer on our roads.

Within the last few weeks officials have been able to agree that accelerated implementation of a number of the proposals in the Action Plan, should produce outcomes to offset the recent increases in the road toll. Hopefully the fact that the measures have been agreed at a national inter-governmental level will enable the political processes to accept quickly official's recommendations.

The social and economic costs of road trauma are so great that we must in a structured way continue to seek cost effective measures which will help to minimise the number of people killed or seriously injured in road crashes.

The National Road Safety Strategy offers the path ahead where each level of Government (Federal, State and local) and the major industry, health, education and consumer sectors play their roles toward an agreed national objective.

Canada

S. Christopher Wilson
Transport Canada

The downward trend in traffic fatalities seen in many of our countries was also evident in Canada. In 1993 we had 3,550 road deaths; in 1990, the year prior to the last ESV Conference, there were 3,960 fatalities. Seat belt use has increased from 74% in 1989 when Federal and Provincial Ministers responsible for highway safety adopted a goal of 95% use by '95 (1995), to 88% in 1993. These trends were a continuation of the longer term trends established in the mid-'70s. We estimate that the seat belts alone have resulted in a saving of almost 14,000 lives since 1980.

I reported in 1991 that we had made it a requirement to equip all new motor vehicles manufactured after December 1, 1989, with daytime running lights (DRL). Our evaluation of the use of DRL indicates that they have brought about a reduction of about 12-1/2% in target collisions - daytime, multi-vehicle collisions (excluding same-direction collisions). Our most recent survey in October 1993 of DRL use found 57% of Canadian passenger cars were being operated with their lights on in the daytime. It is also worth noting that our evaluation of the standard that required center, high mounted stop lamps indicated that it reduced rear end collisions by 15%.

On the policy side, there has been continued interest in truck safety and occupant protection. Anti-lock brakes continue to be more prevalent in new trucks and improved visibility of trucks is resulting from the increased use of reflective products on large trailers. Our accident records indicate that serious trucking accidents are not increasing although we expect more trucks are moving more goods due to the deregulation of the trucking industry, the increased trade with the U.S. and a shift from the railways.

With regard to occupant protection in frontal collisions we have proposed injury criteria associated with dynamic testing that will ensure that our mostly belted occupants receive the maximum protection possible from the restraints available. The 80g head acceleration will greatly reduce the risk of severe head contact for restrained occupants. The 50 mm chest deflection will ensure that the current protection provided by good seat belt systems will not be degraded. The belt fit test device will, we believe, improve the way seat belts fit and reduce the risk of abdominal injuries. Our analysis and research convinces us that these requirements are both practical and attainable at reasonable cost.

It is interesting to note that side impact collisions are resulting in more fatalities than frontal collisions for the first time. We attribute the shift to the high seat belt wearing rates in Canada. Our biomechanical research has focused on side impact collisions and we will be presenting the findings of some of this work at this conference. I might say that we are not convinced that the current proposals for side impact standards are going to be as effective as they could be, by this I mean we do not believe the test devices, dummy and barrier, and test procedures ensure that serious injuries, particularly to the abdominal area, are avoided to the extent necessary or for that matter possible.

Our provinces have tightened up licensing rules for new drivers as two provinces have introduced graduated licensing programs and others are moving in this direction. The provinces are also in the process of introducing demerit points for non-seat belt use. Newfoundland, our most easterly province, has attained seat belt use of 97-98%. It was one of the first provinces to assess demerit points for not using seat belts.

Over the next few years our best gains will come from the same areas of effort, seat belt use and reducing impaired driving that have proven to be so successful in recent years. The increased presence of air bags and DRL will also make a significant contribution to reduced injuries and death.

On the research side we are concerned about the reported increase in whiplash and neck injuries and the overall performance of seat belts. We also plan research into how well drivers are able to adapt to IVHS innovations and the risk of information overload due to navigational and other driving aids.

Although fatalities have fallen by about 40% in the 25 years since our Directorate was formed, we are confident that fatalities and serious injuries will continue to fall over the next 10 years. Canadians appear to be prepared to support the measures that will be required to make this prediction come true.

Japan

Kazunari Kainou
Ministry of International Trade and Industry

ABSTRACT

Accident Statistics of Japan
Accident Investigation
Improvement of Vehicle Safety
- Partial expansion and strengthening revise of vehicle safety standard
- Promotion of safety research

Advanced Technologies
International Harmonization

ACCIDENT STATISTICS OF JAPAN

About 11,000 people lost their life by traffic accident in 1993 in Japan. But though the total amount of vehicle number goes up to 65 million or more, fatal accident is stable around 10,000 in these years.

In Japan, there is a typical tendency of fatalities; we can divide more than 50% of fatalities into 2 types of traffic victims. The first is youths under 24 years old mainly encountered while driving, and the second is aged people over 65 years old while walking. By our analysis on accident type, about 5,000 people, that is 43% of total fatalities lost their life by accidents while driving. The amount of fatalities while driving is increasing in these 5 years, because the usage of seat belt is gradually decreasing in these years.

In the past, motorcycle accidents have had an increase in Japan, but its fatalities decreased 223 in 1993. Now, motorcycle accidents are decreasing in these years and consist of only 2% of the total fatal accident.

28% of fatal injuries accounting for 3,100 people deaths are caused by accidents while walking. More than 50% of pedestrian traffic victims are people over 65 years old.

In Japan, 56% of fatal accidents occur during night.

When we divide fatal accidents into typical cases, vehicle to vehicle accidents consist of 46%, vehicle to pedestrian accidents 28% and single vehicle accidents 26%.

ACCIDENT INVESTIGATION

We know traffic accidents are consisted by 3 factors, factors of vehicle, personnel and road. To avoid an accident, we should aim for a balanced and well organized measures to improve these 3 factors.

The Japanese government, National Police Agency, Ministry of Transport and Ministry of Construction established a non-profit organization called "Institute for Traffic Accident Research and Data Analysis" in March 1992. The purpose of this institute is to integrate various kinds of datum accumulated and used in these 3 ministries and agency. This institute provides basic data and information for public use and helps development of effective measures against traffic accidents.

Moreover, the institute is aiming more effective analysis and surveillance through integration of microscopic investigations consisted by largely assembled accident data. The institute is aiming microscopic investigations and analysis in depth by specialists.

This institute established the Tsukuba Investigations Center in 1993, and they have begun accident investigations and analysis, chiefly microscopic ones.

IMPROVEMENT OF VEHICLE SAFETY

Regarding technological guidelines for vehicle safety, the Transport Technology Council under Ministry of Transportation have issued the 3rd report of the target of improvement of vehicle safety standard in 1992. The council issued its 1st report in 1972, and 2nd in 1980.

The report is divided into 3 major categories, "Accident Avoidance," "Injury Reduction" and "Protection of Damage Enlargement." The report shows the result of technological discussions, guidelines for technical standards and time schedules for individual policy measures.

Now, according to this report, the Ministry of Transportation is promoting vehicle safety policy measures, especially improvement of vehicle safety standards.

PARTIAL EXPANSION AND STRENGTHENING REVISE OF VEHICLE SAFETY STANDARD

Nowadays, Japanese traffic accidents reflect such a social factor as traffic speeds up by dint of highway network construction, shift of living time from day to night and aging of society.

To contend with accidents, the Ministry of Transport revised the vehicle safety standards partially as follows, and these new standards have phased in from April 1994.

- Measures against fatal accidents while driving.
  They set legal requirements for passenger vehicles and a kind of light duty trucks to meet following standards.
  - To meet the frontal crash test with actual vehicle
  - To equip with warning device for seat belt fastening
  - To equip rear outer seats with 3 point type seat belt
- Measures against fatal accidents in the night
  - To strengthen standards of performance and capacity requirements for wipers and defrosters
- Measures against fatal accidents at a high speed
  - To strengthen standards of capability of high speed braking and requirements for driving stability while braking.
- Measures against fatal accidents of medium and heavy duty trucks
  - To require medium and heavy duty trucks to light brake lamps when retarder is in operation.
  - To expand the categories of trucks required ABS equipment
- Measures against fatal accidents of youths and aged people
  - To require brake pedal forces to be reduced for easy controlling
- Other measures
  - To require materials used for seats, inner roofs and inner trims to be a fireproof one.
  - To require accelerator to equip doubled returning springs.

PROMOTION OF SAFETY RESEARCH

By the way, we promote safety research from medium and long term viewpoints. The following research subjects are on going or planned:

- Accident avoidance
  - Research on signal lamps' architecture
  - Research on safety of display in a driving use, such as a navigation system
  - Research on fail-safe systems of electronics equipment
- Injury reduction
  - Research on crash safety of lateral collision
  - Research on pedestrian protection: such as protective exterior body shape
  - Research on bumpers; especially front under run protector for heavy duty trucks
- Other Research
  - Research on fire prevention
  - Research on extricability from crashed vehicle's cabin
  - Research on external driving information exchange
  - Research on new vehicle technology and safety; such as safety of alternative fuel vehicle.

ADVANCED TECHNOLOGIES

Now the Ministry of Transport is promoting an Advanced Safety Vehicle project - called ASV in short - to advance safety technologies since 1991. The ASV project aims to enhance systematic safety with a human and vehicle, and prevent accidents and control to minimize damages. The ASV project enables such an enhanced systematic safety by means of a development of intelligent vehicles using advanced electronics technologies. The ASV project set a target of early in 21st century, and promoting the project with a cooperation of government and private sector. In this project, the key philosophy is placed on that a car is intrinsically driven by a human, not by a machine. So, all the electro-mechanical systems actuate as a subsystem to assist human drivers.

For example, to wake a sleeping driver, they are developing not only an artificial voice warning system but flavor discharge warning system and seat vibration warning system. They are developing crash avoidance systems such as in case of a driver ignored on road obstacles recognized by sensor, vehicles choose and execute braking or steering automatically.

Second, Japanese government regard development of vehicle, road and traffic intelligence system as a very important matter. The Japanese government started VERTIS program January 1994, Vehicle, Road and Transportation Intelligence System. The VERTIS is, in a word, a non-profit organization similar to IVHS-America and ERTICO. We hope ERTICO and IVHS and VERTIS trilateral network will contribute towards worldwide enhancement and improvement of traffic safety.

INTERNATIONAL HARMONIZATION

A nation's vehicle safety standard reflects its own social characteristics, accident characteristics and traffic environment. But we should pay enough attention to international standard harmonization because safety standards effect much to world-wide trade.

The Japanese Ministry of Transport actively joins in ECE WP29 for international standard harmonization. And Japan Automobile Standards Internationalization Center, called JASIC, non-profit organization established in 1987, promotes and supports international harmonization. For example, JASIC and Japan Automobile Research Institute have done a proof test for Europe, United States and Japan international joint research. They tested international joint research subject of low-beam headlighting patterns and so on, last year.

The international joint research has achieved the 1st step subject and they are planning to continue further research from now on.

The European Experimental Vehicles Committee (EEVC)

Bernd Friedel
Bundesanstalt für Straßenwesen

It is my pleasure to present the Status Report of the European Experimental Vehicles Committee (EEVC) on our progress in automotive safety.

Since the Paris conference in November 1991 our efforts have been focussed on frontal and side impact protection, pedestrian protection, front underrun protection for heavy good vehicles and motorcycle safety.

FRONTAL IMPACT

It was reported at the 1991 ESV Conference that Working Group 11 dealing with better protection of car occupants in frontal impacts had been created to consider ways in which the evaluation of vehicles could be improved. Car occupants form the largest category of road casualties in Europe, and the majority of these occur in frontal collisions, so this is likely to be the most productive category to address in any measure to reduce casualties. In order to enhance the international input to the work of this Working Group 11, representatives from NHTSA, the Japanese Ministry of Transport, Transport Canada, and the Federal Office of Road Safety in Australia are cooperating with the EEVC in this study. Furthermore this will improve the possibility of international harmonisation in this area.

The Group commenced by examining the available accident data and existing Regulations to determine whether any of these could be modified to achieve a significant improvement in terms of reductions in deaths and serious injuries. The Group concluded that the most effective way would be to introduce a full scale impact test more representative of the dynamic conditions of frontal car-to-car impacts. The accident data showed that many car to car impacts were offset, involving only part of the frontal structure and were between two deformable objects, rather than the full overlap impact into a perpendicular rigid block that is the condition of the current frontal impact tests. Impact tests showed that, in some cases, cars that performed well in the standard frontal impact tests exhibited large degrees of intrusion in offset car-to-car impacts. Most of the accident studies that considered the problem of intrusion concluded that injury risk increased with the degree of intrusion. Consequently, the group concentrated on the development of an offset test into a deformable barrier in order to better evaluate the crash performance of cars.

A comprehensive programme of impact tests was drawn up comparing offset car-to-deformable barrier tests with car-to-car impacts in order to determine the appropriate characteristics of the proposed EEVC Frontal Impact Test Procedure. Tests performed outside Europe as well as those performed by the EEVC members contributed to this study.

The importance of this work increased in 1992 when it became clear that the EC Member States wished to have a new regulatory requirements to incorporate asymmetric impact tests as being more representative of real-life car-to-car impacts. A proposal was made for a 2-stage approach, the first stage to be based on a 30° angled rigid barrier test with an anti-slide device (30° ASD) and the second stage to be based on the EEVC's recommendations for an offset deformable barrier test which were anticipated to be available in time for this conference.

We understand that the EC has now agreed in principle to this proposal for new vehicle type-approvals, the first stage to be implemented from 1 October 1995 and the second stage from 1 October 1998 but the latter becoming available as an option for type-approval as soon as it is validated as being no less severe than the 30° ASD.

With financial assistance from the European Commission and with good cooperation from all participants, the EEVC Working Group 11 has now completed the necessary test programme and has made detailed recommendations for the offset deformable barrier test procedures in the time required by the type-approval experts in the EC and UN/ECE. These recommendations will be reported by Mr. Lowne, chairman of WG11, during this conference.

The Working Group has now begun the validation phase and anticipates that the test procedure will be confirmed, possibly with some minor modifications, by the end of 1994 as required to meet the legislative time-table.

SIDE IMPACT

Working group 13 dealing with side impact was created to provide technical support for the evolution of the EEVC Side Impact Test Procedure into a legislative requirement. The EEVC completed development of the European side impact test procedure in 1988, but implementation as a regulation has been delayed pending evaluation of the Composite Test Procedure (CTP) proposed as an alternative by l'Association des Constructeurs Europeens d'Automobiles (ACEA). Some of the Group members have acted as expert observers to the programme of tests organised by the UN/ECE Group of Rapporteurs on Passive Safety (GRSP), comparing the full scale test with the alternative CTP.

Accident studies reported to the Working Group have indicated the importance of head injuries through contact with the vehicle interior in side impact accidents. The accident studies show that there is a wide range of contact locations for the head. As the dummy will evaluate mostly only one contact position in the side impact test, there is a need for a supplementary sub-system head impact test. The Group is planning a test programme to consider the appropriate conditions for such a test. This programme will take into consideration the proposed rulemaking from NHTSA on this subject.

PEDESTRIAN PROTECTION

Enhancing the safety of pedestrians has been for many years one of the main goals of EEVC. At the 13th ESV-Conference in Paris in 1991 a test procedure was presented to assess the potential for improving the design of passenger cars' frontal surfaces to reduce injuries to pedestrians in the event of an impact. In this proposal subsystem tests for testing the bumper, the bonnet leading edge and the bonnet are described. Since the Paris conference the design for the lower leg impactor for testing the bumper has been enhanced and prototypes are available. Further evaluation tests have been made with the upper leg impactor for testing the bonnet leading edge and the head impactors for testing the bonnet. More evaluation tests with all impactors, involving TNO, INRETS, TRL and BASt are being performed at the moment. The certification procedures for the impactors will also be evaluated in this ongoing programme.

The test procedures and basic requirements have been finalised sufficiently for negotiations to commence on the basis of the proposals already submitted to the EC Commission in 1991. We will finalize the draft of the whole procedure within the year.

DUMMY DEVELOPMENT

In order to incorporate advances in biomechanical knowledge into dummy design EEVC is considering in Working Group No 12, dealing with dummy development, the need for the improvement of future frontal dummies. We agreed to cooperate with NHTSA with regard to the Advanced Anthropomorphic Test Device programme. We are prepared to join the evaluation of the prototype components as soon as they are available. Our efforts will be addressed to the evaluation of the biofidelity of these components. A thorax has already been delivered and new legs are expected to be released soon.

This working group has also started work on air bag related injuries. From a first analysis, it seems that so far there have been very few cases of severe accidents with air bag deployment.

Also the work to assess facial injuries is continuing. TRL has developed a finite element model of facial bone structure and the model has been calibrated against available cadaver data. The predicted fractures correlate well with the applied force. Further calibration work is under way.

FRONT UNDERRUN PROTECTION

In October 1993, a new working group (No. 14) started further work on front underrun protection, based on the results EEVC achieved as reported in: "Front Underrun Protection of Trucks", published in 1992. This study demonstrated that even a non-energy-absorbing underrun guard fitted to large trucks was likely to be cost-beneficial in saving lives and injuries to occupants of smaller vehicles in frontal collision with them. This new work is to consider the development of a test method and criteria to assess the performance of energy absorbing front underrun designs. It will also include an assessment of the benefits of extending front underrun to lighter trucks of under 7.5 tonnes gross weight. The new group consists of delegates from The Netherlands, Germany, Sweden, Italy, United Kingdom, France and Spain.

A Research Proposal to the EC Commission has been accepted and the working group's programme will contain the following phases: Cost-benefit analysis, accident data and statistics, definition of typical accident type, set up of draft test procedure, validation, demonstration, and presentation and final report. Several sub-phases were defined.

MOTORCYCLE SAFETY

An EEVC Ad-hoc Group was set up to review matters of motorcycle safety, and to consider in what ways safety might be improved by developing the current design of the motorcycle, the rider's clothing, and the road environment. A report is now available from EEVC and a summary will be presented by Dr. Bly in Session 7.

Although motorcycling is a minority mode, it carries a ten times greater risk per kilometer travelled of injury than does riding in a car and accounts for some 5 thousand fatalities annually, in the European Union, a substantial 9 per cent of total road casualties. Head injuries account for about 80 per cent of all fatalities, while about 60 per cent of all serious injuries are to the legs.

Avoiding accidents during braking remains one of the most difficult activities for the rider. Coupled front-rear brakes would enable riders to use more of the available braking force, while antilock braking devices, specially for inexpert riders, seem to offer a worthwhile benefit, particularly when fitted to the front wheel. Improvements in frame design and tyres have reduced some of the handling problems. Use of the headlight has been found to reduce daytime accidents by about 40 per cent.

The report deals also with engineering measures for the minimisation of injuries in an impact. For the optimum application of airbags a way of combining restraint and energy absorption with a beneficial influence on the trajectory of the motordriver after collision has to be found. The problem of leg protection is described in the report in detail. Neither an air bag alone nor leg protection can protect from injury in all circumstances and greater benefit might be obtained in combination with each other and with other safety devices.

Further recommendations are given to the improvement of helmets and other clothing.

COOPERATION IN EUROPE

The EEVC continues to cooperate both with the European Commission and with the UN/ECE to provide research and technical support for the development of vehicle safety regulations. In particular, as previously mentioned, several specific research projects have been carried out under contract to the European Commission who have provided part of the necessary funds.

The European Experimental Vehicles Committee and the Forum of European Road Safety Institutes (FERSI) are both concerned with road safety, but in different fields. EEVC is interested in the engineering of road vehicles for safety as illustrated in the projects described above. FERSI deals with general road safety research topics including driver behaviour, driver training and traffic regulations. EEVC has agreed to liaise with FERSI in the exchange of information.

COOPERATION WITH NON EUROPEAN COUNTRIES

The EEVC was originally founded as a European response to the American initiative of the ESV-programme, and EEVC and NHTSA have cooperated from the very beginning. In these days the cooperation is well established in particular with our efforts concerning the protection of occupants in frontal crashes and the development of more advanced dummies.

Furthermore we would like to mention on this occasion the successful cooperation with the governments of Canada, Japan and Australia. This work is also directed to frontal collision and pedestrian protection. It is our firm intention to continue this international cooperation. This seems to us the most successful way to help the regulatory bodies to reach international worldwide harmonisation of regulations.

OUTLOOK

As we have said at previous ESV conferences, our committee is convinced that it is necessary to continue the work for the improvement of vehicle safety. The importance of this has been increasingly recognised not only by governments but also by consumers and industry. Perhaps the importance of this issue is greater than in former times, as improving knowledge and techniques provide a greater potential for improving safety. Although substantial progress has been made in vehicle safety, there are still some 50,000 deaths and over 1 ½ million casualties each year due to road accidents in the European Union alone. There is much more that can be done. The most pressing issues remain side and front impact protection for car occupants. The EEVC will continue making every effort to identify where further substantial improvements are possible.

Commission of the European Communities

Richard C. Wright
European Commission

ABSTRACT

As head of the unit concerned with the regulatory aspects of vehicle construction in the European Commission, Richard Wright reviews the recent achievements of the EU in safety-related legislation, describes the current activities and outlines the future strategy. By the imminent submission of proposals to the Council and European Parliament for Directives on front and side impact resistance of cars, the first steps will be taken in tackling the areas of vehicle design which will lead to the greatest reduction in road accident casualties.

INTRODUCTION

Mr. Chairman,

I wish to thank you on behalf of the European Commission for the invitation to submit this report of the activity of the European Community on motor vehicle safety.

There have been many developments since the last ESV conference and I am pleased to note that, in spite of significant increases in the numbers of vehicles on our roads and the greater distances being covered, the number of casualties has levelled off.

This is not to imply complacency, the Commission has a remit to press for ever higher standards of safety in order to reduce the number of road accident fatalities, currently in the order of 50,000 per year.

As you will be aware, there are three interacting elements in road safety: the road, the driver and, of course, the vehicle. It is my intention today to restrict my remarks to the activity of the Commission in the area of ***vehicle*** developments which affect road safety.

I think that the most effective way to present this to you is to bring you up to date with respect to significant activities since the last conference, to detail our current work and to outline our plans for the future.

THE PAST

Type Approval

The system of European Whole Vehicle Type Approval for passenger cars came into effect on the first of January 1993, on an optional basis, and it will become mandatory in 1996. It is presently being tested by a number of manufacturers in Europe. From 1996, manufacturers will no longer be able to opt for national approvals - all new vehicle types will have to conform to the 45 or so individual directives contained in the Framework Directive.

New Directives

The framework for vehicle safety standards is well established and most developments are introduced by the adaptation of existing Directives. However, there have been two significant initiatives concerning the safety of heavy vehicles:

Speed Limiters

The fitment of devices to limit the maximum speed of coaches and certain classes of heavy goods vehicles has been made compulsory; and, unusually, the legislation has been made retrospective in that existing vehicles up to a certain age will also have to be fitted with speed limiting devices.

Flammability

In the field of bus and coach safety, the Commission has submitted proposals to the Council for a Directive relating to the flammability of materials used in the interior construction of these vehicles. It is hoped that when this enters into force it will lead to reduced fire risk for bus and coach passengers.

Directives amended

It would be inappropriate to attempt to list all the Directives which have been amended in the light of technical progress since the last conference; perhaps I could highlight just two. In the field of primary safety we have adopted one amendment of the braking Directive and have completed the technical preparations for another, introducing revised provisions for antilock braking, reflecting the work done in Geneva by the UNECE.

We have also amended the Directive relating to steering protection, the standard which prescribes the amount of intrusion of the steering wheel in a frontal impact.

THE PRESENT

In addition to the on-going activity of updating our Directives in the light of technical progress - often by making mandatory the optional provisions developed by the ECE in Geneva - the Commission is presently preparing proposals in a number of key areas aimed at reducing road accident casualties. Let me list the main subjects:

Front & Side Impact Resistance

For years the EU has had only one Directive which covered frontal crashworthiness, and no legislation at all for lateral impact. Technical developments, reported here and elsewhere, together with the results of accident research, have demonstrated that it is now possible to introduce standards for front and side impact that are much more representative of the way in which real accidents occur. Again reflecting the considerable efforts of the various technical committees that have contributed to the development of test specifications, the Commission will shortly be able to present proposals to Council and Parliament representing the first phase of a brace of directives which will eventually lead to new vehicle designs that are much more protective of passengers in accidents.

In case of frontal impact, a two-stage approach will be advanced, beginning with the 30° Angled Barrier Test with Anti-Slide Devices as an interim measure, with the objective of the introduction of the Offset Deformable Barrier Test, as developed by EEVC, as the second stage.

As regards lateral impact test procedures, the Commission will also base its proposals on EEVC research work and the recently agreed Geneva Regulation (Rxx).

Pedestrian Protection

The Commission recognises the need to introduce legislation which will ensure that the front-ends of new cars are "pedestrian-friendly." The technical specifications for the various elements concerned are virtually complete and our 1994 programme includes this subject as one of high priority.

Bus & Coach Safety

Although in relative terms, bus and coach travel is a safe means of transport, there have been a number of serious accidents over recent months in Europe, where passengers have received fatal injuries as a result of being thrown out of the vehicle. Now that seat belt wearing has become widely accepted in cars, it seems incongruous that buses and coaches should not be required to have at least two-point belts in all seats. We are therefore currently investigating the technical requirements for such installations with a view to presenting proposals in the Autumn. These will cover all medium and large passenger vehicles except those designed to take standing passengers.

In parallel with this work, the Commission is also preparing proposals for a new Directive on the construction requirements for buses and coaches. This will include important safety considerations, such as the number, size and location of exits and provisions to limit the risk of roof collapse in the event of a roll-over accident.

The 1958 Geneva Agreement

The revision of the 1958 Geneva Agreement on motor vehicle regulations allows for "...regional economic organisations set up by sovereign countries of the Economic Commission for Europe to which Member States have transferred powers to adhere to the agreement." This covers obviously the case of the European Community. Accession to this agreement for the Community is essential in order to bind the link between regulation-setting in Geneva and the adoption of directives in Europe and to put on a legally sound footing the participation of EC Member States in international agreements of this type.

The ECE and its Working Party 29 have proved their worth as the key international standards setting body in the area of vehicle regulations and safety, and it is essential that an amendment to the 1958 Agreement be brought into force as soon as possible. We very much hope that important motor vehicle producing countries which are not currently Contracting Parties to the Agreement will see fit to join in the international standards-making process in Geneva which is so important to removing obstacles to trade in this area.

THE FUTURE

Much of the work of the Commission in recent years has been, and in some areas still is, the establishment of the system for mandatory whole vehicle type approval. As more categories of vehicle types - buses, coaches, lorries - come on stream in this regard, attention can then be given to the individual directives within each framework to review and, where appropriate, raise the standards in order to increase the level of safety for all categories of road user as far as the vehicle design and construction criteria are concerned.

CONCLUSION

Let me end by congratulating the organisers of this conference on putting together an excellent programme to which we attach considerable importance.

France

Jean-Pierre Médevielle
Institut National de Recherche sur les Transports et leur Sécurité

INTRODUCTION

This report on France highlights the last three years of road safety and research into road safety, in particular when vehicle safety is concerned.

Many actions are no longer devised on national level only, whether they concern regulations and/or standardization, areas in which France contributes to the work of the CEN, ISO, CEVE, ECE, COST or the European Union - or road safety policy in accordance with the respective competencies of the European Union and its member States, or territorial or local administrative units.

ROAD SAFETY EVOLUTION IN FRANCE

The graph below (Figure 1) illustrates the situation of the last three years and sums up the measures undertaken by public authorities, putting them back in the context of the last twenty years.

If the number of fatalities and severe injuries has decreased - more significantly in urban areas - the 1993 year is the first year when the curve recorded is tangent to the 9000 fatalities threshold curve. The severity index remains high, even if the traffic index increases (cf enclosed Figures 1 and 2).

It should be noted that the year 1993 was marked by a very severe highway accident which deeply roused public opinion.

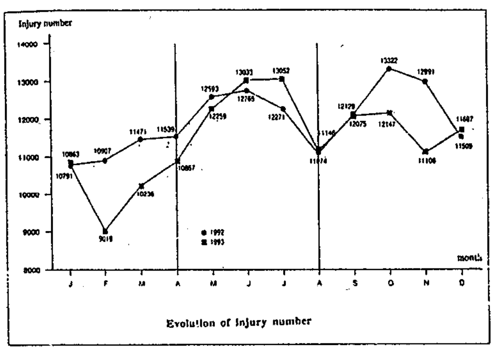


Figure 1

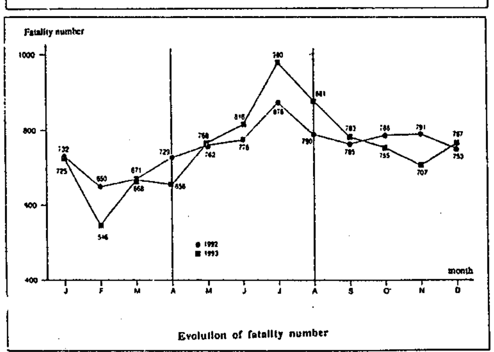


Figure 2

ROAD SAFETY POLICY

The last three years were marked by the implementation of new measures addressing accident prevention, training, penalty-control, control of vehicle and infrastructure improvement.

In 1992:

- Implementation of vehicle technical inspection - for passenger cars and small duty vehicles of less than 3.5 tons - (in complement to existing measures for heavy and public transport vehicles).
- Implementation of compulsory retaining systems for children under ten in passenger cars.
- Implementation of a point-system driving licence, currently with a twelve-point capital. In France, point taking off is conditioned by a court sentence.

In 1993:

- Implementation of a new regulation for hazard goods road transport.
- Enforcement of new article 75 of European Union treaties relating to transport safety.
- In December, meeting of the great Interministerial Committee of Road Safety, which led to the main following decisions:

Prevention

- new partnership with insurance companies
- sight checking every 10 years.

Training

- generalization of the second level school certificate for children in the 4th form.
- road safety certificate required in 1995 for driving a moped.
- new speed limits for young drivers with some advantages for Accompanied Driving Training.

Penalty-Control

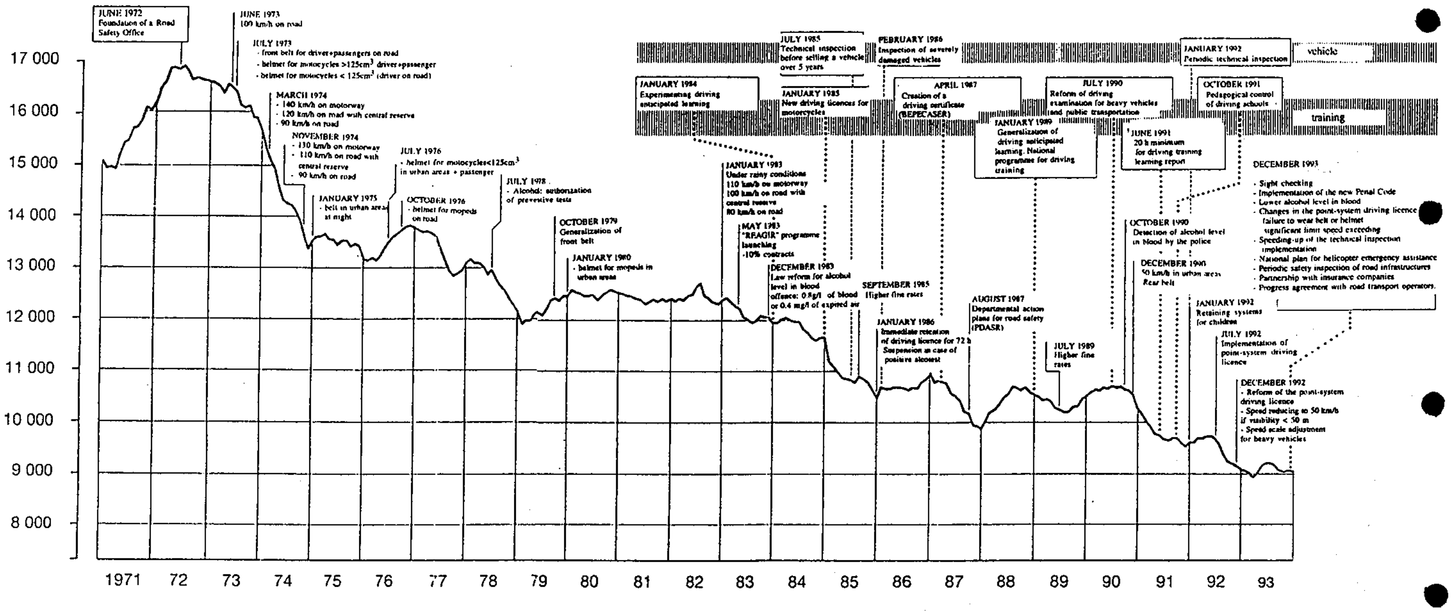
- increased penalty severeness: limit speed exceeding by 50 km/h (6 points).
- failure to wear belt or helmet (1 point) - responsibility of vehicle owners.
- alcohol level in blood: 0.7 g/l.
- interfering with or tampering speed limiting devices and speedographs considered as offences.

Improving Vehicles and road infrastructure

- inspection of vehicles over 4 years from 1995, and then every 2 years.
- development of speed limiting policy in urban areas.

sécurité routière

EVOLUTION OF FATALITY NUMBER



- pilot operation for road infrastructure inspection (on national and local scales).
- development of a new national plan for helicopter emergency assistance.

The progress agreement with road transport operators should be added.

A new Penal Code was implemented on March 1, 1994. Road safety related penalty levels have been increased and a new offence for "endangering other people life" has been created, provided that court assessment could be applied in the road safety field.

EVOLUTION OF RESEARCH AND DEVELOPMENT

In the last status report, five types of work were presented to you.

The first one related to driving simulators for training drivers, whether professional or not, as well as to research simulators. A large simulator common to PSA-RENAULT-INRETS is being developed. INRETS and CNRS already developed or will develop simulators, more specifically designed for research studies into ergonomics or road safety.

The Road Safety Research Institute Forum (FERSI) led to proposing common or comparative research studies (in particular accident detailed studies) as part of European or national plans for preparing the fourth Research and Development Framework Programme.

Research work within the framework of the Eureka Initiative, in particular the Prometheus and Carminat programmes, is continued towards demonstration operations with the participation of French car manufacturers or car equipment manufacturers. As part of the Drive 2 programme, France is also involved in significant experiments and perinormative research.

Finally, the Vehicle and Road Safety programme common to PSA-RENAULT-INRETS was launched following the 1993 agreement of the European Union Commission.

In addition to these 5 types of work, the French current effort addresses four main lines:

- Implementation of new methodologies aimed at meeting the stake of severely injured cases in addition to that of fatality cases, in accordance with the ethics/science relationships (e.g. new epidemiological methods applied to safety, injury mechanisms, simulation-modelling-demonstration-observation)
- Transfer of road safety concepts to new transport modes and conversely (e.g. secondary safety applied to guided transport, implementation of cindynics and human factor engineering on road vehicles)
- Multidisciplinary focussing on the infrastructure-vehicle-driver/passenger pattern, not forgetting society ageing
- Compatibility of vehicles using a same infrastructure.

CONCLUSION

A number of French studies will be presented to you during this conference by car manufacturers, car equipment manufacturers or research institutes. I think all of them will illustrate the challenge the French community wants to meet in the road safety field.

Italy

Claudio Lomonaco
Ministero dei Transporti

When in Paris, during the last ESV Conference, the initiatives on Safety in the different Countries, we pointed out that a new international "view point" was likely to be taken as a "reference point."

After that Conference, a lot of events happened, but the main one is, in our opinion, the European Community establishment of a new frame directive as a reference point of the harmonisation on motor vehicle construction; this event has been the pivot of every action towards Safety.

As the European Community policy is the creation and maintenance of one wide and harmonised area where each Member State can recognize its own identity in every aspect, the Italian expert on Safety matters followed a criterion of consistency with the past in which the Community rules were taken as main reference for the national approval of a vehicle type.

ESV is the crucible of new techniques and progress in Safety, but it is essencial that all this be translated into international standards, so that it is possible to apply them to vehicles.

Italy, during these years, has been forwarding and putting into effect the projects of the new Road Traffic Code, where the national experiences in traffic Safety have found an integration with the European Community guidelines.

As a member of international rulemaking forums, Italian experts participate actively in the process of harmonisation of the European rules on vehicles. In particular, as far as the consequences of road accidents are concerned, Italy put its experience in promoting reasonable compromises in ECE/UNO W29 in Geneva, when discussing frontal and lateral collision regulations. Such compromises were subsequently discussed and accepted within EEC Commission as basis for new Directives on those items.

The Italian committment in this field is not only to get an agreement among EEC Member States, but also to support it along the impervious ratification iter. This because it is extremely important to actuate on the industrial production the new scientific findings in the field of Safety, according to the best technology available by manufacturers and the best cost/benefit ratio for consumers.

We want to stress here the importance of a sensible compromise between the scientific research and the best available technology; it is not possible to transfer scientific concept on the existing fleet of vehicles, without thinking about the industrial difficulties in creating new generations of products at reasonable costs and about the time needed to get a complete renewal of the fleet itself.

For such reasons we think that the most important thing is to define in short time simple and clear rules in which every manufacturer can identify precise guidelines to produce better vehicles to be put on the market in the shortest time, while every Administration can verify that Safety principles are taken into account without misunderstandings.

To the aim of applying important Safety requirements in the short and medium time, we deem advisable to pursue a policy of implementing reliable test tools and methodologies. So doing, the new required performances are easily accepted by manufacturers, as reasonable changes to vehicles, and by users as clearly understandable improvements that are worth the money they spend.

United Kingdom

Malcolm Fendick
Department of Transport

Thank you. Good afternoon everyone. It is my pleasure to present the status report for the United Kingdom.

Since the last conference two years ago, we in the United Kingdom have seen the annual number of fatalities caused by road traffic accidents fall by 16 percent, while serious injuries are down 13 percent. Unfortunately, slight injuries remain at much the same level.

The reasons for this welcome drop in fatal and serious injuries are not clear, but we suspect that the changes in roads and vehicle design must play a major part.

Also, safety is now advertised strongly. The consumer is now more aware of safety than ever before, and this may encourage care. I believe we are now becoming an increasingly more risk-aversion society.

One significant point concerning alcohol is that we have witnessed a real change in public attitude. It is no longer socially acceptable among many, though not all of the population, to be seen to drink and drive.

The wearing of seatbelts continues to be a major contribution to injury reduction, and the increasing use of rear seatbelts is adding to the good record we already have for front seat occupants.

We are also witnessing in Europe renewed efforts from the motor industry to make its products safer with the further development of seatbelts, including pretensioners and web grabbers, as well as child restraints and airbags.

This conference is primarily about vehicles. The United Kingdom has continued to contribute as much as possible to the development of effective safety standards, which are defensible in terms of the cost to the consumer.

In addition to supporting the regular meetings held in Geneva and Brussels, we have consistently supported the work of the European Experimental Vehicles Committee, which was born directly out of these ESV conferences.

Thanks to much international cooperation, the EEVC has produced realistic proposals for European standards, the side impact and frontal impact tests, which will be more representative of the way cars deform and absorb energy, in actual car-to-car crashes.

We look forward, in particular, to the early adoption of the offset deformable barrier test into European legislation.

The EEVC has also developed a test procedure which would require the front of new cars to be designed in a way which minimizes pedestrian injuries. The cost has been said by vehicle manufacturers to be too high to be justifiable in terms of reduced injuries, but cost/benefit studies both in Germany and in the United Kingdom indicate a very worthwhile rate of return.

Moreover, while we argue, nothing is being done about cowcatchers or bullbars, those unnecessary and aggressive accessories, which can only make pedestrian injuries very much worse.

We are studying those relevant accidents, and if it appears that people are being killed or injured unnecessarily by these add-on features, it may become indefensible to sit back and do nothing.

We continue to collect accident data on a nationwide basis, using reports by the police, which must, by law, be compiled for every injury accident. This is used as a basis for deciding our priorities for legislation.

Last year, and recently again this month, we have published leaflets based on this data, giving consumer information on the relative safety of 90 car models; 550,000 copies were distributed last year. Information was given on many of the safety and security features now offered to try to help people choose the more safe and secure cars.

In addition to the nationwide data, a program of in-depth investigation is studying the vehicles and occupants in about 1,500 car crashes a year, most of which are fatal or serious.

We have found from this work that the frequency of facial bone fractures for drivers increased by about 10 percent following the mandatory wearing of safetybelts, and this continues to be the case. We conclude that there is every reason to require either a driver's airbag or a softer steering wheel.

Casualties to motorcyclists remain a serious cause for concern, and a major topic for research. During this conference, the EEVC report on motorcycle safety will be presented by Dr. Bly of the United Kingdom Transport Research Laboratory.

The Department of Transport funds the TR work, which continues to advance the understanding of motorcycle accidents and to develop measures to alleviate the consequences of such accidents.

Indeed, TRL is being funded by the department in cooperation with the motorcycle industry to devise a standard methodology for testing within the ISO forum. This will be used by the TRL to investigate the effectiveness of secondary safety methods for motorcyclists, such as leg protectors and airbags.

We are also carrying out an in-depth study of fatal and serious motorcycle accidents and a two-year study looking into the mechanisms involved in whiplash injuries in rear impacts to cars. Those studies involve the collection and analysis of detailed medical and vehicle data.

The United Kingdom Government, the component and vehicle manufacturers, and the Consumers Association have made a full contribution to the development of improved fixings for child restraint systems. Measures have now been agreed to that encourage vehicle manufacturers to provide information to owners saying what types of restraint can be fitted into each passenger seat.

In the longer term, the universal ISO fix, vehicle and restraint fittings, seem likely to resolve, once and for all, all the difficulties of how to attach rigidly and safely, a child restraint to a soft seat. It is to be hoped that the draft ISO fix, ISO standard, will soon to be agreed, although vehicle manufacturers can now incorporate the standard into their designs under the existing European standard ECE Regulation 44.

To conclude my presentation, it is a real pleasure to see so many friends here this week. Within such a spirit of friendship, we should be able to make genuine progress on a whole range of issues.

But above all, this week, we should be able to create and renew friendships, learn from one another, and go home with much good will and ideas for the next phase of enhanced vehicle safety. Thank you.

Sweden

Kåre Rumar
Swedish National Road Administration

ABSTRACT

Initially an account is given of the development of the accident and injury development in Sweden during the last years. It is clear that the road safety situation in Sweden has improved considerably from 1990. Some ideas about what may have caused this improvement are presented.

Then the changes that have occurred in the organisation of the Swedish road safety work are described. The first of January 1993 the Swedish Road Safety Office was merged into the Swedish National Road Administration (SNRA). SNRA is therefore now the main responsible Swedish authority in the road safety sector.

During 1993 the Swedish Parliament decided that a new strategy for road safety work should be implemented. The problems are in large the same but the working methods are different - both concerning the cooperation between the authorities and between authorities and road users.

The SNRA is in cooperation mainly with the police and the communities presently working with a Swedish road safety programme for the years 1995-2000 based on the principles outlined by the Parliament.

Finally some major road safety actions carried out during the last years, some plans, and some research activities in progress are mentioned.

ACCIDENTS AND INJURIES

From 1990 the road traffic accidents have decreased continuously. The size of the decrease exceeds 10 percent. The largest reductions can be found for single motor vehicle accidents and collisions between motor vehicles --except rear end accidents which has not decreased. Other accident types which have not been reduced are accidents between motor vehicles and bicycles and accidents between motor vehicles and game. The accident reduction is somewhat smaller in urban areas as compared with rural areas. All the reductions are statistically significant.

The largest injury and fatality accident types according to the police reports are collisions between passenger cars and passenger car single accidents. These two types of accidents account for 50 percent of the fatalities. The largest reduction of fatalities is found among pedestrians. Second largest reduction is drivers -- especially young drivers. The smallest reduction of injuries during the last years is found for bicyclists. The total number of killed road users in 1993 (632) is the lowest figure for 40 years. The reduction is about 25 percent compared with the average figure during the last five years.

Most of the impressive reduction is however probably due to the economic recession. Traffic in general has only changed marginally during the last years. It is however obvious that the young people have reduced their driving. They cannot afford to take a driver's license, to buy a car, to buy petrol etc. Due to the recession the number of heavy trucks have also gone down. Both young drivers and heavy trucks are strongly over represented in accident statistics. Furthermore people are known to become more careful in times with economic problems.

Another factor of importance is that the police during the last year has stepped up their surveillance effectivity considerably.

ROAD SAFETY ORGANISATION

The Swedish Road Safety Office was created as an immediate effect of the change over from left to right hand traffic in Sweden 1967. For many years this authority carried out a very good job which moved Sweden to the top of the international road safety ranking. During the 80:ies however the safety improvement came to a halt and the government decided that something had to be done. It was concluded that one of the reasons for the lack of continuous success was that the Swedish Road Safety Office did not have the power and resources to carry out all its good ideas. The implementation and the responsibility problems were overlooked.

The decision was therefore to merge the Swedish Road Safety Office into the Swedish National Road Administration. This change took place first of January 1993. SNRA was since long responsible for the state roads. Now SNRA became responsible not only for the roads but also for the road users and the road vehicles. In other words for the way roads are used (traffic) and the effects of road usage (mobility, access, accidents, environment, economy). SNRA is supposed to have the power and the resources to carry out the road safety actions decided.

A NEW STRATEGY FOR ROAD SAFETY

During 1993 the Swedish Parliament decided that a new strategy for road safety work should be implemented. The main features of this strategy are to:

- treat road accident injuries as a serious public health problem
- base the work on the demand and characteristics of the road users and reduce the uncertainty of road users as far as possible

- create a dialogue between the authorities and the road users
- create a close cooperation between the various actors on the road safety scene - mainly SNRA, the police and the communities
- create a vision of the future safe society towards which all actors and road users should be striving
- try to increase the evaluation of road safety among decision makers and road users thereby increasing both demand for road safety measures and safe behavior of road users
- move the road safety work as close to the citizens as possible using peoples interest in their own local traffic environment
- put more emphasis on the implementation of road safety measures
- work with a clearly defined result management based on continuous measurements and follow-up studies of implemented road safety measures.
- intensify research in order to have a better base for future road safety activities.

A SWEDISH PROGRAMME FOR ROAD SAFETY

In cooperation primarily with the police and the communities SNRA is presently working hard to finalise a new programme for road safety for the years 1995 to 2000. The programme, which is planned to be ready in September 1994, is of course based on the above principles as stated by the Parliament. The main parts in the programme are:

- An account of the Swedish road safety situation with the main safety problems
- A vision of the future society in which road safety has reached the level we aim for
- A description of the strategy that should be followed in the future road safety work. The main part here is a concept called road safety reforms. The idea is to manage road safety work by results instead of by activities, which has previously been the routine. Such a management requires that a goal is set up for each reform and that the status of each reform can be measured.
- A description of the action programme. This contains 11 reforms, governmental and community road investment, road safety education, rules and enforcement and research
- Implementation and follow -up of the various road safety actions.

The eleven reforms, which are the core of the new programme, stated so far are:

- Improve decision maker and road user evaluation of the road safety problems
- Reduce the number of speed limitation violations
- Improve state and community road environment
- Decrease the number of road users under the influence of alcohol
- Reduce the number of other rule violations than speed
- Improve visibility in road traffic
- Increase the usage of seat belts in automobiles
- Increase the usage of helmets among cyclists
- Increase the usage of child seats in cars
- Improve collision performance among the cars sold in Sweden
- Improve the speed and accuracy with which road accident victims are treated and rehabilitated.

SOME RECENT ROAD SAFETY ACTIONS, PLANS AND RESEARCH IN PROGRESS

Two of the main road safety actions taken during the last years are:

- Driver training accepted from the age of 16 under control of accepted experienced driver
- Police surveillance considerably increased through more effective use of staff resources.

Some of the road safety plans presently discussed are:

- Decrease the annual technical inspection of cars and increase the technical control of cars in traffic
- Develope evaluation of an automobile safety index for consumer purposes
- Create a road safety school for laymen and specialists
- Develope methods to test the wear of windshields.

Some of the more interesting road safety research activities in progress are:

- Development of a new automobile lighting system based on ultraviolet light and fluorescent markings
- Test area ARENA in the Gothenburg region is testing various types of RTI equipment for cars and roads to improve driver and authority information
- Possibilities to improve the safety of elderly drivers.

Poland

Wojciech Przybylski
Instytut Transportu Samochodowego

THE PREAMBLE

Good afternoon Ladies and Gentleman,

On behalf of Polish authority I would like to thank you chairmen and all other participating country's representatives for giving me the opportunity to present the current state of our activity in the field of vehicle safety. It is the first time since many years when we have the opportunity to present our findings against such wide international public and we hope that in future we can contribute in greater extend in international efforts direction to enhanced vehicle safety. I am quite sure that the information entry of this event will be very stimulating as well for our authority as for industry works what makes me to say again - thank you very, very much.

STATUS REPORT ON THE POLISH ACTIVITY IN SCOPE OF VEHICLE SAFETY

We all know that the traffic situation, and especially the possibility of a serious accident is determined by three main factors: vehicle, human behavior and road environment. This Report deals with matters connected exclusively with vehicle safety while it should be stressed that we are aware that only broad combine action in the a/m areas could lead to significant improvements in road traffic safety. As the result of important political and economical changes started in Poland in 1980 the enormous rate of growth of the number of motor vehicles has been observed on our roads (this number have been double through last decade reaching in several areas the rate of less than three persons per vehicle). The above fact gives special importance to any activity direction to vehicle safety. Let me now quote several figures highlighting actual data of accident analysis in our country. As it appears from the annexed tables and diagram we have recorded the significant increase of road accidents and number of fatalities during last decade. These figures looks rather dramatic in comparison with our population of around 38 millions. During last few years we have concentrate our works on two main areas of vehicle safety - development of type-approval system and improvements of periodic technical inspection of vehicles in use. It is to be stressed that our legislation in these areas has been positively evaluated by the World Bank Mission in July 1992. Now I would like to describe shortly the a/m activity.

THE DESCRIPTION OF NATIONAL TYPE-APPROVAL SYSTEM (NTA)

The current national type-approval system was established as partial adaptation of the EEC directive on the approximation of member state laws in their national type-approval (Dir. 70/156/EEC) with the insertion of the UN ECE 1958 Geneva Agreement of which Poland had became to be a member in 1979. Being in force since 1983 national type-approval system (NTA) has at its scope as well road vehicles (motor vehicles, agricultural tractors, mopeds and trailers) as their parts. The main goal of the system is the improvement of vehicle constructional safety and the safety of vehicle use together with the protection of environment. The system is also the main data base for registration of vehicles and for periodic technical inspection of vehicles in use. The system has following elements:

- type-approval authority, which means the state administration granting the type-approval (in Poland - Minister of Transport and Maritime Economy);
- technical services responsible for conducting type-approval tests;
- manufacturers, importers and approval objects (vehicles, their equipment and parts).

The relations between the above elements have multidirectional nature and are based on the existing legal prescriptions. The main clauses are given in the diet law from February the 1, 1983 "Road traffic law" (the current version is published in Government Gazette No 11 from Feb. the 6, 1992) which obligate manufacturers or importers of vehicles, their equipment and parts, to receive the type-approval granted by Minister of Transport and Maritime Economy (Art. 56). The other Articles of the chapter (Art. 55, 57 and 58) establish the frame technical requirements, the rules of dangerous goods transportation and authorize Minister of Transport to publish in agreement with other chosen ministers the detailed prescriptions on technical requirements and type-approval procedures. The scope and the manner of type-approval tests as well as the accreditation of technical services, the forms to be used in type-approval and any individual exemptions from established technical requirements are left to the discretion of Minister of Transport. The external relations of type-approval system are given in Art. 64 of the a.m. law (Chapter 3 - Vehicle technical inspection) in which it is written that the new vehicles for which either type-approval was granted or the decision of exemption was made can be registered for the first time without the technical inspection (taxis and vehicles for transport of dangerous goods are excluded from the relaxation). Following the a.m. general law the Minister of Transport has published the next rules connected to type-approval which give the detailed internal relations of NTA system elements and establish two important external relations of the system.

First of the external relations exists between NTA and quality qualification systems (this second system was exchanged to national testing and certification system from the beginning of 1994) and the second deals with international UN ECE type-approval system under the 1958 Geneva Agreement. The further level of detail of internal relations of NTA exists in particular technical requirements given in paragraphs of the ordinance and instructions of Minister of Transport, in signed by Polish Government UN ECE Regulations and in obligatory Polish Standards. It is to be said that in NTA system in Poland exist currently 48 ECE Regulations and 48 national Standards, and the appropriate tests are performed in several testing laboratories having clearly defined scope of competence. The distribution of particular prescriptions among the different aspects of constructional safety is the following:

- active safety - 22 ECE Regulations and 8 national Standards;
- passive safety - 9 ECE Regulations and 11 national Standards;
- environmental protection - 11 ECE Regulations and 4 national Standards;
- other safety aspects - 6 ECE Regulations and 25 national Standards.

THE DESCRIPTION OF PERIODIC TECHNICAL INSPECTION SYSTEM (PTI)

The current national periodic technical inspection system was established as partial adaptation of the ECE consolidated resolution on the road traffic (R.E.1) with the insertion of about 20 year national experiences in the subject. Being in force since 1983 national PTI system has at its scope all registered road vehicles (motor vehicles, agricultural tractors, mopeds and trailers). The main goal of the system is the improvement of the safety of vehicle use together with the protection of environment. The system is also the main data base for registration of vehicles. The system has following elements:

- state authority, which means the state administration establishing PTI rules (in Poland - Minister of Transport and Maritime Economy);
- local authorities, which means local administrations giving the authorization for performing PTI checks to individual inspection stations on their territory and obliged to supervise them;
- inspection stations;
- vehicles.

The relations between the above elements have multidirectional nature and are based on the existing legal prescriptions. The main clauses are given in the diet law from February the 1, 1983 " Road traffic law" (the current version is published in Government Gazette No 11 from Feb. the 6, 1992) which obligate vehicle owners to subject their vehicles to examination on specified periods and cases (Art. 64). The other Articles of the chapter (Art. 65, 66, 67 and 68) establish the competence for authorizing and supervising the inspection stations and authorize Minister of Transport to publish in agreement with other chosen ministers the detailed prescriptions on authorizing and withdrawing of inspection stations, inspectors themselves as well as technical requirements and inspection procedures. The scope and the manner of PTI checks as well as the forms to be used in PTI and any individual exemptions from established technical requirements are left to the discretion of Minister of Transport. The external relations of type-approval system are given in Art. 64 of the a.m. law (Chapter 3 - Vehicle technical inspection) in which it is written that the new vehicles for which either type-approval was granted or the decision of exemption was made can be registered for the first time without the technical inspection (taxis and vehicles for transport of dangerous goods are excluded from the relaxation). Following the a.m. general law the Minister of Transport has published the next rules connected to PTI which give detailed internal relations of the system. It is to be said that in PTI system in Poland exist currently 10 main items to be checked due to their importance for safety of vehicle use and environment protection. Our net of checking stations is also well developed and consists currently of about 3000 authorized stations, 2500 of them of public nature.

THE FUTURE

Intensive works are currently conducted on such development of the NTA system that enables as close as possible unification with European Union. The Directive 92/53/EEC from July the 18, 1992 established 52 particular directives or 53 equivalent ECE Regulations as obligatory to receive the European type-approval. During next two years the set of ECE Regulations in force in Poland is expected to be completed for full consistency with the Directive. In the next step the complete set of administrative provisions of the Directive will be inserted into national law. As for PTI, current development works concentrate on further objectivization of technical checks and establishing the net of information that enables to analyze the inspection results in regional and national scale. The conclusion is that we have to continue our efforts in order to reach the vehicle safety level comparable to one existing in developed countries, bearing in mind that the result of our activity could be observed in the time scale related to the natural exchange of the vehicle stock in operation.

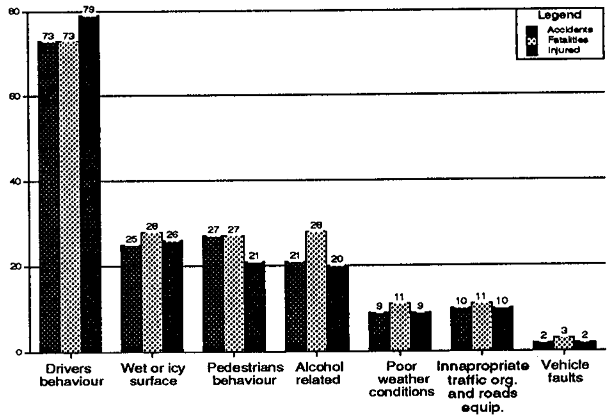


Figure 1. **Causal Factors of Road Traffic Accidents in Poland in 1993 (In Percentages)**

Table 1. Accident Data in Comparison With the Vehicle Stock and Population in Poland in the Period 1980-1993

Year	Number of accidents	Number of Fatalities	Number of Injured person	Number of vehicles [in thousands)	Number of passenger cars [in thousands]	Population [in thousands]
1980	40373	6002	48245	5496	2383	36735
1981	43755	6107	51365	5853	2634	36062
1982	38832	5535	45693	5996	2882	36399
1983	40454	5561	47463	6417	3179	36745
1984	35768	4980	41325	6850	3426	37083
1985	36100	4688	42290	7089	3671	37341
1986	37133	4687	43150	7476	3964	37572
1987	36433	4625	42272	7795	4232	37764
1988	37538	4851	43626	8214	4519	37885
1989	46338	6724	53639	8596	4846	38038
1990	50532	7333	59611	9041	5261	38183
1991	54038	7901	65242	9860	6112	38309
1992	50989	6946	61046	10207	6505	38118
1993	48901	6341	58812	10438	6771	38505

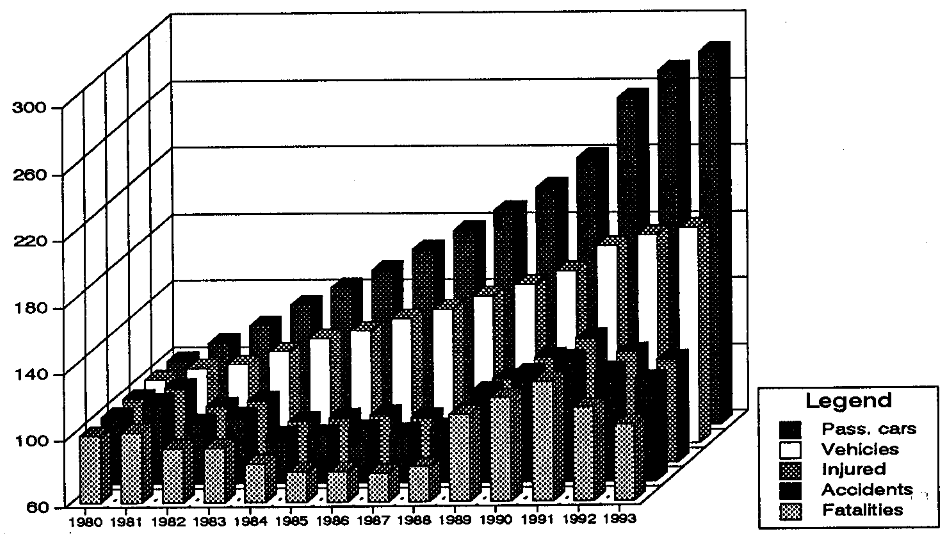


Figure 2. **Road Accidents and Vehicle Stock Percentages in Poland in the Period 1980-1993 (1980 = 100%)**

Figure 1 and Figure 2 Source: Motor Transport Institute, Centre of Road Traffic Safety
ul. Jagiellońska 80, PL-03-301 Warszawa

Hungary

Sándor Szabó
Research Enterprise of the Automotive Industry
György Császár
Ministry of Transport, Telecommunication and Water Management

Mr. Chairman,
Dear Ladies and Gentlemen,

It is a great honour for me to provide information on the safety situation of the road vehicles in Hungary.

In 1993, two and a half million road vehicles were running in the 93.000 square kilometer territory of Hungary, a country with 10,5 million population. The length of the country's paved road network was 70 000 km (300 km of this being motorway), and at average the age of the vehicle fleet was over 10 years, 80 % of these vehicles had been produced in the former CMEA countries.

In Hungary, in 1993 in course of 20 000 registered road accidents 25 000 persons were injured and 1 600 was the number of the fatalities. 1 % of the cases could be explained directly with the technical condition of the vehicles.

The Orders referring to road traffic and road signs and signals applied in Hungary are based on the 1968 Vienna Conventions on Road Traffic and Road Signs and Signals as well as the 1971 European Agreements supplementing them.

Hungarian Orders regulating the admission to traffic of road vehicles were prepared partly on the basis of the Annex 5 of the aforementioned 1968 Vienna Conventions, and partly on the Agreement Concerning the Adoption of Uniform Conditions of Approval and Reciprocal Recognition of Approval of Motor Vehicle Equipment and Parts done at Geneva on March 1958 (henceforth the 1958 Agreement). Hungary by now has adopted 62 regulations from those 92 which until now have been elaborated and annexed to the 1958 Agreement. (50 regulations are concerned with motor vehicles' road safety.)

In Hungary all road vehicles admitted to traffic dispose of compulsory liability insurance.

The maximum speed permitted in Hungary for urban roads is 50 km/h, for highways: 80 km/h, motor roads: 100 km/h and motorways: 120 km/h.

In 1993 the compulsory use of the daytime running light was introduced for roads outside built-up areas, as well as - in case installed in - the use of the back seat safety-belts was made obligatory. Subject to definite conditions, the application of liquefied or compressed gases as fuels has also been permitted.

Notwithstanding that, exclusively for taxi use purposes (Magosix, Ford Eifel) in Hungary in the first half of the century existed a passenger car production, after a five decades' pause, this activity started again in 1993. Thus, in the first year 13 344 Opel Astra passenger cars and 75 741 engines, as well as 14 000 Suzuki Swift passenger cars were assembled respectively in the plants of the General Motors Hungary and the Hungarian Suzuki Ltd. In conformity with the requirements prescribed for passenger cars manufactured in series in Europe, the safety characteristics of these models are appropriate.

Due to well known reasons (collapse of the Eastern market, economic recession etc), subsequent to continuous manufacturing work based on several years' experience - large capacity single-deck rigid and articulated public service vehicles of own design for city and inter-city use, self-propelled chasis and bodies (IKARUS, RÁBA, CSEPEL Automobile Works)- production fell to 25% compared to the 13,383 units registered in 1986.

The safety characteristics of Hungarian-manufactured buses and of the commercial vehicles produced in small series in the Rába and Csepel Automobile Works, meet the provisions elaborated by the UN/ECE regulations and the requirements of those regulations which mostly have been adopted by Hungary, too, namely regulations No 13 on braking of vehicles of categories M, N and O; No 36 on the construction of public service vehicles; No 43 on safety glazing and glazing materials; No 48 on the installation of lighting and light-signalling devices; No 54 on pneumatic tyres of commercial vehicles and their trailers; No 66 on large passenger vehicles with regard to the strength of the superstructure and No 80 on the seats of large passenger vehicles and vehicles with regard to the strength of the seats and their anchorages.

Since decades, Hungarian experts are taking part in the work of several working groups of the United Nations Economic Commission for Europe, namely in the activity of the Working Party on the Construction of Vehicles (WP29) and its subordinated bodies: the group of experts on general safety provisions (GRSG), on lighting and light-signalling (GRE), on brakes and running gear (GRRF) aimed at the elaboration of the pursuant traffic safety provisions.

Hungarian research institutes (Research Enterprise of the Automotive Industry, Institute for Transport Sciences, Hungarian Electrotechnical Controlling Institute), authorized also to perform tests according to the ECE provisions (see the annexed List), as required by European standards, contributed especially in the following fields to the development of road vehicles' safety:

Definition of the safety characteristics of the large (longer than 8 m) single-deck rigid and articulated buses for city and inter-city use: residual space, free and safe flow of passengers, emergency exits, protection against fire risks, strength of superstructure, roll-over strength, strength of seats and their anchorages, steerability, arrangement of the drivers' compartment, front and rear-underrun protection etc.

On the background of much experiment and design activity, in the subjects enlisted above (see the attached photos also), the Hungarian party submitted many draft regulations to the European experts' meetings in order to promote traffic safety and they partially have been included into the uniform provisions of the ECE regulations adopted ultimately.

In Hungary for the enhancement of vehicles' road safety, the Engineers' Union holds annually an Experts' Meeting on Buses (every three years with international participation), while the International Conference on Road Transport and Traffic Safety is organized by the HUNGAROCAMION Ltd. These events -at the occasion of which, contributions from most well known international experts are presented- are supported also by the FISITA and the IRU.

The changing system of the passenger and commercial vehicle manufacturing industry and of the passenger and goods transport in Hungary, as well as the regulatory work attached to it, apply and satisfy the European traffic safety requirements. Great emphasis is being laid upon the systematic periodic inspection for meeting -for traffic safety reasons- the technical requirements and rules, and approving the manufacturing of the new vehicle types, as well as their admission to traffic, being carried out by the General Inspection of Transport established to this aim. Moreover, the traffic department of the Police insists upon the observance of the road safety rules by systematic control (speed measurements, Trafipax etc), random technical inspection tests (concerning lighting, tyres, brakes etc), accidents' investigation and analysis, and by imposing eventual penalties, too. Vehicles' safety characteristics can be improved by using the experiences obtained by the accidents' evaluations.

Ladies and Gentlemen, I hope that this report gave you a short -but by no means complete- overview of the safety status of road vehicles in Hungary.

List of ECE Regulations adopted by Hungary which are annexed to the Agreement concerning the adoption of uniform conditions of approval and reciprocal recognition of approval for motor vehicle equipment and parts concluded in Geneva in 1958

No of ECE Regulation 1.	Subject 2.	Year of application by Hungary 3.	Hungarian technical service 4.
1.	Headlamps with R_2 category filament lamps	1965	MEEI*
2.	Headlamps with incandescent electric lamps	1960	MEEI
3.	Retro-reflecting devices	1965	MEEI
4.	Illumination of rear registration plates	1965	MEEI
5.	Sealed-beam headlamps	1976	MEEI
6.	Direction indicators	1976	MEEI
7.	Position lamps and stop-lamps	1976	MEEI
8.	Headlamps (with $H_{1,2,3}$ lamps)	1976	MEEI
9.	Noise (3 wheeled vehicles)	1976	AUTÓKUT+ KTI
10.	Radio interference suppression (vehicles equipped with high-voltage ignition)	1976	TÜV-KTI
11.	Door latches+retention components (passenger cars)	1976	AUTÓKUT

* For the abbreviations used, please find the necessary information following this table.

1.	2.	3.	4.
13.	Braking (motor cycles excluded)	1976	AUTÓKUT+ TÜV-KTI
14.	Safety-belt anchorages on passenger cars	1976	AUTÓKUT+ TÜV-KTI
16.	Safety-belts	1988	AUTÓKUT
17.	Seats and their anchorages (passenger cars)	1993	AUTÓKUT
18.	Protection against unauthorized use (motor cycles excluded)	1976	AUTÓKUT+ TÜV-KTI
19.	Fog lamps (front)	1976	MEEI
20.	Headlamps (with H_4 lamps)	1976	MEEI
21.	Interior fitting (passenger cars)	1993	AUTÓKUT+ TÜV-KTI
22.	Protective helmet (motor cycles + mopeds)	1979	OMTKI
23.	Reversing lights	1976	MEEI
24.	Pollutants emitted by compression ignition engines	1976	AUTÓKUT+ KTI
25.	Headrests	1993	AUTÓKUT+ TÜV-KTI
26.	External projections (passenger cars)	1976	TÜV-KTI
27.	Advance-warning triangle	1976	MEEI+TÜV-KTI
28.	Audible warning devices	1976	AUTÓKUT+ KTI
29.	Protection of occupants of commercial vehicle cab	1988	AUTÓKUT
30.	Pneumatic tyres (passenger cars)	1984	TÜV-KTI
31.	Halogen sealed-beam unit (HSB) headlamps	1979	MEEI
35.	Arrangement of foot-controls (passenger cars)	1984	TÜV-KTI
36.	Construction of public service vehicles (over 16 occupants)	1979	AUTÓKUT+ TÜV-KTI
37.	Filament lamps	1979	MEEI
38.	Rear fog lamps	1979	MEEI
39.	Speedometer equipment	1979	AUTÓKUT+ TÜV-KTI
40.	Air pollution (motor cycle)	1982	KTI
41.	Noise emitted by motor cylces	1982	KTI
42.	Bumpers (passenger cars)	1993	AUTÓKUT+ TÜV-KTI
43.	Safety glazing and glazing materials	1984	AUTÓKUT
44.	Child restraint systems	1988	AUTÓKUT

1.	2.	3.	4.
45.	Headlamp cleaners	1993	AUTÓKUT
46.	Rear-view mirrors (motor cycle excluded)	1984	AUTÓKUT+ TÜV-KTI
47.	Emission of gaseous pollutants (mopeds)	1984	KTI
48.	Installation of lighting (passenger cars)	1984	TÜV-KTI
49.	Emission of pollutants by compression ignition engines	1984	AUTÓKUT+ KTI
50.	Lamps for motor cycles and mopeds	1988	MEEI
51.	Noise emission of motor vehicles having at least four wheels	1984	AUTÓKUT+ KTI
52.	Small capacity (9-16 occupants) public service vehicles	1993	AUTÓKUT+ TÜV-KTI
53.	Installation of lighting (motor cycles)	1984	TÜV-KTI
54.	Pneumatic tyres for commercial vehicles and their trailers	1984	TÜV-KTI
55.	Mechanical coupling components of combinations of vehicles	1988	AUTÓKUT
56.	Headlamps for mopeds	1988	MEEI
57.	Headlamps for motor cycles	1988	MEEI
58.	Rear underrun protective devices (RUDs)	1988	AUTÓKUT+ TÜV-KTI
59.	Replacement silencing systems	1988	AUTÓKUT+ KTI
63.	Noise emission of mopeds	1988	KTI
65.	Special warning lights	1988	MEEI
66.	Strength of superstructure of large passenger vehicles (capacity over 16 persons)	1987	AUTÓKUT
67.	Specific equipment of motor vehicles using liquefied petroleum gases in their propulsion system	1992	ÁEEF
68.	Measurement of maximum speed	1991	AUTÓKUT+ TÜV-KTI
73.	Lateral protection of goods vehicles, trailers and semi-trailers	1993	AUTÓKUT+ TÜV-KTI
74.	Installation of lighting (mopeds)	1991	TÜV-KTI+ KFF
76.	Headlamps for mopeds emitting a driving beam and a passing beam	1991	MEEI
77.	Parking lamps	1991	MEEI
78.	Braking of category L vehicles (motor cycles)	1991	TÜV-KTI+ KFF
79.	Steering equipment (motor cycles excluded)	1991	AUTÓKUT+ TÜV-KTI

1.	2.	3.	4.
80.	Seats of large passenger vehicles (capacity over 16 persons)	1991	AUTÓKUT+ TÜV-KTI
83.	Emission of pollutants (passenger cars)	1991	KTI+ KFF
84.	Measurement of fuel consumption	1993	AUTÓKUT+ KTI
85.	Method to measure the net power	1993	AUTÓKUT+ KTI

Abbreviations:

			ECE symbol used for designation
KFF	=	Közlekedési Főfelugyelet (General Inspection of Transport) H-1067 Budapest, Teréz krt. 96.	7/A
MEEI	=	Magyar Elektrotechnikai Ellenőrző Intézet (The Hungarian Electrotechnical Controlling Institute) H-1132 Budapest, Váci út 48/a.	7/B
AUTÓKUT	=	Autóipari Kutató és Fejlesztő Vállalat (Research Enterprise of the Automotive Industry) H-1115 Budapest, Csóka u. 7-13.	7/C
OMTKI	=	Országos Munkavédelmi Tudományos Kutató Intézet (Labour Safety Scientific Research Institute) H-1021 Budapest, Ötvös János u. 3-5.	7/D
KTI	=	Közlekedéstudományi Intézet Rt. (Institute for Transport Sciences Ltd.) H-1119 Budapest, Thán K. u. 3-5.	7/E
TÜV-KTI	=	TÜV Hannover - KTI Kft. (TÜV Hannover - KTI Technical Service and Controlling Co. Ltd.) H-1119 Budapest, Thán K. u. 3-5.	7/G
ÁEEF	=	Állami Energetikai és Energiabiztonsági Felügyelet (State Authority for Energy Management and Safety) H-1012 Budapest, Attila út 99.	7/F

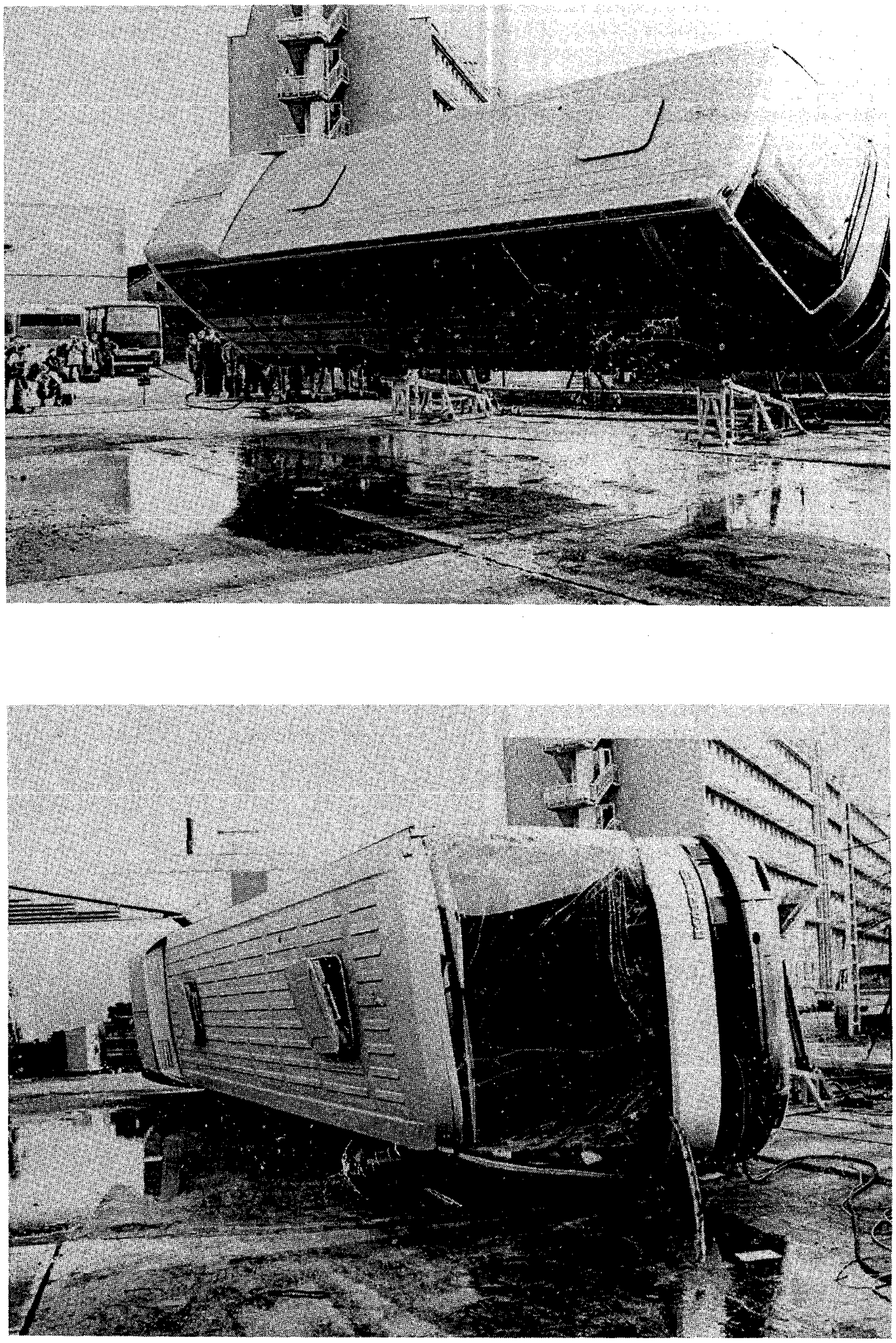


Figure 1. Bus Roll-over Test Pursuant to ECE Regulation No 66

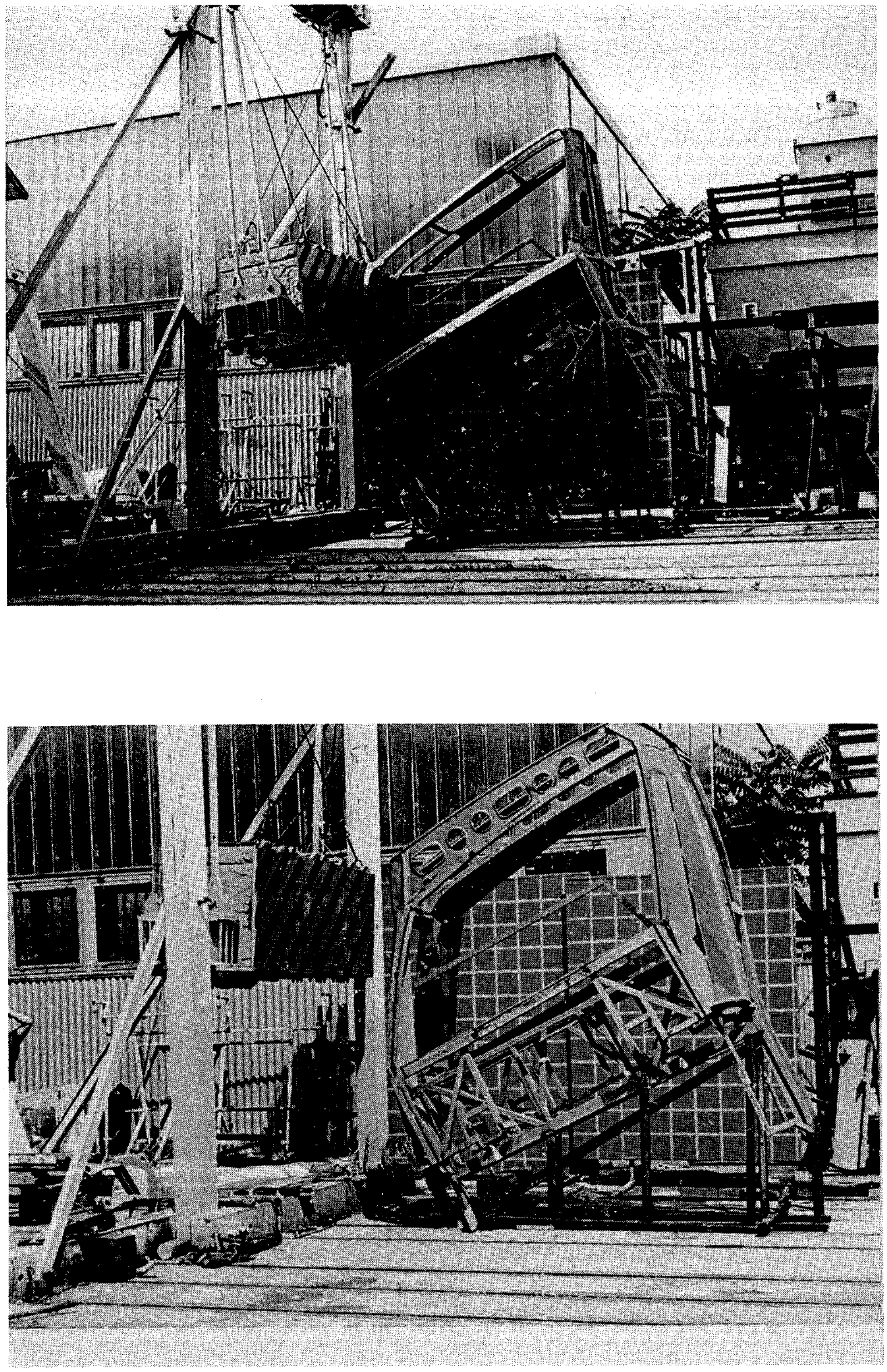


Figure 2. Pendulum Test Carried Out on the Superstructure Section as Described in ECE Regulation No 66

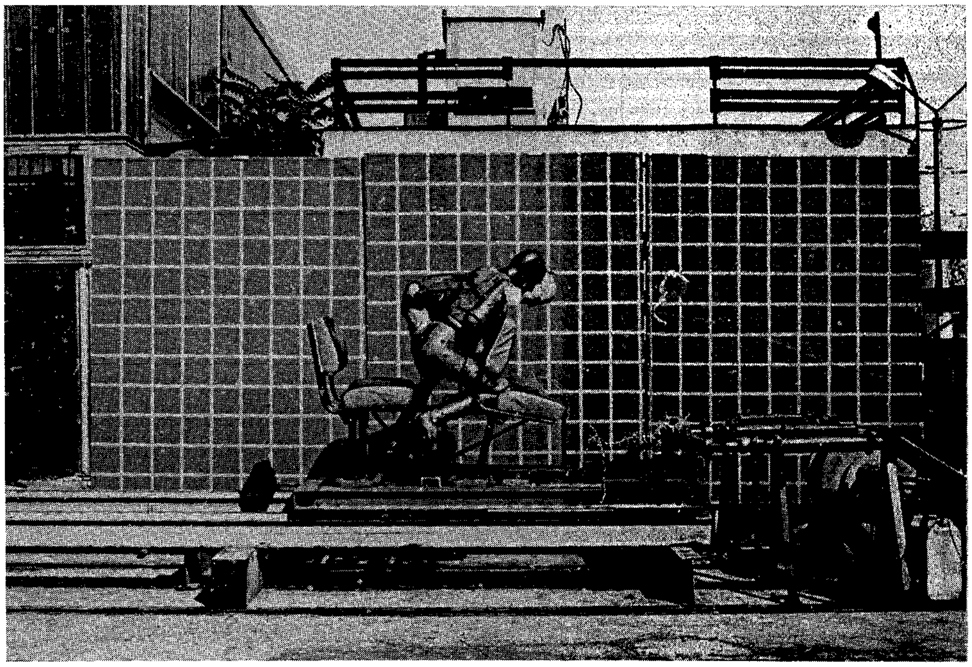


Figure 3. Bus Seat Strength Test Pursuant to ECE Regulation No 80

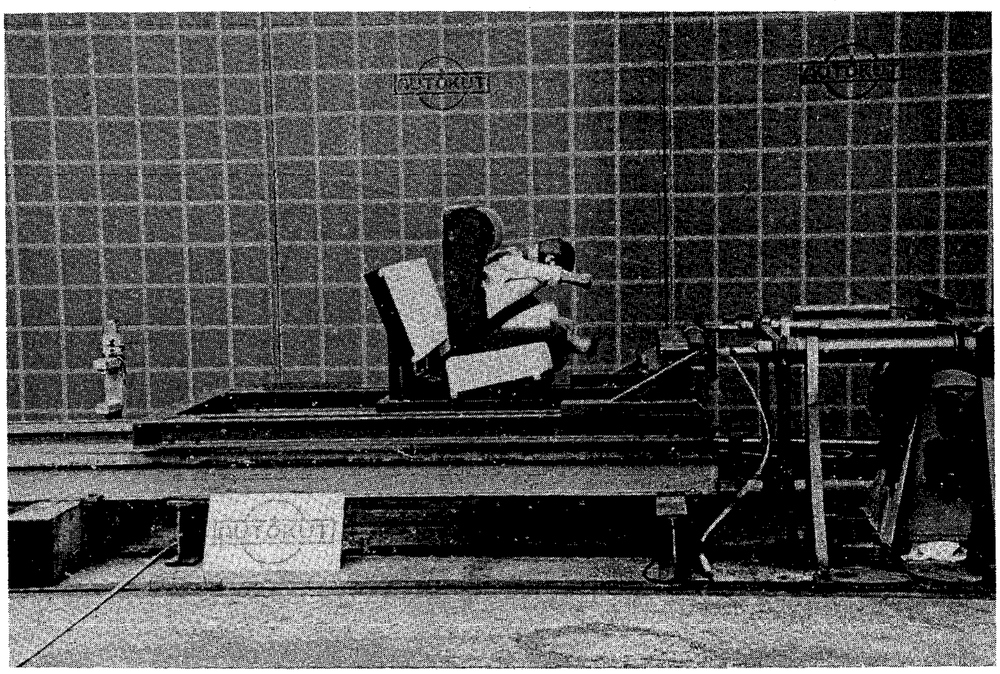


Figure 4. Child's Seat Test According to ECE Regulation No 44

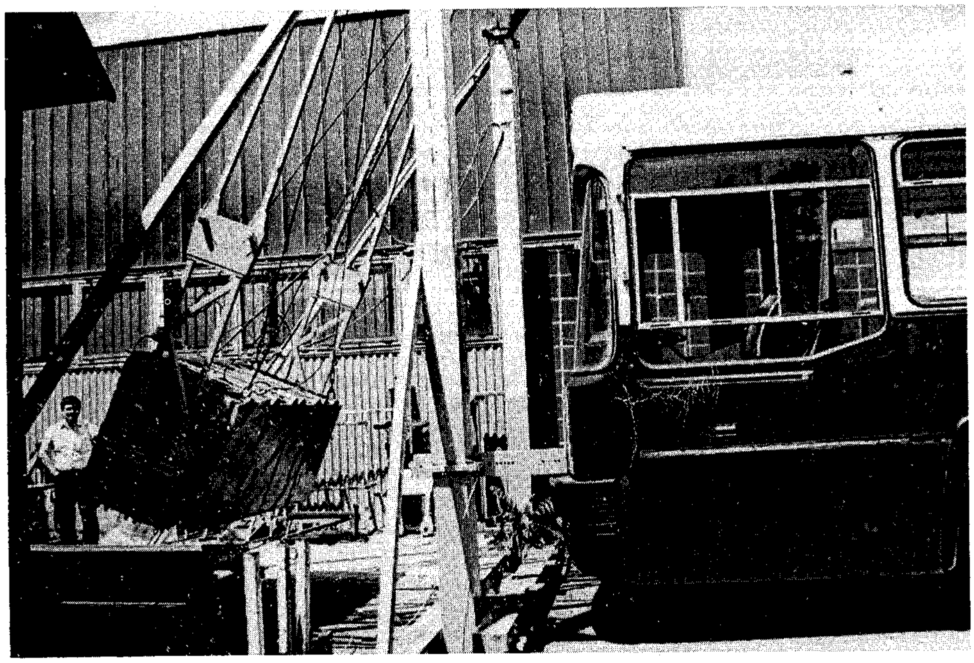


Figure 5. Frontal Impact Test Carried Out With Pendulum on a Bus

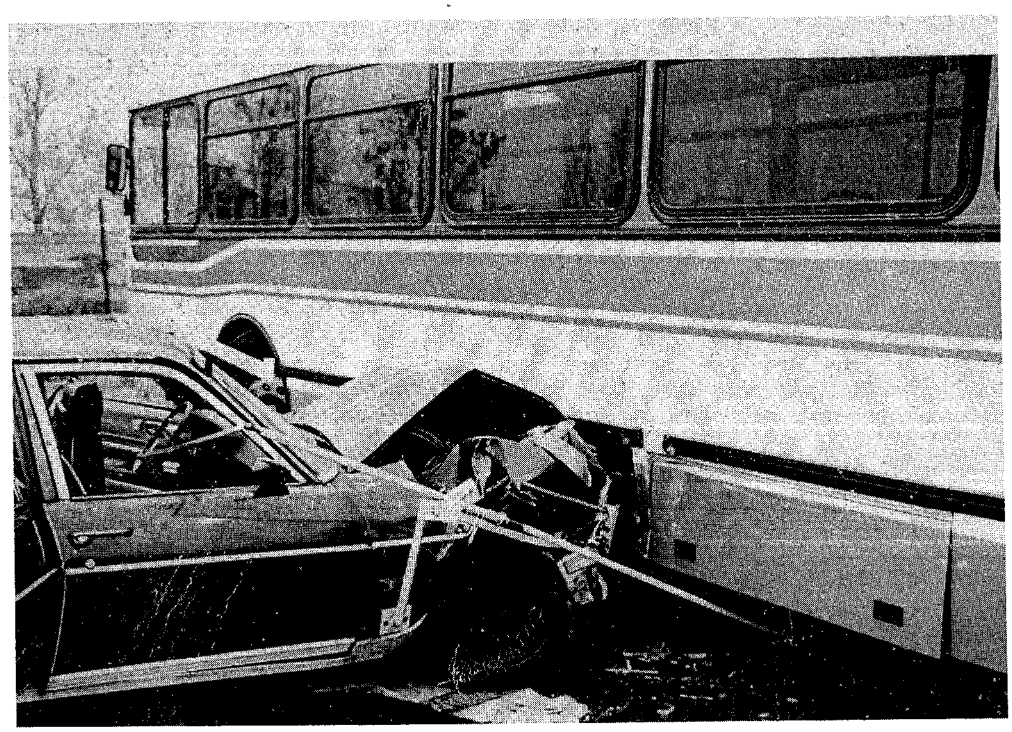


Figure 6. Side Collision Test of a Bus Impacted With Passenger Car According to USA Regulation (Advanced Design Transit Coach Specification)

United States

George L. Parker
National Highway Traffic Safety Administration

As we ready to enter a new millennium, a major challenge for the National Highway Traffic Safety Administration (NHTSA) is to promote, ensure, and enhance the United States Department of Transportation policy to "Promote safe and secure transportation." The NHTSA continues to initiate research, ideas, and initiatives to help ensure that the science of motor vehicle safety continues into the next century. This report will highlight the NHTSA's achievements since the last ESV conference in moving toward the future.

Accident Environment

The NHTSA National Center for Statistics and Analysis, which develops and uses large scale automated data bases to support problem identification, program planning, and program evaluation, reports that from 1990 to 1992 deaths on United States highways declined by 12 percent from 44,599 to 39,235. Police-reported motor vehicle-related injuries in 1992 were 3.07 million, a decline of 5 percent from 3.231 million in 1990.

Since 1971, the fatality rate has been dropping in the United States. The fatality rate per 100 million vehicle miles travelled was 4.5 in 1971; it was 1.8 in 1992. This is a 14 percent decline from the 1990 rate of 2.1. The fatality rate per 100,000 population dropped from 25.4 in 1971 to 15.38 in 1992, almost 14 percent less than the rate of 17.88 in 1990.

Passenger car fatalities remained at 54 percent of total fatalities in 1992, the same as for 1990, and constitute the largest proportion of United States fatalities. Light truck fatalities in 1992 were 20.6 percent of total fatalities, an increase from 19.3 percent in 1990. Motorcyclist fatalities in 1992 were 6.1 percent of total fatalities, a decline from 7.3 percent in 1990. Non-occupant fatalities in 1992 were 16.2 percent of total fatalities compared to 16.7 percent in 1990.

The total number of police-reported crashes in the United Statesin 1992 was estimated by the National Accident Sampling System's (NASS) General Estimate System (GES) to be 6 million, a decline of 7.3 percent from 6.471 million in 1990.

DATA COLLECTION AND ANALYSIS

The NHTSA National Center for Statistics and Analysis has made several important changes to NHTSA's data collection sources which will benefit not only NHTSA, but also the entire highway safety research community, nationally and internationally.

NHTSA's crash data system is composed of several components serving various needs. The Fatal Accident Reporting (FARS) is a census of all fatal crashes occurring on public roads in the United States The National Accident Sampling System (NASS) is a yearly collection of data from a statistically representative sample of crashes occurring in the United States This system is composed of a Crashworthiness Data System (CDS) and a General Estimates System (GES). These two primary crash data systems, FARS and NASS, are complemented by state crash data systems compiled from police accidents reports for a number of states.

Advances in FARS include the addition of 12 new data elements (such as Commercial Driver License Status, Multiple Drug Test Results, Pickup/Van Body Types, Cargo Body Type, Number of Axles, Crash Avoidance Maneuver) and the refinement of attributes for Police Pursuit, Fire, Underride/Override, and Improper Use of Restraints. The FARS Crash Avoidance Maneuver element provides valuable insight to the United States effort in the development of system specifications for the Intelligent Vehicle Highway Systems (IVHS) program. Other advances include linking FARS data to the United States Centers for Disease Control's Multiple Cause of Death file to merge fatal injury data with FARS data.

In 1992, additional rollover causation factors and on-scene data for vehicle roll dynamics were added to NASS CDS. Increased data collection on pre-crash maneuvers to support problem definition for IVHS specifications were added to NASS CDS and GES. In 1993, NASS CDS was converted to metric measurements; trauma classification categories were upgraded; and a pedestrian crash data survey was conducted. The NASS CDS sampling plan was modified recently to increase the number of crashes involving fires to support agency regulatory initiatives. In late 1994, a 3-year Pedestrian Crash Data Study will start in NASS CDS to update pedestrian injury patterns in impacts with late model year passenger vehicles.

NHTSA's State Data Program has as its primary objective the procurement of accident data files from select states and the processing of those files into databases usable by NHTSA. Each year, the accident data files from 17 states are obtained, documented, and converted into Statistical Analysis System (SAS) format. Other specialized databases, such as the CARDFile and Crashworthiness databases, also are created from the raw state data.

Because many of the state accident data files number in the hundreds of thousands of crashes, they are particularly well suited for examining the statistical relationships between vehicle design characteristics, crash involvement, and injury propensity. State data have been used in analyses supporting vehicle defect investigations, light duty vehicle rollover, inadvertent safety belt unlatching, car weight/safety relationship, IVHS, occupant restraint system effectiveness, anti-lock braking systems, and on-board refueling vapor recovery systems.

Through the State Data Program, NHTSA also encourages states to improve the usability of their data for highway safety analysis. One component of the State Data Program is the Critical Automated Data Reporting Elements for Highway Safety Analysis (CADRE) program. CADRE was initiated by NHTSA in 1990 to create national uniformity in a small number of variables that are essential to the use of police-reported accident data for highway traffic safety analyses. CADRE's nationwide implementation plans include activities to increase the safety community's awareness of CADRE, identify institutional and resource barriers to its implementation, and provide technical support to states needing help in adopting CADRE. Six states have added all CADRE elements to their 1994 automated crash files. Thirty-five other states have plans to incorporate some or all of the CADRE elements into their next accident report form revision.

Another component of the State Data Program has NHTSA working with states to encourage the linking of medical outcome databases with crash data. Linking crash data to long-term care and financial data will provide a source of information not available through any of NHTSA's other databases. NHTSA has named this program the Crash Outcome Data Evaluation System (CODES). Through grants to seven states, occupant-specific statewide police-reported crash data are being linked to injury data collected by emergency medical services, emergency departments, hospitals, and rehabilitation and long-term care centers to produce a database for the analysis of the benefits of safety belt and motorcycle helmet use. All seven states have successfully demonstrated the feasibility of linking state crash data to the medical outcome data, and some have also successfully linked to emergency department, trauma/head/spinal cord registries, census, driver licensing, vehicle registration, conviction, death certificate, national automobile insurance files, and/or health insurance files.

With the recent emphasis in the area of public health and cost containment, these databases will provide important information on the injuries and costs of various components of the traffic safety environment. However, while linked data have the potential to provide needed information to the traffic safety community, obstacles to linking in most states remain and experience in utilizing these data is limited.

CRASH AVOIDANCE RESEARCH

Crash avoidance research continues to provide the basis for reducing the number of crashes and/or their severity through changes to the vehicle to improve the vehicle's performance or the match between the driver and the vehicle.

Intelligent Vehicle Highway Systems

The NHTSA Intelligent Vehicle Highway System (IVHS) program made significant progress since the last ESV conference in implementing the agency's strategic plan to facilitate development and early deployment of cost-effective, user-friendly collision avoidance systems and to ensure no loss of safety as these systems are introduced into motor vehicles.

New research tools have been developed that are vital to understanding and documenting the safety benefits and potential liabilities associated with the design and deployment of IVHS products. One of the new tools is a portable driver performance data acquisition system (DASCAR) for acquiring driver-vehicle performance data in a natural setting. Another new tool is a data acquisition and analysis system which quantifies the vehicle motion environment (VME), i.e., normal vehicle motion in traffic relative to the other vehicles present on the roadway. Other activities include development of a protocol for evaluating the effects of the addition of high technology systems on driver safety performance, identification of requirements for an effective in-vehicle warning system design, an assessment of the potential health hazard from IVHS-induced electromagnetic radiation resulting from widespread usage of IVHS collision avoidance systems, and an assessment of the crash avoidance needs of older drivers. Preliminary human factors guidelines for crash warning devices have been developed. Evaluating and validating prototype VME and DASCAR systems will begin in the Fall.

A key element of this program is defining crash avoidance opportunities. This effort is helping to guide the development of crash avoidance technology by carefully analyzing the pre-crash circumstances associated with various crash modes. Countermeasures that address these hazards can then be specified in performance terms that match real needs. The first reports of a series have been published. They address rear-end, backing, and lane change crashes. Reports addressing single-vehicle road departure and intersection crashes will be published in the near future.

One of the most significant accomplishments since the last ESV conference was the awarding of four multi-year research projects worth $16.5 million to develop performance guidelines for collision avoidance systems. These projects will provide a major step forward in demonstrating that advanced technology can practicably enhance the crash avoidance performance of motor vehicles. The projects will address lane change; merging and backing; rear-end, intersection,and roadway departure collisions. Some other areas of research include projects which address vision enhancement systems; systems for detection of driver drowsiness, including work to design devices to directly monitor driver eye activity as a psychophysiological indicator of driver alertness; and systems to automatically notify emergency medical services dispatchers of the occurrence and location of a crash.

Electronics-based rear and side object detection systems for heavy trucks have been evaluated. The study examined detection capability and human factors issues and noted that, while this technology held promise, the current systems need refinement. The results were recently published in a report to Congress.

Public benefits come only through actual commercialization of safety-effective products. Thus, this program includes an emphasis on working with industry to facilitate the development and early deployment of collision avoidance systems. NHTSA has awarded five cooperative agreements with industrial partners in the areas of automatic braking for heavy vehicles, forward looking radar sensors, vehicle-based lane detection, forward crash avoidance systems, and human factors aspects of intelligent cruise control.

The final thrust of our program is assessment of the safety of IVHS systems which entail functions other than crash avoidance, but nevertheless influence the driving task. A fundamental goal of this work is to ensure that mobility- and productivity-enhancing systems do not degrade motor vehicle safety. This is a cooperative effort with the Federal Highway Administration (FHWA) and other partners. Systems which are currently being evaluated are Travtek, ADVANCE, and FAST-TRAC all of which are route-guidance and navigation systems and Travelaid which is an in-vehicle hazard warning/speed advisory system.

Human Factors

The human factors research program supports NHTSA's forward-looking efforts to foster the development of advanced technology "intelligent" collision avoidance systems, as well as the agency's on-going rulemaking development efforts.

Research continues to develop a protocol for evaluating the properties of mirror systems which affect driver performance. A part task simulator has been developed for evaluating drivers' ability to use mirrors. The simulator is being used to categorize the principal aspects of mirror design which affect driver decisions to change lanes.

The NHTSA Driver Performance Data Book has been updated to provide a compendium of recent human factors research information related to driver interaction with IVHS systems, as well as aspects of vehicle design which are most critical to older drivers' ability to operate their vehicles.

Because of concerns about the possible masking of front turn signals by higher intensity daytime running lights (DRL), research is underway to quantify the detectability of turn signals as a function of luminous intensity and distance to the DRL. The goal of this work is to develop minimum acceptability performance criteria relative to this aspect of vehicle design.

Work is underway to develop a simulator-based evaluation protocol to compare alternative rear signalling system concepts, such as fast-rise time center high mounted stop lamps, or possibly "smart" rear brake lights, in terms of following drivers' braking response.

Research is being initiated to study the extent to which various aspects of Head-Up-Displays (HUD) mask drivers' forward visual scene or distract them to the extent that it could negatively affect driver performance.

National Advanced Driving Simulator

Since the last ESV conference, NHTSA has continued its program to develop the National Advanced Driving Simulator (NADS). In January 1992, the Secretary of Transportation formally approved the project and selected the University of Iowa to be the host site for the NADS. NHTSA then implemented a two-phase strategy to develop the NADS. The first phase is a competition between two independent contractors for the NADS preliminary engineering design. At the conclusion of this first phase, NHTSA will evaluate each design then select a single contractor to proceed with the final design and actual construction of the simulator in phase two. In January 1994, NHTSA awarded contracts valued at $1.25 million each to contractor team for the Phase I design competition. The design phase will last approximately 1 year and the construction phase approximately 3 years.

Heavy Vehicles

The two year, in-service field evaluation of 50 anti-lock brake system (ABS)-equipped trailers was completed. The study found that, in general, the systems performed reliably and could successfully be installed on United States heavy trucks and trailers.

The first phase of an industry/government cooperative research program to develop standardized test methods for measuring and reporting truck tire performance properties is nearing completion. A catalogue of data characterizing the range of performance available from current tire designs, various sizes, and various states of wear will be developed in phase two.

A project to determine the feasibility of modifying heavy truck front-end designs to reduce the severity of collisions with smaller vehicles is in progress. NHTSA is in the process of defining appropriate baseline crash conditions that replicate damage patterns seen in cars involved in frontal collisions with heavy trucks.

A cooperative industry/government project to identify and develop component-level testing methodologies to evaluate the truck occupant crash protection capabilities of subsystems within truck cabs (e.g., restraints, steering wheels, windshields, door latches, interior cab surfaces, cab structure, etc.) is on-going. The project includes accident reconstruction to determine deceleration forces on the truck occupant and truck cab; the statistical relationship of the reconstructed accidents to the population of fatal truck crashes; development of a computer model to simulate the occupant trajectory in various crash modes; and development of component level tests to evaluate the occupant interaction with restraint systems, cab interior component crashworthiness, and cab structural integrity.

NHTSA, in cooperation with the FHWA's Office of Motor Carriers, is conducting an in-service fleet evaluation of the operational practicality and costs associated with equipping longer combination vehicles with anti-lock braking systems (ABS) and self-steering double drawbar converter dollies to improve the operational safety of these vehicles.

CRASHWORTHINESS RESEARCH

NHTSA's crashworthiness research program continues to focus on the frontal impact, side impact, and rollover crash modes for occupant protection in passenger cars, light trucks, and vans. The biomechanics research efforts provide the fundamental knowledge required for advances in vehicle crashworthiness. The end result will be the development of cost-effective motor vehicle safety technologies that save lives and prevent or reduce the severity of injuries.

Recently, a vehicle parameter database was created and contains vehicle specification information on 2,271 vehicles from model years 1979 to present. The crash and vehicle parameter data are analyzed to identify the number and types of injuries, the mechanisms causing the injuries, and the associated crash conditions and vehicle characteristics that contributed to the injuries.

Frontal Crash Protection

Even after full implementation of driver and passenger air bags as required by FMVSS 208, it has been estimated that frontal impacts account for up to 8,000 fatalities and 120,000 AIS $\geq$ 2 (i.e., moderate to critical) injuries annually.

A detailed definition of the remaining safety problems in frontal impacts has been initiated. Research is underway to investigate real world crash environments and to project occupant injuries that will occur for an all air bag fleet. This includes summarizing the human loading and injury tolerances relevant to frontal crashes.

This program focusses on the intrusion-type injuries and fatalities and the costly lower extremity injuries we are seeing in crashes involving air bag-equipped vehicles. We believe an offset frontal test best represents the real-world crashes that produce the intrusion-related injuries and fatalities and the severe lower extremity injuries. We have been working to develop an offset frontal test, and we have been considering what new injury modes, injury criteria, and test surrogates might be necessary for this type of test.

Since the last ESV Conference, 11 frontal offset crash tests using air bag equipped production cars have been conducted. The first test series involved eight moving car-to-car tests with a nominal 116 KPH (72 MPH) closing speed and 60 percent engagement of the subject vehicle by the striking or bullet vehicle. A 50th-percentile Hybrid III dummy was used as the test surrogate in the driver's seating position. In a second series, two frontal offset tests were conducted similarly to the first series except that there were engagements of 50 and 70 percent of one of the subject vehicles. The tests were conducted to evaluate the effects of overlap percentage. The evaluation of the effects of overlap percentage showed that 8 out of 9 vehicle types tested passed the FMVSS 208 criteria. All the vehicle types, however, indicated potential injury to lower extremities. An additional test was conducted in this series to evaluate the effect of an oblique impact on the subject vehicle. That evaluation found a test condition that causes a mid-size vehicle to fail the FMVSS 208 chest and femur criteria.

The findings from four high speed full frontal rigid barrier impact tests, which were also conducted, showed that the 95th-percentile Hybrid III dummy failed the FMVSS 208 head injury criteria, however, the 5th-percentile dummy passed the 208 criteria in all aspects.

Sled testing was also conducted using 5th- and 95th percentile dummies, to determine the effects of occupant size on frontal crash protection. These tests evaluated the presence or absence of the lap/shoulder belt in conjunction with the air bag in the frontal crash tests.

A preliminary summary of the results indicate that the air bag appears to be doing the job for which it was intended— protecting the head and thoracic regions of the occupant. There are concerns, however, about inducing undesirable levels of neck loads and moments when the lap/shoulder belt is <u>not</u> used in conjunction with the air bag. Also, lower extremities appear to be significantly effected by the absence of lap/shoulder belt use. Although these types of injuries are generally non-life threatening, they can often be physically disabling and result in long-term care and high medical costs.

Side Impact Research

Side impact accidents result in more than 8,000 fatalities and 800,000 injuries each year. 1994 marks the first year of required compliance to the dynamic FMVSS 214, which establishes minimum requirements for thoracic and pelvic protection for the near-side occupant in side impact crashes. Accident analysis and further testing in support of upgrading dynamic FMVSS 214 to light trucks and vans (LTVs) has been completed. Several crash test series involving pickup trucks, utility vehicles, and vans were conducted using an amended FMVSS 214 dynamic test procedure with a raised and heavier moving deformable barrier. Such a barrier is more representative of the striking vehicle in side impact accidents in which light trucks and vans are involved. Countermeasure tests using side door padding were conducted for small LTVs. The results demonstrate that the specified protection levels for thoracic protection are realizable for the smaller LTVs considered at risk. The mathematical model which was developed to simulate passenger car crashes has been extended to LTVs. This model is currently being upgraded to study three-dimensional kinematics of the occupant and vehicle.

With near term side thorax and pelvic impact research concluding, work is continuing in both the analytical and testing areas. Advanced structural modeling has been initiated with the development and exercise of finite element models of the side impact dummy and a full side impact vehicle. A narrow object testing program including passenger cars and LTVs, conducted jointly with the Federal Highway Administration, is underway.

Rollover Research

Nearly 9,000 fatalities and 100,000 injuries annually are attributable to rollover accidents. NHTSA is conducting a research program to improve rollover crash survival by preventing occupant ejection and by mitigating the severity of impacts that an occupant experiences during rollover. In the area of occupant impact mitigation, NHTSA is investigating improved interior padding, improved restraints, and improved roof support. Research in ejection prevention is centered on improving door latches and ejection resistant glazing.

Occupant ejection through side doors accounts for several thousand fatalities and many more serious injuries each year. Studies of accident cases suggest that lateral and longitudinal loads were placed on the latches during each crash. Test procedures are being developed to measure the combined load. Procedures have also been developed for evaluating door opening from latch mechanism misalignment and full door tests for latch strength and inertial loading in addition to the current FMVSS 206 procedure. A research program to develop a secondary latch as a countermeasure has been initiated.

The improved glazing research program is developing a certification test to reduce ejection through side glazing. Alternative glazings are being tested in experimental crash situations to assess their performance in ejection reduction and occupant safety. These crash data are being used in the certification test development. The capacity for hazing and scratching, and their public acceptance, is also being evaluated.

Analytical models are being developed to increase the understanding of the injury potential to occupants during rollovers. These models are being used to simulate crash tests and real-world crashes to better understand injury mechanisms. These models are being used to explore the feasibility of potential rollover countermeasures.

Biomechanics Research

NHTSA's Biomechanics Program has a four pronged approach for advancing the scientific understanding of the mechanistic process that produces crash injuries and for translating that understanding into physical testing capabilities to guide and evaluate injury prevention and mitigation efforts. The responsibilities of the four research areas are:

- Highway Traffic Injury Studies - To conduct medical and engineering examinations of crashes; injuries; and their treatment, costs, and consequences.
- Human Injury Simulation and Analysis - To develop and apply mathematical modeling techniques to predict the extent and severity of human injuries in differing crash circumstances.
- Impact Injury Research - To conduct laboratory tests of the human impact process and quantify the injurious effects of forces and motions upon the human body.
- Crash Test Dummy Component Development - To develop test equipment and dummy components capable of measuring crash forces and evaluate injury risk in automotive crashes.

Our Highway Traffic Injury Studies have led to significant improvements in the scientific understanding of injuries and their medical costs. A NHTSA-directed study of crash injuries to restrained occupants in frontal crashes conducted by an interdisciplinary team including trauma physicians, engineers, safety statisticians, and crash investigators has discovered a new injury pattern for drivers protected by air bags. Drivers protected by air bags and safety belts often do not have the injuries we used to see, e.g., bleeding, facial laceration, abrasions, etc. In some severe crashes, however, serious internal injuries may occur but not be externally apparent and without the visual cues, no check for internal injuries usually occurs. Internal injuries often are survivable if detected and treated in time, but can be fatal if not detected and treated promptly. Consequently, NHTSA formulated a new protocol for internal injury detection. Because a deformed steering wheel is one accurate indicator of injury, a NHTSA research publication, "Detection of Internal Injuries in Drivers Protected by Air Bags," distributed to all state EMS directors and the research community, advised that a quick "lift and look" under the air bag should be a part of the routine examination of the steering wheel. Any visible deformation of the steering wheel should be regarded as an indicator of potentially serious internal injury and appropriate action should be taken.

These Highway Traffic Injury Studies also have shown that a significant portion of severe frontal crashes have structural intrusion into the compartment. A high incidence of lower extremity injuries appears to be associated with this intrusion. These types of injuries are life threatening, represent a significant portion of the hospital costs, and are associated with long term disability and rehabilitation.

Mathematical simulation efforts have progressed in several anatomical regions. In the head, an analytical algorithm has been developed and implemented into the previously developed skull/brain model which can monitor the brain's response to an impact and determine the amount of brain material, and its location, that experiences excessive and injurious deformations.

Thoracic modeling efforts have increased the realism of the model by incorporating shoulder structures and developing and demonstrating the capability of this chest model to dynamically interact with either a model of a torso belt or an air bag.

An analytical representation of the human anatomical neck has been developed which includes each vertebra, all major ligaments, and vertebral and facet disks which, with the addition of a head, will provide considerable insight into the various injury modes active in the neck.

Considerable efforts have been devoted in the Impact Injury Research area to increasing our understanding of the complex loading and injury processes present in the chest when occupants are involved in frontal crashes with various available restraint combinations. Currently, after analyzing the results of more than 50 tests, several promising thoracic injury criteria have been developed which can provide an unbiased assessment of the level of thoracic injury regardless of which restraint combination is being used.

Additional efforts have been initiated to continue NHTSA's pioneering research efforts in side impact injuries. These efforts will use multiple chest bands to determine the chest's deformational characteristics under various side impact scenarios. The data will be used to develop enhanced specifications for future side impact dummies as well as improved criteria for the determination of injury risk.

To better understand the injury processes of skull fracture, neck injury, and injuries to lower extremities, experimental efforts which are intended to complement and support analytical efforts in these areas have also been initiated.

The Advanced Torso Device (ATD), a chest design presented at the last ESV conference, is now undergoing evaluation by a variety of automotive organizations worldwide.

Other hardware design efforts are active in the neck and lower extremity areas. The neck effort has developed a prototype neck system which can meet specifications derived from previous human cadaveric testing. Expanded instrumentation capability will provide not only the forces and moments applied to both ends of the neck, but also provide a characterization of its deformational mode at any instant of time. Additional developmental efforts have produced prototypes of an advanced lower extremity model, which offers dimensional, inertial, and range of motion characteristics that are similar to those of the human occupant.

RULEMAKING

Since the last ESV Conference in France, NHTSA has published 17 final rules, 21 notices of proposed rulemaking, and 3 notices. The most significant is the regulation issued September 1993 requiring vehicles sold in the United States to have air bags with manual lap/shoulder belts pursuant to the 1991 Intermodal Surface Transportation Efficiency Act. The phase-in time frame is as follows: At least 95 percent of each manufacturer's passenger cars manufactured on or after September 1, 1996, and before September 1, 1997, must be equipped with an air bag and manual lap/shoulder belt at the driver's and right front passenger's position. Every passenger car manufactured on or after September 1, 1997, must be so equipped. At least 80 percent of light trucks manufactured on or after September 1, 1997, must also be so equipped, with 100 percent after September 1, 1998.

A listing of all the regulatory actions taken and notices issued since December 1991 follows.

Crashworthiness

- On December 27, 1991, an advanced notice of proposed rulemaking (ANPRM) was published that proposed two alternative side impact dummies for FMVSS No. 214 in the future and requested comments on the desirability and need for specifying alternative dummies.

- On January 3, 1992, an SNPRM was published proposing requirements for underride prevention guards at the rear of heavy trailers and semitrailers.

- On January 15, 1992, a notice of proposed rulemaking (NPRM) was published proposing to amend FMVSS No. 214 to clarify the quasi-static door strength test procedure for certain types of vehicles with irregular door design configuration.

- On March 3, 1992, a notice was published making technical amendments to the rule concerning the specification of the moving deformable barrier.

- On May 21, 1992, a final rule was published amending FMVSS No. 214 to correct minor errors in previous final rules on dynamic side impact requirements for passenger cars. The final rule amends certain specifications and establishes an effective date for certain of the side impact phase-in reporting requirements.

- On May 29, 1992, the agency published an ANPRM concerning improving safety belt comfort and fit. This notice was in response to the 1991 Intermodal Surface Transportation Efficiency Act. The notice proposed three courses of action. One means would be a requirement that the shoulder portion of safety belts pass within specified zones on the chest and shoulder of four different size test dummies, ranging in size from a 6-year old child dummy to a 95th percentile adult dummy. Another means would be a less specific requirement that the shoulder portion of safety belts be either automatically adjusted or manually adjustable to fit different sized occupants.

- On June 5, 1992, an ANPRM was published to extend the dynamic side impact requirements of FMVSS No. 214 to light trucks, buses and multipurpose passenger vehicles.

- On June 5, 1992, a notice of intent was published announcing that NHTSA would publish, by January 31, 1993, a NPRM proposing to amend FMVSS No. 201 by requiring improved head protection from interior component impacts.

- On July 8, 1992, the agency amended Standard No. 205, "Glazing Materials," to permit a new item of glass-plastic glazing. The new item of glazing permitted Item 15B, Tempered glass plastic glazing, that may be used anywhere in a motor vehicle, excluding the windshield. This glazing can be used voluntarily anywhere except the windshield. The change was effective August 7, 1992.

- On July 13, 1992, a final rule was published amending FMVSS No. 214 in two respects. The final rule establishes a 90 percent and 100 percent phase-in plan for newly-extended quasi-static door strength test requirements and delays the effective date for certain doors.

- On July 24, 1994, a final rule on FMVSS No. 210, "Seat Belt Assembly Anchorages," was published. This notice delayed the effective date of various changes to this regulation. The major changes included in this notice were the addition of attachment hardware into the strength test, increasing the minimum lap belt angle to 30 degrees, simultaneous testing of adjacent anchorages, and modification of the test procedure to avoid test setup problems. These changes became effective September 1, 1993.

- On August 25, 1992, a NPRM was published proposing to delay for one year the effective date of a final rule amending FMVSS No. 216 to extend its requirements to light trucks with a GVWR of 6,000 pounds or less.

- On September 10, 1992, a final rule was published requiring child seat manufacturers to provide a postage paid registration form and to keep records of the registrations received. The purpose of this rulemaking was to facilitate communication with consumers in case of a child safety seat recall or other safety notification.

- On September 10, 1992, a final rule was published to require add-on child restraints to meet the requirements of FMVSS No. 213, "Child Restraint Systems," at each of the angles to which a seat back can be adjusted and at each of the restraint belt routing positions.

- On November 23, 1992, a request for comments notice was published in the Federal Register (57 FR 54958, Docket No. 89-20, Notice 3). This notice sought comments on recent NHTSA analyses and a proposed research plan concerning seat back performance in rear impacts.

- On December 10, 1992, a NPRM was published in the Federal Register (57 FR 58444) proposing to change the injury criteria in non-contact crashes from a head injury criterion to a neck injury criterion. By substituting a neck injury criterion for HIC in non-contact crashes, compliance tests should more accurately assess a vehicle's ability to protect against injury to the cervical spine.

- On December 14, 1992, a request for comments notice was published in the Federal Register (57 FR 59041, Docket No. 92-66, Notice 1). This notice sought comments concerning vehicle fires in passenger cars, light trucks, and vans. NHTSA was considering rulemaking to upgrade the protection provided by the current FMVSS No. 301.

- On January 15, 1993, a final rule addressing wheelchair securement on school buses was published.

- On January 22, 1993, a final rule was published delaying for one year the effective date of a final rule amending FMVSS No. 216 to extend its requirements to light trucks with a GVWR of 6,000 pounds or less.

- On February 8, 1993, a NPRM was published proposing to amend FMVSS No. 201 by requiring improved head protection from impacts to interior components for passenger cars, light trucks, buses, and multipurpose passenger vehicles.

- On March 2, 1993 (58 FR 11975), a final rule was published to provide manufacturers of certain trucks and multi-purpose passenger vehicles designed to be driven by persons with disabilities an alternative to complying with the existing occupant restraint requirements. These manufacturers will be permitted to install manual safety belts that have not been dynamically tested at the front outboard seating positions instead of complying with the existing requirements for installing dynamically tested manual safety belts. This final rule also permits substitution of manual safety belts in satisfaction of the requirements issued, but not yet effective, for the installation of dynamically tested automatic restraints in those positions.

- On March 8, 1993, a supplementary notice of proposed rulemaking (SNPRM) was published in the Federal Register (58 FR 12921, Docket No. 96-16, Notice 2) to establish more appropriate test procedures for pedestal seats. A previous notice of proposed rulemaking was issued in 1990. The main difference between this supplementary notice and the 1990 proposal concerns the definitions of a pedestal seat.

- On March 16, 1993, a final rule was published amending FMVSS No. 214 to provide test procedures for conducting quasi-static tests of certain doors on light trucks, buses and multi-purpose passenger vehicles.

- On April 16, 1993, a final rule was published to extend FMVSS NO. 213's coverage for built-in child restraints to vehicles other than passenger cars.

- On May 4, 1993, a final rule for FMVSS No. 203, "Impact Protection for the Driver From the Steering Control System" was published. This amendment updated the SAE Recommended Practice J944, the Blak Tuffy test, to the June 1980 versions.

- On May 10, 1993 (58 FR 27517), a NPRM was published in the Federal Register to allow manufacturers of replacement seat belt assemblies a choice of two means of providing information regarding the seating positions and vehicle models for which the assemblies are appropriate. These choices consist of an installation instruction sheet or a label on the belt.

- On September 2, 1993 (58 FR 46551), a final rule was published requiring that future vehicles sold in the United States have air bags with manual lap/shoulder belts pursuant to the 1991 Intermodal Surface Transportation Efficiency Act. In addition, labels are required to provide certain precautions about air bags, and additional information about air bags must be included in the vehicle owner's manual. The effective date for the owner's manual information was March 1, 1994; for the label requirement, September 1, 1994. The number of vehicles complying with this final rule was phased in as follows: At least 95 percent of each manufacturer's passenger cars manufactured on or after September 1, 1996, and before September 1, 1997, must be equipped with an air bag and manual lap/shoulder belt at the driver's and right front passenger's position. Every passenger car manufactured on or after September 1, 1997, must be so equipped.

At least 80 percent of each manufacturer's light trucks manufactured on or after September 1, 1997, and before September 1, 1998, must also be so equipped, with 100 percent thereafter.

- On September 3, 1993, a NPRM was published addressing child booster seats. It specifically proposed amending FMVSS No. 213 to permit the manufacture and sale of belt-positioning seats by removing the impediments in the standard to the production of those seats. This is a Congressionally mandated rulemaking.

- On September 15, 1993, a notice of termination of rulemaking was published regarding the use of alternative test dummies for FMVSS No. 214.

- On October 13, 1993 (58 FR 52922), a final rule was published requiring that the lap belt or lap belt portion of a lap/shoulder belt be able to tightly secure a child safety seat, without the necessity of the user's attaching any device to the seat belt webbing retractor or any other part of the vehicle. This requirement was termed "lockability" and was introduced to ensure that safety belts are both comfortable for adult occupants and capable of securing child safety seats. The rule is effective September 1, 1995.

- On October 20, 1993, a notice was published to re-open the comment period for the February 8, 1993, NPRM on the improved head protection and to announce a public meeting to facilitate the comment process.

- On November 8, 1993, a final rule was published in the Federal Register (58 FR 59189) requiring the use of the Hybrid III test dummy for all compliance testing under FMVSS No. 208. The Hybrid III test dummy was selected because it appears to be more representative of human responses in a frontal crash and because the Hybrid III allows the assessment of more types of potential injuries. The rule is effective on September 1, 1997.

- On December 1993, a report on vehicle safety issues associated with EPA's On Board Refueling Vapor Recovery requirements was submitted to the docket.

- On February 16, 1994, a final rule was published requiring rear facing child restraints to have a warning label warning against using these restraints in a vehicle seat equipped with an air bag.

- On March 16, 1994, a NPRM was published proposing to add a greater array of test dummies to FMVSS No. 213 for use in compliance tests.

- On April 5, 1994, a final rule was published amending FMVSS No. 213, Child Restraint Systems, to change the adjustment position requirements to permit production of restraints specially designed for infants with apnea or other breathing problems.

Crash Avoidance

- On December 2, 1992, a final rule was published amending FMVSS No. 111, Rear View Mirrors, to require an increased view of pedestrians around the bus by a school bus driver.

- On February 23, 1993, a NPRM was published proposing to reinstate stopping distance requirements in FMVSS No. 121, "Air Brake Systems." The proposed amendments would require vehicles to stop in a specified distance from 60 mph when tested on a surface with a peak friction coefficient (PFC) of 0.9; loaded truck tractors would be tested with an unbraked control trailer.

- On February 23, 1993, a NPRM was published proposing to extend stopping distance requirements in FMVSS No. 105, "Hydraulic Brake Systems," to medium and heavy vehicles with a gross vehicle weight rating (GVWR) greater than 10,000 pounds. The proposed amendments would require vehicles to stop in a specified distance from 60 mph when tested on a surface with a PFC of 0.9. These notices are part of a comprehensive effort by the agency to improve the braking performance of heavy vehicles.

- On September 28, 1993, a NPRM was published proposing to amend FMVSS No. 105, "Hydraulic Brake Systems," and FMVSS No. 121, "Air Brake Systems," to require medium and heavy vehicles to be equipped with an anti-lock brake system (ABS) to improve the lateral stability and control of these vehicles during braking. The ABS requirement would be supplemented by a 30 mph braking-in-a-curve test on a low coefficient of friction surface with a PFC of 0.5, using a full brake application. These proposals are intended to increase heavy vehicle stability and control during braking. The notice also proposes to require an in-cab ABS malfunction lamp and an external lamp (for an eight-year period) on trailers to warn drivers of an ABS malfunction on trailers.

- On January 4, 1994, an ANPRM was published to obtain responses to questions regarding the braking performance of passenger cars and other light vehicles, and the need to require anti-lock brake systems (ABS) on these vehicles. This notice is a response to the Intermodal Surface Transportation Efficiency Act of 1991, directing initiation of rulemaking to consider the need for any additional brake performance standards for passenger cars, including anti-lock brake standards.

SUMMARY

Lifesaving progress has been made because of safety improvements. It is estimated that almost 35,000 lives were saved by the use of safety belts from 1983 through 1992. Since 1982, more than 2,000 children's lives have been saved by using child restraints. We also estimate that the minimum drinking age law of 21 years old has saved more than 13,000 lives since 1975. Air bags are beginning to show substantial benefits as the number of air bag-equipped vehicles in the fleet continues to rise. Between 1988 and 1992, an estimated 132,000 air bags were deployed in crashes; an estimated 558 lives were saved; and 40,000 moderate-to-critical injuries were prevented.

Germany

Karl-Friedrich Ditsch
Bundesministerium für Verkehr

We are very pleased that the ESV Conference is once again held in the Federal Republic of Germany. As you know, we organized the 2nd ESV Conference in Sindelfingen in 1971 and the 8th ESV Conference in Wolfsburg in 1980, and I am honoured to present my government's status report for the 14th Conference this year.

UNITED GERMANY

Since the unification of Germany on 03 October 1990, it has been the aim of the government's policies to advance social and economic unity and narrow the gap between the living conditions.

An essential prerequisite for economic takeoff is an efficient and environmentally compatible traffic infrastructure.

The 1992 Federal Traffic Infrastructure Plan was adopted by the German Parliament in the middle of 1993. It serves as the basis for the development of the traffic infrastructure in Germany during the next 20 years. With an investment volume of more than DM 450 billion up to the year 2012, it sets high targets for the development of the traffic infrastructure. It will, however, not be possible to finance this development by the federal budget alone. Therefore, some projects are to be financed by the private sector.

At the end of November 1993, the 4th Law amending the Law on the Development of Federal Trunk Roads (requirement plan "road") as well as the Law on the Development of the Railway Infrastructure entered into force. Thus, projects of first priority for the development of the railway infrastructure were for the first time established by law, as has been usual practice in the road sector for a long time already.

The Law on the Simplification of Planning of 23 December 1993, provides the preconditions for making the planning procedure for traffic infrastructures more speedy, more efficient and cheaper in the whole of Germany.

The German railways were fundamentally restructured with the aim to stronger participate in the traffic growth than has been the case up to now and to reduce the burden on the public budgets.

The Law on the Abolition of Tariffs of August 1993 has abolished all state-regulated tariffs in domestic road haulage and inland waterway transport and, within the course of the railway reform, also the tariffs in domestic goods transport by rail as from 1 January 1994. Thus, an important step towards the adaptation of the domestic market regime to border-crossing transport has been made where the tariffs have been set independently for some years already. With the deregulation of prices in road haulage an important contribution to open competition between domestic and foreign transport operators is made. The liberalization of cabotage as is envisaged within the framework of the European Union will thus come to full effect.

The structural condition of trunk roads was poor at the time of opening up the inner-German border. About 45% of all roadways were considerably or badly damaged and autobahns lacked shoulders, median and noise barriers. Emergency telephones (which used to be installed on the central reserve) existed only on one third of the autobahns, whereas autobahn segments of a total length of 430 km lacked them entirely. With few exceptions, service facilities, rest areas and maintenance units along autobahns were in a desperate state. Nearly 70% of all bridges and other engineering structures were older than 50 years.

Capital spending policies on the transport sector had to be adjusted to meet the new requirements and changed conditions. During the time period between the monetary union and the end of 1992, an estimated DM 5.5 billion were spent on highway improvements in Germany's new federal states.

The autobahn and highway improvement measures concentrated mainly on the following primary areas of activities:

- removal of the most serious accident black spots and accident causes
- removal of major bottlenecks or rendering them harmless by "closing-the-gap measures," and
- preparation and speedy beginning of the repair and improvement of bridges on autobahns and highways.

Of the many measures thus undertaken till the end of 1992, the following should be pointed out in particular:

- 59 "closing-the-gap measures"
- renewal of some 5,600 km of roadways among them: the construction of twelve by-pass roads
- 110 km of new highway structures and highway improvements
- rehabilitation and construction of a total of 770 bridges among them: 20 large bridge structures
- safety equipment of highways, further required improvements or repair measures.

In addition to the improvement of autobahns and highways, the government has also promoted investments to improve local and municipal road construction.

In order to improve road safety, traffic engineering measures were undertaken at the beginning. Central reserves of the entire autobahn network in Germany's new federal states were equipped with median barriers.

Traffic lights were installed at accident black spots, junctions improved and signposting and roadway markings within the entire highway network renewed or improved, where necessary.

Up to the end of 1992, the emergency telephones existing on the central reserves were moved to the roadside on roughly 600 km of autobahns. Most of the other autobahn segments where emergency telephones had been lacking have meanwhile been equipped with new emergency telephones.

To sum up it can be said:

- that, on average, 70% of the rehabilitation and improvement measures which could be planned in the short term have already been completed or
- that their opening to traffic is impendent.

Administrative and technical planning procedures have been started for all long term projects (new construction measures, widening of roadways), in particular for the 'German Unity' transport projects. The implementation of these projects takes priority in the requirement plan for the development of autobahns and federal highways up to the year 2010, which will be passed this year. The total financing requirements for these projects amount to DM 23.5 billion of which an estimated DM 19 billion shall be invested by the year 2000 (5th Five-year plan).

From the present point of view, it is expected that the most important routes will have been improved in capacity and level of service by the turn of the century, linking all the economic centres deemed important as well as developing the tourist areas of interest.

After decades of travel restrictions and the restrictions imposed on the purchase of cars, the degree of motorization in Germany's new federal states is increasingly approaching that of the old federal states.

Along with the increase in the degree of motorization the accident development in Germany's new federal states, including Berlin (East), also showed an upward trend in 1991. In 1992, a decrease in the number of road fatalities was observed for the first time. The number of injured accident victims, however, rose again by about 8%. Despite the downward trend observed, the risk of being involved in a fatal accident, estimated at 210 traffic deaths per one million inhabitants, is nearly twice as high as in Germany's old federal states.

Already since 1989, the budgetary means traditionally allocated to traffic education measures and road safety campaigns have been increased for the new federal states by drawing on special funds (1991: DM 34 million; 1992: DM 36.1 million; 1993: DM 35.3 million).

Since 1991, the money was used by the Federal Ministry of Transport for the re-organization of road safety work in Germany's new federal states and for the launching of target group oriented road safety campaigns (e.g. "It pays to be courteous") in cooperation with the German Road Safety Council (DVR). These measures have contributed to bringing about a reverse in trends as regards serious accidents in the new federal states.

Work done on the deplorable accident development in Germany's new federal states, the traffic infrastructure deficits and the lack of empirical research also tied up funds of the 1991-92 Road Safety Research Programme of the Federal Highway Research Institute (BASt), namely about 50% of the research funds allocated and 20% of the safety research staff who were assigned to projects in the new federal states.

As regards the emergency medical services (EMS), the re-organization is more or less completed. The new federal states have enacted their own state rescue services laws.

A tight network of helicopter stations run by the civil defence, the Armed Forces, the air rescue services of the German Automobile Club (ADAC), the German and International Air Rescue Services has been established in order to back up the local EMS systems.

LEGISLATION GOVERNING ROAD TRAFFIC

On 01 April 1993, a provision was incorporated into the German Road Traffic Regulations specifying that children up to the age of 12 years or up to a height of 1.50 m may not be transported on passenger car seats fitted with seat belts unless secured by suitable and officially approved child restraint systems, tested according to ECE R 44.

By an amendment of 01 October 1993 to the German Road Traffic Regulations, driving school education for bus drivers was made mandatory. This had been caused by major bus accidents in 1992 and 1993.

On 01 April 1993 the regulations pertaining to the transposition of foreign driving licences into German driving licences were changed. A modification of the catalogue of fines for traffic offences raised, among other things, the fines for two contraventions of the German Road Traffic Regulations resulting in an accident. Driving licence suspension now threatens passenger car drivers exceeding speed limits inside built-up areas by 31 km/h and by 41 km/h outside built-up areas. In addition, the fines for the so-called stop light offences are now weighted as a function of the stop light time, having been severely increased for stop light times exceeding one second.

In the fields of the design and equipment standards for road vehicles, the incorporation of international standards into national law and the use of the remaining scope for a more detailed definition of national standards have contributed substantially to improving technical safety. This applies, for instance, to the following issues:

- The harmonization of automotive engineering standards for passenger cars in EC member countries, which has been largely completed. The regulations in force are now being revised step by step for the adoption of the harmonized EC directives.
- The harmonization of the standards of EC member countries pertaining to commercial vehicles, farm and forestry equipment as well as two-wheel and three-wheel vehicles is being vigorously pursued.
- In recent years, the number of stolen--and not recovered--passenger cars has dramatically gone up. The European Community has already responded, submitting a draft directive in April 1993 for safety features preventing the unauthorized use of motor vehicle.
- The adoption of 93 regulations by the U.N. Economic Commission for Europe (ECE) which comprise harmonized standards for motor vehicles and their trailers. About 70 of these regulations can be applied in Germany.
- The regular technical inspection of motor vehicles in EC countries. Specific inspection intervals are already being imposed by the EC directive 77/143/EEC on busses, taxis, ambulances, passenger cars, and commercial vehicles. The incorporation of motorcycles and caravans into an EC-wide technical inspection system has already been proposed by Germany.

At EC discussions, the German government has been urging a more precise definition of the scope of technical inspections, and the adoption of clear testing criteria and one of the tests comparable to the German special brake-system check for heavy goods vehicles.

The Council adopted Directive 92/6/EEC of 10 February 1992 on the installation and use of speed limitation devices for certain categories of motor vehicles in the Community and the Council Directive 92/24/EEC of 31 March 1992 on speed limitation devices for certain categories of motor vehicles. In accordance with these directives, busses with a gross vehicle weight exceeding 10 t and trucks and semi-trailer tractors with a gross vehicle weight exceeding 12 t in each case have to be equipped with a speed limitation device. The setting of the speed limitation device in each case has to ensure that busses no longer go faster than 100 km/h, the speed limit for trucks and semi-trailer tractors being set at 85 km/h. This has been introduced in particular to improve road safety, environmental protection, and the saving of resources. By an amendment to the German Vehicle Code, these EC Directives have been incorporated into German law.

ACCIDENT STATISTICS

Accident trends in the area of the Federal Republic before 03 October 1990 and that of the five new federal states have not developed in a uniform manner. For that reason they are examined separately in the following.

In the Federal Republic as it existed prior to that date, the number of road accidents over the period 1990 to 1993 dropped by about 9% to an estimated 1.83 million. This must be seen against an increase in vehicle travel of 6%.

The number of road fatalities has fallen by nearly two thirds since 1970 while the number of vehicles on the road has increased from 17 to 38 million over the same period and vehicle travel by 107%.

The number of fatalities attributable to road accidents in the Federal Republic (excluding the new federal states and Berlin (East)) came to approx. 7,900 in 1990, roughly 7,500 in 1991, and approx. 7,300 in 1992. The total of approx. 6,900 fatalities in 1993 represents the lowest figure since 1953.

Accident trends in the five new federal states need to be examined separately after German unification in October 1990. Some 3,140 road fatalities were registered on this territory in 1990, around 3,760 fatalities in 1991 and some 3,300 in 1992. The figure for 1993 dropped to approx. 3,020. Compared with the year before (roughly 2,200 passenger car occupant fatalities), the number of car occupants killed has decreased.

ACCIDENT RESEARCH

As was mentioned at the last ESV Conference, the activities of the federal government, the automobile industry and the motor insurance companies once again have been prominent in the field of accident research. As regards governmental accident research, which is funded by the Federal Ministry of Research and Technology and the Federal Ministry of Transport, the following can be reported:

The Federal Ministry of Research and Technology (BMFT) continues to lend support to research and development projects contributing to active and passive safety improvements in road traffic. The transport of hazardous goods is currently still receiving a considerable amount of state support.

In the last status report of November 1991, the THESEUS project, i.e., "Tanker truck with maximum safety attained through experimental accident simulation," was presented to follow up the TOPAS project. The new project, which is jointly carried out by several research institutes, motor vehicle and body manufacturers, has the objective of studying the overall 'tanker truck' system, including its active and passive safety features and equipment as well as the accidents involving tanker trucks. BMFT subsidizes the THESEUS project with a total of DM 10 million. The experimental part of the THESEUS project is nearly complete (crash tests and tests on vehicle dynamics). Information about the truck and tanker improvements possible in future can be expected as soon as all trials have been evaluated. Based on the analyzed typical courses of accidents, calculation models to simulate tanker and material failure and for the simulation of the dynamics of these vehicles have been developed. However, their agreement with real-life conditions still needs to be thoroughly checked in the impendent final phase of the project.

The development of the TOPAS safety tanker truck, which has been successfully promoted by BMFT, has led to truck features which are essential in safety terms, such as, e.g., the lowering of the centre of gravity, the widening of the track width and double tank bottoms, which have been incorporated into today's production tanker trucks. The safety level of modern vehicles carrying hazardous goods in the Federal Republic of Germany has thus been decisively improved. It goes without saying that this involves competitive drawbacks for German haulers since the safety regulations imposed on the other European haulers are less stringent.

The EUREKA project PROMETHEUS, which has been subsidized by BMFT with more than DM 100 million since 1986, will also lead to considerable road safety benefits in future. The deficits existing as regards up-to-date and complete information on traffic conditions, information for traffic management and road users will be reduced by the data collection and communication systems and the guidance and information techniques (telematics systems) currently being developed and tested. After the introduction of these systems, the early detection of critical situations will help drivers effectively in coping with risky situations.

A wide spectrum of safety-relevant systems from previous PROMETHEUS projects have already been tested with promising results in a large number of demonstration vehicles. Some autonomous vehicle systems should be mentioned in particular, such as, for instance,

- speed limiting and ranging systems and
- systems monitoring and displaying tire-road interaction.

In addition there are the infrastructure supported systems

- supplying, for instance, advance information to drivers, i.e., the communication of safety-relevant information about pavement conditions or traffic congestion ahead which will contribute to raising the level of safety.

Without anticipating the result of the decision making process about the introduction of such systems, this much can already be considered as certain:

- Among other things, clear improvements of road safety can be expected from telematics.
- The technical feasibility has been confirmed for most of the systems.
- A part of the systems will be available for series production in the short or medium term.

With the planned introduction of electric vehicles in the United States, especially in California from 1998, the safety of these new motor vehicles will be a relevant issue for car makers worldwide. The mass concentration of the energy accumulators in the vehicles and the possible effects of substance release in road accidents will require new studies, crash tests, and internationally agreed regulations.

Within the framework of the demonstration project "Testing the most recent generation of electric vehicles on the Isle of Rügen," promoted by BMFT, the German car industry has already undertaken such safety studies as a preliminary measure. After developing the adjustments required, the first crash tests using conversion design electric vehicles have brought similarly good results as have been obtained with comparable gasoline or diesel engine production cars, despite their different geometries and mass distributions. Since the evaluation of the studies still has to be completed, results cannot be presented as yet.

The Federal Ministry of Transport has continued its extensive research work. The results have been presented at EC and ECE discussions. The Federal Highway Research Institute (BASt) is playing a major part in the research work. At-the-scene accident investigations have been continued. The data obtained have been used in a series of special evaluations (e.g. the effectiveness of the airbag).

The investigation into optimal markings for trucks by means of retroreflective foils revealed that line or contour markings are a suitable means of improving the perception and visibility of these vehicles and of clearly reducing the accident figures. In addition, a study is currently underway to establish the boundary conditions for the permissibility of retroreflective advertisements within contour markings in order to stop the proliferation of coloured ads.

A literature study on head up displays revealed that this type of displaying information important for drivers has been technically considerably improved and allows older drivers to better perceive the information they need.

The electric discharge lamp is a possible successor of the halogen lamp and leads to a much better illumination of the areas covered by the upper and lower beams. Therefore a study was conducted which resulted, among other things, in indications as to the protection against the high tension parts as well as pointing out how dazzle might be reduced or even prevented. Initial experiences from test subjects have been positive.

A purely theoretical study was conducted on the road safety relevance of the so-called driving aids (ALS, four-wheel steering, anti-slip control, etc.). The results have shown that ALS and the anti-slip control offer the largest accident prevention potential of the driving aids studied. However, this also requires that normal drivers know how to handle them correctly which is not yet quite the case. Within the framework of another research project a test method is being developed to allow an objective assessment of the traction-slip control systems of passenger cars to be made. A correlation analysis of subjective driver behaviour assessments and objective measuring data revealed that the driving manoeuvre "acceleration in a steady-state circular test" can be used in such a test procedure.

The accident data recorder (UDS) has been developed in Germany primarily for the purpose of improving legal security. But it also provides the opportunity to record--directly in the pre-crash phase--the data important for the development of an accident, thus making them available for the accident analysis. The possibilities and limitations of accident data recorders as a source of information for accident research and their advantages and drawbacks in comparison with the results of at-the-scene accident investigations are currently the subject of a research project.

Based on a special survey of vehicle and accident data in the State of North-Rhine/Westphalia, the accident involvement of riders of high-powered motorcycles (> 74 kW) could be studied. The study revealed an increase in these accident involvements (based on the total number of these vehicles) up to the year 1989, whereas decreasing accident figures were found for a comparison group (riders of the power class 51 - 74 kW) in the same time period. During the years 1988 - 1990, the riders of motorcycles above 74 kW reached a level of accident involvement exceeding that of the comparison group by approx. 70%.

The light transmission capacity of windows in passenger cars, once installed, should not be below about 65% to ensure the required visibility, also under unfavourable luminance conditions. The study has been extended to the identification of low-contrast objects by people with reduced scotopic acuity.

From the studies currently in progress, the following should be mentioned by way of example:

Based on the results of previous research into bicycle safety, further studies are being undertaken to establish the requirements the current equipment of bicycles and bicycle riders should meet to improve their safety. The main aspects in this context are the serviceability of bicycles and the technical requirements for the electric equipment to ensure corrosion resistance and operational safety.

As regards the passive safety of motor vehicles, the following can be reported:

The protective effect of the airbag in conjunction with the three-point seat belt is undisputed. The question which is now increasingly being discussed is whether airbags in passenger cars should be mandatory for the driver only or for both front seat occupants. A statement by BASt on this point has been requested by the Federal Ministry of Transport. The evaluation of at-the-scene accident investigations revealed that 60% of all accidents are frontal collisions or multiple crashes involving the fronts of vehicles. In 87% of these cases, the impact angle had been up to 30° to the right and left of the longitudinal axis of the vehicles. Only in these types of accidents can airbags be effective as protection device. A very optimistic assessment of the airbag's benefits yielded for the driver's airbag benefits of roughly DM 1.7 billion p.a. and about DM 200 million p.a. for the front seat passenger's airbag, or a total of DM 1.9 billion. These total benefits of DM 1.9 billion from airbags for both front seat occupants would have to be seen against the costs of DM 3.4 billion, based on an equipment price of DM 1,000 per car and the number of newly registered cars on the road in 1992. Airbags for both front seats are thus not a cost-effective measure. If only drivers' airbags were fitted, the benefits would conceivably exceed the costs only if the costs per airbag remained below DM 500. Considering the more realistic injury reduction effects of airbags determined at between 5% and 20% in United States studies, the costs for a driver's airbag would have to lie between DM 150 and DM 200 to obtain a balanced cost-benefit relationship.

In another study, the accident severity reduction potential if all cyclists were to wear bicycle helmets was assessed. In 1990, about every 11th road fatality had been a cyclist, the percentage of cyclists in all road casualties (injured and fatal casualties) amounted to approx. 14%. Bicycle accidents occur mostly inside built-up areas. However, due to the higher collision speeds outside built-up areas, the fatality figures outside and inside built-up areas are about the same. Cycling involves a particular risk for older people. About two thirds of all fatal cyclist casualties are older than 50 years. Cyclists collide most frequently with passenger cars. But if they collide with trucks, the accident consequences are particularly serious. About one half of all cyclists suffer head injuries in an accident. The protection range of the cyclist helmets available today covers about a half of all head injuries whose injury severity could in turn be reduced by 50% if the helmets were worn. Assuming a helmet wearing rate of 100%, the number of fatal cyclist casualties could be reduced by about 11% to 12%. The Federal Government therefore recommends that all cyclists make use of these protection features.

In order to improve the protective effect of motorcycle helmets, various test series were carried out by means of the helmet testing device of BASt. The interest here focused on the definition of suitable requirements on the permissible head acceleration if the so-called secondary impact test of ECE R 22 should be deleted. A testing procedure for the helmet chin strap forces is currently under test, applying static and dynamic loads to the retention systems of motorcycle and bicycle helmets.

Commissioned by a third party, several frontal crash tests were carried out on mobile homes. After alarming test results were published, the industry responded promptly by eliminating the serious shortcomings.

From October 1995, ECE and EC plan to introduce a test method for testing the behaviour of passenger cars in lateral impacts. As proposed by the car industry, this test method will be supplemented by the so-called composite test procedure (CTP). By means of quasi-static tests and the application of mathematical models, it will thus be possible to test the safety level of car bodies at an early stage of their development. Within the framework of an international research agreement, BASt has carried out tests on complete vehicles which are to serve as a comparison basis for CTP tests on the same type of vehicles. It is still not quite clear whether the 2nd phase of the CTP comparison tests including full scale tests will be conducted.

Legislation has been active once more with respect to a test method for testing vehicle fronts. The introduction of a corresponding ECE Regulation is planned from October 1995. The test method provides for a frontal impact against a 30° rigid wall at 50 km/h. The inclination of the wall must ensure that the driver's side of the car in question impacts the wall first. From about 1998, this test method is to be replaced by a more realistic impact test currently being drafted by EEVC. The planned test procedure will provide for a frontal impact against a deformable block. The strength of the block shall correspond to the average stiffness of European car fronts. The front area of the car to be tested shall hit the element with a partial overlap only. Current test series have indicated that the requirements on the strength of the passenger compartment will be high in this test. You will hear more on this point in the course of this conference.

The proposed test method for cars to improve the protection of exterior road users in the event of an impact, which was presented at the last ESV Conference, has been under discussion at EC level. The test method includes three component tests: simulated leg-bumper impact, simulated hip-leading bonnet edge impact, and simulated head-rear bonnet area impact. The test method is currently being tested worldwide. The application of this test method has been the subject of other research work as well. Safari grids on off-road vehicles, for instance, were tested with respect to their injury potential. In order to counter the industry's arguments, a cost-benefit analysis has been carried out revealing that pedestrian protection measures on vehicles up to DM 50 can be carried out, the cost-benefit quotient being less than one up to this amount.

As a result of a great variety of test series, the requirements of ECE R 44 for child restraints have been continuously improved. The Federal Ministry of Transport awarded its 1993 Road Safety Prize for work on the protection of children in lateral impacts.

The type approval tests carried out according to ECE R 22 on protective helmets with shells of glass fibre reinforced plastic (GfK), polycarbonate and polyamide did not reveal any material aging detrimentally affecting the protective effect of the helmets.

Airbag systems might be a means of effectively improving the passive safety of motorcycles. There are several proposals for equipping today's motorcycles with sensors for this purpose, which have to be fitted in such a way that their response ensures the timely activation of the airbags in the event of a crash.

With respect to the emergency medical service (EMS) systems, the following can be mentioned:

The share of road accidents in the total number of emergencies has been decreasing steadily in recent years, amounting to 12.4% in 1992-93 while lying at 27.2% 20 years previously. Nearly every second injury accident is attended by an emergency physician. The total number of emergency missions has been steadily increasing over the years; it now lies at 3.2 million missions per year (2.5 million in Germany's old and 0.67 million missions in Germany's new federal states).

The effectiveness and efficiency of EMS systems are largely determined by the appropriateness of the means used in emergency cases, namely how often inappropriate emergency equipment and overqualified or underqualified staff are dispatched in emergencies. Recent studies have revealed that in 8% of the emergency missions ambulances had been dispatched without an emergency physician although he/she would have been needed, requiring subsequent calls for such a physician to be made. Inappropriate means in terms of overqualification are much more often the case.

In recent years, the improvement of the training of paramedics has been the focus of attention. The time of on-scene arrival is a criterion determining the efficiency of EMS. It is defined as the time lapse between the emergency call at the rescue communication centre and the arrival of the rescue team at the scene. It amounts to an average of nine minutes.

Since 1990, German motor insurance companies have concentrated on updating their databases on casualty accidents.

In 1990, every fourth accident involving car occupant fatalities had been recorded. The evaluations were completed by the end of 1993. The following accident data are thus available for 1990:

- 15,000 car-car accidents
- 1,000 single car accidents
- 500 motorcycle accidents
- 2,000 accidents involving trucks.

Based on these databases, the following accident and safety research issues are being looked into: collision types, accident structure, driver-vehicle characteristics, compatibility problems, assessment of the effectiveness of occupant protection measures, biomechanics/injuries and safety measures.

Even though belt usage rates on car front seats in Germany have now reached a level of above 90%, several independent studies of the HUK Association revealed that roughly a third of all car front seat occupants killed in accidents had not been belted. According to the HUK studies, the lives of approx. 15% of all killed car occupants in Germany (i.e., about 1,000 people per year) would have been saved had the belt usage rate been 100% and all cars fitted with a driver's and front seat passenger's airbag.

Another focal point of activities has been the analysis of the causes of rear-end accidents and the injuries resulting therefrom. The number of rear-end accidents increases with the increase in traffic volumes. Almost 40% of all injured rear-end accident victims nowadays reportedly suffer from injuries to the cervical spine. The biomechanical aspects of injuries to the cervical spine were investigated in 1993, in cooperation with the Orthopaedic University Hospital in Frankfurt. The medical evaluation criteria for cervical spine injuries need to be urgently improved. Field studies additionally revealed that about three fourths of all head rests in passenger cars are not properly adjusted. It is necessary that those active in safety research and motor vehicle development intensify their attention to these types of injuries which--even if the injury severity is slight--represent an important socio-economic problem.

Frontal impacts are predominant among the very serious accidents, even if occupants are belted. The relative importance of lateral impacts has also increased. With respect to the frontal impact, the German motor insurers promote the use of an impact on a wall with full overlap and a 40% offset test, in each case at 0°. These tests would largely cover the real-life conditions of a frontal crash and also ensure a separate assessment of the requirements on the restraint systems and the vehicle structure.

The work on child safety, which was started years ago, has been continued. First surveys of the HUK Association after the introduction of the mandatory use of child restraints in motor vehicles on 01 April 1993 revealed that though the response of parents is positive, the desired high securing rates have not yet been attained. In a BASt research project, which is undertaken by the HUK Association, the attitudes of parents are studied as well as ways and means to further improve child restraint systems from the technical and psychological viewpoint. In the use of child restraints, misuse is still a great problem.

The work undertaken by the German motor insurers contributed to improving the ECE R 44 as regards more realistic test conditions. Nevertheless, there are still some problems as, for instance, the biomechanical tolerance limits of the cervical spine and the abdomen or the loads in lateral impacts.

A new database of motorcycle accidents resulting in serious or fatal injuries to two-wheel users confirmed the relative importance of serious leg injuries which are suffered in approx. 40% of all accidents. The German motor insurers are continuing their work on the subjects "Optimizing the trajectory" and "Improved leg protection," also conducting tests in these fields.

Years of analysis efforts of the German motor insurers have accomplished a decisive step in the field of truck safety with the drafting of ECE R 93 "Front underrun guards for trucks." Based on the HUK accident database, intensive work is already underway in cooperation with other European institutions on the requirements to be met by the energy-absorbing designs of underrun guards. According to the studies undertaken by HUK, energy-absorbing underrun guards could prevent fatal injuries to between 10% and 20% of all car occupants who otherwise would be killed in truck-car accidents.

As concerns the rear underrun guards for trucks defined in ECE R 58, recent studies confirmed that their effects are still not satisfactory. This applies particularly to truck trailers, semi-trailers, and the so-called "centre axle trailers" which from the viewpoint of safety technology are a problem, anyway.

The contributions of the German automobile industry will be presented at the various technical sessions of this Conference.

We shall follow with great interest the status reports of the other governments and the technical contributions during the coming days. We wish the Conference every success.

Section 3
International Harmonization of Safety Requirements

Chairperson: Claudio Lomonaco, Italy

Germany

Karl-Friederich Ditsch
(on behalf of WP 29)
Bundesministerium für Verkehr

Paper not available.

Belgium

Herbert Henssler
Commission of the European Communities

ENHANCED SAFETY REQUIREMENTS IN THE FRAMEWORK OF THE EC TYPE-APPROVAL PROCEDURE FOR MOTOR VEHICLES

The European Community has had a great deal of experience with the harmonization of the technical requirements of its Member States. Such requirements generally constituted so-called non-tariff barriers to trade, and had to be eliminated in view of achieving one of the major objectives of the EC, the Single Market.

In the motor vehicle sector this required the harmonization of national type-approval systems. As a result, the EC type-approval procedure was established by Directive 70/156, which set out the framework for all the technical requirements with which vehicles have to comply if they are intended for sale and registration in the EC.

The EC type approval has been made operational by Directive 92/53, and has been applied on an optional basis since 1.1.1993. It becomes mandatory on 1.1.1996 for new vehicle types, and on 1.1.1998 for all new vehicles registered in the EC. In the interim period between 1993 and 1996, the Member States can maintain their national type-approval systems, and the manufacturers have the choice between the national and the EC systems. The Member States are obliged to accept, i.e. to allow registration and bringing into service without any technical checks, all vehicles to which an EC approval has been granted in one Member State on their domestic own markets. The national type-approval systems will cease to apply to mass-produced light passenger vehicles by 1.1.1996, and national approvals for such vehicles will cease to be valid by 31.12.1997.

It follows that any technical requirements which are intended to have an effect at EC level in the future have to be integrated in the EC type-approval procedure. At present, this procedure is based on 44 technical requirements contained in so-called separate directives. Most of these directives address issues relating to active and passive safety, i.e. accident avoidance and occupant protection. The competence to adapt these directives to technical progress has been assigned to the Commission, which has, in the past, made wide use of this competence to keep the most important of these Community requirements, e.g. those on braking, safety belts and their anchorages, in line with the state of the art. If, over the last years, the number of fatalities in the Community has been fairly constant despite its enlargement to many new members and a considerable increase of the number of vehicles and the yearly mileage performed on its roads, this is due to a great extent to the Commission's efforts in ensuring that high standards are set for these requirements.

However, new regulatory concepts such as global assessment of the protective characteristics of vehicles in frontal and lateral impacts require new additional directives which would have to be added to the exhaustive list of requirements to be satisfied in order for a vehicle to be granted EC type-approval. New directives have to be adopted through a complex decision-making process, the so-called Co-decision procedure, i.e. by the Council and the European Parliament together.

The need for integrated requirements on frontal and lateral impact was identified at EC level several years ago, in particular as far as lateral impact is concerned. In the late seventies and the early eighties the Commission spent more than 3 MECU in order to establish the biomechanical protection criteria and to define the appropriate test dummy EUROSID. A special working group called ERGA-Safety was established in order to develop the first draft of a European regulation on this matter.

Being of a more long-term interest, the discussions were later continued in the UN/ECE's Working Party 29, in accordance with the well-established practice of worksharing between the two organizations. The EC Member States always took a particular interest in this issue, and the main features as well as the implementation date (1.10.1995) of the new regulation were proposed by their representatives. This included the compromise solution on the three controversial issues: the height of the lower barrier edge, the "Viscous Criterion," and the seat position for the test.

The EC Member States also initiated the two-stage approach for the new regulation on frontal impact, i.e. "30° ASD" on 1.10.95 and "offset deformable barrier" on 1.10.98.

The EC has now been asked to translate the two new ECE regulations which resulted from these discussions into its own type-approval system. Otherwise, the whole effort would have been in vain for the EC Member States, because they would not be allowed to apply these regulations. In addition, this would put the Member States in an embarrassing position in relation to their partner countries in ECE.

Another field which requires new, additional, EC requirements was identified more recently: the protection of so-called vulnerable road users, i.e. pedestrians, bicycle riders, as regards impact with cars. Here, the EC is awaiting the results of the work of EEVC with which it has traditionally good relations when it comes to defining the basis for new requirements involving scientific criteria.

The work on these new global Directives does not prevent the EC from striving for improvement of the existing Directives addressing specific issues like safety belts and their anchorages, the behavior of steering devices in impacts and also the important aspects of active safety, like braking, lighting etc. As explained above, such improvements are carried out by the European Commission within the framework of its competence for adapting existing directives to technical progress.

Altogether, these activities of the EC have one objective: to ensure a high level of protection in its regulatory requirements in the automobile sector where, since the achievement of the internal market, it has acquired exclusive regulatory competence. The harmonization requirements will soon substitute for those of the individual Member States.

Japan

Noritoshi Horigome
Ministry of Transport

Paper not available.

Canada

S. Christopher Wilson
Transport Canada

Certainly, harmonization from our point of view is not only desirable from a trade perspective, which we have heard a lot about, but we also believe there are safety benefits and environmental benefits by being able to move quickly by adopting regulations from other areas.

We, too, of course, are concerned about the process that seems to be very slow sometimes in international agreements. But on the other hand, developments for a relatively small country like Canada, in the area of vehicle design and the characteristics of the technical development of standards, we find it advantageous, obviously, and quicker to pick up good ideas from other areas.

In that context, of course, our standards primarily follow those of the United States, as we have a common industry and vehicle fleet. We also, though, have referenced standards from ECE. We adopted, as an option, the lighting standard more than 20 years ago. So that we have, for a long time, had a record of examining and selecting those that are appropriate.

We do participate in WP-29 and in some of the working groups of EEVC, and again, these are useful to understand the technical background for these standards.

There is, on the horizon, two other groups that may have similar responsibilities. Under the North American Free Trade Agreement, there is the establishment of an automotive standards council, and actually the terms of reference for this standards council are not unlike those for WP-29 and ECE.

They were established as part of a trade agreement, but also recognizing the importance of safety and pollution and energy standards in any of the free movement of vehicles throughout the three countries that are members of the North American Free Trade Agreement.

In addition, the Asian/Pacific Economic Group is also looking at this problem, because of the same kind of issues, and of course, Canada and the United States and Mexico are also members of this Asian/Pacific Group, and Australia is taking the lead in trying to pull together some semblance of order there.

What we see, continually in the harmonization area, is a desire and a mechanism set up to improve harmonization. But as our Japanese colleagues have just suggested, the actual commitment to harmonize is not always there. This must begin at the scientific level and carry through to the government levels.

I don't think we will ever see -- certainly, I doubt in the North American context -- a willingness to give our authority to establish those standards that are best for our citizens. But when it comes to the technical specifications of those standards and the test methods associated with them, then we are prepared to work and try to develop common practices.

Recently, we have been looking seriously at some of what we believe to be deficiencies in the frontal protection area of FMVSS-208. However, we have constrained ourselves to adopting variations that use the same test methods and the same basic analysis.

Now, we don't particularly like a couple of the ways that data is used, and we are using different -- for example, chest deflections of 50 millimeters instead of 76, as in FMVSS-208 -- but that comes off the very same test, and from our testing and research, is easily attainable with current three-point belts.

So this is the kind of thing that we are looking at, but even then, I guess, we are guilty of the fact that if you want real harmonization, you have to compromise and you have to accept the points of view of others. There has to be credibility given to the science and the work that is done in all countries and not just of the major motor vehicle manufacturing countries. Thank you.

Australia

Peter Makeham
Department of Transportation and Commerce

HARMONISATION OF SAFETY REQUIREMENTS - AN AUSTRALIAN PERSPECTIVE

ABSTRACT

The international vehicle industry faces pressures which will lead to increased support for harmonisation of regulation as part of the drive to contain costs and facilitate trade.

Australia has achieved significant reductions in the road toll through an integrated national approach based on sound research and statistical analysis.

The three major systems of vehicle regulation - European/ECE, North American and Japanese have common broad objectives but quite different regimes to achieve the objectives.

There is a need for a truly international forum to facilitate international harmonisation, bringing in the nations with recently developed vehicle manufacturing industries. Australia supports the need to move towards international harmonisation, and believes ECE/WP29 offers the best opportunity to achieve that objective. Australian industry is today export oriented and supports international harmonisation as one mechanism to facilitate trade.

Australia supports the moves to revise the 1958 Agreement to allow WP29 to fulfill the role as the forum for international harmonisation. Australia notes the issues arising from developments in the European Union, and the support for harmonisation of standards in other international areas such as the Asia Pacific Economic Cooperation forum. Australia believes the current review of the 1958 Agreement is an essential first step towards developing a long term strategy to move towards international harmonisation.

THE VEHICLE INDUSTRY

In considering harmonisation of regulation it is important to recognise the parameters of the vehicle industry. Today it is a truly international industry, characterised by intense competition and a search for efficiency. The current Ford restructuring of its world wide operations epitomises the issues.

Quite clearly the motor vehicle industry should support international harmonisation, although there have been occasions where they see regulation as a non tariff barrier to protect their markets. Hopefully these days are past. Overall, harmonisation offers the potential for significant savings for the manufacturers as we move into an era of "world designs."

The industry faces pressure on a number of fronts

safety
emissions
fuel efficiency
price.

These factors are often in conflict ie enhanced safety often adds weight, increased weight means increased fuel consumption.

Governments insist on tighter requirements. Customers demand more for their money. Both Government and industry need to strike a sensitive balance for the best result.

Each of the regulatory areas has its own constituency - often in different sectors with poor communication. In Australia we are fortunate in that my office has responsibilities in each area. This does also have some challenges.

ROAD SAFETY

As social mobility becomes an attainable goal, so the potential for road trauma increases markedly. Consequently road trauma is emerging as a priority issue in many countries - both developed economies and less developed economies.

Australia has achieved siginificant reductions in road fatalities over the past ten years. This has been made possible by a combination of factors - one of which was the recession. Australia now faces the rest of the nineties under pressure to consolidate and improve on our achievements.

Australian road safety achievements are built on a blend of vehicle regulation, public education, road user regulation - all based on statistical and behavioural research to identify the problem areas and potential remedies. These programs have achieved community acceptance of the need to address road trauma actively and strong support at the political level.

INTERNATIONAL VEHICLE REGULATION

In the light of the preceding it is perhaps surprising to find several entrenched systems of vehicle regulation today. There are three major systems

European - ECE
North American
Japanese

with some common elements but some significant differences.

Many countries, like Australia, have a blend of North American, ECE and Japanese influences. "Asian Tiger" economies, the South American producers and India have yet to adopt a firm commitment to any particular regime.

When one considers that the objective of vehicle regulation is to protect human occupants - generally agreed to be structurally consistent across the world - it is perhaps unfortunate that this divergence exists. On the other hand it does leave an opporytunity to pick the best approaches - something Australia has been able to do.

Australia has been able to benefit from the divergent regulatory systems and to piggyback on research across the world. Today Australia is able to play a part in the development of new regulations. However, Australia recognises the potential benefits of moving towards international harmonisation and has publicly supported such moves.

Taking a broader perspective one has to consider the "new" vehicle producers - the Asia Pacific region. The vehicle markets in these countries are booming and production increasing at a time when major developed markets are stable or even depressed. A regime of vehicle standards which does not include these countries, some of whom are set to be - or already are - major exporters, can hardly aspire to be truly international.

ISSUES FOR AUSTRALIA

Australia has a well developed, highly motorised society. The Australian Design Rules have been in place since the early seventies. Initially the rules were based on US NHTSA standards and more recently have focused on ECE standards. Australia's requirements are over 60% harmonised with ECE.

Australia has led the world in fitting seatbelts and currently wearing rates exceed 95% in the front seat. Australia was also among the first to mandate unleaded petrol.

Overall Australia has been very active in vehicle safety regulation and we are proud of our record. The results speak for themselves.

Australian industry comprises four local manufacturers, two with US parents and two Japanese. Only five models are produced and volumes are small. Only one vehicle type is unique to Australia.

The market is completed through imports, mainly from Japan and Europe. Cars are right hand drive and left hand drive vehicles are not accepted.

Australia's vehicle industry policy is export oriented and there are increasing exports of both vehicles and components. Industry policy is predicated on exports to derive volumes that support internationally competitive production costs. Industry is supportive of international harmonisation and looks to cost savings as harmonisation is achieved.

Given this, what does Australia look to see from international harmonisation? First Australia looks to achieving the best. Australia would not be party to a lowest common denominator approach.

Second Australia looks to mutual recognition. Australia wants Australian systems of type approval and conformity recognised and accepted in other markets. As a preliminary Australia wants competence to test and approve to a standard recognised so that our manufacturers can test in Australia for export markets.

Thirdly Australia wants to see a truly international system of vehicle regulation which involves all the parties. The current proposals for reforming WP29 go a long way toward addressing these issues but remain overly "Euro centric." Indeed at the last WP29 meeting in March it was evident that some parties still regard WP29 as a "greater Europe" club, and do not recognise wider interests.

FUTURE FOR INTERNATIONAL HARMONISATION

There are three key issues

- review of 1958 Agreement
- role of EU
- the new vehicle producing countries.

As noted already it is essential that WP29 becomes truly international in outlook. If WP29 is seen as a "greater Europe" club then the revisions to the 1958 Agreement will fail in their key objective.

One only has to also look at forums such as APEC to see that there are high level concerns regarding harmonisation of regulation as one aspect of trade facilitation If the "technical experts" cannot address this issue they may well find it taken out of their hands.

It is relevant to also consider the role of EEC/EU in international harmonisation. One of the reasons for the drive to review the 1958 Agreement was, quite bluntly, to retain a valid role for WP29 in a situation where EEC/EU developed a parallel regime. If the ECE regime was not seen to be able to deliver the "free trade" aspects of vehicle trade within EEC/EU, then it was clear that the 1958 Agreement needed revision to function effectively as a forum focussed on international harmonisation of vehicle regulation.

As arrangements have evolved in WP29, EEC/EU is now recognized while each member remains a member of WP29. One unfortunate aspect of this is a tendency for EEC/EU positions to be put at WP29 as a "fait accompli" and not subject to free debate or amendment because individual EEC/EU member states are bound to support the coordinated position.

From a viewpoint outside Europe, if this trend continues, such developments could raise serious questions as to the potential effectiveness of WP29 as a truly international forum.

Finally it is important to consider the countries with newly established vehicle industries. An effective international vehicle regulation regime cannot ignore the major vehicle producing countries outside the traditional Europe-Japan-America axis. WP29 must address this issue and take positive steps to encourage a broader membership. If the current review process simply leads to arrangements which are attractive to those currently attending meetings of WP29, a major opportunity will be lost and the long term future for international harmonisation prejudiced.

THE WAY AHEAD

Australia is committed to ECE/WP29/1958 Agreement as the best route to move towards international harmonisation. However there are still significant concerns and signs that the old culture may be resistant to fundamental change.

There are developments in the other forums such as APEC which need to be encompassed in future planning. There are also the vehicle producing countries who are not party to the current regime.

Perhaps what is needed is to focus on completing the current review, but in parallel to develop a long term strategy to move towards the common goal of true international harmonisation. This strategy would need to address the issues outlined above and encompass all the relevant parties.

The current review of WP29 would be an essential step along the way to the long term objective.

United States

Francis J. Turpin
National Highway Traffic Safety Administration

At the last ESV Conference in 1991, it was reported on the progress in three main areas that we have agreed to work on for the past, 10, 12 years, and that is brakes and running gear, lighting and light signaling devices and side impact protection.

At the end of that presentation, we also briefly discussed the efforts underway to review and revise the "1958 Agreement."

Since that conference, progress has been made in all three areas. Some new areas have been added, and there have been some disappointments.

In passenger car braking, agreement has been reached on a test procedure known as 13-H in the ECE, and we expect to publish a final rule in harmony with the 13-H this year.

In lighting, we have had several successes. We now have compatible regulations dealing with yellow rear turn signals, replaceable bulb headlamps. Center high mounted stop lamps are now harmonized among Europe and the United States. And the vertical location of lighting devices has largely been harmonized, and side marker lamps are also close, if not harmonized at present.

The development of a harmonized low beam pattern, or passing beam pattern, is still being worked on, and the horizontal harmonization of location of lighting devices is progressing.

One of the new areas added since that last ESV was the frontal impact protection area. Europe has agreed on a first step of a two-step approach, a frontal impact protection regulation that uses a 30 degree angle barrier with antislide devices, with 30 mile per hour test speed, and injury criteria similar to FMVSS-208.

The second step is the offset crash test, which will be discussed extensively here at the conference in the coming sessions.

Australia and Japan have adopted a modified FMVSS-208, essentially still a full frontal crash test, with a 30 mile per hour frontal crash test with belted occupants and the well-known FMVSS-208 injury criteria.

On side impact protection, Europe has recently, at the March meeting of WP-29, adopted a new regulation on side impact.

That regulation uses a viscous criterion, whose value is tentatively set of 1 meter per second at this time, pending a two-year trial period, during which the criterion will be measured for those types that are approved to the new regulation. Afterwards, the criterion will be set on the basis of the review of the data.

The United States issued its final rule on side impact protection, as you know, in October 1990. As you know, that rule established chest and pelvic injury criteria to be used in full-scale crash tests.

As I mentioned earlier, there have been some disappointments, at least on the part of the United States, in the crash protection regulations established through the ECE. Although vehicles designed to meet FMVSS-208 will meet and probably exceed the performance limits set for the 30 degree angle barrier test, EC regulation imposes an additional test. Thus, manufacturers certifying to 208 will have to crash test another vehicle to enable sale of that vehicle in both markets.

On side impact, we suggested that since the viscous criterion was to be evaluated over a period of two years, why not instrument the dummy, to measure the thoracic trauma index, the criterion in use in FMVSS-214, at the same time?

Thus, after two years, should the viscous criterion measurements prove to be variable or preclude their use for some reason or other, then at least you have the TTI criterion measurements to fall back on if you still wanted to preserve a regulation. That suggestion was rejected.

Finally, what is being done about the future course of WP-29 with regard to harmonization? As you know, the 1958 Agreement, which is administered by WP-29, has been under review since 1989, with a view to broadening its scope to make it truly "international," in recognition of the global nature of the regulated automative product sector.

This review culminated in a proposed revised agreement labeled WP-29, R-615, Rev. 2, and it is a publication that you can probably get either from your government representatives or possibly industry association members.

This was submitted to the signatories in October of 1993 -- since then the United States, having obtained negotiating authority through the State Department, prepared a proposal which was briefly described by its delegation at the March 1994 session of WP-29.

This proposal would amend the existing agreement into an umbrella agreement, which would include R-615, Rev. 2, in order to preserve the rulemaking process used by the European countries. For all intents and purposes, WP-29 of the ECE is essentially the European rulemaking process. It has been very successful.

In fact if it hadn't been for the 1958 Agreement, I don't think you would have an integrated market within the EC right now. It has essentially provided a basis for putting together the 44 regulations that are currently going to be used in whole vehicle type approval within the European Union.

The more detailed proposed draft revision was prepared as a result of that short three-page so-called non-paper at WP-29 in March and has been fully coordinated, with other agencies of the U.S. government that have a stake in this process, namely, the U.S. Trade Representative's Office; the Department of Commerce; the Environmental Protection Agency; the U.S. Department of Transportation; NHTSA; and of course, the United States State Department.

We put together a detailed proposal, and that proposal will be submitted with very few changes from what is currently being sent around to the various governments -- at the June meeting of WP-29.

That proposal was mailed and faxed out last week, before I came to this conference to all the signatories of the 1958 Agreement; to delegates that have been there who are not signatories, but who have been to WP-29 over the past couple of years; and to industry associations; consumer organizations; and the relevant committee staff of the U.S. Congress.

Now, the draft U.S. revision will do the following: It would create an agreement with an expanded scope, such that non-European countries would be more likely to become contracting parties, and thus, would establish WP-29 as a world forum with regard to safety, pollution, and energy standards and regulations attendant to vehicles and engines.

It would provide a credible world forum for the development of common or compatible "global" standards and regulations that foster fully global trade by reducing the potential for technical barriers.

It would provide a global registry under the United Nations of applicable national, regional, and global standards and regulations of contracting parties and WP-29, respectively, that can be adopted into national law by any country.

It would preserve -- and this is extremely important, because the current 1958 Agreement does that as well, as well as the R-615, Rev. 2, which is the proposal that is currently on the table, put together by the Europeans -- it would preserve the sovereign right of any country adopting into law a regulation from the global registry to set its domestic level of protection. In other words, these are still purely voluntary standards, or voluntary regulations.

I should use the word "regulations." Standards are sometimes confused with regulations. Regulations are the force of law. They are mandatory and they are enforced by governments. Standards are generally voluntary technical requirements. They are set sometimes by industry or in cooperation with government, but they are of a different nature. They are not enforced by anybody unless a manufacturer specifies them to a supplier or so forth.

The last three things it would do is would ensure through this global registry, this proposal that we have made, that national and regional regulations applicable to vehicles and engines receive appropriate consideration in the development of global regulations.

It would preserve regional cooperative regulatory development and mutual recognition agreements, such as that between the member states of the European Union, or amongst those countries who are not part of the European Union, but have subscribed to the 1958 Agreement.

And it would also allow manufacturer self-certification. In other words, the agreement would no longer be tied to a specific type of regulatory system. You could either have a type approval system or a self-certification system and still be a signatory to this agreement.

I trust that the above explanation, which is rather short, of a document that is about 10 pages long, and has all the necessary articles and so forth in it, will be of some use to you. The copies of this agreement are in the hands of most government representatives. When you go home, if you want to get in touch with them, I am sure they will be able to provide them to you. Thank you very much.

Germany

Dieter Matthes
Verband der Automobilindustrie e.V.

HARMONIZATION OF SAFETY REQUIREMENTS THE ROLE OF THE AUTOMOBILE INDUSTRY

ABSTRACT

International harmonization of safety requirements results in benefits for manufacturers and users of motor vehicles. It is a difficult and time consuming process which needs the dedicated effort of experts from government and industry. Existing committee structures permit such harmonization on a worldwide basis.

Automobile manufacturers and their suppliers are responsible for the safety of their products. Every manufacturer has his own in-house safety and reliability standards which are intended to ensure that vehicles will perform as safe as possible under all practical conditions of operation.

Requirements promulgated and enforced by the authorities must be integrated into the safety package which goes into the design and construction of a new or modified vehicle model. Such requirements normally are contained in the conventional construction and use regulations for motor vehicles and their trailers; they may also be found in other areas such as occupational health and safety, transport of dangerous goods or explosives.

Safety requirements in a government regulation cannot and do not stand alone. They are accompanied by demonstration procedures, rules for certification and/or approval and a schedule of application dates. Each of these elements is of primary importance to manufacturers because it may affect the introduction and the sale of new or improved vehicle types.

Automobile manufacturers have learned to live with different safety regulations in different markets. They also understand that such regulations often have a political or even an economic background and cannot be changed at short notice. However, the development in Europe shows that safety regulations can be harmonized in all their aspects if governments, industry, researchers and consumers are cooperating actively. The existing system of ECE Regulations and EEC Directives covers all aspects of active and passive safety. The automobile industry has taken an active part in this work from the beginning. Experts from the manufacturers and their associations are contributing in the preparation of new and amended regulations. In numerous areas such as lighting and braking, industry experts have drafted the standards and carried out the tests which later became part of the final regulation.

The benefits of uniform technical regulations for vehicle users and operators are obvious: Cost reduction and the same high level of safety.

Production and marketing of automobiles today is a worldwide system, in particular for passenger cars and similar vehicles in this market sector such as off-road vehicles, large-size passenger cars, vans and small trucks. Road traffic conditions and also traffic problems are becoming identical in many parts of the world. It is therefore logical to extend the system of international harmonization which has proved successful in Europe to the worldwide level. This is by no means a new idea. As early as October 1975 the ECE-WP 29 set up a special group on harmonization between United States and European regulations. This work was discontinued after a few years because it was found that it was not possible to obtain any definite results, A more modest approach was initiated at an informal meeting of ECE-WP 29 delegations in October 1987. At that time three priority areas were identified as candidates for international harmonization:

Lighting and light signaling
Braking systems
Occupant protection in side impact

The present state for these items can briefly be described as follows:

LIGHTING AND LIGHT SIGNALING

Around 1987 an international group of experts initiated work on the harmonization of requirements regarding all aspects of installation of lighting/signaling devices on motor vehicles: Number and location of devices, angles of geometric visibility, electrical connections. The final draft has recently been completed and will be submitted to the competent ECE-WP 29 group of experts with a view of amending the relevant ECE Regulation.

BRAKING SYSTEMS

The ECE group on braking (GRRF) started work on a harmonized braking standard for passenger cars around 1980 which would take the form of a new ECE Regulation and a new Federal Motor Vehicle Safety Standard. Both documents were developed in a series of informal meetings. In 1985 NHTSA published a notice of proposed rulemaking which would introduce a new FMVSS 135 for Passenger Car Brake Systems. This draft has since been reviewed in the light of extensive comments from GRRF. A final rule has not yet been published. The definite ECE draft Regulation was circulated in 1992.

SIDE IMPACT

Both the United States and Europe have independently developed and published a regulation based on an integrated test procedure with a deformable moving barrier. Considerable differences exist in the impact conditions, the mass and deformation characteristics of the barrier, the dummy and the biomechanical criteria.

The conclusions which can be drawn from these facts are twofold:

Worldwide harmonization is a long-term project which needs the concentrated effort and good will of the partners.

It is necessary to have a forum for a continuous and systematic dialogue between the experts from government, industry and standardization.

Effort and good will is there, the competent forum is ECE-WP 29.

Section 4
Technical Sessions

Technical Session 1

Biomechanics and Dummy Development

Chairpersons: Rolf Eppinger, United States
Eric Welbourne, Canada

Prediction of Thoracic Injuries by Means of Accelerations, Deflections and the Viscous Criteria Derived From Full-Scale Side-Impacts

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94-S1-O-01

ABSTRACT

In the DOC.TRANS/SC1WP 29/GRSP/R 48 a future European Side-Impact Test Procedure in addition to the existing US-FMVSS 214 has been proposed. Besides the new Dummy "EURO-SID" and instead of TTI two new protection criteria are to be introduced:

- the thorax compression (C) and
- the viscous response (VC) defined by the rate sensitive torso compression. VC is the maximum product of the velocity of torso deformation and the instantaneous relative torso compression

VC = V (t) x C (t)/D

Consequently, for the first time in the field of Passive Safety two different protection criteria are existing to certify the protection level for one and the same car occupant.

In order to compare the injury predictive qualities of the proposed injury criteria, FAT carried out an additional analysis of the FAT/Heidelberg side impact test series from 1985.

By means of a double integration of the accelerometer readings this case-by-case study leads to meaningful compression versus time histories for the thorax. The VC was calculated on the basis of the full thorax compression and the deflection of the half thorax as well.

As seen in the previous FAT-study [3] the most influencing parameters are human factors like age and other anthropometrical dimensions. TTI, VC or C are of minor injury predictive quality.

A reasonable estimate of thoracic and often associated abdominal injuries (hard thorax injuries) is given by the TTI.

To facilitate the procedure in compliance tests a single protection criterion for both thoracic and abdominal injuries is most appropriate.

INTRODUCTION

The "Forschungsgemeinschaft Automobiltechnik (FAT)" is a Research Association of the German Automobile manufacturers which sponsors research in all areas of automotive engineering and related basic areas. It is organised by "Arbeitskreise (AK)", working groups that deal with special fields. The AK 3 "Unfallforschung und Biomechanik" deals with accident research and biomechanics. It is the merge of the former AK 3 "Unfallforschung" and AK 5 "Biomechanik". The work of AK 5 was to conduct a number of tests that allow the identification of injury criteria in side impact. These tests were conducted at Heidelberg university, Institut für Rechtsmedizin, and were already used to derive basic knowledge for side-impact protection. It is appreciated that the Heidelberg research on biomechanics positively influenced our knowledge on the injury mechanisms in vehicle accidents. From the scientific point of view it is necessary that this research will continue. Only if the real causes of injuries are known, the dummy signals can be interpreted in such a way that safety of human beings is increased by optimisation of the dummy response.

The data of 58 car-to-car-type side collisions [1] were thoroughly checked by the Fraunhofer-Institut für Informations- und Datenverarbeitung. All signals were carefully adjusted to zero. The accelerations were integrated and the motion that is defined by the acceleration signal was compared to the high-speed-film. Due to this comparison, some of the cases were eliminated. Thus, 47 cases are the basis of the following study.

THE DATA

For each case, three groups of data are available:

<u>Anthropometric data</u>

Age, height, weight, sex, lateral thorax width, seating height, abdominal girth, a degree of slenderness (seating height/abdominal girth) and the BENE-parameter, the energy that breaks the bone.

<u>Dummy-load-type data</u>

Viscous Criterion VC, based on the compression of the full and of the half thorax ,

Thoracic Trauma Index TTI, based on FIR-filtered data (TTIF) and on the 3-ms-peak-value (TTI3).

The TTI is available as Kernel without age and mass and as full TTI with

TTI = 1.4 * AGE * TTI_Kernel * MASS/75.

The compression of the full and of the half thorax is available absolutely (in cm) and relatively in percent of the full and half thorax, respectively. It should be noted that these values are not measured at the dummy. Thus, by corresponding dummy tests, the corresponding dummy values have to be determined. They will be different for different dummys (e.g.US-SID and EUROSID).

<u>Injury-related data</u>

Number of rib fractures

Thorax-AIS

Abdominal AIS

Spine AIS

(The AIS was recoded to AIS 90.)

Injury Cost Scale ICS, the monetary evaluation of the injury. The ICS is described in FAT-Schriftenreihe.Nr. 73 [2].

The test velocity was in the range of 40 km/h and 61 km/h. Identical vehicles and barriers were used in all tests.

THE CORRELATION OF THE ANTHROPOMETRIC DATA

Regarding statistical relationships, there are five groups of anthropometric data:

The weight-group consists of the weight, the thorax-width, and the abdominal girth. These three parameters show high and positive Spearman correlation coefficients:

	Weight	Th.-width	Abd.girth
Weight	-	65.6 %	47.8 %
Thorax-width	65.6 %	-	81.3 %
Abd. girth	47.8 %	81.3 %	-

Table 1: The Spearman correlation of the weight-group

Thorax width shows a higher correlation to the weight than the abdominal girth.

The second group is the size-group which consists of total height and seating height. The Spearman correlation between both is 60.1 %.

The other parameters are age, slenderness, and BENE, the energy that breaks the bone. Age and BENE are negatively correlated by - 39.3 %. The slenderness is the ratio between seating height and the abdominal girth. It is negatively correlated to the weight group, - 28.0 % to weight, - 57.3 % to thorax width, and - 79.2 % to abdominal girth. So it makes sense to regard the inverse of slenderness as a part of the weight group, and to regard age and the inverse of BENE as one group. The age group has positive correlation to the weight group and only small correlation to the size group. Weight group and size group show only little correlation.

It should be pointed out that all correlations are Spearman correlations of the sample of 47 persons which were examined post mortem. Table 5 shows the levels of significance for the Spearman Rank correlation.

THE ANTHROPOMETRIC DATA AND THE INJURIES

Before injury criteria can be detected, it should be pointed out, how much information can be derived from the anthropometric data itself. This will show that for side-impact protection only a small amount of protection can be ensured by the safety performance of the vehicle. The ability of human beings of different age to tolerate lateral shocks is the main problem of side-impact protection. Anthropometric data explain a large part of the findings of the 47 tests. Table 2 shows the averages for men and women and for different age groups.

The average impact velocity is lower for the female and for the older age groups. So the lower injuries for the females may be explained by this fact. But the higher injury level of the older age group is observed in spite of this fact. The data underestimate the influence of age. The higher BENE-level of the women might be explained by the lower average age of the sample. The relation of weight to age is as it

Averages for different subgroups of the sample						
	Men	Women	..35 years	36..55 years	56..years	All
Number of cases	36	11	20	18	9	47
Impact velocity [km/h]	48,8	46,2	49,1	48,1	46,6	48,2
Age group						
Age	41,7	34,6	25,9	45,2	61,1	40,0
BENE	7,5	8,3	10,7	6,4	3,4	7,7
Weight group						
Weight [kg]	71,7	59,3	66,0	69,4	73,7	68,8
Thorax width [cm]	31,4	29,2	29,7	31,6	32,3	30,9
Abdominal girth [cm]	83,6	78,4	76,2	86,2	88,3	82,3
Slenderness	1,1	1,2	1,2	1,1	0,9	1,1
Size group						
Size [cm]	175,1	164,3	174,2	171,8	170,4	172,6
Seating height [cm]	92,9	88,5	93,4	90,7	90,8	91,9
Injuries						
Injury cost scale	1,327	1,033	0,764	1,321	2,110	1,158
No.of rib fractures	14,1	11,2	7,2	17,3	19,6	13,4
Thorax AIS	3,5	2,8	2,4	4,0	4,2	3,3
Abdominal AIS	1,3	0,7	1,2	1,2	1,1	1,1
Spine AIS	1,2	1,1	1,0	1,2	1,4	1,2
Load						
VC lower (full thorax)	0,9	0,8	0,9	0,8	0,9	0,9
VC lower (half thorax)	0,8	0,7	0,7	0,8	1,0	0,8
TTI (FIR) Kernel	120,9	123,2	125,0	119,7	117,3	121,5
TTI (3ms) Kernel	101,8	96,9	103,7	97,1	100,8	100,6
TTI (FIR)	174,0	145,4	146,6	174,6	198,9	167,3
TTI (3ms)	155,7	124,8	127,9	154,2	182,8	148,5
Lower compression						
Full thorax [cm]	7,7	6,8	7,2	7,5	8,1	7,5
Half thorax [cm]	4,6	3,5	4,0	4,1	5,3	4,3
Full thorax [%]	24,4	23,7	24,3	23,9	25,0	24,3
Half thorax [%]	29,1	24,6	27,5	26,5	32,5	28,0

Table 2: The test design regarding sex and age. The impact velocity and the age of the female was smaller than of the male. The impact speed decreased for higher age.

should be expected, weight increases with the age. Size decreases, while Injury increases with the age groups. To show that the impact velocity is nearly independent to age it is referred to the Spearman correlation coefficient of - 14 % (Table 3) and to figure 1. (Compare also table 5)

The number of rib fractures increases tremendously from age group under 35 years to age group 36 to 55 years. The increase for age group 56+ years is not so significant. Figure 2 shows that the age of 40 seems to be the critical age. Up to an age of 30 years there is a good chance of no injury. Thorax AIS reflects this: AIS = 0 ends at age 30, AIS ≤ 3 at age 47 (Figure 3). Abdominal and spine AIS shows no obvious relation to age. (Table 3)

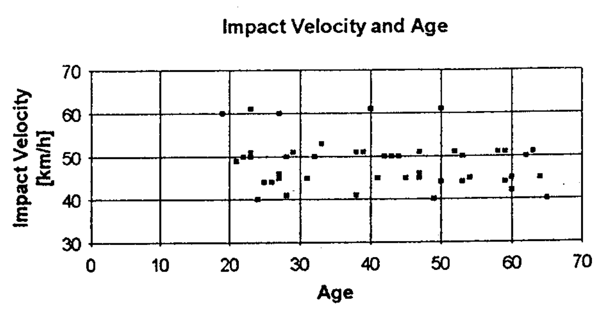

Figure 1: The impact velocity and the age in the 47 tests.

Spearman Rank Correlation	Age
Impact velocity [km/h]	-14.3%
Weight group	
Weight [kg]	30.2%
Thorax width [cm]	42.1%
Abdominal girth [cm]	52.5%
Size group	
Size [cm]	-22.8%
Seating height [cm]	-29.0%
Other Biometrics	
Slenderness	-54.1%
BENE	-50.2%
Load values	
TTI (FIR) Kernel	-19.1%
TTI (FIR)	54.4%
VC lower resp. full thorax	1.6%
Compression lower (full thorax) [cm]	8.6%
Compression lower (full thorax) [%]	4.5%
Injuries	
Injury cost scale	26.3%
Number of rib fractures	69.1%
Thorax AIS	52.9%
Abdominal AIS	2.8%
Spine AIS	23.4%

Table 3: The Spearman correlation with age.

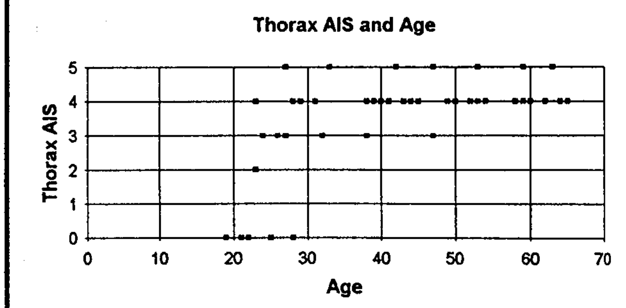

Figure 3: Thorax AIS and Age. Uninjured thorax is found only for age under 30 years. With more than 50 years, thorax AIS is at least 4.

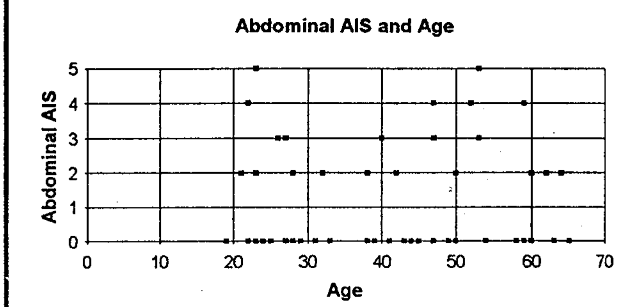

Figure 4: Abdominal AIS and Age. No obvious relationship can be detected.

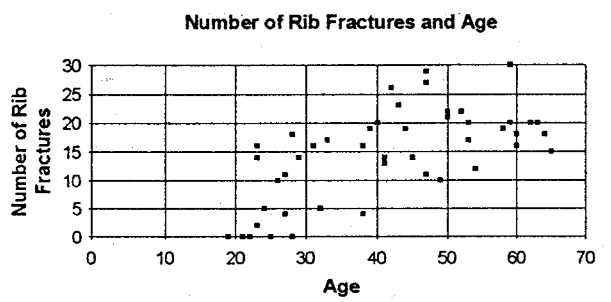

Figure 2: The number of rib fractures and age. At the age of 40, a minimum level of 10 rib fractures is reached.

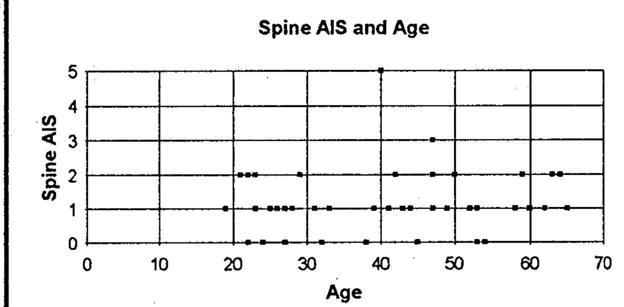

Figure 5: Spine AIS and age. No obvious relationship can be detected.

	No.of rib fractures	Thorax AIS	Abdominal AIS	Spine AIS	Injury cost scale
VC lower resp. full thorax	38,53%	32,24%	-22,31%	19,63%	12,66%
TTI (FIR) Kernel	23,38%	19,70%	-15,04%	8,18%	27,96%
TTI (FIR)	70,11%	44,06%	-23,67%	7,74%	34,90%
Compression lower (full thorax) [cm]	34,20%	28,02%	-24,49%	10,31%	8,58%
Compression lower (full thorax) [%]	32,35%	22,04%	-28,01%	25,45%	6,90%

Table 4: The Spearman Rank Correlation of injuries of different body areas to possible predictors. Statistically significant is a value of more than 28.5 % on the 5-%-level, 37.0 % on the 1-%-level, and 47 % on the 0.1-%-level. (Compare table 5)

LOAD INDICES

The relationship between age and thoracic injury has to be kept in mind, when the injury criteria are checked. The capability of an injury criterion to predict injuries was carefully examined by different statistical methods.

This paper will only compare the currently used dummy load parameters. There is a lot of concern that we use different dummies, and different dummy load values in the U.S. and in Europe and the question will be, whether there is a significant distinction between both, so that the use of two sets of dummy loads is justified.

The Spearman Rank Correlation gives an idea, how ranking of the severity by load values like TTI, VC, and compression fits to ranking in terms of the severity by injury (Table 4). For statistical significance compare table 5.

A level of significance of 0.1 % can only be reached by a combination of biometric and load values (TTI).

The 5-%-level is never reached for abdominal AIS. So on the 5-%-level no correlation of any of the load values to abdominal-AIS exists. For spine AIS the 5 %-level is reached by VC of full thorax only. For the number of rib fractures the 5-%-level is reached by all load values except kernel of TTI. For thorax AIS the 5-%-level is reached by VC, TTI, and by the absolute compression of the full thorax.

The overall injuries are described by the injury cost scale [2]. Here the TTI and the kernel of the TTI show the highest correlation. VC and compression are not significant and much less correlated to injury severity.

On balance the TTI seems to describe the overall injury severity best. For the TTI kernel this is not in every case true. But there is no other load value that shows a significant better correlation, which would justify a switch from TTI to another criterion.

The relations between injury severity and different predictive parameter candidates are visualized in figures 6 to 10. There, the same finding can be observed. These figures show clearly that there is no chance to derive a load-level which avoids special injuries. In the range of the small load-levels there is always a high injury-level, e. g. the lowest compression (3.8 cm) of the lower, full thorax was observed with a thorax AIS 4. The same is true for VC (0.2). The thorax AIS 4 is distributed from compression 3.8 cm to 12.1 cm. Only TTI, including biometric information, shows a more appropriate behaviour. Similar observations can be made for the number of rib fractures and the injury cost scale ICS. The comparison of the ranges clarifies that these observations are not singularities. So the thorax AIS 4 is nearly equally distributed between compression of 4 cm and 10 cm with one case at 12 cm, thorax AIS 0 shows nearly the same range.

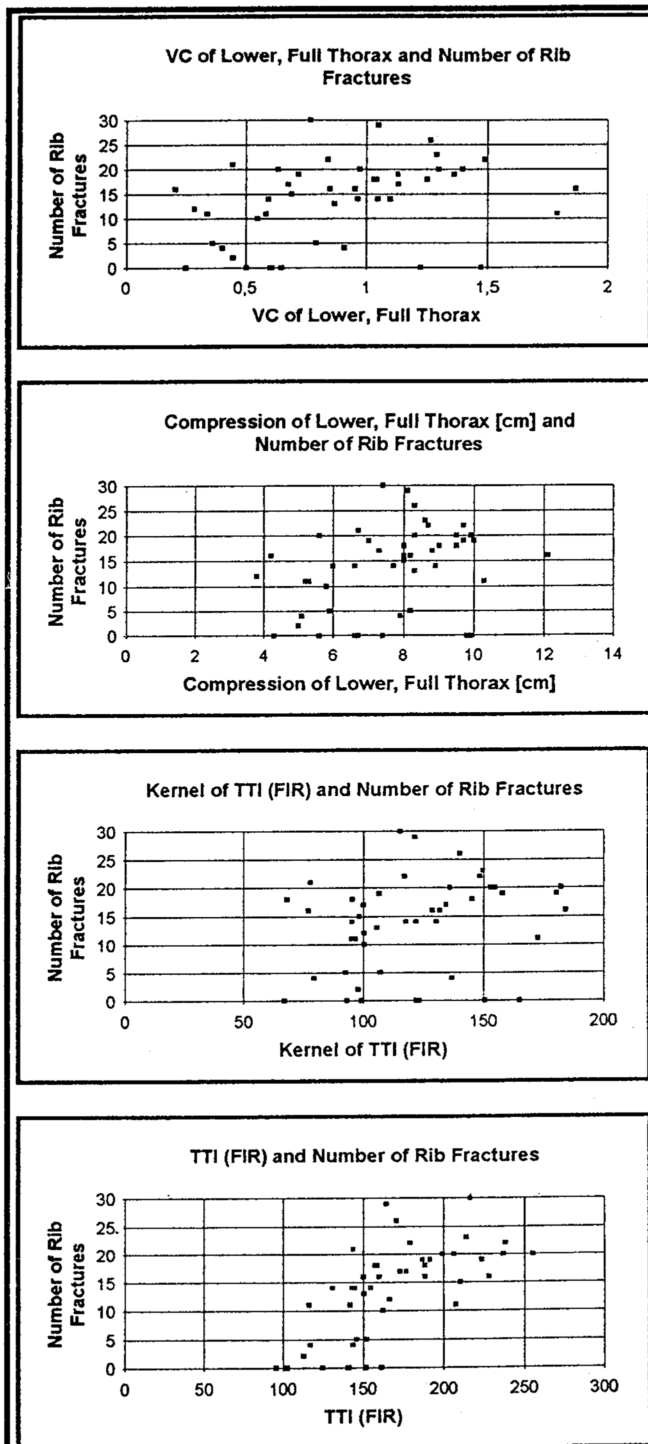

Figure 6: Candidates for the prediction of injuries and the number of rib fractures.

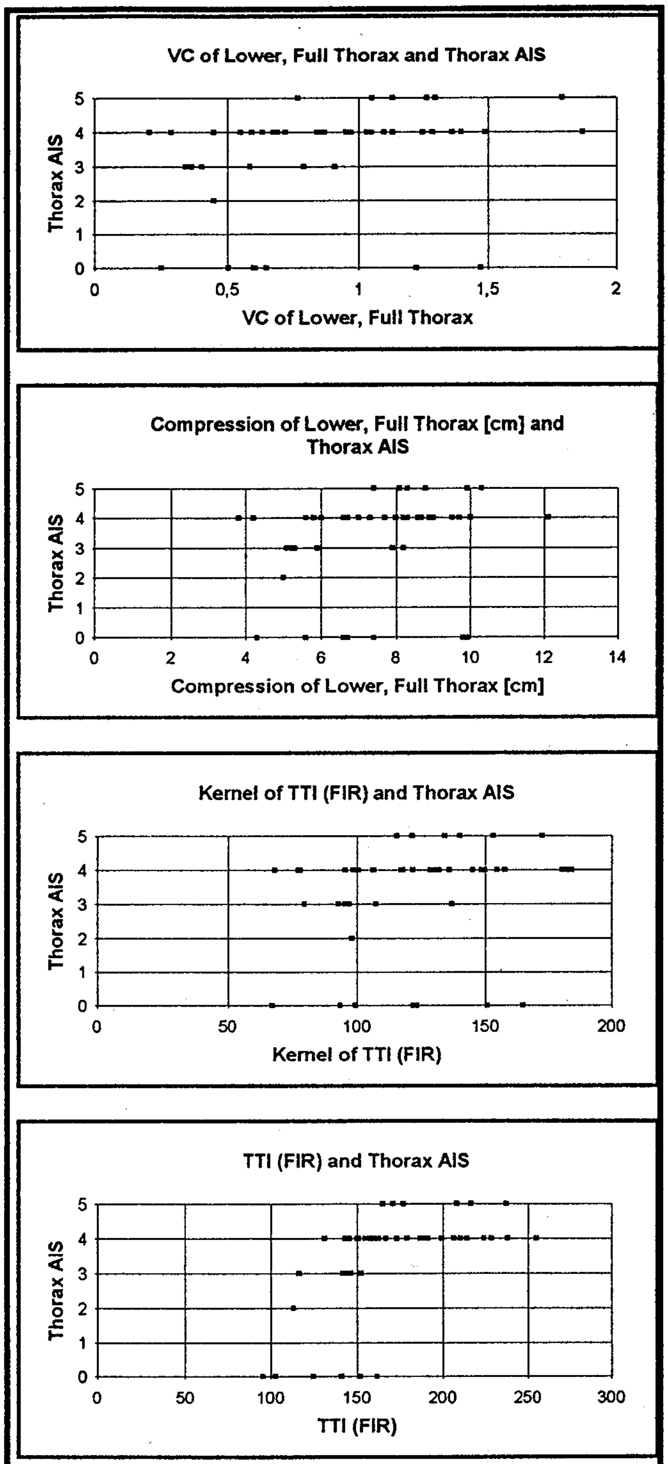

Figure 7: Candidates for the prediction of injuries and thorax AIS.

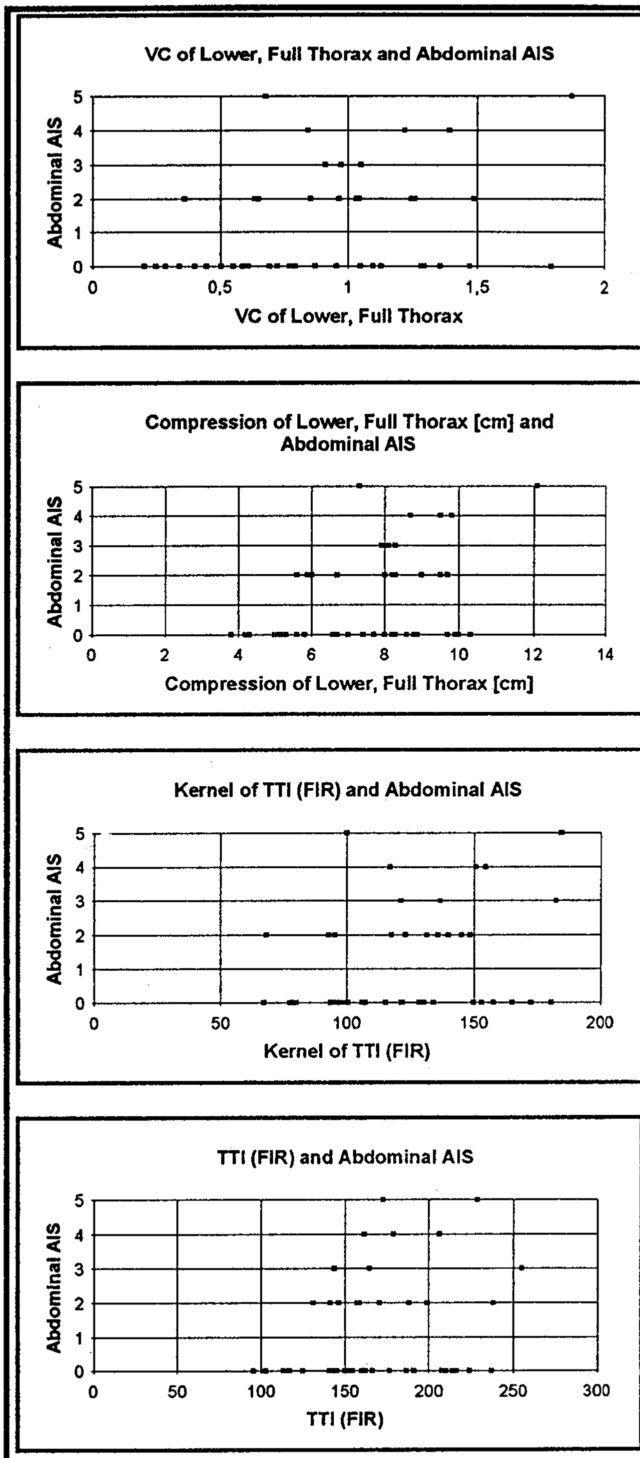

Figure 8: Candidates for the prediction of injuries and abdominal AIS.

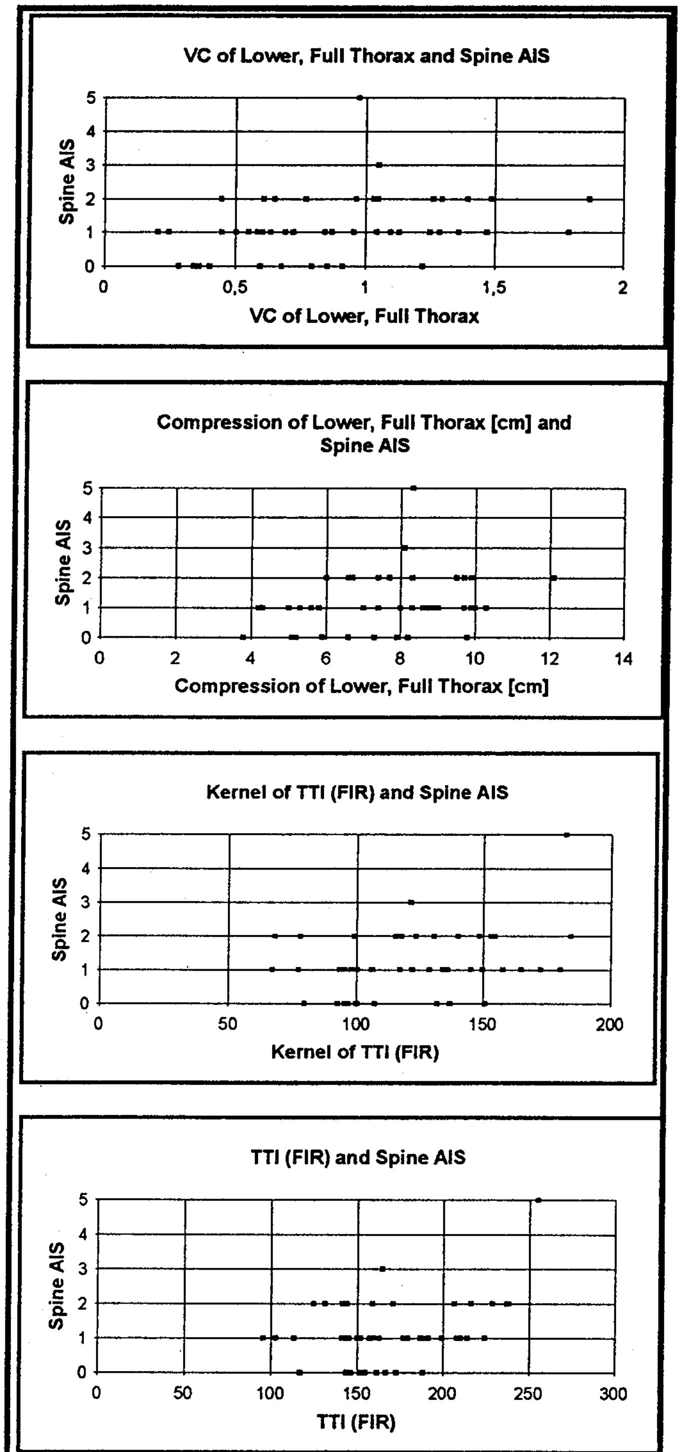

Figure 9: Candidates for the prediction of injuries and spine AIS.

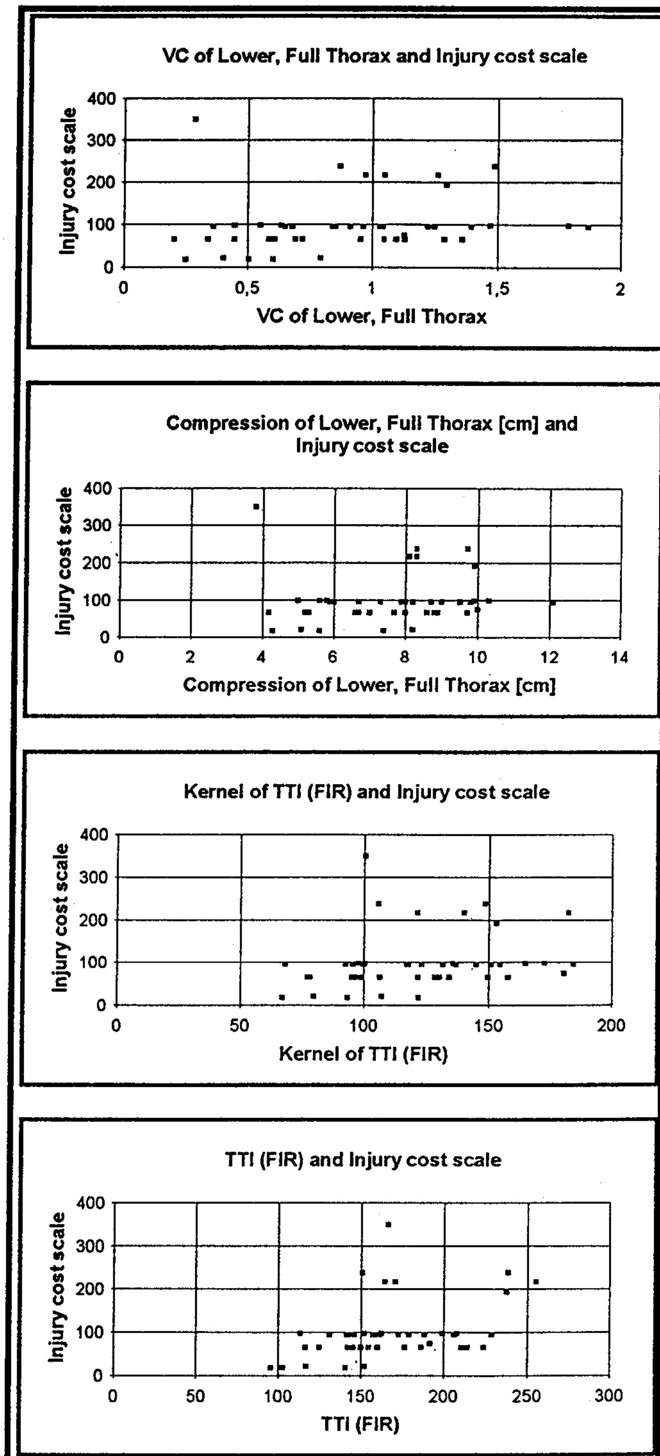

Figure 10: Candidates for the prediction of injuries and injury cost scale.

And again the same observation can be made for VC and the Kernel of TTI. These basic observations make clear that we still do not understand the biomechanics of lateral impact sufficiently.

The most effective measure would be to reduce the age of the car driving population to 30 or 40 years. Injury cost scale shows that TTI has some potential to reduce injury severity, even the kernel of TTI. All criteria show some ability to predict higher AIS of abdominal injuries. Compression might have some advantages to predict spine AIS. On the whole the plots in fig. 6 .. 10 show that we are far away from a clear idea how to protect in case of side impact.

AGE GROUPS

Some of the relationships that are found in the figures of the last section might be accidental due to the age dependence of the injuries. Hence the data were classified by three age groups. The age up to 35 years with 20 cases, the age of 36 to 55 years with 18 cases, and the age of more than 55 years with 9 cases. The Spearman Rank coefficient for these three age groups was computed (Table 6). The value must be read very carefully, since due to the smaller number of cases in these groups, the significance of the correlation is lower than for the total sample.

	Level of significance		
Number of tests	5%	1%	0.1%
47	28.5%	37.0%	47.0%
20	37.9%	52.0%	65.9%
18	39,9%	54,8%	69,0%
9	58,3%	76,7%	90,0%

Table 5: The relevance of the Spearman Rank Correlation coefficients to detect relations between load value and injury.

0..35 Years 20 Tests	Number of Rib Frakturs	Thorax AIS90	Abdominal AIS90	Spine AIS90	Maximum ICS
VC of Lower, Full Thorax	20,4%	32,8%	-29,7%	13,2%	18,4%
Kernel of TTI (FIR)	16,3%	25,4%	1,3%	0,4%	52,9%
TTI (FIR)	35,1%	44,1%	-14,4%	-18,4%	31,6%
Compression of Lower, Full Thorax [cm]	7,4%	22,6%	-37,1%	-6,8%	8,5%
Compression of Lower, Full Thorax [%]	7,6%	20,2%	-35,0%	-7,9%	7,1%

36..55 Years 18 Tests	Number of Rib Frakturs	Thorax AIS90	Abdominal AIS90	Spine AIS90	Maximum ICS
VC of Lower, Full Thorax	64,7%	-26,1%	-29,9%	44,0%	13,5%
Kernel of TTI (FIR)	69,7%	-10,6%	-9,7%	47,1%	26,9%
TTI (FIR)	63,5%	-29,4%	8,5%	20,0%	27,8%
Compression of Lower, Full Thorax [cm]	49,9%	-44,4%	-25,7%	23,8%	7,0%
Compression of Lower, Full Thorax [%]	43,9%	-31,1%	-42,9%	20,0%	-9,0%

56 Years .. 9 Tests	Number of Rib Frakturs	Thorax AIS90	Abdominal AIS90	Spine AIS90	Maximum ICS
VC of Lower, Full Thorax	35,0%	-46,7%	4,2%	21,7%	-11,7%
Kernel of TTI (FIR)	58,3%	-35,0%	-34,2%	-11,7%	1,7%
TTI (FIR)	55,0%	11,7%	-82,5%	5,0%	21,7%
Compression of Lower, Full Thorax [cm]	22,5%	-25,8%	-26,7%	22,5%	-7,5%
Compression of Lower, Full Thorax [%]	20,0%	-35,0%	-0,8%	38,3%	-1,7%

Table 6: The Spearman Rank Correlation of injuries of different body areas to possible pedictors and differentiated to three age groups.

Table 6 shows clearly that no statistical significant result can be reached by Spearman correlation. When used without the age parameter, the load values are not able to detect injury probability. Regarding age up to 35 years, only the maximum injury cost scale is estimated by TTI with statistical significance. Regarding age of 36 to 55 years, TTI, VC, and compression significantly predict the number of rib fractures. Other injuries are not predicted. Regarding the age group of more than 55 years, no prediction is possible. The following example with the number of rib fractures shows that even the high percentage of 58.3% for TTI and the number of rib fractures means nearly nothing. (Figure 11..13)

Because it is of main concern, regarding the injuries in side impact, we look at the risk of rib fractures in different age groups by studying the raw data.

Figure 11 shows the results for the VC. For the age up to 35 years, when the best relationship between load and injury should be expected, at VC=0.35 we have already 11 rib fractures and at VC=1.45 we have still cases with no rib fracture. For the ages of 36 to 55 years there is a slight trend. But the maximum of 29 rib fractures occurs at VC=1 and the trend above this value becomes negative. At an age of more than 55 years no relationship to any load value can be seen. In this age group, crash avoidance seems to be the only countermeasure.

The observation for the compression is similar (Figure 12). There seems to be no relationship in the age group up to 35 years, a slight trend in the "middle age", and no relationship at more than 55 years. In figure 13 the kernel of the TTI is plotted. In the age group up to 35 years, it describes the risk better than VC and compression: Although there are uninjured ribs for all TTI-values between 60g and 170g, the span, the maximum number of broken ribs for a special TTI value increases obviously from TTI 70g to TTI 150g. In the age group 36 to 55 years, the TTI shows a clear trend between 80g to 130g. Above 130g, the trend becomes negative, too. For age group of more than 55 years, the TTI, too, shows constant high risk.

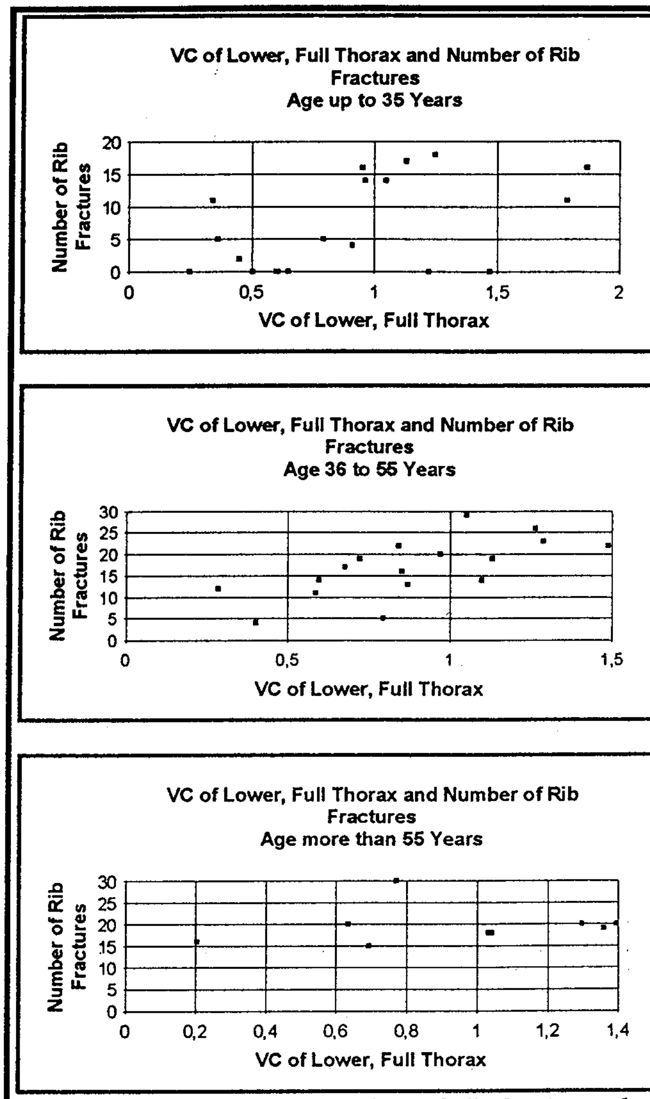

Figure 11: VC and the number of rib fractures for three age groups.

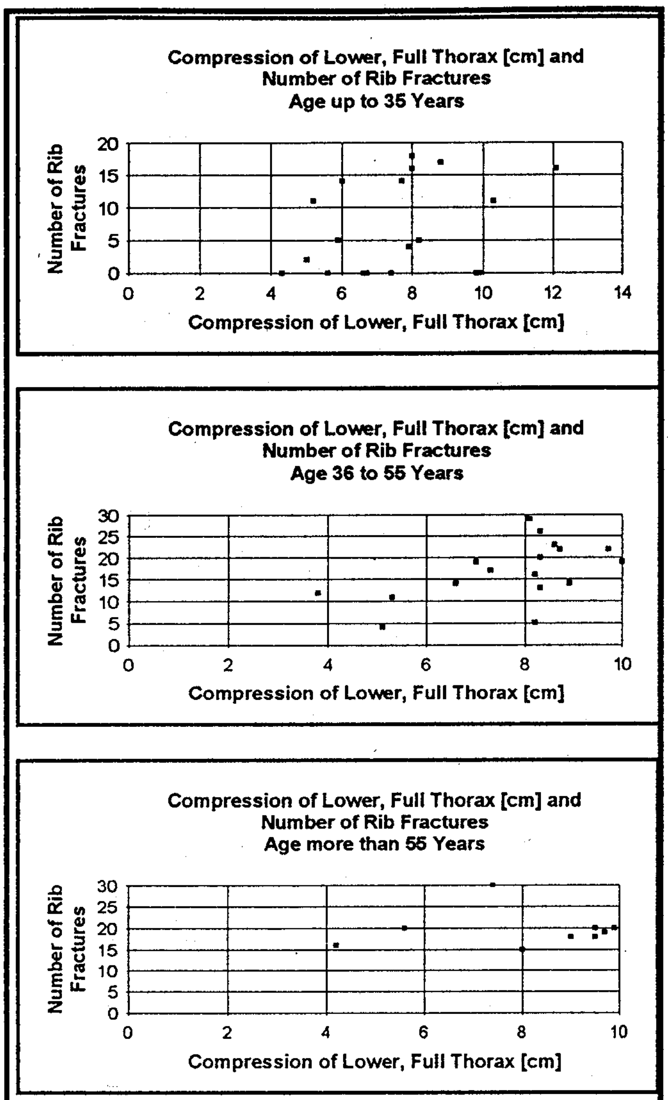

Figure 12: Compression and the number of rib fractures for three age groups.

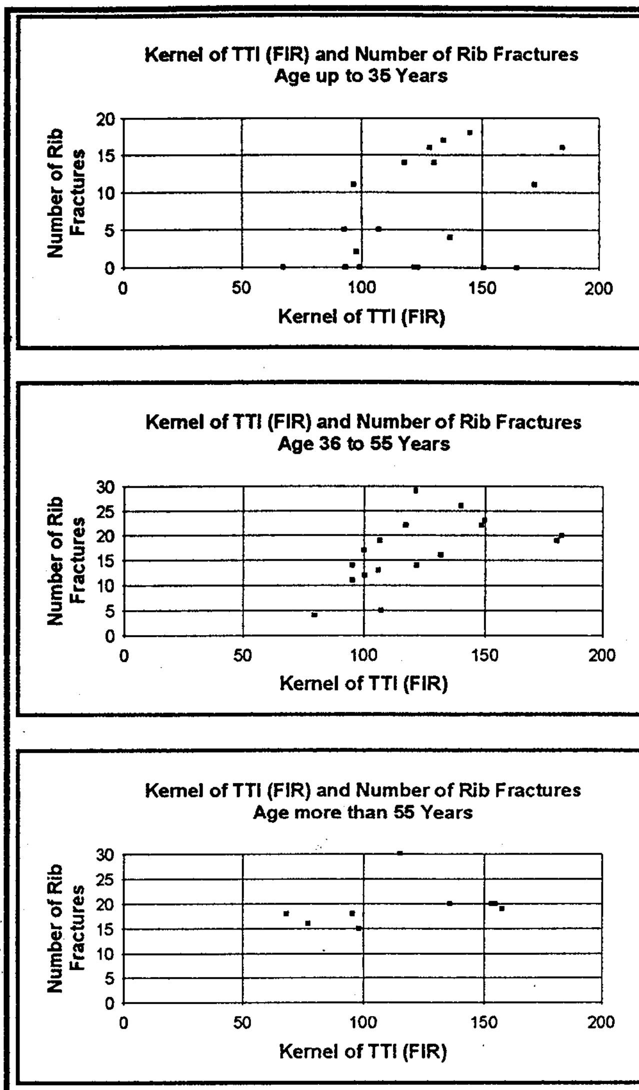

Figure 13: The kernel of TTI (FIR) and the number of rib fractures for three age groups.

REPEATABILITY

The repeatability of the tests should be taken into account, too. The ability of a test procedure to describe the risk of injury, results from the ability of the dummy load values, to predict injuries. But it results also from the precision of the dummy load values of a single test. The repeatability study which was conducted at several test sites in 1993 [3] with the EEVC test procedure shows, how much the amount of information is reduced by the uncertainty of the test result (Table 6). So when we combine both, the incertainty of the dummy load value, to predict injury, and the incertainty of the test procedure, to determine the correct dummy load values, there is nearly no information that can be derived from such a test in terms of safety of the occupant. The question is still open, what the real safety features for side protection are, and by what means they can be determined and evaluated.

Repeatability of 4 EEVC-Tests per Vehicle						
	Vehicle					
	Small		Mid-Size		Large	
	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
Viscous Criterion	0,64	20%	1,43	33%	0,49	34%
Compression	34,5	9%	48,3	18%	27,5	22%
Abdomen	3,3	27%	1,1	30%	1,2	20%
Pubic Symphysis	5,7	9%	2,0	35%	3,0	6%

Table 6: Results of an European Repeatability Study with 4 EEVC side impact tests with Eurosid 1 dummy for 3 different vehicles.

CONCLUSION

Predominant for injuries in lateral collisions is the age and the biometric condition of the occupant. There is only minor amount of information that can be derived from load values like TTI, VC, or compression. If one neglects this and compares the three load values, there is no clear answer, whether TTI, compression, or VC are better predicting the injury. The overall severity, which is reflected by the injury cost scale ICS, is best predicted by TTI. Since the overall severity is of main interest for the person injured, there are some advantages for TTI. At least there is no reason, to switch from TTI to compression and/or VC, since they do not offer advantages compared to TTI. So the result of the FAT research is to use TTI, and to look for an improved performance criterion, which is worth to pay the cost of a change. The European plans to use compression and later VC are not worth the additional money which they cost the consumer. Additional cost results from the different criteria because the measures in the vehicle that are forced by the different dummy loads are quite different and sometimes contradictory. This is not justifiable on the background that neither VC nor compression offer real advantages compared to TTI. As we know today the full-scale tests that have to be conducted have a poor repeatability. So the small amount of biomechanical information that can be derived from the dummy load will be lost because of the scattering of the test. A paper on this subject will be published on this conference [3]. If these figures are used to derive tolerance levels and limits, it must be pointed out that there is quite a difference between a TTI of a human being and a dummy TTI. And there is a difference between US-SID-TTI and EUROSID-TTI. So if TTI is used for the EUROSID, it needs a calibration to get an appropriate limit to e. g. 90 g on the US-SID, because of the different rib masses.

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Protection for the Thorax Injury Severity in the 90-Degree Lateral Collision

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94-S1-O-02

ABSTRACT

The qualities of the prediction of the Thoracic Trauma Index (TTI) and the Viscous Criterion (VC) for the torso injury severity according to AIS will be tested at the 90-degree car to car lateral collision and impact of the left torso against a rigid or a padded wall. Forty-two restrained human corpses in the age range 18 to 65 years, located at the near-side front passenger seat were used. The impact velocity amounted 40 to 60 km/h, left and right side impacts were simulated by using standard or modified car side structures. By the second group tested, the left side of the test subjects were impacted under one of two different test conditions: 24 km/h rigid wall and 32 km/h padded wall.

The thorax deformation has been evaluated by a double integration of the acceleration difference at the 4th and 8th rib, near-side and far-side. In the above mentioned loading conditions occurred deformation maxima of 6 to 138 mm (mean value 69 mm) and VC values of 0.3 to 4.7 m/s (mean value 1.6m/s) and TTI values of 85 to 252 (mean value 163). The torso injury severity amounted between AIS 0 and AIS 5.

The statistical analysis showed a stronger influence of the age among the test conditions in regard to the injury severity than the loading criteria in the investigated collective. The TTI shows the highest correlation with thorax AIS and the number of rib fractures. VC is more suitable to predict abdomen AIS severity.

The results will be critically discussed with respect to the conditions needed for the injury criteria and the safety qualifying potentials of these criteria.

INTRODUCTION

The discussion about the most suitable injury criterion in order to review the extent of the safety level of cars in a 90-degree lateral collision is not concluded yet. The TTI, a chest acceleration-based measurement, combined with anthropometric data was developed by the National Highway Traffic Safety Administration (Eppinger et al., 1984 , Morgan et al. , 1986) and is included in the Federal Motor Vehicle Standard No. 214 (FMVSS 214), side impact protection. Per FMVSS 214, the TTI (d) limit is 85 for four-door cars and 90 for two-door cars.

Lau and Viano (1986) have proposed the VC , a time function formed by the product of the velocity of deformation, V(t), and the instantaneous compression, C(t). VC is discussed at the time for an European side protection criterion.

The aim of the paper is to investigate the suitability of the above mentioned criteria for prediction of injury severity in a realistic loading of the human trunk.

METHOD

Test Subjects

The surrogates used in the lateral impact tests were unembalmed uninjured human corpses in the age range 18 to 65 years, with a mean age of 40 years.

Test Equipment

The tests were performed on the Institute's deceleration sled devices by using two different configurations:

a) 90° Car/Car Lateral Collision

The striking vehicle was the sled, already available, a part of the CCMC barrier frame and the CCMC deformation element (Gabbels, 1985) were mounted onto the front of the sled. The mass of the striking vehicle was 950 kg (Fig. 1). The impact velocity of the striking vehicle was 40 to 60 km/h.

The struck vehicle was a two or a four door car body shell of a lower or an upper medium class vehicle mounted on a moveable platform (dolly). The mass of the struck vehicle, including the corpse, was 950 and 1100 kg. Each vehicle was impacted in a part of the tests only on the right side, in a second collective the left and right side was impacted.

The corpse was located in the near side front passenger seat and restrained by a 3-point belt. The struck vehicle was initially at rest (Fig. 1).

b) Wall Collision

A bench seat with an instrumented side panel was mounted on the sled transverse to the direction of the travel. The side panel was instrumented with load cells at the thoracic level and at the pelvic level. The corpses were positioned on the bench seat distal to the side panel and remained in this position until the sled began to decelerate, the subject then slid across the bench finally impacting against the side panel at approximately the pre-deceleration sled velocity. All tests were performed with the arm on the impact side down. A lateral low friction sliding movement was achieved by dressing the subject and sitting it on two plastic sheets. The mass of the fully assembled sled with subject was 710 kg (Fig. 2).
Sixtythree tests were performed in both impact configurations.

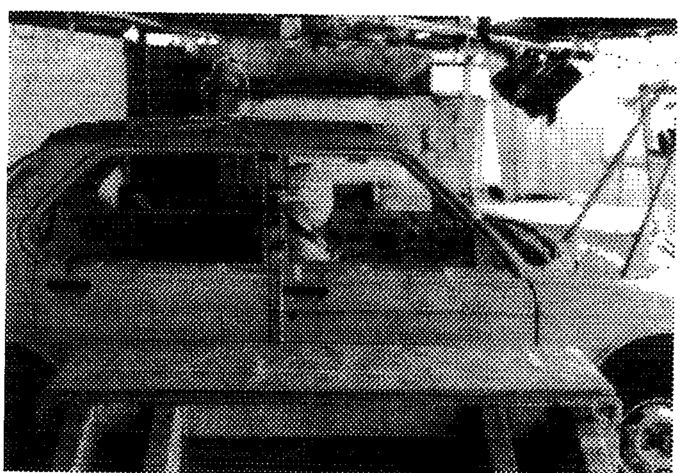


Figure 1. 90° Car/Car Lateral Collision

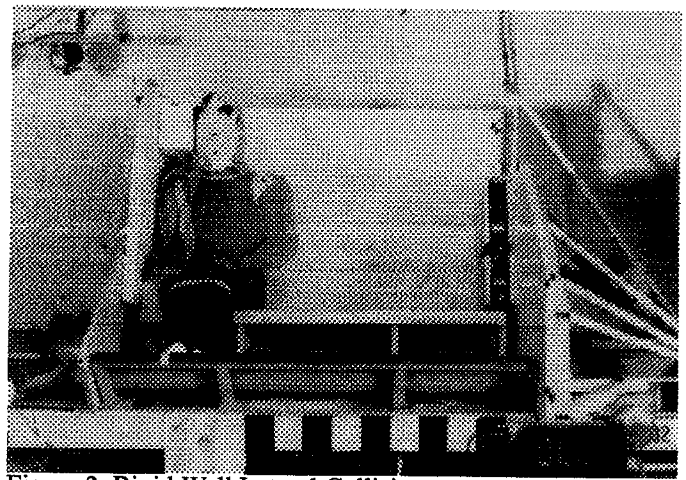


Figure 2. Rigid Wall Lateral Collision

Test Matrix:

Car/Car side impact	*Impact velocity [km/h]*				
Impact side	**40**	**45**	**50**	**60**	*Σ*
Left	3	8	3	1	*15*
Right	2	8	17	0	*27*
Σ	*5*	*16*	*20*	*1*	*42*

Wall impact	*Impact velocity [km/h]*		
Wall	**24**	**32**	*Σ*
Padded	0	5	*5*
Rigid	7	9	*16*
Σ	*7*	*14*	*21*

Instrumentation

The corpses were instrumented with the twelve accelerometer thoracic array as developed by Robbins et al. (1976) and were used by Eppinger et al. (1978) to instrument the ribs, sternum, and thoracic vertebrae. All rib accelerometers were mounted so that lateral rib accelerations were measured. The sacrum was instrumented with a triaxial accelerometer.

Autopsy - Injury Severity

A detailed autopsy was carried out with special attention on shoulder, thoracic, abdominal and pelvic injuries. The injuries were coded according to the AIS 1990.

Calculation of TTI

The acceleration data from the accelerometers mounted on the ribs and spine were digitized at 1600 samples per second and digitally filtered using a finite impulse response (FIR) filter having a band pass frequency of 100 Hz. The TTI was calculated according the formula:

$$TTI = 1.4 \cdot AGE + 0.5(RIBY + T12Y)MASS \,/\, M_{std}$$

where:

AGE = age of test subject (in years)

RIBY = higher maximum acceleration value of the 4th or 8th rib struck side

T12Y = maximum acceleration value of the 12th thoracic vertebrae, y-direction

MASS = subject's mass (kg)

M_{std} = standard mass (75 kg)

Calculation of VC

The rib acceleration data were filtered with a Butterworth channel class 180 digitalfilter. A curve was constructed for both the 4th. and 8th. ribs from the acceleration difference (ADIF) between accelerometers mounted at the impact side (AIMP) and the opposite side (AOPP).

$$ADIF(t) = AIMP(t) - AOPP(t)$$

This curve was then integrated twice producing deformation (DEF) at the level 4th. and 8th. ribs with respect to time.

$$DEF(t) = \iint ADIF(t)\, dt$$

Due to the double integration process and the inherent noise in the original data, it was necessary to calculate a correction factor for deformation. The integration procedure produced curves which constantly rose or fell during times where deformation was no longer possible. For this observation and to simplify the procedure it was assumed that there was a constant error in the original acceleration data that was transformed into a quadratic function through the double integration. As the deformation should be zero before and after the impact a satisfactory polynomial function was found using the least square method, thus fitting a parabola through the first and the last points on the deformation curve. This parabola was then subtracted from the deformation curve so as to estimate the actual deformation. Finally, the Viscous Criterion (VC) was calculated in the normal manner from this corrected deformation data.

$$VC(t) = \frac{\delta D(t)}{\delta t} \cdot \frac{D(t)}{D}$$

D(t) is the deformation and D the breadth of the body in mm.

This mathematical method was validated by 15 EUROSID tests in which VC values from measured (VCm) and calculated (VCc) thoracic deformations were compared (Mattern et al, 1994).

Statistical Methods

At first a Spearman Correlation analysis was performed with the more important anthropometric data and the mechanical responses. The probability of injury severities, AIS scale, as functions of cadaver anthropometric data, TTI and VC either individually or in combination, were calculated using standard logistic regression models, which were then compared using goodness of fit models.

Analysis of Goodness of Fit

The goodness of fit was assessed by four criteria of similar importance.

1. The ratio of correctly predicted observations (PRED). The number of correctly predicted observations, i.e. correct AIS severity, was divided by the total number of observations.
2. The ratio of correctly ordered pairs (PAIRS). With this method all pairs of observations with different AIS values were formed. The fit was assessed by observing whether this pairs remained in the same order than predicted, i.e. higher and lower severity. When the pairs were predicted with the equal severity they were removed from the analysis. The goodness of fit was therefore based on the share of correctly predicted ordered pairs from the total number of ordered pairs with different AIS severities.
3. The mean AIS difference (AISDIF). The mean absolute difference between observed and predicted AIS values.
4. The mean probability difference (PDIF). The mean absolute difference between the estimated probabilities for the observed and predicted AIS values.

RESULTS

Mechanical Responses

Figure 3 shows frequency distributions of measured and according to the measured the ëvaluated mechanical responses. The highest accelerations measured were observed at the level of the 8th impacted rib, about the same level at the 4th rib and the twelfth thoracic vertebrae (Fig 3a, 3b, 3g). The higher acceleration values at the level of the 8th rib result in also higher deflections at this region (80 mm to 120 mm) in comparison to the level of the 4th rib (45 mm to 90 mm) (Fig. 3d, 3c). Similar behaviour show the VC values, they are higher at the level of the 8th rib (Fig. 3f, 3e).

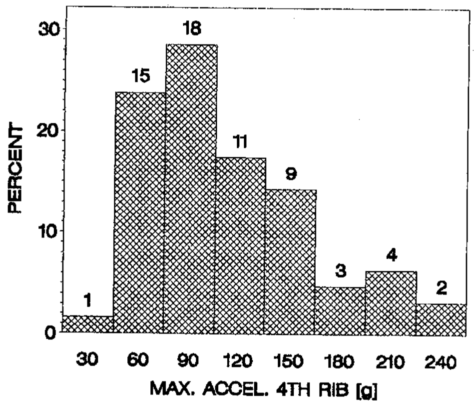


Figure 3a.

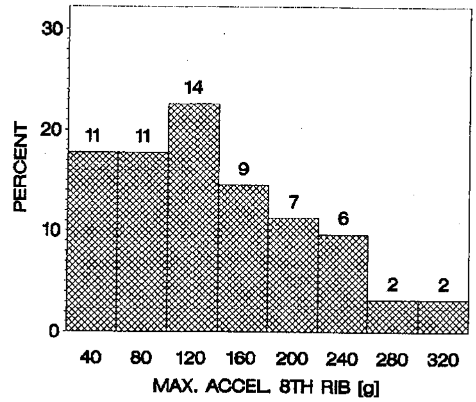


Figure 3b.

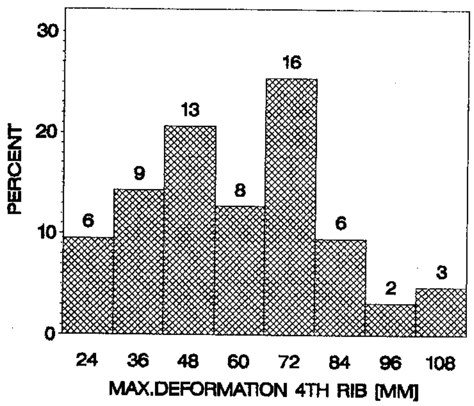


Figure 3c.

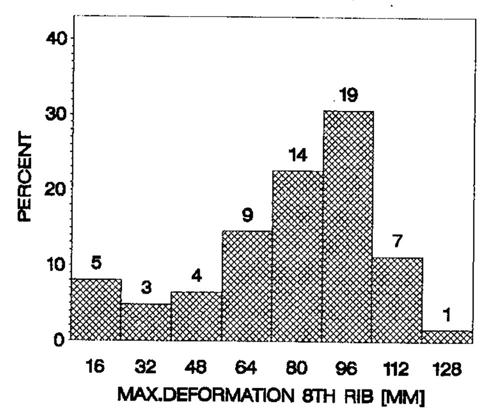


Figure 3d.

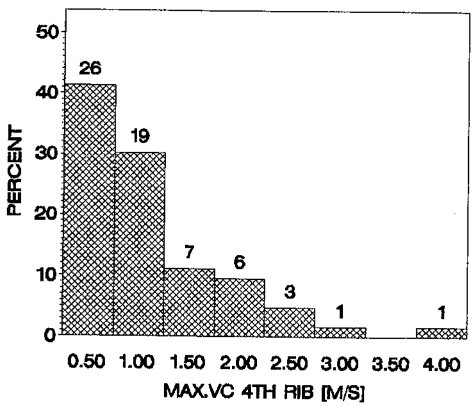


Figure 3e.

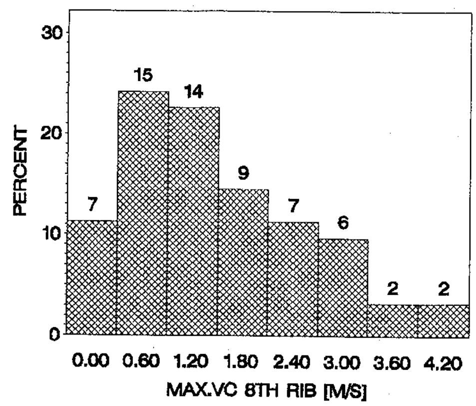


Figure 3f.

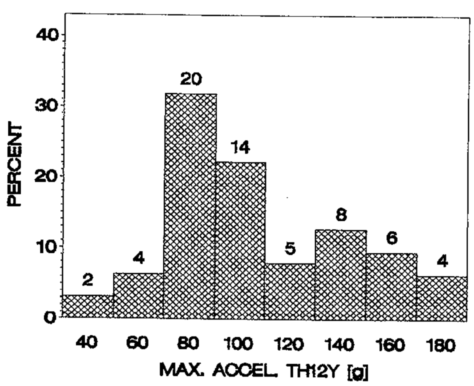


Figure 3g.

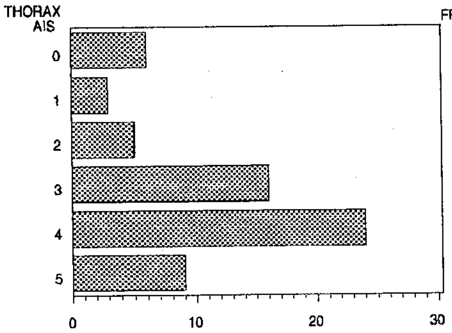
Figure 3. Frequency distributions of measured and evaluated mechanical responses.

a) Acceleration at the 4th impacted rib.
b) Acceleration at the 8th impacted rib.
c) Deformation at the level of the 4th impacted rib.
d) Deformation at the level of the 8th impacted rib.
e) VC at the level of the 4th rib.
f) VC at the level of the 8th rib.
g) Acceleration at the 12th thoracic vertebrae.

Medical Findings

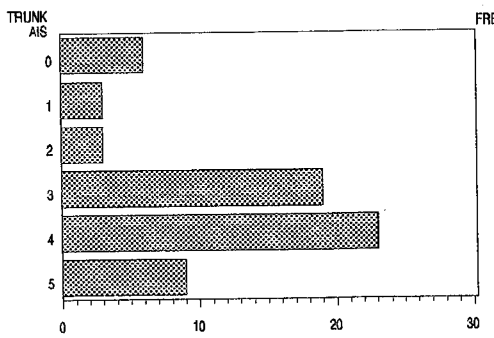
The thoracic injury severity was defined through the number of the rib fractures, which were located predominantly at the impact exposed body side; fractures at the far-side trunk region were rarely observed. Up to 36 rib fractures were found (Fig. 4d). Eleven to twenty were the most frequent number of rib fractures observed (40%). For thorax AIS the most frequent injury levels were AIS 3 (25,4%) and AIS 4 (38,1%) as shown in Fig. 4a. The trunk injury severity, defined as the higher thorax AIS or abdomen AIS, is determined through the thorax injury severity, therefore the AIS levels 3 and 4 are also for the trunk the most frequent ones (30,2% and 36,5% / Fig. 4b, 4c). Rib fractures are on the other hand dependent upon the age. The Spearman Correlation Coefficient between age and number of rib fractures amounts 0.74 (Fig. 5d), with the thorax AIS 0.70 (Fig. 5a) and the trunk AIS 0.72 (Fig. 5b). Furthermore high correlations of 0.58 with the number of rib fractures, the thorax AIS and the trunk AIS shows the age dependent TTI (Fig. 5a, 5b, 5d). 63,5% of the cases tested showed no abdomen injuries; the most frequent injury was the laceration of the capsule of the liver with a deep lesser then 3 cm, injury severity, AIS 2 (16%). In 11% of the cases tested an abdomen AIS severity of the level 3 was found, which means laceration of the liver or spleen (Fig. 4c).

In contrast to the thorax, the abdomen injury severity is influenced of the body side impacted and is lesser dependent of the age. Liver ruptures were the most frequent injuries in right side impacts. Furthermore no high correlations were found between the abdomen AIS and mechanical responses. The highest correlation with abdomen AIS shows the VC calculated at the level of the 4th rib (r=0.52, r=0.44) followed of the TTI (r=0.43, r=0.38) and the deflection calculated at the level of the 4th rib (r=0.44, r=0.37) in left side and side independent impacts (left and right side impacts summarized / Fig. 5c, 5e). In right side impacts only lower correlations with the parameters testet were found (Fig. 5f).



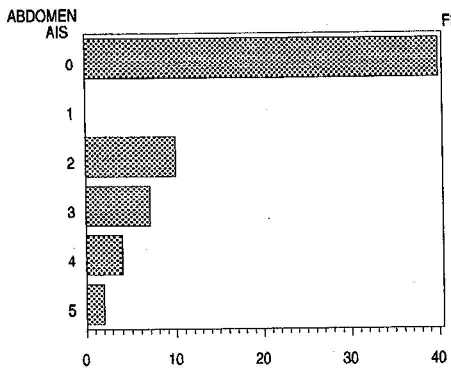
THORAX AIS	FREQ.	CUM. FREQ.	PCT.	CUM. PCT.
0	6	6	9.52	9.52
1	3	9	4.76	14.29
2	5	14	7.94	22.22
3	16	30	25.40	47.62
4	24	54		85.71
5	9	63	14.29	

Figure 4a. Thoracic injury severity



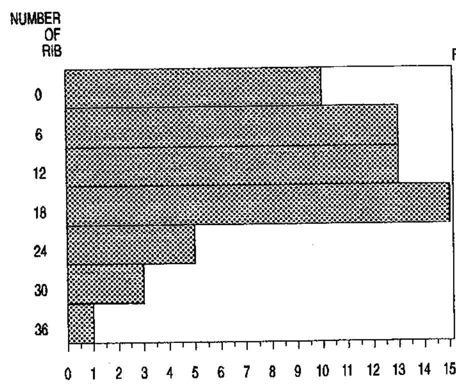
TRUNK AIS	FREQ.	CUM. FREQ.	PCT.	CUM. PCT.
0	6	6	9.52	9.52
1	3	9	4.76	14.29
2	3	12	4.76	19.05
3	19	31		49.21
4	23	54		85.71
5	9	63	14.29	

Figure 4b. Trunk injury severity



ABDOMEN AIS	FREQ.	CUM. FREQ.	PCT.	CUM. PCT.
0	40	40		
1				
2	10	50	15.87	79.37
3	7	57	11.11	
4	4	61	6.35	
5	2	63	3.17	

Figure 4c. Abdominal injury severity



NUMBER OF RIB	FREQ.	CUM. FREQ.	PCT.	CUM. PCT.
0	10	10	16.67	16.67
6	13	23	21.67	
12	13	36	21.67	
18	15	51	25.00	
24	5	56		
30	3	59	5.00	
36	1	60	1.67	

Figure 4d. Number of rib fractures

Figure 4. Frequency of the injury severity of thoracic, abdominal and trunk injuries.

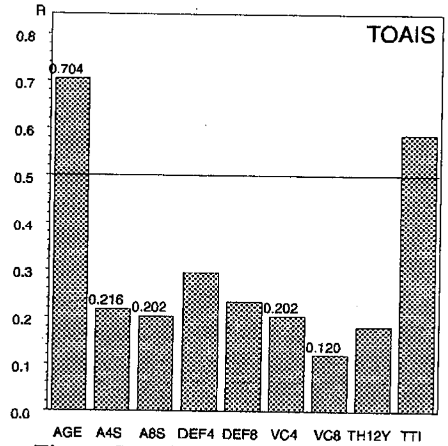


Figure 5a. Thoracic injury severity

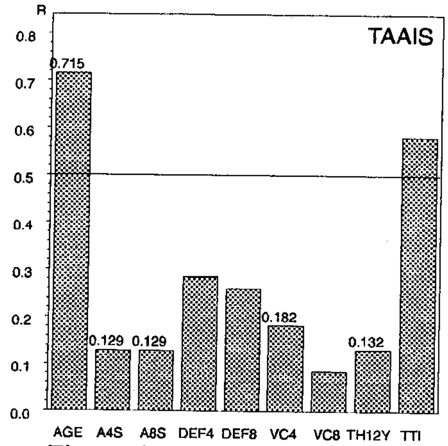


Figure 5b. Trunk injury severity

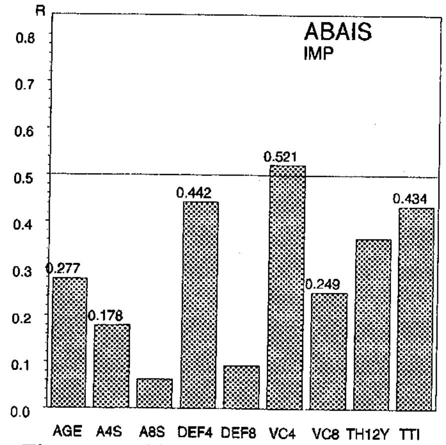


Figure 5c. Abdominal injury severity (left side impact)

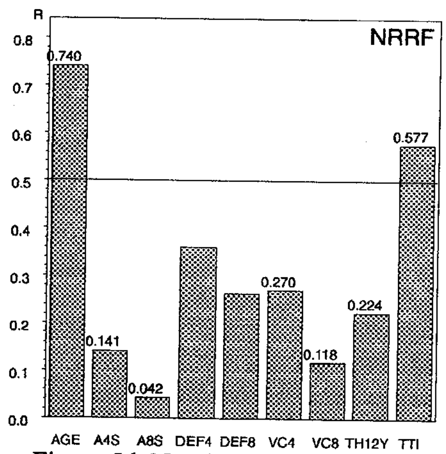


Figure 5d. Number of rib fractures

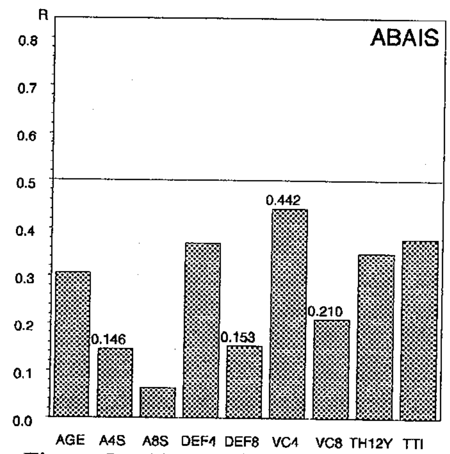


Figure 5e. Abdominal injury severity

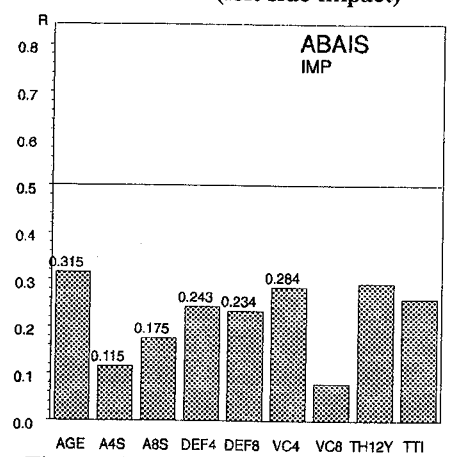


Figure 5f. Abdominal injury severity (right side impact)

Figure 5. Spearman correlation of thoracic, trunk and abdominal injury severity vs age, measured and evaluated mechanical responses.

Injury Criteria

Logistic regression analysis were performed with anthropometric data (age) and biomechanical responses (peak acceleration, compression, VC) or combination (TTI, acceleration with age, VC with age) thereof occurring to the thorax, abdomen and trunk injury severity. Table 1a shows the probability analysis according the four chosen goodness of fit criteria. In the analysis all the injury severity degrees (AIS 0 to AIS 5) were observed. The highest reliability to predict thorax injury severity , as uniparametric magnitude, gives the subject's age (49% correctly predicted observations, 80% correctly ordered pairs), followed by the mechanical response deflection at the level of the 8th rib, acceleration maximum at the Th12, y-direction and the VC evaluated at the level of the 4th rib, further the acceleration maximum at the 4th rib impacted side, the VC evaluated at the level of the 8th rib, the acceleration maximum at the 8th rib impacted side and at last, the compression at the level of the 4th rib (37% correctly predicted observations, 58% correctly ordered pairs). The TTI, which is a combination of subject's age and mechanical responses, shows higher prediction probabilities (52% correctly predicted observations, 75% correctly ordered pairs), the highest prediction probability was observed with the combination of the mechanical response, maximum acceleration at the Th12, y-direction with the age (60% correctly predicted observations, 84% correctly ordered pairs).

If two injury severity groups for the thorax (AIS < 4 and AIS ≥ 4) were used for the logistic regression model, then higher numbers of correctly predicted observations were found; the highest uniparametric variable is the age with about 86% correctly predicted observations, the highest biparametric model, the combination of age and compression at the level of the 4th rib showed about 89% correctly predicted observations (Table 1b).

The investigated models for abdomen injury severity showed a higher number of correctly predicted observations in relation to the thoracic AIS models; this results through the high number of the uninjured cases, the collective investigated includes 40 uninjured cases, which were also correctly predicted

(Table 2a). The same observations were made if two injury severity groups (abdomen AIS=0 and abdomen AIS>0) for the evaluation were used; however, the percentage of the correctly predicted observations is lower in relation to the thoracic injury severity (Table 2b). For the trunk injury severity (the higher AIS-value of thorax or abdomen) the model has shown lower numbers of correctly predicted observations (Table 3).

Table 1
Probability Analysis of the Thoracic Injury Severity with the Age, Measured and Evaluated Mechanical Responses According the Four Chosen Goodness of Fit Criteria

a) TOAIS 0 to TOAIS 5

Goodness of fit criteria for the different models of the thoracic AIS severity (all levels).

Model	PRED	PAIRS	AIS DIF	PDIF
AGE	0,49	0,80	0,70	0,13
TTI	0,52	0,75	0,81	0,13
VC4	0,40	0,58	1,06	0,13
VC8	0,39	0,54	1,08	0,14
DEF4	0,37	0,62	1,10	0,13
DEF8	0,40	0,59	1,08	0,13
TH12Y	0,40	0,57	1,06	0,13
A4S	0,39	0,58	1,08	0,13
A8S	0,38	0,58	1,10	0,13
C4	0,37	0,58	1,08	0,13
C8	0,39	0,52	1,07	0,14
AGE,VC4	0,56	0,83	0,75	0,13
AGE, VC8	0,52	0,83	0,71	0,14
AGE, DEF4	0,46	0,83	0,81	0,14
AGE, DEF8	0,50	0,81	0,79	0,15
AGE, A4S	0,52	0,81	0,73	0,13
AGE, A8S	0,53	0,80	0,71	0,14
AGE, C4	0,52	0,84	0,74	0,14
AGE, C8	0,51	0,83	0,77	0,16
AGE, TH12Y	0,60	0,84	0,60	0,13

b) TOAIS < 4 and TOAIS ≥ 4

Goodness of fit criteria for the different models of the thoracic AIS severity (<4 or >=4).

Model	COUNT	PRED
AGE	54	0,86
TH12Y	32	0,51
TTI	45	0,71
A4S	37	0,59
A8S	36	0,57
C4	33	0,52
C8	35	0,56
DEF4	36	0,57
DEF8	34	0,54
VC4	36	0,57
VC8	36	0,57
AGE, TH12Y	54	0,86
AGE, A4S	54	0,86
AGE, A8S	55	0,87
AGE, C4	56	0,89
AGE, C8	55	0,87
AGE, DEF4	55	0,87
AGE, DEF8	55	0,87
AGE, VC4	55	0,87
AGE, VC8	54	0,86

Table 2
Probability Analysis of the Abdominal Injury Severity with the Age, Measured and Evaluated Mechanical Responses According the Four Chosen Goodness of Fit Criteria

a) ABAIS 0 to ABAIS 5

Goodness of fit criteria for the different models of the abdominal AIS severity (all levels).

Model	PRED	PAIRS	AIS DIF	PDIF
AGE	0,63	0,65	1,06	0,16
TTI	0,62	0,70	1,11	0,16
VC4	0,63	0,73	1,00	0,16
DEF4	0,65	0,70	0,92	0,14
TH12Y	0,65	0,68	1,02	0,16
C4	0,65	0,69	1,00	0,15
AGE, DEF4	0,63	0,74	0,95	0,13
AGE, C4	0,62	0,74	0,95	0,13
AGE, VC4	0,65	0,78	0,86	0,13
AGE, TH12Y	0,60	0,77	1,13	0,13

b) ABAIS = 0 and ABAIS > 0

Goodness of fit criteria for the different models of the abdominal AIS severity (=0 or >0).

Model	COUNT	PRED
TH12Y	40	0,63
TTI	40	0,63
A4S	41	0,65
A8S	41	0,65
C8	42	0,67
C4	43	0,68
DEF8	40	0,63
DEF4	42	0,67
VC4	43	0,68
VC8	39	0,62
AGE, TH12Y	48	0,76
AGE, A4S	41	0,65
AGE, A8S	42	0,67
AGE, C4	48	0,76
AGE, C8	44	0,70
AGE, DEF4	48	0,76
AGE, DEF8	41	0,65
AGE, VC4	48	0,76

Table 3
Probability Analysis of the Trunk Injury Severity with the Age, Measured and Evaluated Mechanical Responses According the Four Chosen Goodness of Fit Criteria
TAAIS 0 to TAAIS 5

Goodness of fit criteria for the different models of the trunk AIS severity (all levels).

Model	PRED	PAIRS	AIS DIF	PDIF
AGE	0,44	0,78	0,83	0,13
TTI	0,46	0,75	0,87	0,13
VC4	0,32	0,58	1,13	0,11
DEF4	0,37	0,62	1,08	0,11
TH12Y	0,37	0,58	1,08	0,11
C4	0,33	0,58	1,11	0,11
AGE, DEF4	0,52	0,82	0,75	0,13
AGE, C4	0,54	0,83	0,69	0,14
AGE, VC4	0,56	0,81	0,75	0,12
AGE, TH12Y	0,57	0,83	0,68	0,13
AGE, VC8	0,51	0,82	0,73	0,13

Logistic analysis of the probability of severe thorax injury (AIS ≥ 4) versus age and selected biomechanical responses are shown in Figures 6a-6i. 50 to 50 change of inducing thoracic injury severity of AIS ≥ 4 is for : age =38 years, acceleration at the 4th rib near side = 95 g, acceleration at the 8th rib near side = 120 g, deflection at the level of the 4th rib = 57 mm, deflection at the level of the 8th rib = 68 mm, acceleration at the level of the 12th thoracic vertebrae y-direction = 90 g, VC at the level of the 4th rib = 0,83 m/s, VC at the level of the 8th rib =0,5 m/s, and TTI = 155.

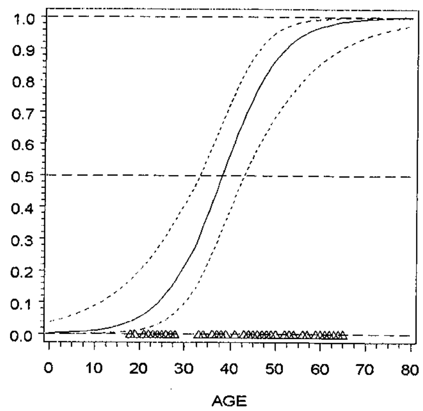


Figure 6a.

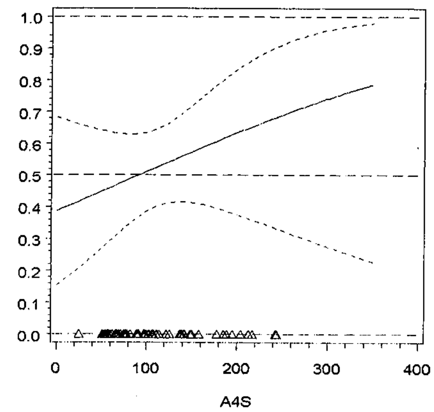


Figure 6b.

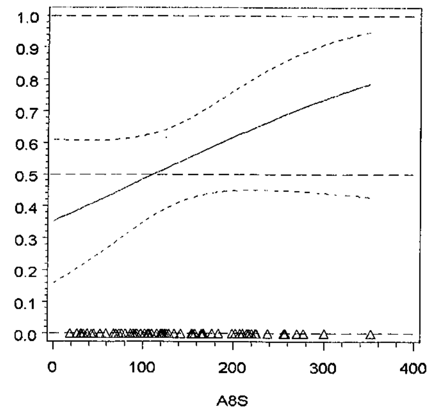


Figure 6c.

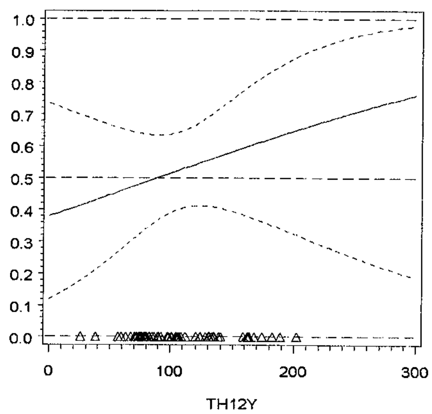


Figure 6d.

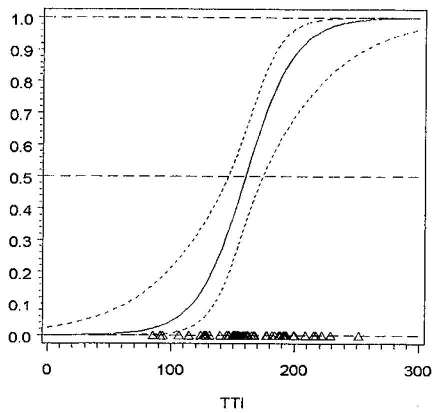


Figure 6e.

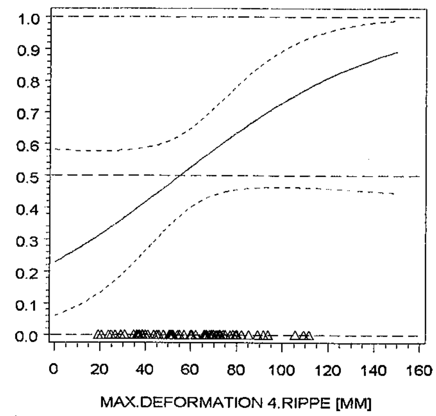


Figure 6f.

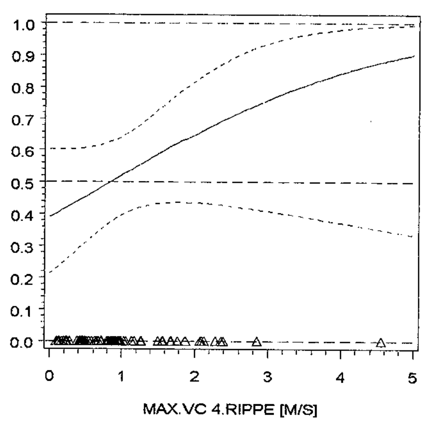


Figure 6g.

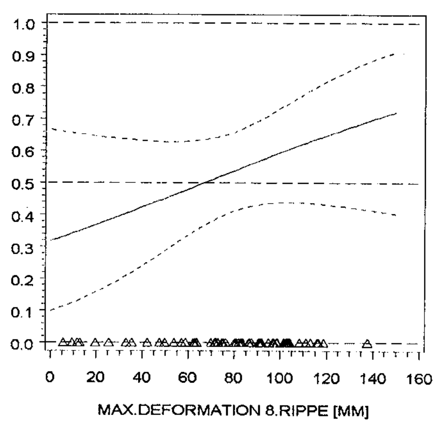


Figure 6h.

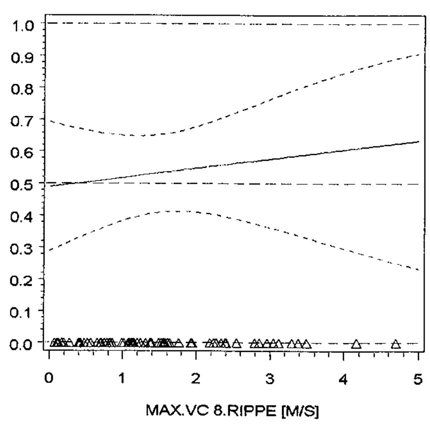


Figure 6i.

Figure 6. Logistic plots of probability of thoracic injury severity vs age and selected biomechanical responses. a) Age. b) Acceleration at the 4th rib. c) Acceleration at the 8th rib. d) Acceleration at the 12th thoracic vertebrae. e) TTI. f) Deformation at the level of the 4th rib. g) VC at the level of the 4th rib. h) Deformation at the level of the 8th rib. i) VC at the level of the 8th rib. (The triangles at the bottom mark the range of the corresponding data).

Logistic plots of probability of AIS 4 or greater to the thorax versus the mechanical responses Th12y and VC4, two magnitudes which show high numbers of correctly predicted observations, are evaluated by fixed age of 20, 40, and 60 years in Fig. 7a, 7b. The 50 to 50 change is significant influenced from the age, 20 years old subjects tolerate high values of acceleration at Th12y or VC.

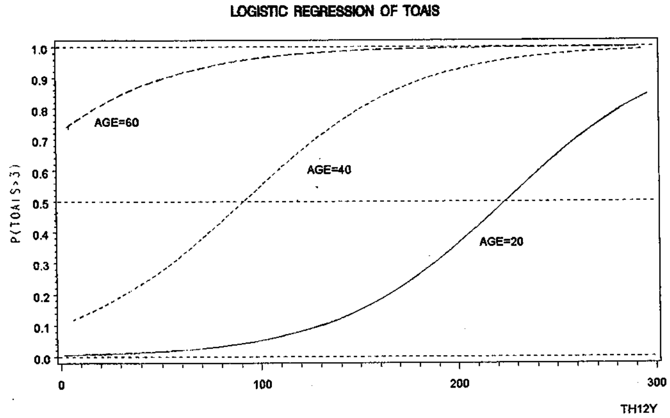


Figure 7a.

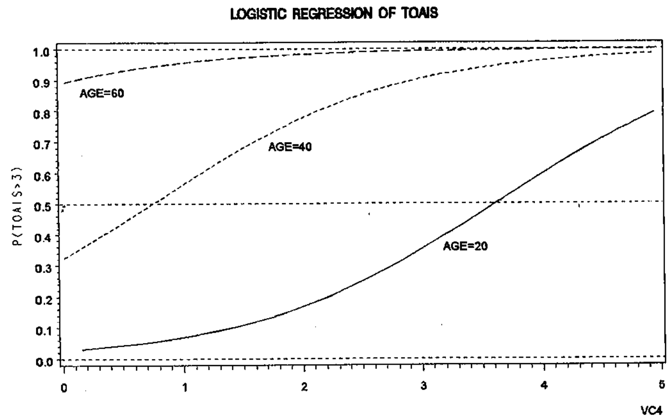


Figure 7b.

Figure 7. Logistic plots of probability of thoracic injury severity vs the mechanical responses TH12Y (a) and VC4 (b) by fixed age 20, 40 and 60 years.

At least, the predicted probability curves of thorax AIS versus the combination of the anthropometric variable age and the mechanical response acceleration at Th12y-direction are shown as an example in Fig. 8. This combination shows the highest number of correctly predicted observations, the most at the injury severity level AIS 3 and AIS 4, a few also at AIS 5 and AIS 0, as it is visible in Fig. 8.

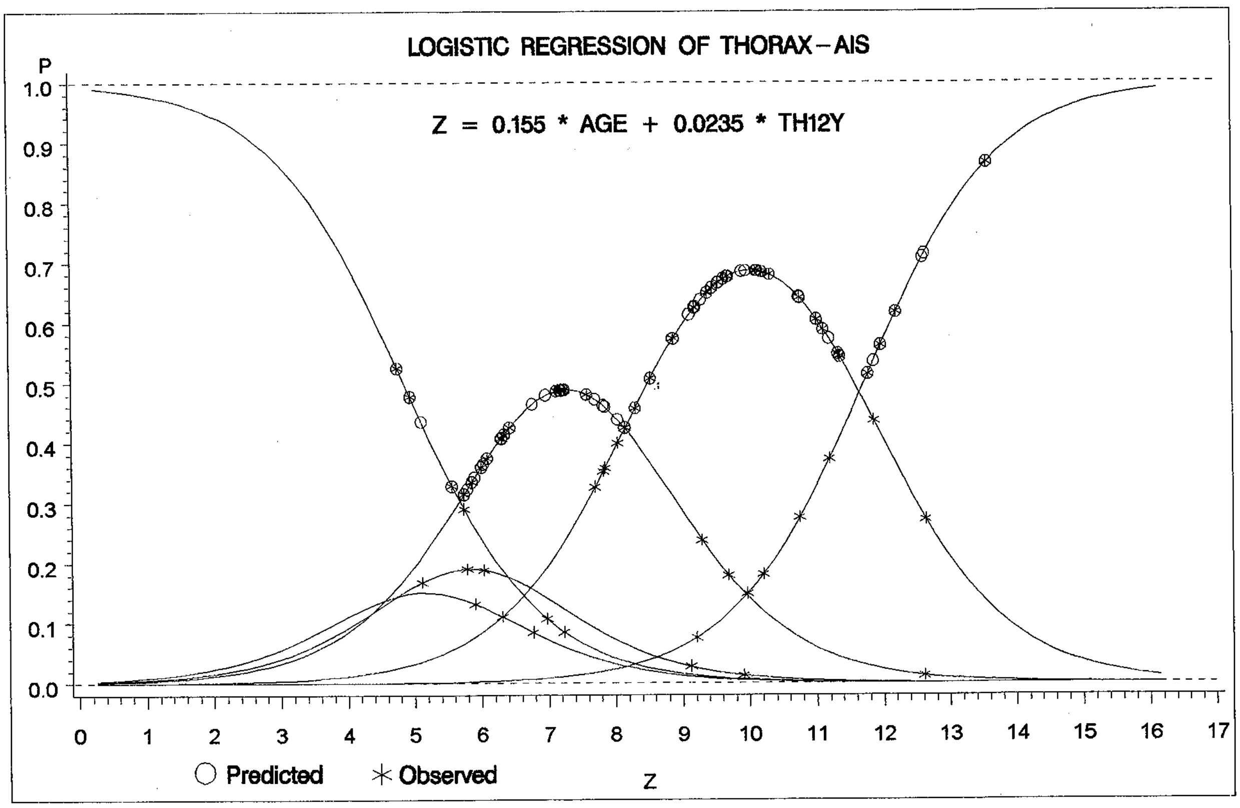


Figure 8. Probability curves of thoracic injury severity vs the combination of age and the acceleration at the 12th thoracic vertebrae.

DISCUSSION

Sixtythree side impact tests with human corpses in two different test configurations were performed. It is found that, the thoracic injury severity is independent of the body side impacted, the abdominal injuries were more severe in right side impacts; these observations are in accordance with Brun-Cassan et al. (1987). The most important parameter to define the number of the rib fractures was the subject's age. Rib fractures define also the thorax and trunk injury severity. Therefore the higher injury severity-AIS 4 and AIS 5 (flail chest) were only observed by using older test subjects or at higher impact severities. The cases with liver injuries were reduced by using of struck vehicles with improved side impact protection. It was observed, that in the impact severity range of ΔV=24 to 30 Km/h a high acceleration is introduced to the subject's body. The highest was found at the level of the 8th near side rib, which means, the level of the 8th rib was impacted more directly. This level shows also the highest evaluated deformation; the highest frequency (22 cases) of the deformation amounted 80 to 100 mm. The acceleration at the 12th thoracic vertebrae, y-direction, measured at about the same level as the 8th rib acceleration shows lower values, a result of the energy absorption of the half thorax.

The deformation at the level of the 4th and 8th rib was evaluated through twofold integration of the acceleration difference of near side and opposite side measurements, a calculated and no measured deformation-time history, but we think, that this method shows the same accuracy as the optical evaluation. In the future, tests are planned by using the chest band (Eppinger 1989).

The Spearman Correlation analysis performed, shows that, according to the age of the subject the highest correlation is with the thoracic and trunk AIS, furthermore with the number of rib fractures (r = 0.7). The second highest correlation coefficient of r = 0.6 with the same injury severities shows the TTI. This is a difference to the observations of Talantikite et al (1993), who found no correlation of TTI with the number of rib fractures (r = 0.14), however, a high correlation (r = 0.71) of the VC with the AIS. In our collective investigated, the VC (VC4, VC8) shows no correlation (r = 0.085 - 0.270) with the number of rib fractures, thoracic and trunk AIS. Little higher correlations show the deflections at the level of the 4th and 8th rib. Surprising is the high correlation coefficient of r= 0.44 - 0.52 of VC evaluated at the level of the 4th rib with abdomen AIS, instead the VC of the 8th rib.

We found the TTI as the best predictor for the thoracic injury severity; deformation, compression, VC and acceleration measured at the 4th and 8th rib near side and the 12th thoracic vertebrae, y- direction were also found to be good predictors of thoracic injury. These observations differ to the conclusions of Viano (1989), who found the VC to be the best predictor.

For a 50 to 50 change to induce thoracic injury severity of AIS 4 and greater amounts the TTI = 155, a value which is about at the same range with observations by Cavanaugh et al. (1993, TTI = 143). For the same injury risk (50% probability of serious thoracic injury) a VC-value of 0.83 m/s (level of the 4th rib) was observed; in comparison to 0.9 m/s found by Cavanaugh et al. (1993) and to 1.6 m/s reported by Viano (1989). The acceleration value at the 12th thoracic vertebrae, y-direction of 90 g's for a 50% probability of serious thoracic injury is too high in comparison to the value of 40 g's given by Cavanaugh et al. (1993). According to the high influence of the subject's age to the thoracic injury severity, the age of the occupant must be considered for the definition of the injury criteria. The evaluation of the probability of VC by fixed age of the subject of 20, 40 and 60 years shows this influence; for example: the 50% probability of serious thoracic injury with the VC, evaluated at the level of 4th rib amounts for a fixed age of 20 years: 3.65 m/s in comparison to a fixed age of 40 years: 0.75 m/s.

CONCLUSIONS

1. The highest correlation with the thoracic injury severity shows the subject's age.
2. The best logistic regression model to predict the probability of thoracic injury severity from corpses impact responses is the one based on the TTI.
3. Only the subject's age shows a high probability to predict thoracic injury severity.
4. Deformation, compression, VC and acceleration measured at the 4th and 8th rib near side and the 12th thoracic vertebrae, y- direction are also well-suited predictors of the thoracic injury.

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Thoracic and Pelvis Human Response to Impact

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ABSTRACT

This paper gives a new approach to provide information on the human tolerance against the impacts with selected unembalmed cadavers ; whose principal physical characteristics follow the distribution of the 5th, the 50th and the 95th percentile male.

A series of tests was conducted with a horizontal steel bar impactor. The extremity area is plan and rigid. Two energy levels used were intended to be without bone fracture and to cause bone fracture for two impacted areas ; the thorax at the mid-sternum in frontal impact or sub-axillary in lateral impact and the pelvis at the H point in lateral impact.

Before the tests, each subject was intrumented. Three mounting plates for tri-axial accelerometer were screwed to the lumbar spine at D1, D12 and at the sacrum. Three small balls were installed on each accelerometer to serve as points of reference in the 3 dimentional analysis with the films from three high speed cameras. The impactor acceleration and the impactor forces were recorded.

After each impact, the subject was examined, photographed and positioned to the next impact. After the final impact, the subject was removed for autopsiy to determine the injuries.

This experimental work contribute for the evaluation and the validation for tri-dimentional space haman model.

PREFACE

The main purpose of this study is to model the behaviour of a human occupant of a vehicle when subjected to frontal and lateral impacts.

Several French laboratories have worked together on this project:

- Laboratory of Biomechanics and Accidentology
  PSA PEUGEOT CITROEN - RENAULT (LAB)
  Segment studied: Head, neck, thorax and abdomen.

- Laboratory of Biomechanics
  Ecole Nationale Supérieure d'Arts et Métiers (ENSAM)
  Segment studied: Pelvis.

- Laboratory of Fundamental Biomechanics
  Université Claude Bernard Lyon I (UCBL)
  Segments studied: Upper limbs.

- Laboratory of Impacts and Biomechanics
  Institut National de Recherche sur les Transport et leur Sécurité (INRETS)

The first three laboratories worked on the mathematical model for one or several segments of the human body; INRETS carried out dynamic tests on human subjects.

INTRODUCTION

Within the scope of its participation in preparing a new mathematical model for the human body, INRETS Impact and Biomechanical laboratory offered to carry out the experimental phase necessary to validate the different segments of this model. The collaboration of the Lyon anatomical laboratory of the Faculty of Medicine was vital for carrying out this work successfully.

In this study, all dynamic tests will be analysed so that a data base can be made which can be used during the "biofidelity" verification of the anthropometric dummies or the mathematical models being developed.

In the report which follows, the analysis primarily concerns the response of the pelvis to a lateral or frontal impact and of the thorax to a frontal impact. In both cases, the collision element is a guided impact hammer. As the experimental phase has not been completely finished the lateral shock analysis of the thorax will not be treated in this paper.

TEST SET UP

The tests were carried out using a 23.4 kg. linear impact hammer. The striking surface is flat and rigid. In the thorax impact case (figure 1), the impacting surface is in the form of a 152 mm diameter circle; and for the pelvis impact (figure 2) the impacting surface is in the form of a 100 x 200 mm rectangle. In both cases, the mass located in front of the load transducer is 1.9 kg. To obtain the applied load at the contact point we apply a coefficient of 1.088 to the measured load corresponding to the ratio of the total mass to the mass behind the transducer.

Positioning the Subject (figure 1 & 2)

The subject is seated on a horizontal Teflon plate in contact with a height adjustable Teflon covered support. The subject is kept in the correct seating position, with head and shoulders straight, by means of an electromagnet and then freed for a few milliseconds just before the impact. The body is suspended by the head using a nylon cord separated in two parts by a traction force transducer. This latter enables the tension to be verified and thus be sure that the body is free at the moment of impact.

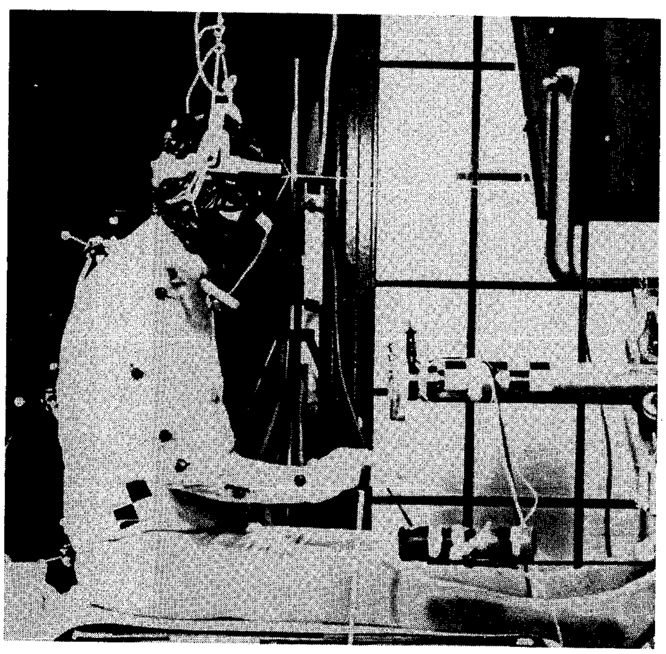

Figure 1 : Thorax subjected to a frontal impact.

Cinematic Environment

In order to make a three dimensional analysis of the movements from the cameras, a space calibration was recorded prior to each test. This calibration was achieved by using variously coloured spherical sights fixed at the top of a parallelepiped whose dimensions are fixed and positions very precisely indexed. Three or four cameras operating at 1000 frames/second were used during these tests.

Selection and Preparation of Subjects

At the start of the study, the conditions were to select subjects representative of certain people categories: men whose weight and height were close to values representative of the 5th, 50th or 95th percentile. Any bodies outside these values can be considered as "rare". Looking at table 1, we can consider that 2 subjects correspond to the 5th percentile, 4 to the 50th and 1 to the 95th percentile.

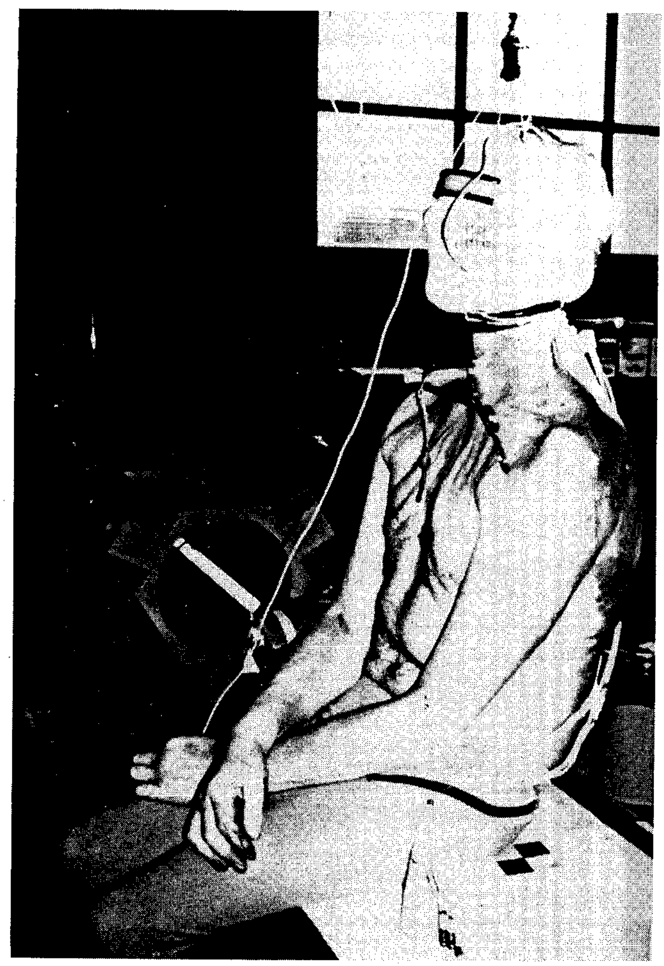

Figure 2 : Pelvis subjected to a lateral impact.

The experiments were carried out on fresh unembalmed corpses, having died within the last four days, conserved in cold storage at (2°C) and removed from the latter several hours before the test. thirty four anthropometric measurements were systematically taken.

A tracheotomy was done on the subject. An injection of air prior to each impact on the thorax enabled the intrathoracic viscera to be put back in place.

Three triaxial accelerometers were fixed to the spinal column at the following points: first and twelfth dorsal vertebrae (T1 and T12) and sacrum. Each triax is mounted on a metal plate which in turn is rigidly maintained against the column with four screws which penetrate into the vertebrae.

Three spherical sights were also connected to each triax to assure easy indexing on the films.

Objectives in terms of anthropometric characteristics :

Subject category	Weight (kg)	Height (m)
5ème percentile	58.0 ± 3.0	1.61 ± 2%
50ème percentile	73.5 ± 3.5	1.72 ± 2%
95ème percentile	94.5 ± 4.5	1.83 ± 2%

Male subject, maximum age is 70 yrs

Subject Number	Weight (kg)	Height (m)	Age
MRT 01	82	1.73	76
MRT 02	76	1.74	57
MRT 03	69	1.72	66
MRT 04	52	1.64	69
MRT 05	54	1.62	69
MRT 06	86	1.81	38
MRT 07	60	1.70	63
Average	68.4	170.9	62.6

Table 1 : Main anthropometric characteristics of the subjects.

TESTING

Each body was subjected to four impacts. the impact zone and impact hammer speed are given in table 2 below:

Subject N°	Test N°	Impact zone	Impact speed (m/s)
MRT 01	MRB 01	L. Pelvis	3.50
	MRB 02	L. Pelvis	6.74
	MRS 01	Sternum	3.36
	MRS 02	Sternum	6.83
MRT 02	MRB 03	R. Pelvis	3.40
	MRB 04	R. Pelvis	6.50
	MRS 03	Sternum	3.43
	MRS 04	Sternum	5.81
MRT 03	MRB 05	R. Pelvis	3.41
	MRB 06	R. Pelvis	6.77
	MRS 05	Sternum	3.39
	MRS 06	Sternum	5.88
MRT 04	MRB 07	R. Pelvis	3.43
	MRB 08	R. Pelvis	6.46
	MRS 07	Sternum	3.40
	MRS 08	Sternum	5.77
MRT 05	MRB 09	R. Pelvis	3.29
	MRB 10	R. Pelvis	6.??
	MRL 01	R. Thorax	3.23
	MRM 01	L. Arm	5.79
MRT 06	MRB 11	R. Pelvis	3.34
	MRB 12	R. Pelvis	6.64
	MRL 02	R. Thorax	3.31
	MRL 03	R. Thorax	5.68
MRT 07	MRB 13	R. Pelvis	3.35
	MRB 14	R. Pelvis	6.44
	MRL 04	R. Thorax	3.26

Table 2 : Test list
R. = right side impact   L.= left side impact

ANALYSIS OF RESULTS

To be able to compare the results of the measurements taken it was necessary to take into account the weight and height differences of the subjects. Some correction coefficients were defined to correct either the force or acceleration values. The principle adopted is that the force value is inversely proportional to both weight and height; whereas the acceleration value is inversely proportional to the height and proportional to the weight. In the MERTZ method, these so called standardisation coefficients given in table 3 were calculated by taking a standard subject; of height 1.74 m and weight 76 kg. In this study the number of subjects per category (5th, 50th and 95th percentiles)

	Mt kg	Ht cm	Weight ratio Rm 76 / Mt	Height ratio Rk 174 / Ht	Force Standardisation Factor Rf √ (Rm * Rk)	Acceleration Standardisation factor Ra √ Rk / √ Rm
MRT 01	82	173	0.927	1.006	0.96550	1.04172
MRT 02	76	174	1.000	1.000	1.00000	1.00000
MRT 03	69	172	1.101	1.012	1.05558	0.95836
MRT 04	52	164	1.462	1.061	1.24525	0.85202
MRT 05	54	162	1.407	1.074	1.22950	0.87359
MRT 06	86	181	0.884	0.961	0.92171	1.04298
MRT 07	60	170	1.267	1.024	1.13863	0.89892

Table 3 : Standardisation coefficients

was too small to enable the results to be separated. The corrective calculations were therefore carried out to standardise all the results obtained in relation to the 50th percentile.

Before superimposing the measurement curves recorded during the test, we therefore applied the standardisation factors to both the force and accelerations values.

The results analysis is broken down into two major parts:

- Behaviour of the pelvis to lateral shocks
- Behaviour of the pelvis to frontal shocks

PELVIS BEHAVIOUR TO LATERAL SHOCK

Each of the seven corpses used were subjected to two dynamic tests (see table 4). The first shock was carried out at a low energy level and normally did not cause any fracture; the second shock was carried out at an energy level likely to initiate the first fractures, a fact verified 6 times out of 7. Only the youngest body (38 yrs) correctly resisted such a loading. A 500 Joules energy level can thus be considered as a first bony lesion threshold of the pelvis, and this knowing the average age of the subjects tested is 62.6 years. The results published by Viano (33rd STAPP 892432) about pelvis shocks using a 23.4 g pendulum, indicated that the two fractured bodies out of the five tested at high speed corresponded to the oldest people and that an energy level in excess of 1,000 Joules did not cause any damage to the bodies of the younger subjects.

Two main measurements were chosen to carry out the superposings. These relate to the force obtained at the tip of the impact hammer and the transverse acceleration measured on the subjects sacrum. The curves of each graph obtained were sufficiently close to ênable corridors to be defined representative of the human body's behaviour. To clarify matters further, the results obtained at low speeds (figures 3 and 4) were separated from the high speed ones (figures 5 & 6).

Lateral shock tests on the pelvis were analysed by Viano (33 rd STAPP 892432). Although these tests were carried out by using a pendulum on a suspended body, it was interesting to compare the impact forces, because the striking weight was the same in both cases. In figure 11, the upper and lower corridor limits proposed by Viano were superposed onto those previously defined (figures 9 and 10). The impact speeds were not the same, but it appeared that the maximum force levels fully develop as a function of these average speeds. The testing and recording conditions at the moment of impact could be the cause of the slight time lag of the force peaks.

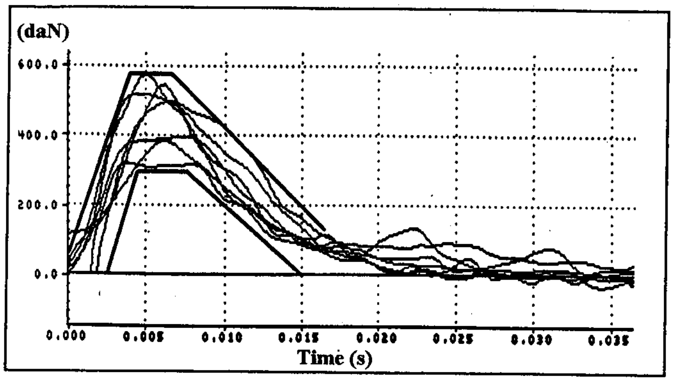

Figure 3 : Superposition of the force curves as a function of time obtained at the pelvis during the low speed tests.

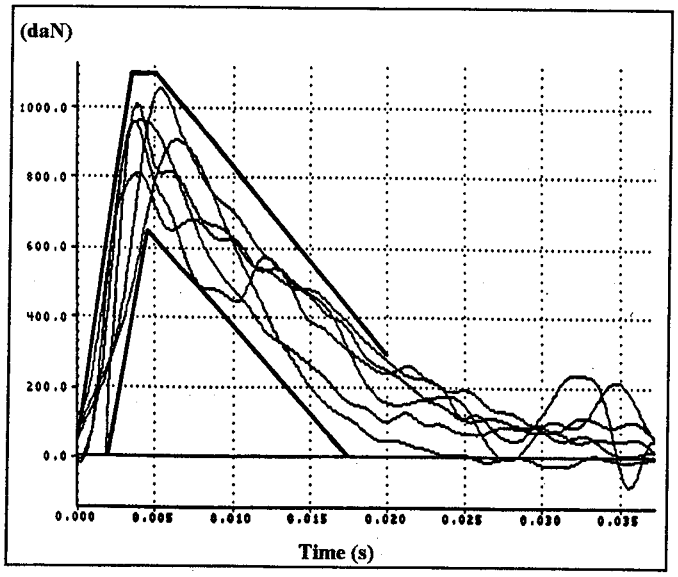

Figure 4 : Superposition of the force curves as a function of time obtained at the pelvis during the high speed tests.

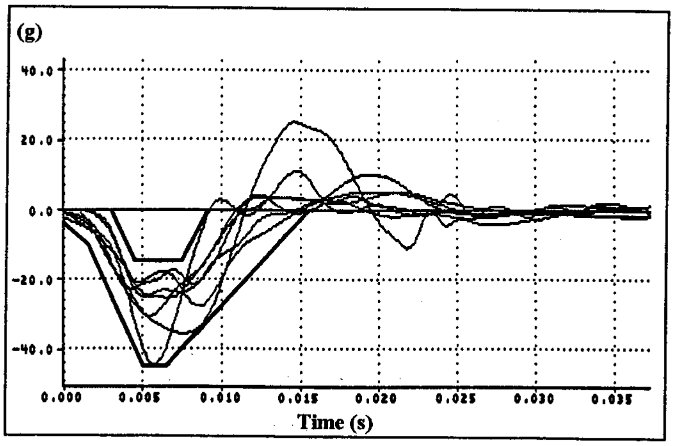

Figure 5 : Superposition of the acceleration curves as a function of time obtained at the sacrum level of the pelvis during low speed tests.

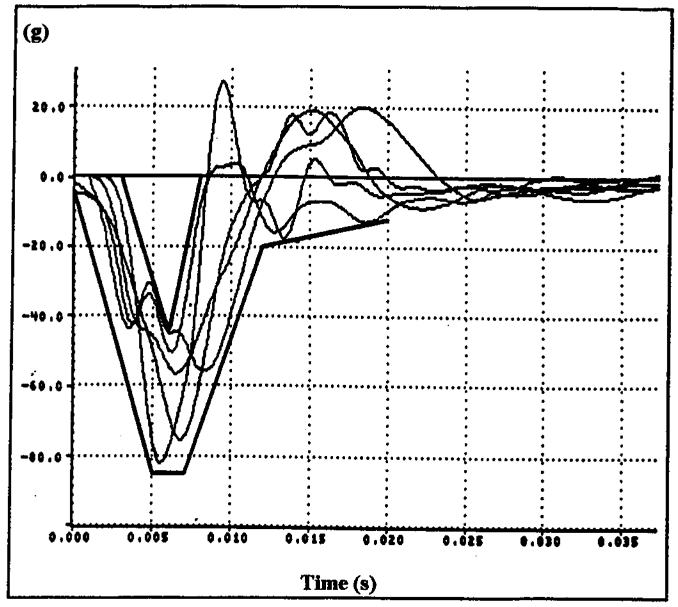

Figure 6 : Superposition of the acceleration curves as a function of time obtained at the sacrum level of the pelvis during high speed tests.

Upper corridor		Lower corridor	
Time seconds	Acceleration G	Time seconds	Acceleration G
0.003	+0	0	-4
0.0045	-15	0.0015	-10
0.0075	-15	0.005	-45
0.009	+0	0.0065	-45
		0.0155	+0

Table 5 : Tests at 3.46 m/s: Upper and lower acceleration corridor limits.

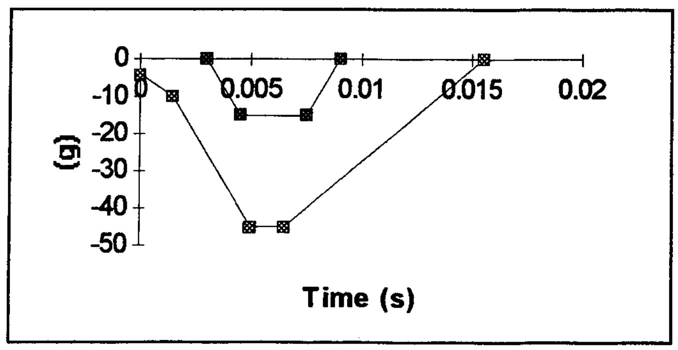

Figure 7 : Tests at 3.46 m/s: Upper and lower acceleration corridor limits.

	Speed (m/s)	Energy (J)	Fractures identified at autopsy
Left side shocks			
MRB 01	3.50	143	
MRB 02	6.74	531	2 branches illium and left ischium pubis + irradiation at the cotyle
Right side shocks			
MRB 03	3.40	135	
MRB 04	6.50	494	1 right side ischium pubis branch
MRB 05	3.41	136	
MRB 06	6.77	536	1 right side ischium pubis branch
MRB 07	3.43	138	
MRB 08	6.46	488	1 right side ischium pubis branch
MRB 09	3.29	126	
MRB 10	6.75	533	comminuted fracture of right cotyle
MRB 11	3.34	130	
MRB 12	6.64	516	no fracture
MRB 13	3.35	131	
MRB 14	6.43	484	latero pubis fracture + irradiation at the coyle
Average :			
Low speed	3.463	134	
High speed	6.663	512	

Table 4 : Results of pelvis autopsies

Upper corridor		Lower corridor	
Time seconds	Acceleratio G	Time seconds	Acceleratio G
0.003	0	0	-5
0.006	-45	0.005	-85
0.008	0	0.007	-85
		0.012	-20
		0.02	-12

Table 6 : Tests at 6.66 m/s: Upper and lower acceleration corridor limits.

Lower corridor		Upper corridor	
Time seconds	Force daN	Time seconds	Force daN
0.0025	0	0	60
0.0045	300	0.004	580
0.0075	300	0.0065	580
0.015	0	0.0165	130

Table 7 : Tests at 3.46 m/s: Upper and lower impact force corridor limits.

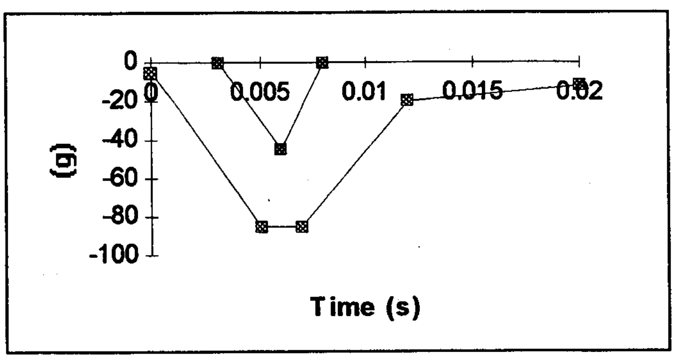

Figure 8 : Tests at 6.66 m/s: Upper and lower acceleration corridor limits.

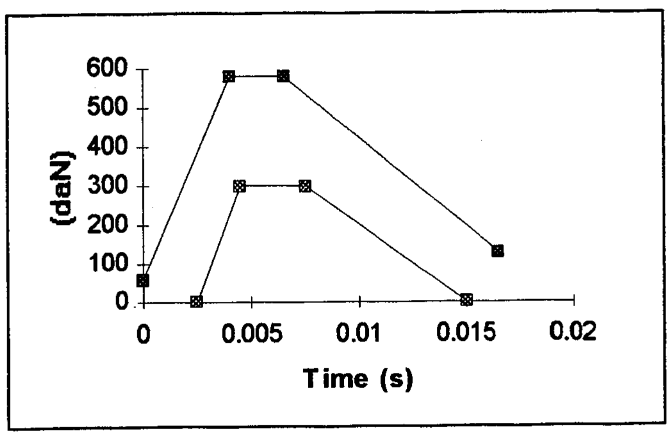

Figure 9 : Tests at 3.46 m/s: Upper and lower impact force corridor limits.

Lower corridor		Upper corridor	
Time seconds	Force daN	Time seconds	Force daN
0.002	0	0	50
0.0045	650	0.0035	1100
0.0175	0	0.005	1100
		0.02	290

Table 8 : Tests at 6.66 m/s: Upper and lower impact force corridor limits.

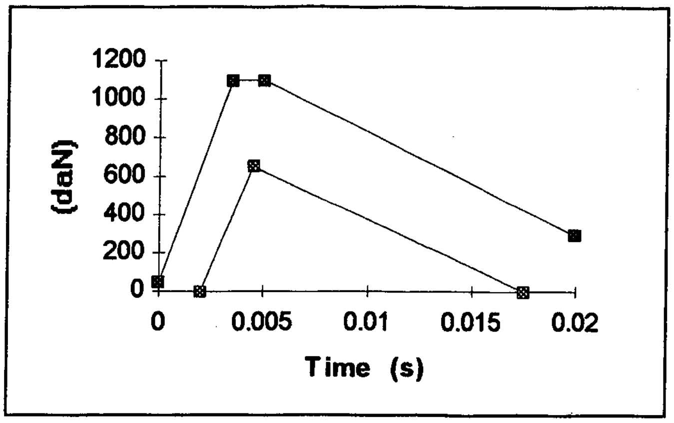

Figure 10 : Tests at 6.66 m/s: Upper and lower impact force corridor limits.

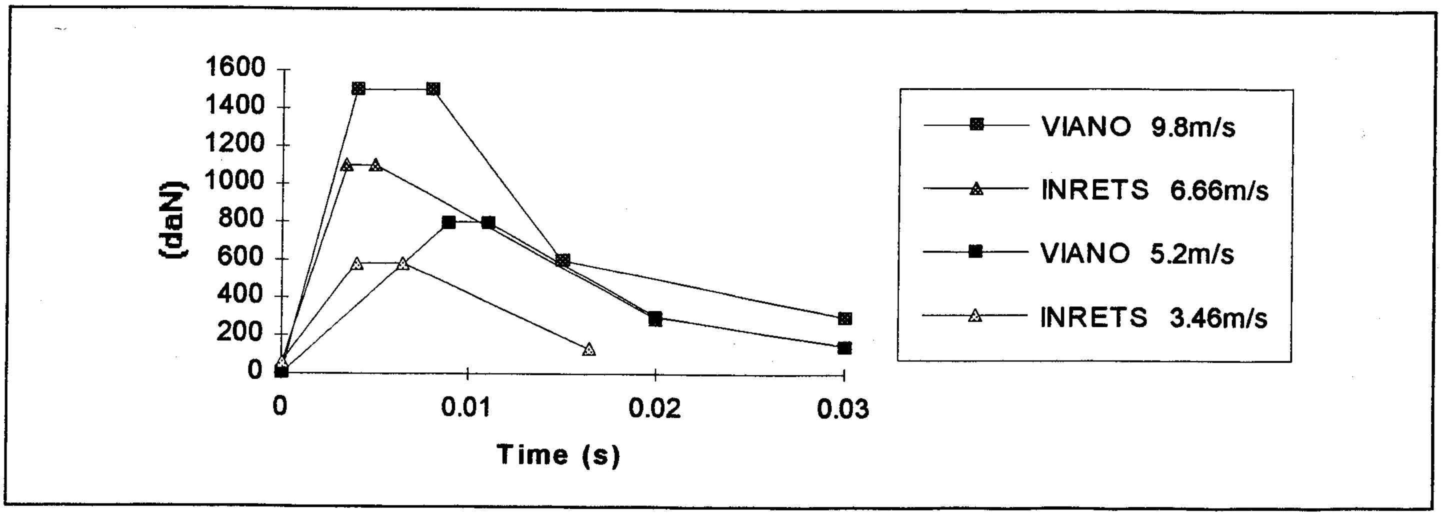

Figure 11 : Superposition of the upper impact force corridor limits as a function of time.

THORAX BEHAVIOUR TO A FRONTAL SHOCK

Each of the first four bodies available for this test series was subjected to two impacts on the sternum. A first impact was made at low speed to avoid any thorax injuries. The second shock should result in a few fractures. Table 9 below summarises the observations made during the autopsies. We obtained very serious damage on the thorax of the first body tested, so we reduced the impact hammer speed during the second impact on subsequent bodies.

The thoracic compression was determined from the cinematic analyses. The available markers were located at points D1 and D12 on the spinal column. To evaluate the thoracic compression, it was necessary to measure the distance variation between the central point of the impact hammer's front face and a fixed datum of the straight line linking points D1 and D12. The analysis was carried out at about 100 ms for each test except for body MRT1 (no film); which gave 20 frames per test at 5 ms intervals. Figures 12, 13 & 14 show how this compression on bodies N°2, 3 & 4 develops with time.

No analysis was done on the bone samples taken on the thorax but the calcination carried out on the illium and ischium pubium branches gave the following information: The ratio of the calcinated bone weight to its dry weight was about 50% for bodies 2 and 3, whereas for body 4 it was about 30%. It is a fact that body N° 4 had a more fragile skeleton that the others.

Body N° & Test Date	Axillary Thoracic Thickness	Sub-sternal Thoracic Thickness	Thorax Fractures	Rib Number
MRT 01	25	25	Middle arch right	2, 3, 4, 5
2/19/92			Anterior arch right	3, 4, 5, 6, 7
			Middle arch left	2, 4, 5, 6
			Anterior arch left	3, 4, 5, 7
			Sternum	*
			TOTAL	18 fractures
MRT 02	22	23	Anterior arch right	5
3/30/92			TOTAL	1 fracture
MRT 03	21	21	Middle arch right	5, 6
4/15/92			Anterior arch right	2, 3, 4
			Middle arch left	2, 3, 4, 5, 6, 7
			Sternum	*
			TOTAL	12 fractures
MRT 04	21	21	Middle arch right	2, 3, 4, 5, 6, 9
4/17/92			Middle arch left	2, 3, 4, 5, 6
			TOTAL	11 fractures

Table 9 : Thorax autopsy results.

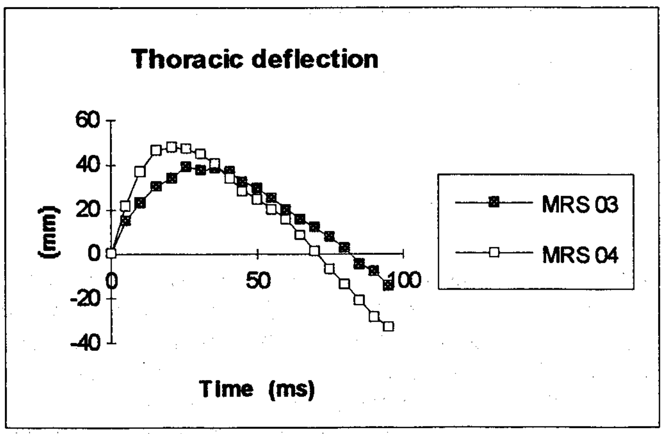

Figure 12 : Thoracic deflection of body N°2 at low and high speeds.

The thoracic compression reverts to zero before 80 ms because there is only one rib fracture during the second test. The thorax's elasticity remained good, and gave part of its energy back to the impact hammer; which explains the rapid separation of the thorax and impact hammer.

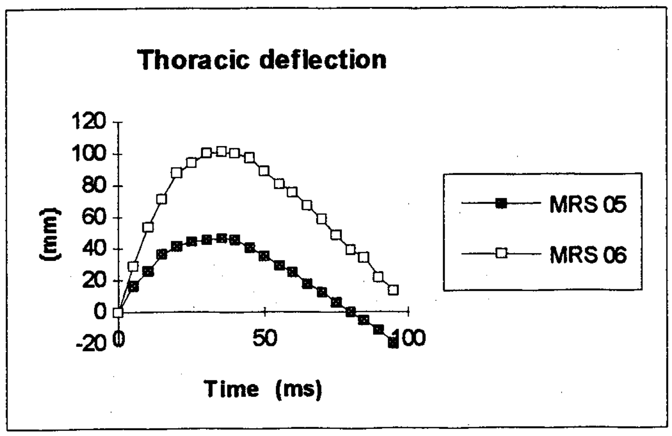

Figure 13 : Thoracic deflection of body N° 3 at low and high speeds.

The thorax elasticity of body N° 3 during the second test was less than that in test N° 2. This was due to the fractured 12 ribs counted. The rebound of the impact hammer after the shock was slower.

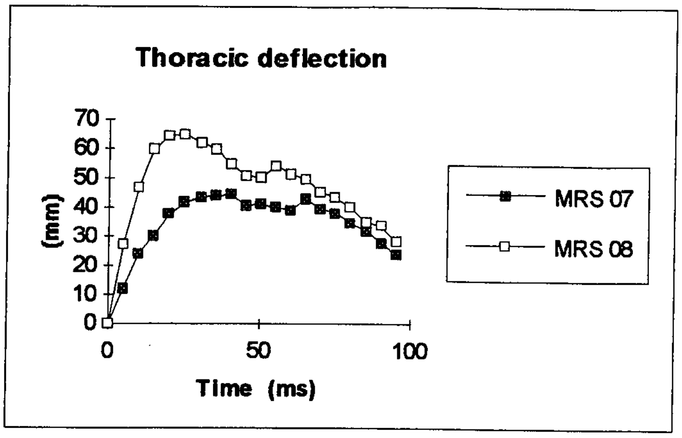

Figure 14 : Thoracic deflection of body N° 4 at low and high speeds.

The results show that this thorax was partly broken during the first low speed test, because the impact hammer stayed longer than normal in contact with the thorax.

During the low speed impacts applied against each of the 4 bodies, the thorax depression value obtained from the film analysis were respectively 63, 39, 46, and 44, which represents 25, 17, 22 and 21% of the thorax's thickness. These depression percentages are normally well supported by the human body.

During the high speed impacts, only the tests on bodies 2, 3, and 4 were filmed. The measured depressions were very different: 48, 100 and 65 mm being 21, 48 and 31% of the thorax's thickness. For body N° 2 the depression seemed to be underestimated but was in agreement with the fact that only one rib was broken. The other two cases corresponded closely to critical situations which would normally result in multiple fractures.

The measurements carried out during the shocks were corrected by applying standardisation coefficients. The acceleration curves measured at the 12th dorsal vertebra level (D12) (figure 15) and the force curves taken at the sternum (figures 17 & 19) were superimposed. Two corridors were defined in table 10 and 11 and figures 16 & 18. the acceleration superimposition at the D12 level was only carried out for the high speed tests, because in the other tests the acceleration levels were very low and always below 5G. For this reason creating a low speed corridor was not considered.

Although the impact time for the four bodies lasted about 60 ms (figure 19), the forces obtained at the sternum during the high speed tests were difficult to interpret. The tests on body N° 1 occurred at a higher speed than in the other tests; thus logically giving higher values. Being frail body N° 4 quickly succumbed under the force applied. Only bodies 2 and 3 gave results sufficient close to manifest the reactions of a normal body. Nevertheless, a small difference existed at the very start of the shock as shown by a quite sharp peak. A similar reaction was found for body N° 1. Complimentary tests will be required to better analyse this situation. Under these conditions therefore no corridor was considered.

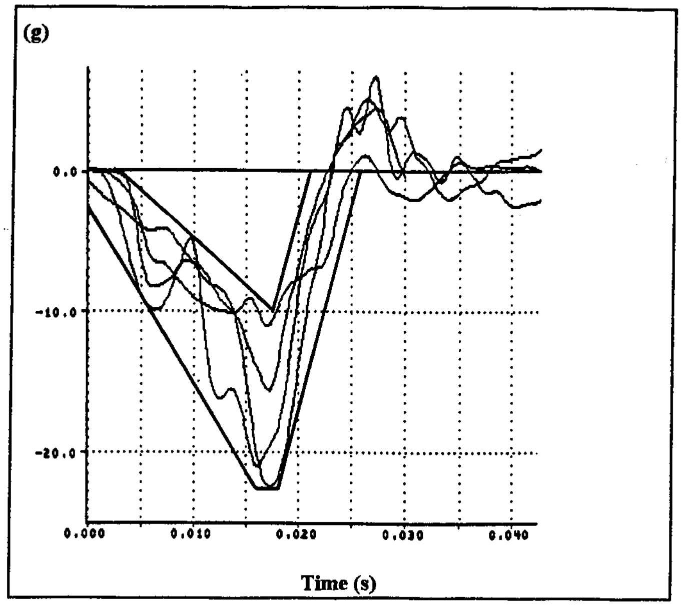

Figure 15 : Superimposing the acceleration curves (g) as a function of time (s) obtained at the 12th dorsal vertebra level during a test at 5,8 m/s.

Upper corridor		Lower corridor	
Time seconds	Acceleration G	Time seconds	Acceleration G
0.0025	0	0	-2.5
0.0175	-10	0.016	-22.5
0.021	0	0.018	-22.5
		0.026	0

Table 10 : Test at 5.8 m/s: Upper and lower corridor limits of accelerations at D.12.

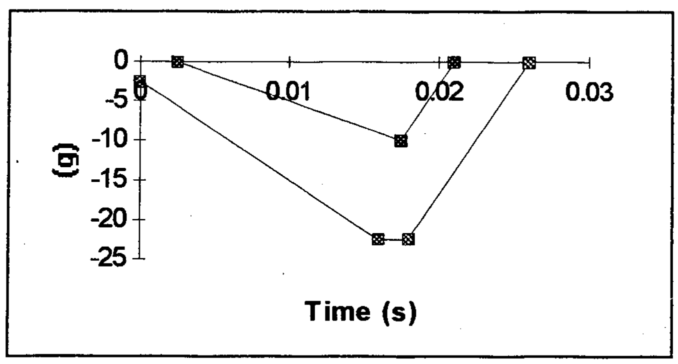

Figure 16 : Tests at 5.8 m/s: Upper and lower corridor limits of accelerations measured at D12 and standardised.

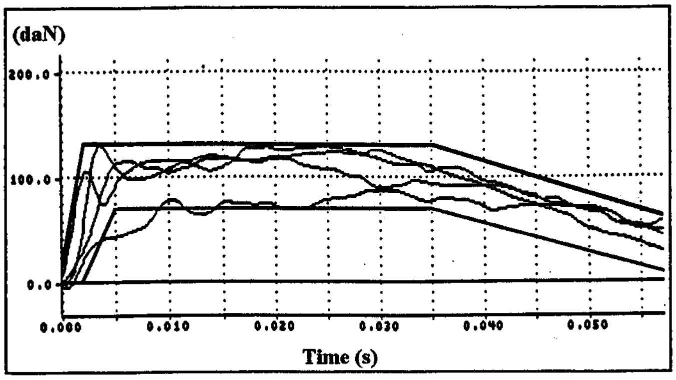

Figure 17 : Superimposing the force curves obtained at the sternum during low speed tests (3.5 m/s) as a function of time.

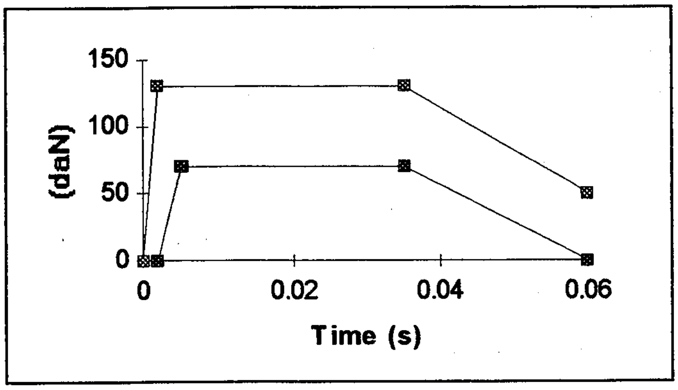

Figure 18 : Tests on the sternum at 3.5 m/s; upper and lower corridor limits of the standardised impact forces.

CONCLUSION

In order to have a new data base on the human body's behaviour when subjected to a guided impact hammer, INRETS Biomechanical and Shock Laboratory carried out a series of tests. In this report, a large part of the results obtained with the first seven bodies were analysed in the form of two independent studies:

1) Pelvis reactions induced by a lateral shock.
2) Thorax reactions induced by a frontal shock.

Although the foreseen experimental programme has not yet been finished, it was considered worthwhile regrouping the initial results and analysing them.

Each of the seven available subjects were subjected to two shocks on the pelvis. The first was an infra-lesional shock and the second a higher energy shock to produce lesions. Each body was then impacted at the thorax. The first four bodies were subjected to frontal shocks and the other three to lateral shocks. As the experimental programme on the thorax response to a lateral shock was limited, no results were analysed.

The seven low speed and high speed tests on the pelvis were sufficiently homogeneous to represent a very good data base. Although the tests analysed by VIANO (33rd STAPP N° 892432), were not done under the same conditions, the results were compatible and complementary.

Lower corridor		Upper corridor	
Time seconds	Force daN	Time seconds	Force daN
0.002	0	0	0
0.005	70	0.002	130
0.035	70	0.035	130
0.06	0	0.06	50

Table 11 : Tests on the sternum at 3.5 m/s: Upper and lower corridor limits of the standardised impact forces.

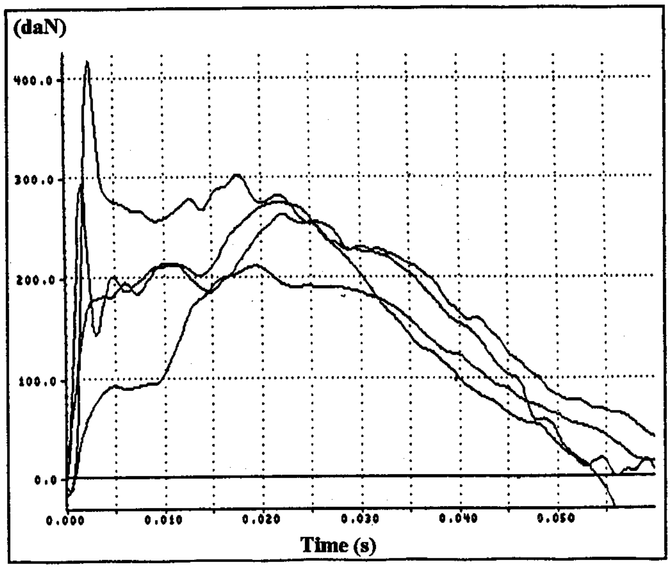

Figure 19 : Superimposing the force curves obtained at the sternum during high speed tests (5.8 m/s) as a function of time.

Concerning the thorax however, when subjected to frontal shock, the situation was more difficult to exploit because only four bodies were subjected to frontal shocks. The low speed results gave relatively homogeneous responses. The high speed tests however gave a very high dispersion which would require complementary tests to better delimit the thorax's response in the configuration chosen at INRETS laboratory.

The information gathered during the dynamic tests was standardised to be representative of the 50th percentile, then regrouped to produce the corridors delimiting the behaviour of the sections of the human body when subjected to shocks. These corridors will be the objectives to be achieved during the behavioural verifications of the mechanical or mathematical models.

Evaluation of Thoracic Trauma in a Frontal Impact

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ABSTRACT

The objective of the study was to determine the biomechanics of the human thorax in a simulated frontal collision. Sled tests were conducted using unembalmed human cadavers at velocities of 32 or 48 kph. Specimens were restrained using air bag - knee bolster, air bag - lap belt, or air bag - three-point belt combinations. Two chest bands were placed at the upper and lower levels of the thorax to derive the deformation contours during impact. Radiography and detailed pathological evaluations were conducted. Differences in thoracic deformation contours between the upper and lower levels of the chest as well as among the various restraint system combinations were analyzed. High-speed photographs from the onboard and offboard cameras were analyzed for the quantification of specimen kinematics during impact. Thoracic trauma was assessed based on the abbreviated injury scale using autopsy findings; the trauma using clinical radiographs were compared with the injuries identified at autopsy. Three-point bending experiments were conducted on isolated rib specimens from each test according to accepted procedures.

Deformation contours derived from the chest bands indicated regional differences in the biodynamic response. Nondisplaced rib fractures occurred without internal injuries or without the laceration of the costal pleura through the fractured rib. Furthermore, the number of rib fractures identified on routine clinical radiographs were consistently smaller than the number found at autopsy. These results indicate that there may be an overrating of thoracic trauma based on the abbreviated injury scale using rib fractures identified at autopsy in contrast to clinical radiography. Further studies are however, required to develop a scaling factor for the thoracic trauma based on autopsy findings. The mechanism of rib trauma was determined to be compression and/or bending-related for the air bag - three-point belt restraint system wherein fractures were concentrated around the shoulder harness region and the lateral-most area of the rib cage on the right side. The mechanism of skeletal injury for the air bag - knee bolster system was secondary to a compressive force directed along the anteroposterior axis and applied bilaterally over the lower regions of the torso. Based on analysis of the contours, kinematics and injury mechanisms, the biomechanical response of the thorax is different between air bag - three-point belt loading, compared to the air bag - knee bolster restraint combinations.

INTRODUCTION

The human thorax is one of the most frequently injured regions in frontal impact. Biomechanical evaluation should be based not only on epidemiological studies, but also on controlled laboratory investigations (4,13,14). While epidemiological studies reveal the type of trauma and may disclose about injury mechanisms, it fails to characterize the dynamic biomechanical response of the human body during impact. One of the ways to conduct a laboratory investigation is to use an unembalmed human cadaver and subject the specimen to deceleration forces using a sled equipment. Under this environment it is also possible to use realistic restraint combinations, such as air bag, knee bolster, lap and/or three-point belts. Although the human cadaver is not an exact replica of the living human, because of the similarity in anatomy and biomechanical parameters, the results obtained in human cadaver studies will serve as a first step to understand the biodynamic response of the living human. This data can also be used in the delineation of human tolerance, identification of injuries to hard and soft tissues, advancement of mathematical models, development of anthropomorphic test devices with improved biofidelity, and to evaluate the injury mitigating characteristics of the vehicle interiors.

Although significant research have been conducted in the past to delineate the biomechanical response of the human thorax using cadavers and/or animal models, little information is available that describes the behavior of the thorax under realistic restraint systems. For example, the majority of the previous research focused on the response of the human thorax to blunt impact loading conditions. In principle, these data are applicable to an unrestrained occupant but do not simulate the effect of restraint loading, such as air bag or seatbelts, in a frontal impact situation (13,14). One of the earlier experimental air bag and lap belt studies using living animals were conducted at the Holoman Air Force Base (9). These studies indicated that the baboon tolerance to frontal impacts of 48 to 64 kph exceeds 57 G. Due to lack of appropriate instrumentation on the thorax, it is not possible to use the data from previous human cadaver data from car-to-car as well as sled tests to derive the thoracic deformation contours and correlate thetrauma with biomechanics. Therefore, this study was developed to investigate the biodynamics of the human thorax under simulated frontal impacts using air bag - knee bolster, air bag - lap belt, and air bag - three-point belt systems. The study also was designed to determine the differences, if any, in the thoracic trauma quantified using autopsy procedures in contrast to the thoracic trauma assessed using clinical radiography. Furthermore, the mechanisms of skeletal damage in a frontal impact under these restraint combinations are delineated.

MATERIALS AND METHODS

Fourteen unembalmed human cadavers, ranging in age from 29 to 81 years, height from 150 to 182 cm, weight from 41 to 84 kg were used. The subjects selected were screened for Hepatitis A, B and C, as well as the human immunodeficiency virus. Further, specimens were selected based on an evaluation of medical records and x-rays to exclude specimens with severe degenerative disease, and/or metastatic disease. All studies were performed in a hospital environment and even though the specimens were negative for infections, precautions similar to those in an operating room were followed during the study. Following specimen procurement, they were prepared and anthropomorphic data, such as seated height, chest circumference and chest depth, were obtained in accordance with the National Highway Traffic Safety Administration (NHTSA) specifications. Specimens were pressurized to approximate the *in vivo* pulmonary and vascular characteristics. Two chest bands were mounted on each preparation; the first or the upper level chest band covered the midsternum region approximately at the anterior level of the fourth rib, and the second or the lower level chest band covered the xyphoid process approximately at the level of the sixth rib anteriorly (4,7). The specimens were also prepared with accelerometers rigidly fixed to the skull in the temporal region. Accelerometers at the C7/T1 spinous process and T12 spinous process were used to record the spinal accelerations. To document the kinematics of the specimen during impact, photo targets at the head, first thoracic vertebral level, hip, knee and shoulder regions were used. Specimens were placed in the driver's seat of a custom designed buck which was placed on the platform of a deceleration sled. Depending on the restraint combination, force transducers were placed to document the belt loads. The standard lap and shoulder belt combination (6% elongation) was used for the three-point belt test, and an extruded polystyrene foam was used to simulate the knee bolster. The polystyrene foam was cut into the shape of a knee bolster but with increased thickness, and attached to the sled buck. Initial sled tests were conducted with the anthropomorphic Hybrid III manikin at velocities of 32 and 48 kph to determine the knee excursion limits and indentation into the knee bolster to evaluate the suitability for specimen tests.

All tests were conducted using a horizontal deceleration sled. The test was filmed at 1000 f/sec with an onboard camera placed on the left side. The kinematics of the specimen obtained using the photo targets and the 16 mm onboard camera was transferred into a motion analyzer for further data processing. For each test a new restraint system and new steering column was used. All biomechanical data from the chest bands, accelerometers, and the force transducers were recorded using an onboard data acquisition system and according to the Society of Automotive Engineers SAE J211b specifications. Data processing of the chest band output signals included a transformation of the individual curvature signals to obtain the deformation histories. The thoracic deformation contours were compared using RBAND_PC software from NHTSA (7). From these histories, the pattern, the peak deformation, and the time of occurrence of the peak chest deflections were extracted for the upper and lower chest bands.

Post-test radiographs were used to identify the pathology. In addition, macroscopic evaluations at autopsy were used to determine the extent of the thoracic trauma. To examine the interrelationship, if any, between the rib morphology and strength with the restraint system and the specimen related demographics, isolated tests of the ribs were conducted using three-point bending procedures (6). The load, the deflection, and the stiffness of each rib were determined. A total of four ribs from each specimen were used in these studies.

RESULTS

Primary results of the thoracic deformation contours and the overall kinematics of the specimens using the photo targets have been presented at the 37th Stapp Conference (14). Briefly, the kinematics of the specimen varied among the three restraint combinations. In the air bag - knee bolster restraint system experiments, the specimen kinematics indicated the contact of the knee with the knee bolster to occur approximately at the time of full deployment of the air bag (40 ms). With the knees further loading the knee bolster, the lower torso initially contacted the air bag in the region of the lower rim of the steering wheel. The upper torso loaded the air bag and lower regions of the thorax continued to load the air bag and the lower wheel rim. In the air bag - lap belt experiments, the pelvis was restrained by the lap belt during the period of full deployment of the air bag (40 ms). The upper torso pivoted around the restraint and contacted the air bag following its full deployment. In the air bag - three-point belt restraint system, the belt loaded the specimen prior to air bag contact. The shoulder belt reached its peak forces during the time at which the specimen was in contact with the air bag. In the air bag - lap belt and the air bag - knee bolster tests, permanent deformations of the steering wheel occurred. In contrast, little or no residual steering wheel and column deformations occurred in the air bag - three-point belt restraint tests.

Normalized peak chest deflections at the upper thoracic levels for the air bag - lap belt and the air bag - three-point belt systems were greater compared to the normalized chest deflections at the lower thoracic level. In contrast, the air bag - knee bolster combinations indicated higher levels of normalized chest deflections in the lower level compared to the upper thoracic level. While no differences were observed in the time of occurrence of the upper and lower peak chest deflections between the air bag - knee bolster and air bag - lap belt combinations, the introduction of the three-point belt system produced early peaks, both at the lower and upper levels of the thorax. These differences were significant ($p<0.01$). An examination of the thoracic deformation contours indicated a uniform compression of the thorax in the anterior region for the air bag - knee bolster and the air bag - lap belt systems; in contrast, for the air bag - three-point belt systems, thoracic deformation contours indicated a region of localized loading of the thorax by the shoulder harness.

The injury patterns for the air bag - three-point belt combinations demonstrated rib fractures to occur in the region where the shoulder belt loaded the chest or on the lateral-most aspect of the rib cage on the right. Routinely, ribs two to eight showed skeletal damage (Figure 1). In contrast, in the air bag - knee bolster tests, bilateral rib fractures occurred primarily in the lower portion of the rib cage secondary to the contact of the chest with the lower medial portion of the steering wheel and rim. In this case, ribs four to seven demonstrated skeletal trauma with no fractures in the lateral aspect of the rib cage compared to the shoulder harness - air bag combination (Figure 1). The lowest number or fractures occurred in the air bag - lap belt system combination. There were more right sided rib fractures in the other two restraints compared to the air bag - lap belt combination

A total of 59 rib fractures were identified at autopsy from these fourteen specimen tests. In contrast, only eleven rib fractures were identified from the clinical radiographs. It should however, be emphasized that all the rib fractures identified at autopsy were such that no laceration of the costal pleura occurred. In addition, no internal vital organ trauma occurred under any of the restraint combinations.

Results from the rib bending tests indicated the following: If all the 52 ribs from the 13 specimens (4 ribs per specimen) were grouped, mean stiffness was 547 N/cm (± 41). Figure 3 shows a bar chart indicating the mean stiffness for each specimen under each restraint combination. For the air bag - lap belt, air bag - three-point belt and air bag - knee bolster, peak loads were: 143 N (± 43), 116 N (± 65), 147 N (± 69); the corresponding stiffnesses were: 606 N/cm (± 186), 498 N/cm (± 168), 532 N/cm (± 90), respectively. The differences among these variables were not statistically different when sorted according to restraint system. The pattern of failure following the three-point bending test conducted in a quasistatic mode was primarily the fracture of the bone on the tension side. There were no significant differences in the peak load or the stiffness with respect to rib location (Table 1).

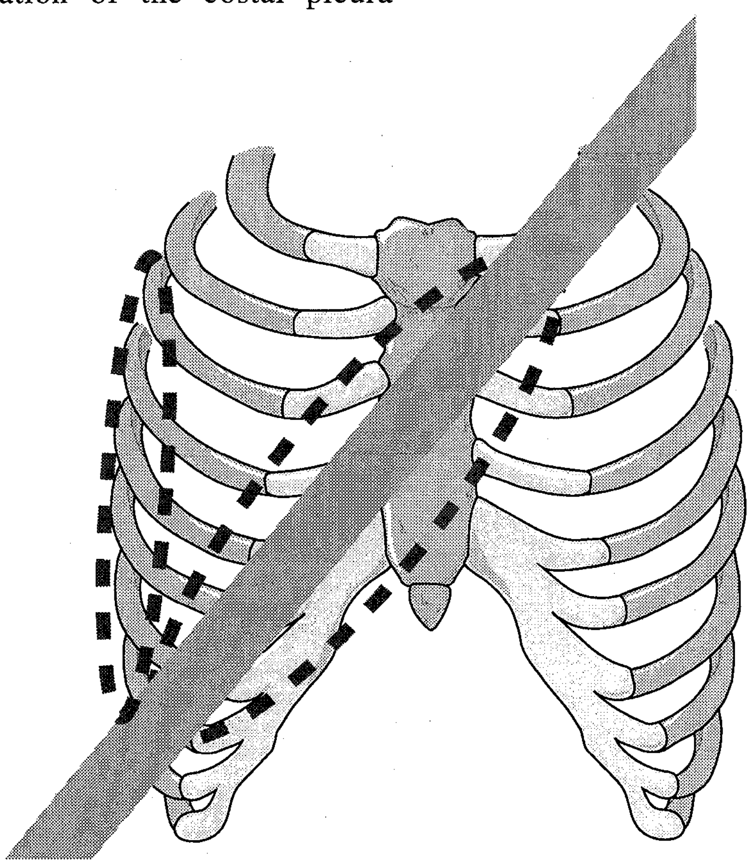

Figure 1. Schematic diagram illustrating the position of the shoulder belt (shown in the diagonal shaded region) across the rib cage. The dotted line around the shoulder harness indicates the rib damage observed in the study. Fractures were also observed in the area enclosed by the dotted lines in the right lateral region of the rib cage. Refer to text for the mechanism of injury.

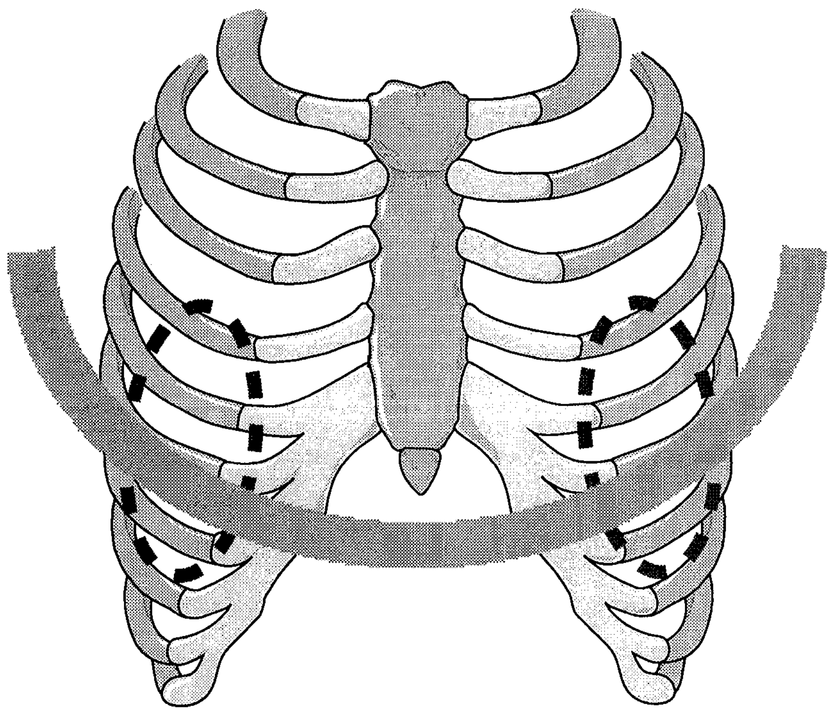

Figure 2. Schematic diagram illustrating the rib cage and the contact of the lower torso with the lower part of the steering wheel - air bag (shown shaded). Rib fractures were identified bilaterally in the enclosed region of the dotted lines. This pattern of injury was observed for air bag - knee bolster experiments. Refer to the text for the mechanism of injury.

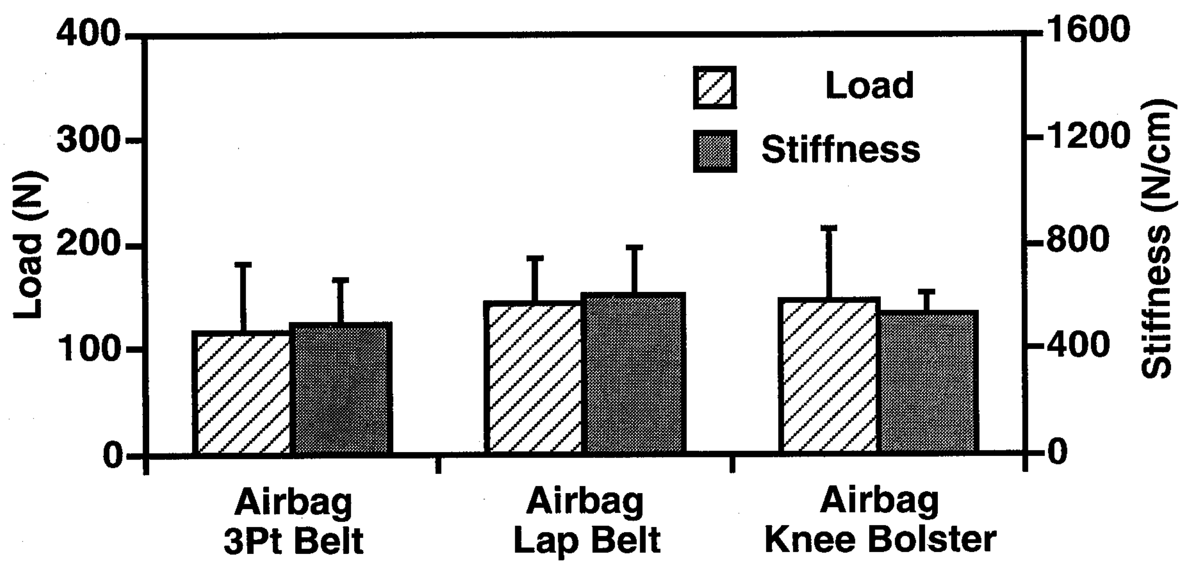

Figure 3. Bar chart of the load and stiffness of the ribs as a function of restraint system.

Table 1
Rib Test Data

Description	Load (N)	Stiffness (N/mm)
Right sided ribs	145 ± 15	550 ± 59
Left sided ribs	133 ± 14	544 ± 60
Rib #7 (left and right)	138 ± 13	587 ± 57
Rib #8 (left and right))	136 ± 16	501 ± 62
Male	168 ± 19	678 ± 76
Female	94 ± 31	338 ± 92

DISCUSSION

Rib fractures were consistently identified in all (except one) specimens during autopsy. As stated earlier, the rib fractures were such that the costal pleura was not torn. Clinical radiography however, did not identify all these fractures. In fact, only one out of five fractures were apparent on x-rays. Although routine posteroanterior films were used to make this assessment, anteroposterior, and in some cases, lateral chest images did not identify additional rib fractures. It should be emphasized that, the classic clinical procedure is to obtain an upright posteroanterior chest film in an *in vivo* situation to study the human chest. The present cadaveric studies support this approach as other x-rays were relatively unsuccessful in assessing additional rib damage. These additional radiographs may be necessary in certain cases to better diagnose the patient in terms of trauma other than rib damage. Another important aspect is that rib fractures alone do not constitute a life threatening injury except in severe cases such as a flail chest which may occur secondary to multiple bilateral rib trauma (1-3,11). It should also be noted that the physical findings of a rib fracture are often non-specific and the routine clinical impression of the likelihood of rib fracture is not always reliable due to the functional characteristics of the thorax. Clinically, a negative chest film does not rule out rib fracture.

The majority of previous biomechanical studies have used autopsy data, particularly the rib fractures, to quantify the thoracic trauma based on the Abbreviated Injury Scale (AIS). One of the principal reasons for adopting this methodology is that it obviates the need to have radiographic equipment and more trauma can be visualized during a detailed autopsy. While this approach is logical, it should be emphasized that the AIS is developed for the living human where clinical findings are used to assess the severity of the injury (10). Human cadavers do not permit similar evaluations. Therefore, it may be appropriate to develop a scaling factor if the AIS rating is based on autopsy in human cadaver experiments.

The striking differences in the identification of the rib fractures between the autopsy and clinical radiography stems from the complex three-dimensional anatomy of the thoracic rib cage combined with the varying densities of its contents. Ribs are less dense structures compared to long bones, and therefore, do not show up as well on radiographs. Furthermore, the severity of the fracture, i.e., hair line or nondisplaced type can affect its identification on a radiograph. Abnormal distribution of fluids in the chest cavity of the unembalmed cadaver may have also contributed to the differences. These factors must be critically evaluated while transforming thoracic injury data from the autopsy to the living human.

While the present study identified skeletal trauma in all specimens, no internal organ injuries occurred in any case. This result is in good agreement with literature (12). The absence of the internal organ trauma may be due to postmortem changes that occur in the cadaver. For example, Pope et al, observed the higher susceptibility of rib fractures in cadaveric swines compared to anesthetized swines under blunt chest impact (8). Foret-Bruno et al, in another study of 92 belted occupants in real-world crashes and human cadaver tests found significant differences in chest injuries between the two types of tissues (5). In particular, the study estimated a difference of three to five rib fractures. Clinically, thoracic trauma is principally governed by the status of the intrathoracic components and often assessed as hemopneumothorax, major vascular trauma and pulmonary contusion. These types of trauma cannot be easily assessed in an unembalmed cadaver. Differences in the intrathoracic pressure dynamics between the living human and the cadaver, and the absence of respiration in a cadaver are among the contributing factors. The type of trauma observed in the present study may also be due to the severity of impact. All tests were conducted at 32 or 48 kph. At higher changes in velocity (e.g., 56 kph) it is reasonable to hypothesize that the significant increase in kinetic energy may induce more severe rib cage trauma and instability thus resulting in penetrating the costal pleura and/or soft tissue trauma to the human thorax.

Based on the pattern and location of the rib fractures identified at autopsy, as well as the kinematics during impact, mechanisms of rib injury can be derived. In the air bag - three-point belt restraint system, injuries were concentrated typically along the right edge of the shoulder harness and along the lateral-most region of the rib cage on the right side. Fractures along the belt are initiated by the focal compressive forces in the anteroposterior direction. This compressive load increases the radius of curvature at the lateral edge of the rib, thereby initiating fractures due to a bending reaction. Depending on the local yield and failure characteristics, fracture may occur at one or both of these regions in the rib cage (Figure 2). A similar pattern of trauma was observed in our previous sled studies with three-point belt restraint (13). These findings suggest that the air bag - three-point belt restraint loading is similar to the three-point belt restraint (in the absence of the air bag) loading on the human thorax to result in the chest injuries. In other words, it is likely that the skeletal trauma is induced by the harness belt prior to air bag loading the thorax. Consequently, it may be appropriate to study the stiffness, elongation, and loading characteristics of the belt if these injuries are to be mitigated.

For the air bag - knee bolster tests, bilateral injuries to the anterior region of the rib cage were observed with no injuries to the lateral areas. The mechanism of injury is secondary to the direct contact of the lower torso with the lower portion of the steering wheel rim resulting in fractures at this region without concomitant propagated skeletal trauma at the lateral site (Figure 3). A similar mechanism of injury could be adopted to explain the rib fractures sustained in the air bag - lap belt experiments. The pivoting action of the harness around the hip and the likely lesser area of contact of the torso with the air bag may explain the fewer fractures observed.

The purpose of the three-point bending tests on isolated ribs was to examine the relationship, if any, between rib fractures and the type of restraint system and demographics of the subject. The stiffness and load carrying capacity were greater for male compared to female specimens (Table 1). This may be due to the physiologic degradation of the bone that occurs to the female population secondary to a loss of remodeling after menopause. It should be noted that all (except one) specimens belonged to the mature adult category. Low correlations were found between rib mechanical strength and the number of rib fractures (stiffness versus fracture, $r = 0.15$; ultimate load versus fracture, $r = 0.08$). Restraint system or the velocity was also found to be a nonsignificant determinant (ANOVA) for the number of rib fractures. As expected, variations in properties of the ribs were smaller within one cadaver specimen compared to variations between individual cadavers irrespective of the restraint combinations used in the study. The restraints were randomly selected for each test specimen. Because of a large number of prospective dependent parameters in these tests, the statistical model to better predict the number of rib fractures would necessitate a larger sample size. The isolated rib tests were conducted in a quasistatic mode, while the sled equipment induced dynamic loading. Being a viscoelastic material, it is prudent to expect differences between the two modes of loading. For the above reasons, additional studies are required to further explore the effect of these variables on the injury mechanics.

ACKNOWLEDGMENT:

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Abdominal Response to Steering Wheel Loading

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ABSTRACT

Occupant kinematics in automotive collisions can result in loading of the abdominal region for the unbelted or belted occupant. Abdominal response may affect kinematics of other body regions and it is therefore, important for determining the response of an occupant during a crash. Toward this end, the impact response of the thoraco-abdominal region was investigated utilizing un-embalmed repressurized human cadavers subjected to frontal impact with a non-deforming steering wheel lower rim. The focus of this research program was on the response of the soft-tissue in the abdominal region as well as the kinematic response of the lower section of the thoracic cage. This paper will describe a unique method, which merges accelerometer and film date, to determine abdominal response to impact loading conditions. In addition, abdominal response corridors will also be presented.

INTRODUCTION

Although the literature on abdominal trauma addresses many of the mechanical and physiological processes that take place during blunt impact to the thorax-abdomen region, only a limited number of studies have attempted to obtain force-deflection data that could be used to determine the abdominal response of a steering wheel rim loading the abdomen. For example, Cavanaugh et al (1) performed studies of frontal impact to the lower abdomen of unembalmed human cadavers using a rigid cylindrical aluminum bar impactor. The impactor loaded the abdomen at the level of the third lumbar vertebra with the cylinder perpendicular to the long axis of the spine. The subjects were placed on a table with their legs straight out and the torso suspended upright.

The torso was free to move during impact. The table was covered with a plastic sheet to reduce the coefficient of friction. The 38cm long by 25 cm diameter cylinder was attached to a 32 kg or 64 kg mass impactor which was accelerated by a pneumatically accelerated piston. Impact velocities were measured immediately prior to impact by a magnetic pick-up and varied from 4.9 m/s to 13.0 m/s. The deflection data were obtained by film analysis.

Miller (2) performed dynamic experiments with anesthetized porcine subjects. A 5 cm lap belt was used to deliver the load. The tests were done on a supine subject using a closed-loop, controlled-stroke hydraulic test machine with an inverted yoke-like fixture. The belt was attached to the ends of the yoke and initially positioned in contact with the abdomen. The impact consisted of downward motion of the yoke a preset distance and at a preset velocity. Miller reported the axial force and stroke data. However, because of belt stretch the actual deflection of the abdomen may have been different from the stroke reported by Miller.

Nusholtz et al, (3) conducted a series of steering wheel tests on unembalmed repressurized human cadavers. The impactors consisted of either a 25 or a 65 kg ballistic pendulum fitted with a steering wheel assembly. A load cell was affixed to the steering column to measure the axial steering wheel force. The accelerations and displacements of various points on the thoracic cage was measured. Although force deflection measurement were not presented because of the complexity of the experiments and the difficulty of determining precise load paths, the response of the subject was documented in terms of impedances.

This paper analyzes the results of a biomechanics research program conducted at the University of Michigan Transportation Resource Institute (12). The study investigated the response of the abdomen of unembalmed repressurized human cadavers[2]. A free traveling 18 kg impactor struck the subject in the thoroco-abdominal region. A unique method of merging film and accelerometer data was used to obtain: deflection, velocity of deflection, and the change of velocity of deflection. These results were then used to characterize the abdominal response.

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[1] This research was conducted when the authors were at the University of Michigan Transportation Research Institute (UMTRI).

(2) The protocol for use of cadavers in this study was approved by the University of Michigan Medical Center and followed guidelines established by the U.S. Public Health Service and recommended by the National Academy of Sciences, National Research Council.

METHODOLOGY

The instrumented, repressurized stationary test subject was struck by a steering wheel assembly affixed to an 18 kg moving mass impactor at velocities up to 11 m/s. Six accelerometers affixed on the thoracic skeletal system documented impact response. Vascular pressure in the descending aorta was measured. In addition, gross whole body motion was recorded through the use of high-speed photokinemetrics.

The techniques used to perform the impact tests are outlined below. Further detail on these procedures can be found in the references [3-6].

Pneumatic Ballistic Pendulum Impact Device

The impact device (Figure 1) consists of an 18 kg ballistic pendulum mechanically coupled to a pneumatic accelerator (cannon). The cannon consists of: an air reservoir, a ground and honed cylinder, and a metal-alloy piston connected to the ballistic pendulum with a nylon cable. Compressed air from the air reservoir chamber propels the piston through the cylinder, accelerating the ballistic pendulum. The piston is arrested and the pendulum becomes a free-travelling mass. A magnetic probe rigidly affixed to the side of the pendulum is used to obtain displacement and velocity.

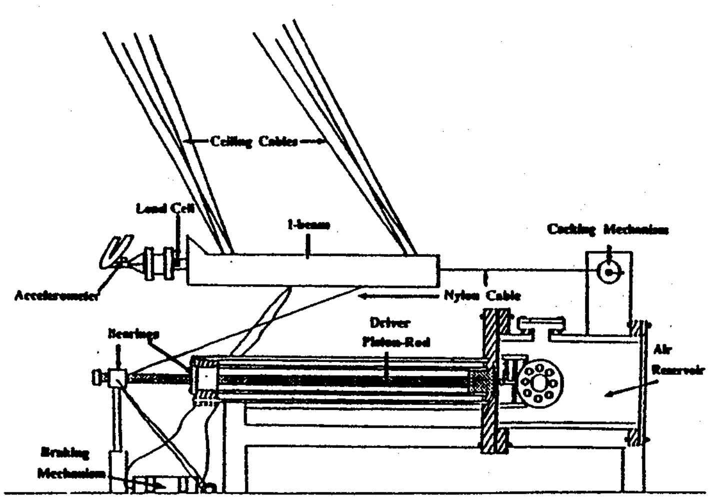

Figure 1 . Impact test device.

Steering Wheel Model -

The striker is a rigid structure with the impacting geometry similar to that of the lower half of a steering wheel. A semi-circular tube is supported at the bottom so that the angle of the half steering whe is similar to that found in the automotive environmen The support structure is rigidly mounted to an inertiε compensated load cell.

Subject Preparation and Instrumentation

The unembalmed cadavers used in these test were obtained from The University of Michiga Department of Anatomy and stored in a cooler at degrees centigrade. All cadavers were x-rayed as par of the screening for anomalies, surgical implants, and pre-existing injuries. Cadavers accepted for testin were measured using standard anthropometri techniques. Next, the cadavers were sanitarily and surgically prepared, dressed in vinyl and cottor clothing, and fitted with head and torso harnesses.

Surgical instrumentation of the subjects included rigidly affixing a triaxial accelerometer mounting platform on thoracic vertebra T12, inserting a tube for pulmonary repressurization, inserting a tube and catheters for abdominal vascular repressurization and the final sealing of incisions after the transducers had been attached to the mounting platform or tubes.

Cardiovascular Tube and Catheters:

Surgical insertion of foley catheters follows three patterns, depending on whether access through the femoral arteries is possible. Through an incision in the femoral artery, a catheter is guided up the arterial system; at the tip of the catheter is an inflatable balloon which can be used to occluded the aortic termination. Another catheter is guided through an incision in the common carotid artery into the descending aorta to occlude it slightly above the diaphragm. When the femoral arteries cannot be used due to plaque accumulation, either a double-balloon catheter is used to occlude the aorta below the diaphragm and at the common iliac arteries, or two catheters, one in each common carotid artery, are used to occlude the aorta below the diaphragm and at the common iliac arteries. In addition, through an incision in the carotid artery, a cardiovascular tube is inserted and secured. A Kulite pressure transducer, guided through the carotid artery tube and positioned in the descending aorta just below the diaphragm, monitored both the degree of initial repressurization and the change during impact. As part of the pre-test procedures occurring in the impact laboratory, the repressurizing fluid was introduced via the catheters through a channel in the center of the two occluding balloons. All incisions are sealed to contain body fluids.

Film measurement of spinal displacement:

Phototargets were attached to the accelerometer mount on T12. In addition, calibration targets were also visible. The film was digitized and used to assist in determining the displacement of T12 in the laboratory reference frame. The motion was obtained by using a Hycam camera at 1000 frames per second.

Contact Region - Each subject was placed in a seated position on a mobile, adjustable-height platform. The platform was covered with friction-reducing clear sheets of plastic, and the subject was supported from a ceiling hoist with the head and torso harnesses. The "steering wheel" was positioned to impact the abdomen of each subject, approximately at the second lumbar vetebra region.

Acceleration, Displacement, and Velocity Parameters - Displacement and velocity of the spine and pendulum were obtained from the "principal-direction" acceleration using the concept of a moving frame. For a more in-depth discussion of the moving frame concept, see references 8, 9, and 12. The displacement and velocity of the spine and pendulum then were used to compute the deflection of the spine at thoracic vertebra T12, as well as the velocity associated with that deflection.

During impact, the acceleration response of the spine manifests itself, primarily, as a change in speed as opposed to a change in direction. The tangential acceleration is the rate of change of speed of the velocity, i.e., the rate of change of the resultant velocity. Therefore, even though the motion of a given point on the thoraco-abdomen, such as thoracic vertebra T12 is three-dimensional to some degree the best one-dimensional estimate of that motion is obtained through the use of the tangential acceleration. This approximation can be used when all six degrees of freedom (i.e., three translations and three rotations) are available, as they are when nine or more accelerometers are used. Although a good estimate of the tangential acceleration can be obtained through the use of the principal-direction acceleration when only the data from a triaxial accelerometer cluster are available, the displacement of such a point generally cannot be obtained from the principal-direction acceleration because of the low-frequency noise in the signals and rotation of the point of interest.

To correct the principle direction acceleration its second intergal is adjusted to match the film data. This is done by performing a double integration of the principal-direction acceleration and comparing the result to the spinal displacement obtained from the high-speed film. When the doubly-integrated acceleration begins to diverge from the displacement value obtained from the high-speed film, a rotation of the principal-direction acceleration triad is initiated. The rotation of the principal-direction unit vector is in the plane of the principal and secondary direction and its magnitude is adjusted at each time step to ensure that the doubly-integrated principal-direction spinal acceleration produces results that are similar to the results obtained from the high-speed film. Since this processes essentially "smooths" the film data, it can be viewed as an adaptive filter similar to that used in (11). Therefore, the velocity of the spine and velocity of the pendulum can be obtained from an integration of the adjusted principal-direction accelerations.

Dynamic Variables and Injury Assessment - These test subjects were used in previous low velocity impacts to the thoroco-abdominal region, therefore, it is not reasonable to relate injuries to impact variables. Some precondition of the tissues could contaminate the injury response. The dynamic variables obtained were steering rim force, impact velocity, pendulum acceleration, spinal acceleration, and pulmonary pressure/abdominal vascular pressure. In addition, displacement at thoracic vertebra T12 was derived from high-speed photogrammetry.

Calculation of Values of the Five Injury Criteria

The techniques used to analyze the tests to obtain the parameters needed for calculating values for five injury criteria (Deflection, Viscous, $V_{max}C_{max}$ Specific Absorbed Energy, and Spinal Acceleration) are outlined below. Further detail can be found in references 1-4, 6-10, and 12.

Definitions of the Injury Criteria Variables -

(1) The Deflection Criterion is based on the relative displacement between the spine and the impactor during impact.

(2) The Viscous Criterion is based on the product of the relative displacement of the spine and the impactor, and the velocity associated with that relative displacement. The viscous response is a time function formed by the product of the normalized deflection and the velocity associated with that deflection. (Reference 7)

(3) The $V_{max}C_{max}$ Criterion is based on the product of the maximum impact velocity and the maximum relative displacement of the spine and the impactor. Viscous

(VC_{max}) is the product of the maximum of the impact velocity time-history and the maximum of the normalized deflection time-history. (Reference 8)

(4) The Specific Absorbed Energy Criterion (SAE) is based on the energy transferred to the thorax and is defined as:

$$SAE = [m_{c35} * m_p/(m_{c35} + m_p)]V_i^2$$

where m_{c35} is 35% of the mass of a subject, m_p is the pendulum mass, m_c is a subject's mass, and V_1 is the impact velocity, as described by Eppinger and Marcus.(9)

(5) The Spinal Acceleration Criterion is based on the resulting acceleration. The spinal-acceleration response is the resulting spinal acceleration measured at thoracic vertebra T12.

Additional Variables - Each dynamic parameter associated with an injury criterion represents, to some degree, one or more aspects of the energy flow and/or management of that energy. Assuming that injuries produced during impact are related to the energy absorbed by a test subject [9, 10], it is reasonable to compute a quantity such as Energy Loss which represents the total energy absorbed by a test subject at the end of impact. This quantity differs to some degree from the Absorbed Energy Criterion defined by Eppinger and Marcus [9], but is similar to that defined by Lau, et al [10]. Therefore, in addition to the five injury criteria variables, three other variables were computed: Energy Loss, [V*D]max, and $V_{max}D_{max}$.

(6) Transferred thoracic energy loss (EL) was determined through the use of mechanical impedance (Z), which relates the force at a given point and resulting velocity of a remote point. Analysis of the low frequency components of the mechanical transfer impedance data for the spinal principal-direction acceleration was used to determine the effective mass of the thoraco-abdomen system (m_e). The energy loss during impact was then calculated as:

$$EL = 1/2\ m_p\ (V_{i2} - V_{f2}) - 1/2\ m_e v_{t2} \qquad (2)$$

where V_i is the initial velocity of the pendulum and V_f and V_t are the post-impact velocities of the pendulum and thorax respectively determined at the time when impact force has decreased to 50% of its peak value.

RESULTS

A summary of the results are presented in Tables 1-3. Table 1 summarizes the dynamic responds associated with the injury criteria. Table 2 is the correlation matrix of variables associated with the injury criteria. The correlation is obtained through the use of linear regression. Table 3 is the anthropometry of each subject.

Test No.	86M006	86M016	86M026	86M042	86M052	86M062
Velocity m/s	10.0	6.5	7.5	10.8	9.3	3.9
Peak Force N	8900	5300	6700	8400	6700	3000
Energy Loss[2] N-m	520	260	320	570	480	140
Specific[1] Absorbed Energy N-m/kg	7.42	4.13	4.63	11.02	6.40	1.29
Peak Spinal Acc. m/s/s	620	560	400	420	300	170
Peak Viscous V*C m/s	2.34	1.04	1.00	1.69	1.42	0.35
Peak Viscous V*D m2/s	0.75	0.25	0.28	0.49	0.44	0.12
Peak Normalized Deflection - C %	53	38	36	48	48	21
Peak Deflection D	0.17	0.09	0.10	0.14	0.15	0.07
Vmax X Cmax m/s	5.31	2.50	2.68	5.17	4.52	0.79
Vmax X Dmax m2/x	1.70	0.60	0.75	1.50	1.40	0.27

[1] Based on ESV procedure [10].

[2] Based on effective mass from mechanical impedance. Series 000-060: 26, 16, 26, 38, 38, 24 kg.

TABLE 1

Table 2
Correlation Matrix of
Variables Associated with the Injury Criteria

VARIABLE	1	2	3	4	5	6	7	8	9	10
Velocity (1)	1.0000									
Peak Force (2)	.9588	1.0000								
Energy Loss (3)	:9916	.9341	1.0000							
Specific Absorbed Energy (4)	.9486	.8846	.9463	1.0000						
Peak Spinal Acceleration (5)	.5049	.6522	.4356	.4280	1.0000					
Peak Viscous $V_{max} * C_{max}$ (6)	.8917	.9357	.8911	.7885	.7145	1.0000				
Peak Viscous $V_{max} * D_{max}$ (7)	.8562	.9020	.8711	.7391	.6323	.9878	1.0000			
Peak Normalized Deflection (8)	.9515	.9287	.9391	.8389	.6482	.9459	.9093	1.0000		
Peak Deflection (9)	.9108	.8847	.9338	.7790	.4688	.9416	.9561	.9446	1.0000	
$V_{max} * C_{max}$ (10)	.9841	.9445	.9888	.9128	.5348	.9405	.9184	.9760	.9610	1.000 0
$V_{max} * D_{max}$ (11)	.9569	.9224	.9760	.8671	.4752	.9447	.9459	.9541	.9876	.9885

Number in a Sample = 6
Degrees of Freedom = 4

Confidence Intervals
P5% = 0.8114
P1% = 0.9172

Table 3
Cadaver Anthropometry
(all dimensions in centimeters)

Measurement	Number 86M001	86M010	86M020	86M040	86M050	86M060
Stature	180.0	168.4	164.5	176.2	161/8	178.4
Weight * (Kilograms)	70.1	40.2	57.5	50.0	70.3	61.9
Head Circumference	58.5	54.0	55.3	58.8	54.5	55.1
Head Length	19.5	17.2	18.8	17.1	19.1	19.2
Head Breadth	16.0	15.0	15.2	15.7	15.6	14.1
Menton-Vertex	22.2	21.7	22.6	22.7	19.5	21.8
Menton-Supra-sternale	11.2	13.2	7.5	8.6	7.2	9.5
Neck Circumference	34.5	30.0	30.9	33.0	38.0	33.8
Acromion Height	26.7	22.3	23.9	23.3	23.2	22.7
Suprasternale Height	33.4	31.3	30.8	41.4	27.1	31.8
Substernale Height	54.5	49.4	48.7	49.5	39.3	52.5
Substernale Circumference	93.0	75.0	76.0	78.5	92.2	90.0
Axillary Breadth	27.2	28.4	26.2	26.0	28.6	28.7
Chest Breadth	31.0	27.0	25.6	26.8	30.7	29.7

(FILE:GUY#1:CADAVERS.GSN)

Obtaining the Dynamic Parameters -

The pendulum displacements obtained from the doubly-integrated pendulum principal-direction accelerations matched those of the pendulum film displacement data and those of the pendulum magnetic digital transducer data without the use of the principal-direction rotation procedure. However, when the principal-direction spinal acceleration data were compensated by use of the high-speed film spinal displacement data, the doubly integrated spinal displacement data, the doubly integrated spinal acceleration produced results which were similar to the high-speed displacement film data, Figure 2. An example of force, deflection and Viscous time history obtained by this method is given in Figures 3 and 4. An overlay of the force deflection obtained from this procedure can be found in Figure 5 .

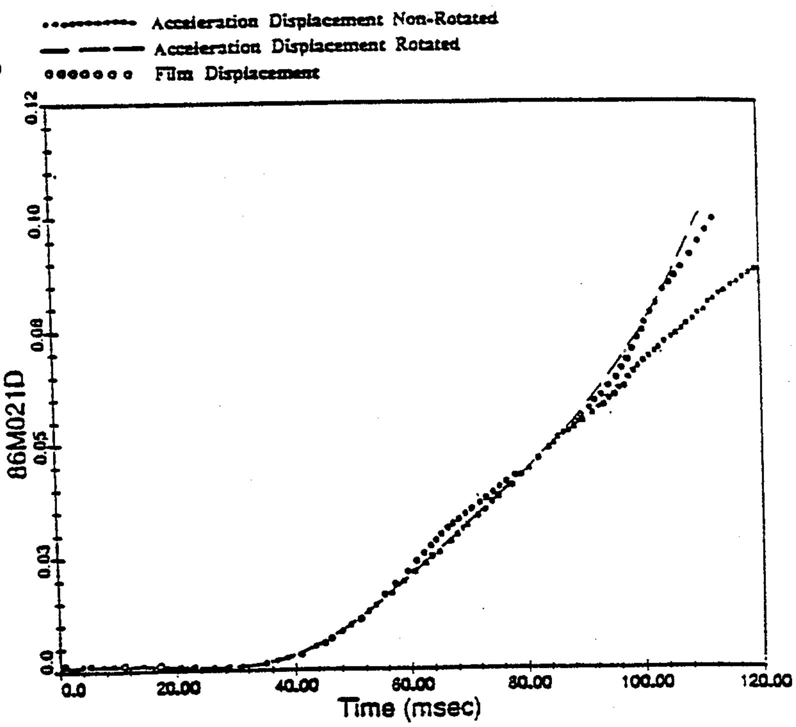

Figure 2. Comparison of film to double integrated acceleration.

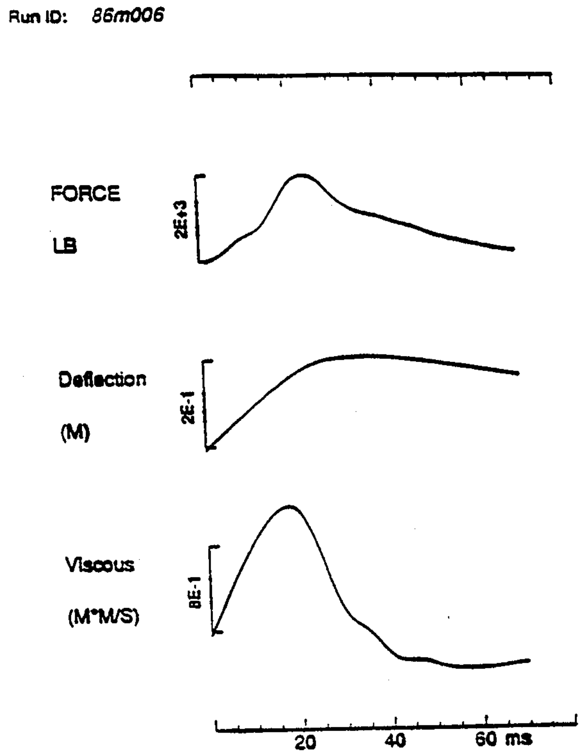

Figure 3. Kinematic time history.

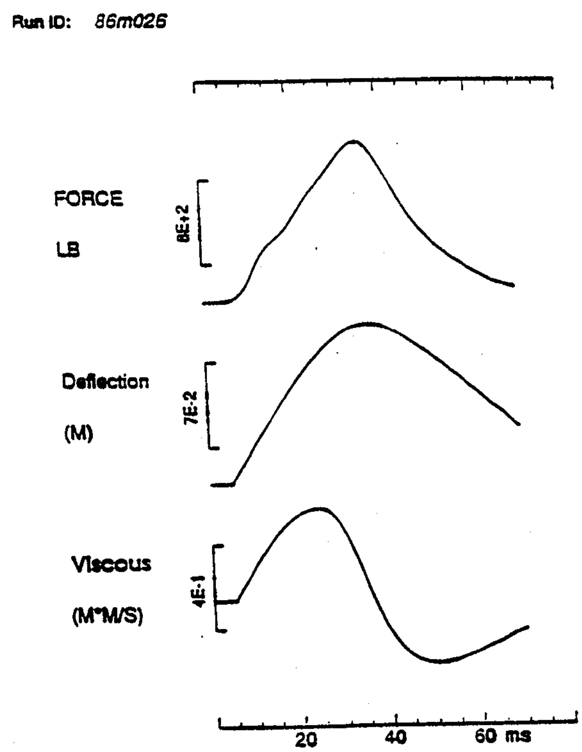

Figure 4. Kinematic time history.

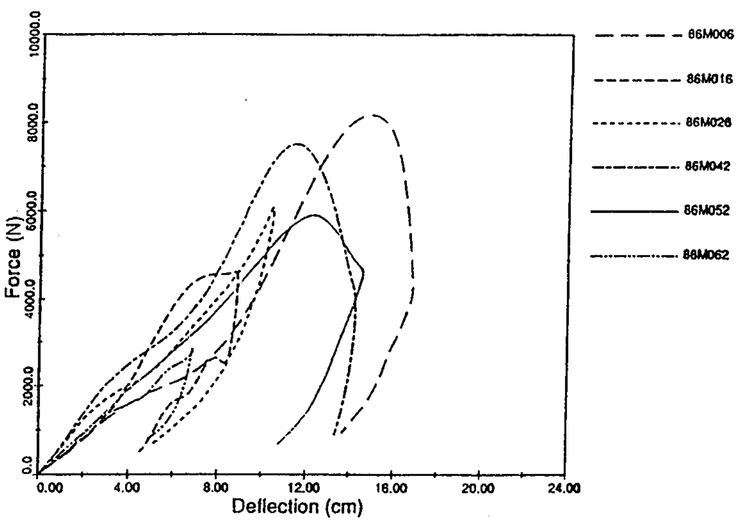

Figure 5. Force time history.

Force-Deflection Variability - The force-deflection curves represents the responses of the "soft" abdomen for different test subjects at different velocities, Figures 5 and 6. In terms of force-deflection, the tests showed considerably different responses. However, there was some similarity between tests for deflections up to 4-5 cm.

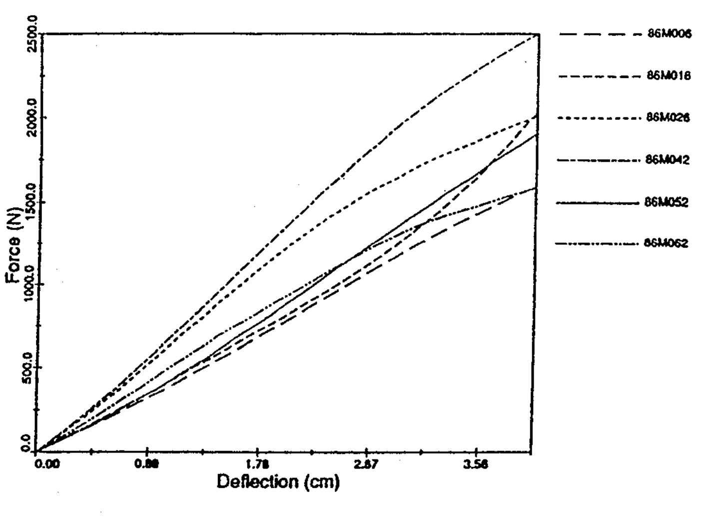

Figure 6. Force deflection up to 4 cm.

Before the test results can be used to characterize the impact response of the abdomen, it is desirable to consider some of the factors other than subject biovariability that may have caused the observed variability in force-deflection response among tests. These include: 1) off-axis loading of the steering rim load cell, 2) pendulum mass relative to a subject's body mass, and 3) three-dimensional motion of the test subjects.

It was decided upon review of the high-speed films that some off-axis loading of the steering wheel rim which would have affected the force-deflection response might have occurred just after the time of maximum force. The effect of potential off-axis loading of the steering rim load cell was evaluated quantitatively in the following manner. As Eppinger and Marcus [9] have proposed, the mass of the thorax was estimated to be 35% of a subject's weight. The product of this mass and the inferior-superior direction spinal acceleration was used to estimate the force perpendicular to the impact direction. This force then was applied to the steering wheel rim, and its effect on the axial force measurement was determined. The results showed that off-axis loading forces would not have exceeded 15% of the actual force value, and most likely was considerably less than that.

Another factor which could have affected the variability in the response of the subjects was the mass of the pendulum which was only 18 kg. Differences in the effective mass of test subjects would significantly affect the amount and rate of energy transferred to a subject from the pendulum and, therefore, would affect the response. This would have been particularly important, even for a linear system, if that response was rate- or velocity-sensitive.

Three-dimensional motion of the test subjects could have affected the force-deflection responses which are presented in this report as one-dimensional responses with the impactor at the second lumbar vetebra and the accelerometer at the twelve thoracic vertebra. Observations from the high-speed films indicate that this should be an acceptable assumption up to the occurrence of peak force, but during the recovery phase of the force-time histories, a two- or three-dimensional description may be needed.

Subject Biovariability

Table 3 summarizes the subject anthropometry. Mean subject weight was 56.7 kg with a standard deviation of 10.7, ranging from 40 --> 70 kg, and mean subject height was 170.8 cm with a standard deviation of 6.8, ranging from 161-180 cm. The mean age was 54.4 years with a standard deviation of 9.3, ranging from 44-63 years. Subject biovariability may be very significant because with only six test subjects there is a respectable variation in age, weight, and height. In addition, dimorphic effects are probably greater because the sample consisted of three males and three females.

In addition, subject biovariabilities may also affect response in some unusual ways, for example: Some variability in the force-deflection response may be attributed to non-linearity in the response of the test subjects. For example, consider Figure 5 which represents the force-deflection curve for Test 86M006. The increase in the slope half way between the initiation of impact and peak force may be due to bottoming out of the abdominal tissue against the spine. This appears to be a general trend in which an increase in slope occurs in those tests having higher penetrations of the abdomen. However, Test 86M062 may be an exception to this generalization. The test data shows that different levels of penetration produce different impact responses. This is an important consideration for determining the maximum penetration for a given force.

However, it is difficult to separate out how much of the variability in the force-deflection response was due to the factors just mentioned and how much of it was due to other biovariability of the test subjects. Therefore, because of the small sample size and the constraints imposed by the limitations of this type of data, it is not possible to generate a single force deflection curve that would give an average value.

Relationships Among Injury Criteria Variables

Table 2 summarizes the correlation between the variables associated with the injury criteria values. All of the variables correlated well with each other, except for Peak Spinal Acceleration. This shows that four of the five criteria are based upon similar aspects of the energy transferred to, or absorbed by, a test subject. When the Deflection variable is normalized, then the correlation between Energy Loss and either the $V_{max}C_{max}$ or viscous variables is improved.

IV. DISCUSSION

The focus of this analysis was to develop the tools to determine the parameters needed for computation of injury criteria values from the dynamic test data. In addition, evaluation of the relative predictive abilities of the different thoracic criteria for abdominal trauma was addressed. Although it is not possible to relate these injury criteria values to the observed injuries directly, it is possible to evaluate the five criteria in terms of the amount of energy transferred to, or absorbed by, a test subject and with regard to their inherent limitations in representing dynamic parameters and definitions.

Energy Transferred to, or Absorbed by, a Test Subject

Although in this analysis the injury criteria values cannot be directly related to the observed injuries, analyses made by other researchers of their own data show that there is considerable controversy over which of the five injury criteria is the best indicator of thoracic injury. For example, Lau, et al, [10] believe the Viscous Criterion is the best indicator of thoracic injury; Eppinger and Marcus [9] believe the Specific Absorbed Energy Criterion is the best indicator of thoracic injury; and Kroell, et al, [8] believe the $V_{max}C_{max}$ Criterion is the best indicator of thoracic injury. Which of these might be the best indicator of abdominal injury? The consensus among these researchers seems to be that injury is a function of the energy transferred to, or absorbed by, a test subject during impact. Therefore, it was thought worthwhile in this study to develop a clearer definition of energy flow and to attempt to measure it. The Energy Loss variable represents an attempt to accomplish the measurement of a clearly defined energy flow to a subject during impact.

For all of the injury criteria, it is assumed that injury is related to the amount of energy transferred to, or absorbed by, a test subject [8-10]. Each dynamic variable associated with an injury criterion represents, to some degree, one or more aspects of the energy flow and/or management of that energy. For example, deflection represents, to some degree, the work needed to deform the thorax. The Viscous response and the $V_{max}C_{max}$ response represent, to some degree, the energy dissipated during impact. The question becomes which variables represent the energy flow and/or management of that energy in such a way that abdominal injury, or a threshold of abdominal injury, can be predicted accurately.

<u>Close Correlation of Four of the Criteria</u> - The numerical values of the injury criteria variables determined from the current dynamic test data and information were correlated. It was determined that all of the variables correlated well with each other, except for Peak Spinal Acceleration, as shown by Table 4. It is expected that since the Viscous, Specific Absorbed Energy, and $V_{max}C_{max}$ responses are representative of the energy loss that they would correlate well with

Energy Loss. Yet Peak Force, Deflection, and Impactor Velocity also correlate well with Energy Loss. That these parameters correlate well with each other makes it difficult to determine which of these injury criteria might prove to be superior for this type of testing. If, at some future date, all of these four injury criteria are found to predict abdominal injury successfully, the injury criterion that is "best" might simply be the easiest one to obtain. The only injury criteria that did not correlate well with the others was spinal acceleration. Therefore, spinal acceleration is not a good indicator of injury or, it is the only good injury criteria.

CONCLUSIONS

This was a limited study of the impact and injury response of the abdomen used to develop procedures and techniques necessary for computation of values for five thoracic injury criteria from dynamic laboratory data and test information as one means of assisting in the evaluation of these criteria for abdominal trauma. Values were calculated for the Deflection Criterion, Viscous Criterion, $V_{max}C_{max}$ Criterion, Specific Absorbed Energy Criterion, and Spinal Acceleration Criterion. The experiments utilized special impact conditions, for example, an idealized rigid lower one-third of a steering wheel rim was used as the impact surface and multiple impacts were conducted. The results and conclusions presented apply only to a limited analysis of the test data. More analysis of the data needs to be performed before general conclusions about the kinematic response of the thoraco-abdomen can be drawn. In addition, more tests need to be performed before general conclusions about the abdominal injury predictive capabilities of four of the five injury criteria can be drawn. However, the following limited conclusions can be drawn:

1. The kinematic variables associated with the five injury criteria can be calculated from data obtained from triaxial accelerometers in conjunction with photogrammetry of high-speed films.

2. Spinal acceleration is not a good indicator of injury, ot it is the only good injury indicator.

3. In the experiments presented here, ranging in velocity from 4 to 12 m/s, there is no important difference in the force-deflection curves for the first 4 cm of penetration. This implies that the initial response of the abdomenis is not impact-velocity dependent.

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Comparison of Human Facial Tolerance and Mechanical Models

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ABSTRACT

Facial injury detection in the crash laboratory needs new test devices and procedures. The increasing usage of improved restraint systems has reduced the severe head injuries. Instead a pattern of less severe facial injuries has emerged, e.g. the facial airbag contact.

The paper presents a comparison of the stiffness characteristics and the initial kinematics response of the facial of cadavers and mechanical models. The two mechanical models, based on a modified Hybrid III dummy head, detect localized facial forces. One was equipped with a frangible facial insert, and for the second, a load sensing face (LSF) was developed with piezoelectric sensors providing pressure times histories. Design properties and characteristics of the LSF are described as well as the sensor technique used.

Cadavers and dummy were fitted with triaxial accelerometers installed in the sagittal plane of the head at the coronal and lambdoidal sutures. The faces of all test subjects were impacted at the sub-nasal maxilla and nasion by a horizontal steel bar of 25 mm diameter.

Furthemore, a mathematical model of the human face is now in progress in an explicit finite element code.

To complete the knowledge of bone injuries obtained previously, specifics tests to analyse the soft tissue injuries, were carried out.

All these results from tests are used to appreciate the means to evaluate the facial lesions and to understand the facial behaviour such as an interface, e.g. between the airbag and the head.

ACCIDENTOLOGY

An accident data about the lesion typology was carried out, at INRETS, firstly in 1982-83 and then finally ten years after.

The aims of these two studies were to highlight the lesion typology by the types of all the roadusers, and to verify the possible evolution through these two periods of the lesions nature which should be correlated with the vehicle safety evolution and the environment evolution.

The first study (1982-1983) underscore a high frequency of face lesions, 33% of the road accident victims and 31.2% for light vehicle users. In 1993, the number of the face lesions increases for the first category to 37.2% and for the second to 35%.

We are mainly interested in lesions of the small car users forwhich proection solutions are in progress towards sophisticated devices, for a long time.

In 1982-1983 (Ramet, Vallet, 1987), 60% of the lesions of the face and the eyes belong to the small car users. Ten years after, the small car users represent 70% of the face injuries while all the others categories are slightly in reduction.

The drivers represent 68% of face injuries. In fact the front seat passenger are injured in 22% whereas the rear seat passenger in 10%.

The table 1 shows the repartition of lesion types in the two studies.

Tableau 1: Distribution of facial injuries

LESION NATURE	*TYPOLOGY 1982/1983*	*TYPOLOGY 1993/1994*
Laceration	80%	81.7%
Nasal Bone Fracture	10.2%	9.6%
Inferieur Maxilla Fr.	3.9%	4.3%
Naso-Maxillary Fr.	4.9%	1.4%
Cranio-Faciale Disjunction	0.08%	2.4%

We constate that if the frequency of facial lesions increase, the lesion nature and their allocation are very similar and that although the seat belt are more and more fasten. When we realize crash tests in laboratories, the dummy head hit the rim of the wheel despite the fact that the dummy thorax is more rigid than an average small car user, and the neck flexion are more limited than a human neck.

The face lesion origin are mainly due to the contacts with the steering wheel and specially with the wheel rim (Karlson, 1986).

We found quite the same lesion allocation in the literature (Jettner et al, 1986), (Chapman, 1985) and a typology difference notion in function of the contact type with the steering wheel. Principally face lesion origins are due to the contact with the wheel rim, while the contact with steering spider create cerebra lesions.

Why are we questionning us about the type of lesions ? Effectively, if these lesions are numerous, they are seldom serious. According to the AIS scale, fractures of the face are coded minor or moderate.

On 208 small car user who have face injuries ; 198 are coded AIS 1, 26 are coded 2 and only 7 are evaluated AIS 3.

But the consequences for the injured individual are considerable because of the long term psychic and cosmetic sequelae.These lesions give considerable damages and the plasitc and reconstructive surgery acts are very expensive. A study (Viano, 1985) shows effectively that face lesions cost two times more for the society than cerebral lesions.

In fact, if the nasal bone fractures give seldom partial permanent disability superior to 10%, the laceration and many face fractures can give partial permanent disability between 20% and 50% (Fournier, 1978), (Karlson, 1986).

FACIAL INJURY BIOMECHANICS

Anatomy

The face is the front part of the head: it is defined as the area from the forehead to the lower jaw and includes fourteen bones, onely, the mandibule is free and has two movable joints attached to the base of the skull. The face is covered by skin and muscles. The skin is very thin particularly along the Langer lines (Fig.1).

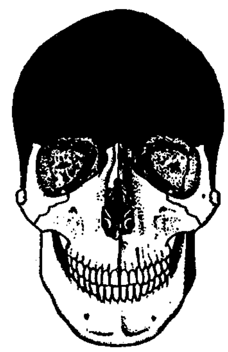

Figure 1 : Facial bones.

Facial skin tolerance

Facial skin is very thin. Soft tissue injuries of the face are abrasion or laceration more or less (AIS 1 or 2). These types of injuries decreased with the use of laminated winshield and seat-belt use.

A lacerative index was defined by Leug (1977) using tests performed on human skin, (living person or fresh cadavers) the data obtained found that the severities of laceration injures are depending to the lacerative resistançe, the applied load and the shape of the impactor. The lacerative index is a 4 points sytem (0-4).

In the same way, the VRTC developed a chamois laceration scale to take into account cuts sustained by this "skin": The CLS is divided with 6 divisions (Jettner, Hiltner, 1986).

Facial bones tolerance

Identified in 1900 by Le Fort which gives his name to complexe types of facial fractures, automotive accidents are the leading cause of facial lesions, especially mandibular fractures (Fig.2).

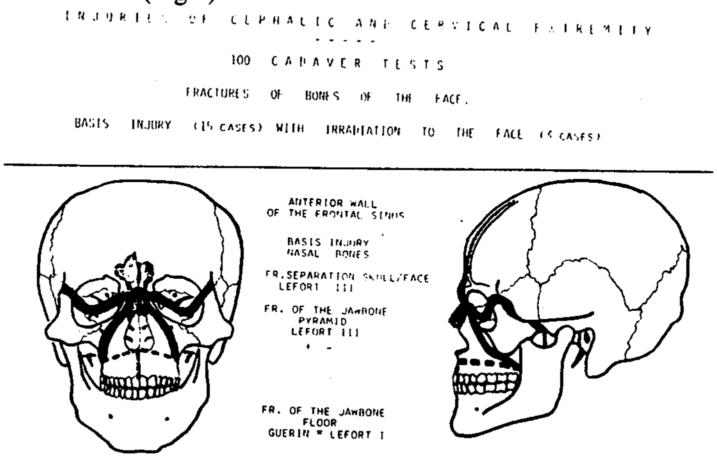

Figure 2 : Illustration of facial fracture.

The most frequents studies concern the mid-face and are conducted on fresh cadavers. The accident data indicate that the steering, specially the rim : so, numerous tests used an impactor which is an horizontal steel bar of 25mm diameter which can be compered to the ring of the steering wheel.

Cadavers tests

A serie of tests was conducted at INRETS Laboratory to provide information on the fracture tolerance of bonny face.

Height fresh human cadavers are impacted under impact conditions simulating an impact on the steering wheel rim.The results are compared with tests conducted under similar conditions on Hybrid III dummy equipped with a frangible face.

Cadavers are impacted with a T shaped head of which the horizontal steel bar was of 25 mm diameter : The subjects are seated in front of the impactor and the sequence of impacts consisted of the following.

- Sub-injurious impact to the chin at 45° to the Franfort plane.
- Sub-injurious impact to the chin parallel with the Franfort plane.
- Potentially injurious impact to the maxilla.
- Potentially injurious impact to the nasion.

Results of these tests

Table 2 : Mandibule tests

	impact speed (m/s)	*impactor kinetic energy(j)*	*maximum force (N)*	*Remarks*
1	1,40	16,3	387	no injury
2	1,85	28,4	352	no injury
3	1,94	32,2	525	no injury
4	2,67	59,2	663	cutaneus erosion
5	3,11	80,3	683	condyle fracture
6	3,06	77,7	654	wound, no fracture
7	0,00			
8	2,24	43,6	426	no injury

Table 3 : Sub-nasal maxilla tests

	impact speed (m/s)	*impactor kinetic energy(j)*	*maximum force (N)*	*Remarks*
1	1,40	16,2	516	fracture of nasal spine
2	1,35	15,1	660	no fracture
3	1,98	32,5	673	no fracture
4	3,14	81,7	1254	fracture of nasal spine
5	1,95	31,5	788	partial fracture of nasal spine
6	2,30	43,8	1148	fracture of nasal spine
7	3,19	88,2	1361	fracture of nasal spine
8	3,22	89,9	1049	no fracture

Table 4 : Nasion tests

	impact speed (m/s)	*impactor kinetic energy(j)*	*maximum force (N)*	*Remarks*
1	3,25	87,5	2503	fracture of nasal bone and septum
2	3,08	78,6	2918	no fracture
3	3,86	123,4	2781	Lefort III fracture
4	3,03	76,1	3403	no fracture
5	3,67	111,6	3760	fracture at jonction of nasal and frontal bones
6	3,67	111,6	2225	Lefort III fracture
7	2,27	44,7	1875	fracture of nasal bones
8	2,26	44,2	1789	fracture at jonction of nasal and frontal bones

A single impact was made at each site on each subject. During each impact, the motion of the head was recorded by high speed cameras and 6 head accelerations, the impactor acceleration and the impactor forces were recorded.

After the 4 tests, the subject was X ray radiographed. An autopsy is made and the head is defleshed to identify the fractures (Figure 3).

Figure 3 : Nasal bone fractures.

MECHANICAL DEVICES

A frangible face

This work provide tolerance data and permet to compare them with results obtain on frangible face (figure 4).

The same tests are conducted at INRETS (Welbourne, 1989) with hybrid III dummy equipped with a frangible face, but only to the nasion and to the sub nasal maxilla.

The data from the frangible face showed well defined thresholds at both impact sites. The frangible face provide a quite coinservative indication of the strength of the human face of the maxilla. For the nasion, the fracture threshold of the frangible face coincides approximately with the 40th percentile of the distribution of the cadaver tolerance data.

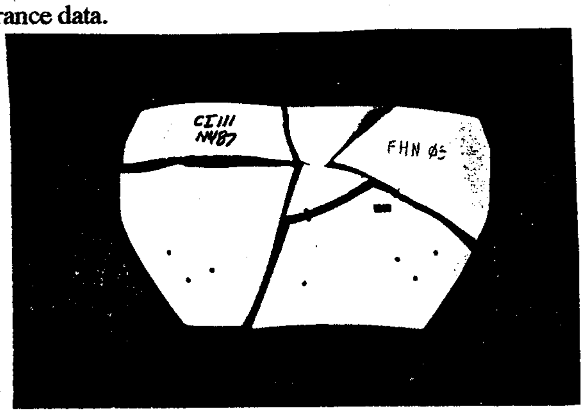

Figure 4 : Cracked frangible face.

A load sensing face

It seams that the FMVSS 208 procedure concerning head accelerations at the head gravity center are not sufficient to detect most important facial injuries.

So, works are conducted to realize a load sensing dummy face, qui should enable researchers and designers to progress in amenagements of vehicles interior surfaces (Warner, 1986).

Impactor tests carried out at INRETS with a load Sensing Face (LSF) equipped dummy (Planat, 1988). The sensing face is the face of an Hybrid II dummy covered by twenty five piezo-electrics sensors. An instrumented face form can record time histories of impact, releated to pressures.

Results are showed in figure 5.

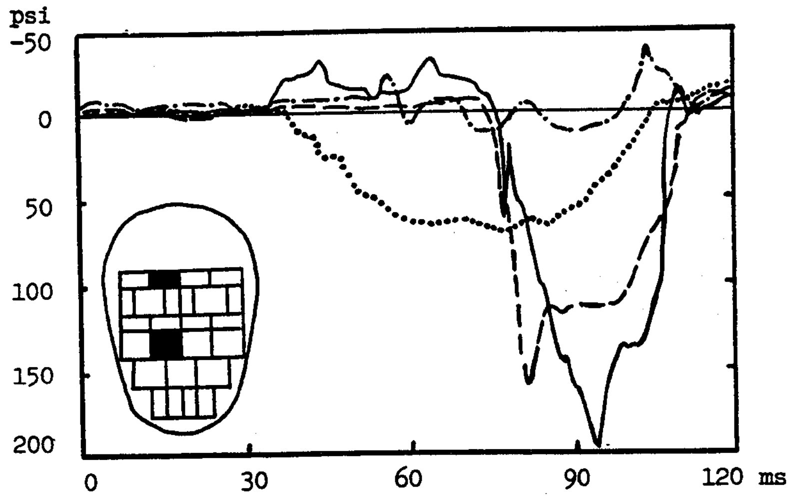

Figure 5 : Pressure time histories from LSF.

The Bimass 150 principle

The aim of a study (Willinger, 1993) is to transfer the biomechanical head study results to a physical model intended for "measuring" the shock severity. The chosen principle is that of two masses which model the brain and skull and whose mechanical liaison has a rigidity such that the systems natural fraquency is at 150 Hz. The validation of the model relies on the superimposition of the mechanical impedance physical model with the mechanical impedance of the human head in vivo.

The tests were carried out at INRETS on an impacting device setting a 16.6 kg mass in motion. The model was fixed in the neck of a Hybrid III Dummy placed in front of the impactor as illustrated in figure 6.

Figure 6 : Bimass 150 tests.

Remarks

The frangible face, as the load sensing face, as the bimass 150 are some needs to can measure induced trauma to the occupant face. An alternative and complementary way of the mechanical models and the cadaver tests is the mathematical model approach, to improve the knowledge in the field of the human head tolerance against the impacts.

MATHEMATICAL MODEL

Mathematical model interests

A validated model can provide a rational basis for injury prevention and treatment. Experimental and mathematical modeling of head injury are two parallel methods used by head injury researchers to perform their head injury simulations. In experimental models, animals, cadavers and anthropomorphic dummies are. used. Experimental modeling of head injury yields measured force, acceleration, displacement, related to injury tolerance, injury severity and type. These data help the Bioengineer in the understanding of human response and tolerance and also permits him to validate the mathematical models of head impact.

On the other hand mathematical modeling of head injury applies the principles of mechanics and numerical analysis to define the problem, formulate the solution and predict the potential of injuries. Mathematical models furnish the head trauma analysts with a powerful tool to extrapolate major experimental findings in animals and other surrogates to the human and to correlate mechanical parameters to clinical observations. In addition to that, the use of these models represents considerable cost reduction when compared to physical tests on actual specimens in the laboratory and also parameters that are virtually impossible to measure in the laboratory can be examined in detail with these simulations.

Human head models

The development of a validated mathematical human head model has challenged many head injury researchers. If such a model can simulate the response of a living head, it will help us to answer many questions in head injury. Due to the complex geometry of the head, its non-linear material property of head impact and the difficulty of the numerical computations, mathematical models always need certain idealizations, assumptions and simplifications.

Early, the geometry was restricted to simple spherical or cylindrical shapes. A few models represented the human head more closely by finite element method. Models developed up to the 1980's have been summarized in two survey papers by King and Chou (1976), and Liu (1979).

More recently, Cheng et al (1990) formulated a two dimensional finite element model representing a coronal section of the brain to study the diffuse axonal injury (DAI) problem.

A plane strain model of a parasagittal section of an average human head was created by Chu and Lee (1991) to study the mechanisms of cerebral contusion.

Ruan et al (1991) formulated three finite element models, an axisymmetric model, a plane strain model of coronal section of human head with and without the falx and tentorium, respectively, to study the response of the head to side impact.

DiMasi et al (1991) have developed a 3-D brain model to study DAI on the premise that it is caused by cerebral strain. The model predicted shear and normal strains in the brain in response to an impact of the head to an automotive A-pillar. The model was that of on upper cerebral cortex with a longitudinal fissure to provide distinctive sagittal and coronal geometric feature and the surrounding dura including the falx partition. The dura and cortex were enclosed by a relatively rigid skull to simulate direct impact events with padded and unpadded A-pillars.

A three dimensional human head model simulating a three-layered skull, cerebral spinal fluid and brain has been developed by Ruan et al (1994) to study in more detail the coup/contrecoup response in the brain. This model was validated against cadaveric intracranial pressure reported by Nahum et al (1977). It predicted higher skull stresses and higher negative intracranial pressures in contrecoup region from occipital impact than from frontal impact. This result explains the clinical observations that more severe contrecoup injuries are presented in occipital impacts than frontal impacts.

Based on the 3-D geometry, previously presented (Ruan et al, 1994), a new 3-D human head finite element model has been developed (Jesse et al, 1993). A feature of this model was the compution of the impact force due to impact by a rigid cylinder moving at a given initial velocity, simulating the cadaveric tests of Nahum's et al (1977) whose data allowed to validate the model.

Willinger et al (1992) proposed a theoretical modal analysis of a finite element model of the human head in its sagittal plane. The results applications to the crash biomechanics field are presented. For the model validation, this approach allowed them to determine the mechanical properties of the material used to model the subarachnoid space so as to obtain the first natural frequency and mode shape in accordance with mechanical impedance recorded on the human head in vivo.

Remarks

Such models previously mentioned have been developed essentially for simulating the biomechanic response of the brain to dynamic loading which is vitally important for understanding brain injury mechanisms but most of them still lack prominent anatomical feature of the human head or have not been validated.

Methodology of the skull model

Geometry of the skull model

A 3D mathematical model of the human skull allowing the analysis of the human skull fracture tolerance is under development at the INRETS.

This model, utilizing the three-dimensional non-linear explicit finite element computer code PAM-CRASH (1992), is based on a real human skull, which gives a complexity structure.

The current skull model represents the face of the human that is a skull without its top and without the inferior jaw.

To obtained the geometry of a real skull, their internals and externals surfaces are punctually swept with the stylet from on ultrasonic device (GP8 from Science Accessories Corporation), which gives on a file the three dimensional coordinates of the point reached.

A mesh was drawn by hand on the real skull. The nodes of the mesh where chosen to defined volume element (most of them are represented by 8-node solid brick elements). The skull model is discretized with around 400 nodes and 200 elements

The figure 7 shows the human skull model.

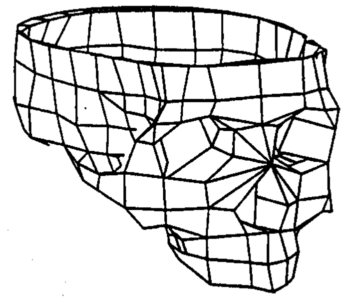

Figure 7 : Skull model.

Material properties of the skull

The bone of the skull is mainly cortical bones. However, certain part are composed with bone more or less dense. This influence the mechanical behaviour of the bone. So the skull model have to be shared in regard with the mechanical properties. Although there is more reliable information available on bone than any other material since it is easier to measure the constitutive properties of a hard, stiff material such as bone than to measure the properties of the softer more compliant human tissues, we did not found the specific mechanical properties of the skull bone. Also we take for the human skull model bone properties those which were estimated from available data about other bones like those from the human leg bones.

Mechanical properties of bones

The characteristic of the bone (Burstein et al, 1976, Keaveny et al, 1993), (table 5) is viscoelastic quality. Cortical bone is similar in properties to other fibrous materials such as wood, and has substantially more compliance than engineering materials such as metals, but more rigidity than spongy bone. Bone is one of the most rigid biological materials in the body and has a significantly greater stress carrying capacity than soft tissues which are frequently used to link long bones through joints or cover the musculoskeletal system.

Table 5 :Mechanical properties of bones

Cortical bone	*Femur*	*Tibia*
Density : kg/m^3	1900	1900
Elastic modulus : N/m^2	$17.6\ 10^9$	$18.4\ 10^9$
Plastic modulus : N/m^2	$0.754\ 10^9$	$1.2\ 10^9$
Yield stress : N/m^2	$0.12\ 10^9$	$0.13\ 10^9$
Ultimate stress : N/m^2	$0.14\ 10^9$	$0.15\ 10^9$
Poisson's ratio	0.326	0.326

Impactor description and model validation

To validate the human face model, it is impacted first at the nasion by a horizontal cylinder of 25 mm diameter to simulate the cadaveric tests performed at both Wayne State University (Nyquist et al, 1986) and Institut National de REcherche sur les Transports et leur Sécurité (Welbourne et al, 1989). Hence, a similar rigid impactor was built with solid brick elements.

All the impactor nodes can displace in the only direction of the impact to be in the same conditions as the experimental tests (Nyquist et al, 1986 - Welbourne et al, 1989). The model responses will be compared with the measured cadaveric test data in terms of head acceleration and impactor penetration or fracture tolerance (probability of fracture as a function of impact energy).

The analysis is performed by the PAM-CRASH finite element code (1992). This is an explicit, large displacement, Lagrangian, dynamic finite element program which is commonly used in crash worthiness analysis. The simulations are both qualitative and quantitative.

The graphical output of the post-processor (Daisy) presents the investigator with pictures that form important qualitative impressions that contribute to his ability to judge the reasonableness of the simulation and may suggest further changes in the model (e.g., mesh rezoning, changes in geometry, etc.) to improve its performance. Quantitative data is available in the form of element time histories of selected stresses and strains and nodal time histories of displacement, velocity and acceleration. In addition, the ability to plot stress and strain contours on selected cross sections of the model is also available.

CONCLUSIONS

The aim of this paper was to compile different approaches of facial tolerance : cadavers tests, mechanical models and mathematical models.

Facial fractures are numerous and the consequences for the injured people are considerable

Moreover the fracture and collapse of the facial bones during distributed loading reduces the peak forces and resulting head accelerations in comparison to those produced by similar impact tests to the skull.

The skull model in frontal impact with Finite Element Method gives information about the internal mechanical behaviour, the kinematics, the displacement, the velocity, the acceleration, the maximum effective surface stress, the Von Mises stress and the contact force between the impactor and the tibia. We still have to simulate other use conditions of the model as a function of the stiffness, the speed or the energy of the impactor.

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Assessing Steering Wheel Impacts Using a Hybrid III and Deformable Load Sensing Face.

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ABSTRACT

Accident data, from many countries, have identified the head and face as the body region most frequently injured in frontal car collisions. The steering wheel is one of the car interior components most responsible for these injuries.

This investigation conducted comparative performance tests of energy absorption characteristics for a number of current production steering wheels. Emphasis was on evaluating the performance of steering wheels in Australian cars. This paper describes the development of a test procedure which provides information on the performance variability between steering wheel types. Features that contribute towards better performance were also identified. The test involved the head of a Hybrid III dummy impacting against the steering wheel, and the resulting Head Injury Criterion (HIC) value used to compare steering wheels. Comparative testing was also conducted using the Deformable Load Sensing Face (DLSF).

The test methodology proved reliable and repeatable. An analysis of the comparative testing reinforces the view that significant differences in injury potential exist, due to steering wheel styling differences.

INTRODUCTION

Mandatory seat belt wearing legislation, in Australia and most other countries, has proved to be very effective in reducing occupant fatalities. The normal lap/sash belt has significantly reduced driver contact with certain parts of the car's interior such as the windscreen, as well as preventing occupant ejection from the vehicle. It has been suggested by a number of studies (1,2) that the wearing of a seat belt may halve the probability of death. However, this widespread wearing of seat belts has caused a considerable shift in the mechanism and type of injury experienced in crashes. Of those that are injured, there is a larger percentage of facial injuries caused by the driver's head impacting with the steering wheel.

Many recent overseas and Australian accident research studies, have identified the head and face as the body region most frequently injured in frontal collisions (3-7). An Australian study (4) has found that 47% of crashes on Australian roads were frontal impacts resulting in the driver being the most frequently injured occupant, compared to the front passenger, by a ratio of almost three to one. The steering wheel and column assembly was identified as contributing to the high injury rate by the Australian study and by many field studies of accidents from different parts of the world (1,3,7,8,9).

Numerous researchers have reported the frequency of head to steering wheel impacts. For example, Gloyns et al (6) reports that 67% of the drivers studied, sustained a head or face strike on the steering wheel. In the analysis of Tarriere et al (10), 18% of the drivers involved in frontal collisions sustained a head strike on the steering wheel.

Others report that over 40% of belted drivers with serious injuries had struck the steering wheel with their face or head (2,11). Therefore, head or facial contact against the steering system is found to be relatively frequent and severe.

Further research shows that since the introduction of compulsory seat belt wearing, the injuries sustained by drivers hitting the steering wheel, even in relatively slow impacts, are typically facial bone fractures, soft tissue injuries, contusions, lacerations and abrasions (7,8). Taking all severities into account, 65% of all the detected contacts were found to be on the hub and spokes of the steering wheel. These are areas that have great potential for improvement if energy absorbing methods (ie. padding and yielding) were to be incorporated.

AUSTRALIAN DESIGN RULES FOR THE STEERING SYSTEM.

In Australia, the function of 'Australian Design Rule 10/01' is to minimise crushing or penetrating injuries to drivers due to the steering column as a result of frontal impact (12).

To date, there are two test procedures set out in the standards for vehicle component design and compliance addressing the steering assembly:

1. The Body Block Test - a simulation of the (unrestrained) driver impacting on the steering wheel and column. Under defined test conditions the maximum load on a body block (chest), moving at no less than 6.7 m/s, by the steering column and wheel assembly should not exceed 11.1 kN, except for intervals whose cumulative duration is not more than 3 milliseconds.

2. Barrier Impact Test - a full scale test at 48 km/h measuring the penetration of the steering column into the occupant's compartment.

At present there is no Australian standard which specifies steering system performance to protect the driver from the consequences of a head impact with the steering wheel.

PRELIMINARY INVESTIGATION

In order to objectively simulate a frontal collision resulting in a head to steering wheel impact, a better understanding and appreciation of the conditions and kinematics of the impact was required. Below, is a description of the method used to conduct the preliminary research, as well as the results obtained, discussion and conclusions drawn.

The Roads and Traffic Authority's Crashlab conducts both full scale barrier tests and crash simulator/sled tests. For this project sled testing data was utilised. The sled tests used a Hybrid III dummy restrained by a standard Australian design three point lap/sash seat belt. Tests were conducted at a 24g deceleration pulse at 48 km/h.

Film analysis of these tests showed considerable dummy forward displacement resulting in head and chest contact with the steering wheel. Initial facial contact was predominately found to be between the lower forehead region and the nose level, with the upper portion of the steering wheel rim. The average approach velocity of the head towards the steering wheel was calculated to be 11.12 m/s.

The main factors that influence steering wheel-occupant interaction are the size of the occupant and the layout of the seating and steering wheel assembly. For example, a person of small stature would be more likely to make contact with the hub of the steering wheel than a taller person. The distance of the steering wheel from the seat is another contributing factor associated with size.

A further complication is the possibility of dynamic movement of the steering system prior to contact. Dynamic movement results from steering system intrusion into the occupant compartment, or from chest contact prior to facial contact with the steering wheel. The latter was evident in the high speed film that was analysed.

The speed of the head prior to impact was determined from the high speed footage and found to be in the range of 7.82 - 12.50 m/s (28.15 - 45.00 km/h). This is in good agreement with Gloyns et al (6), who states that in a 50 km/h sled test, head to steering wheel contact speeds for the restrained driver may be in the range 30 - 40 km/h. Therefore, it is important to investigate the performance of the steering system at a range of speeds because testing at one set speed may underestimate the performance of the system.

Steering wheel orientation at the moment of occupant contact is random in a real collision, and therefore impact can occur anywhere on the wheel. Some general reasons for this are :

- the driver often rotates the wheel as part of a means to avoid a collision,
- an impact involving load application to the front wheels can cause steering wheel rotation before the driver contacts the wheel (13),
- an offset impact.

In conclusion there are many factors that govern the kinematics and impact location, hence the resulting type and severity of injury experienced by an occupant involved in a collision.

TEST METHODOLOGY

In developing an appropriate test method for evaluating the energy absorbing properties of steering wheels several requirements are to be addressed:

- the selected test must be an objective test which best mimics actual impacts and conditions which produce injury,
- the injury measure used must be applicable to the test condition and the injury to be evaluated (14),
- accurate, repeatable, cost effective.

The objective of the testing was to simulate a frontal collision resulting in a steering wheel impact. A number of commercially available, current model steering wheels were used to conduct a comparative performance test for the evaluation of their energy absorption characteristics. The steering wheels which were tested are identified in this paper as Types A, B, C, D and E. Steering wheel Type E is the purpose designed Transport Road Research Laboratory, TRRL, frangible wheel.

Due to the many parameters and factors associated in accurately reconstructing the impact, it was necessary to simplify the conditions of impact. It was decided to constrain motion to a single plane and position the test device (Hybrid III or DLSF) such that the impact point and head centre of gravity were collinear and in line with the direction of travel (Figure 1). With this configuration rotational acceleration is minimised, the deceleration vector is in the direction of the head centre of gravity, thereby simplifying the comparative impact analysis.

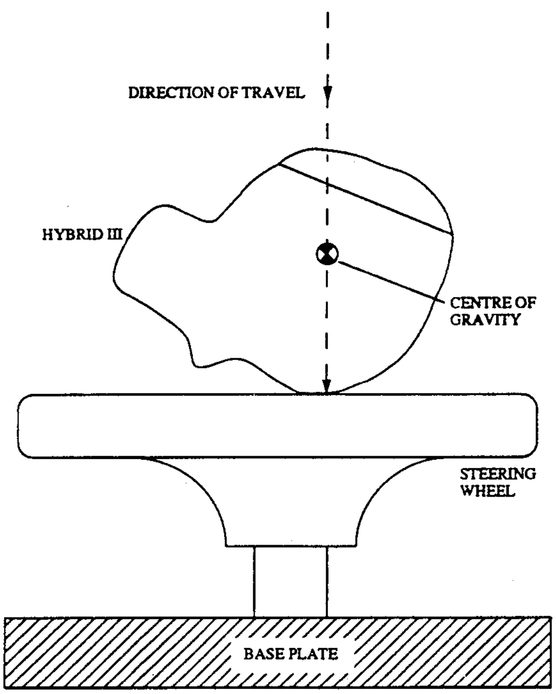

Figure 1. Impact Configuration

The selected impact site was the forehead of the headform for three main reasons:

i. the forehead is one of the regions of the head most frequently injured in frontal collisions,
ii. site simplicity,
iii. it is the area which is calibrated for objectivity in measuring HIC (14).

To constrain motion to a single plane it was decided to use a vertical drop impact test system (Figure 2). The test involved the vertical drop of the Hybrid III (or DLSF) headform down two equally spaced guide wire cables suspended from the ceiling of the building. This system allows the headform to accelerate to the desired impact velocity. The guided impact ensures that the impact point will be successfully achieved at all times. As the headform nears the end of its fall it triggers a light gate which is located just above the steering wheel impact point. This in turn triggers the PC based Data Acquisition System which records the impact velocity and other information from the instrumentation. The acquired data is filtered and the HIC calculated together with other relevant data.

To ensure that the test rig was suitable, it was necessary for it to meet the following requirements:

- capable of accelerating the impacting device to the required velocity,
- provide variability for different sized steering wheels and different impact locations,
- be able to withstand large impact forces without significant deflections,
- allow for the mounting of a surrogate headform.

The speed of impact was taken to be 6.7 m/s (24.12 km/h) and the mass of the Hybrid III and DLSF headform were 4.45 and 4.75 kg respectively. Both Hybrid III and DLSF were fitted with triaxial accelerometers mounted at the headform centre of gravity. Special attention was given to the calibration of the DLSF load cells and strict following of the calibration procedure manual is paramount (15). The DLSF headform used in the testing was designed by GMH Engineering as part of a joint venture with Collision Safety Engineering and Volvo Car Corporation.

TESTING PROGRAM

The testing program can be subdivided into three main stages:

Stage 1 - Repeatability and reproducibility of the test and test results, using the Hybrid III as the test device.

Stage 2 - Repeatability and reproducibility of the test and test results, using the DLSF as the test device.

Stage 3 - Comparative testing of a number of different steering wheels using the Hybrid III headform.

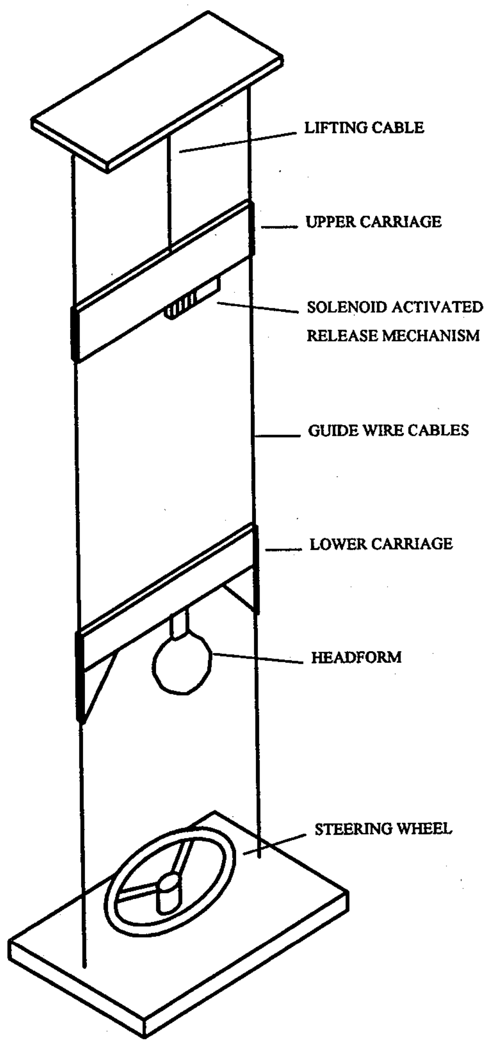

Figure 2. Vertical Drop Impact Rig

RESULTS - Stage 1

Stage 1 involved performing the same test three times on three new steering wheels of the same type. The reasoning for this was to check the repeatability and reliability of the equipment, and to see if the biomechanical response of the Hybrid III was consistent and reproducible in each case.

The results of these tests (Table 1) show that the device, when dropped from a height of 2.29 metres, achieves an average velocity of 23.00 km/h and stays within 0.5 km/h. Table 1 shows that the experimental set up proved to be repeatable with mean HIC values of 1692.3 and 225.6, for hub and spoke/rim respectively, with a standard deviation expressed as a percentage of the mean being less than 5%.

Figure 3 shows the force versus time triplicate histories experienced by the headform due to a hub impact. Whereas, Figure 4 depicts the spoke/rim impacts. Note, the acceleration - time histories were multiplied by the mass of the headform so as to later compare with the DLSF, which gives output in newtons.

The force time response overlay plots for both impacts, clearly show that the Hybrid III together with the experimental setup produces repeatable results.

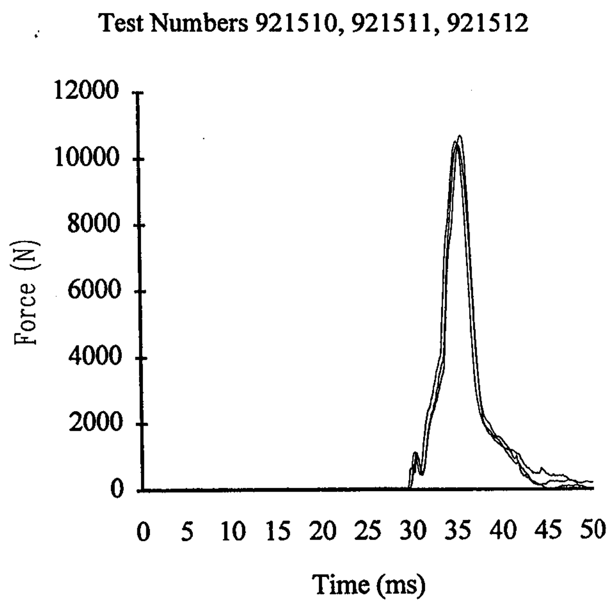

Figure 3. Hub Impact using Hybrid III

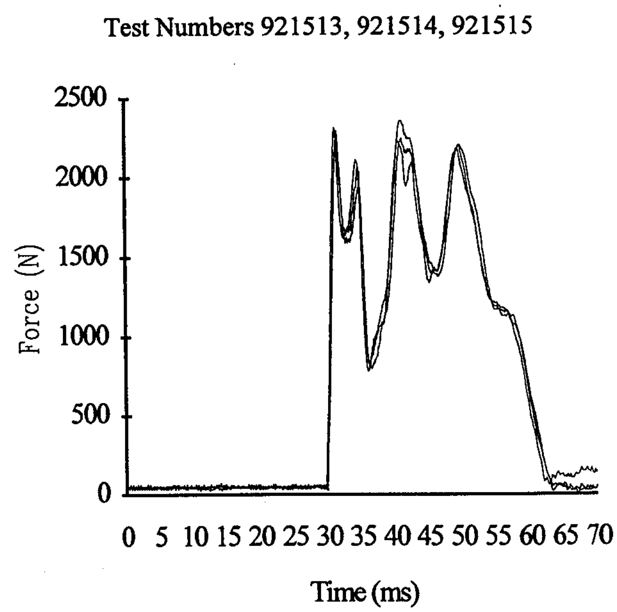

Figure 4. Spoke/Rim Impact using Hybrid III

Table 1 - Repeatability Test Results for Hybrid III

RUN NUMBER	IMPACT POINT	VELOCITY (km/h)	PEAK DECELERATION (g)	WHEEL DEFORMATION (mm)	HIC
921510	HUB	23.08	239.3	- *	1706.0
921511	HUB	22.75	241.3	- *	1677.2
921512	HUB	22.92	245.1	- *	1693.8
921513	SPOKE/RIM	23.43	52.9	52.6	221.7
921514	SPOKE/RIM	22.72	53.9	54.7	233.6
921515	SPOKE/RIM	23.10	52.5	56.5	221.4

* hub deformations were impractical to measure

RESULTS - Stage 2

Stage 2 was a repeat of Stage 1, but in this part of the testing program the DLSF was tested for consistency. Stage 1 in conjunction with Stage 2 provided a means to compare the biomechanical response of the DLSF with the Hybrid III headform.

Table 2 shows that the device, when dropped from the same height as in Stage 1, achieves an average velocity of 23.50 km/h and stays within 0.5 km/h. Table 2 shows that the experimental set up proved to be repeatable with mean HIC values of 1834.5 and 233.6, for hub and spoke/rim respectively, with a standard deviation expressed as a percentage of the mean being less than 5%.

Figures 5 and 6 are the resultant force time histories for hub and spoke/rim impacts, respectively. Both overlay plots confirm that the DLSF test device provides a consistent and accurate response.

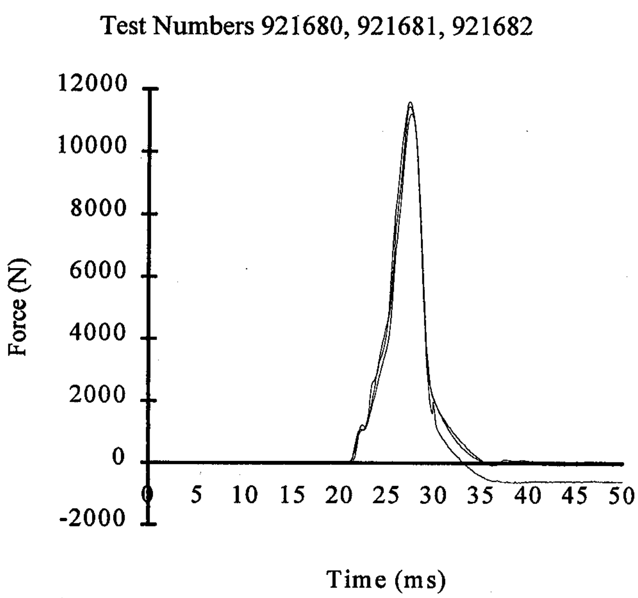

Figure 5. Hub Impact using DLSF

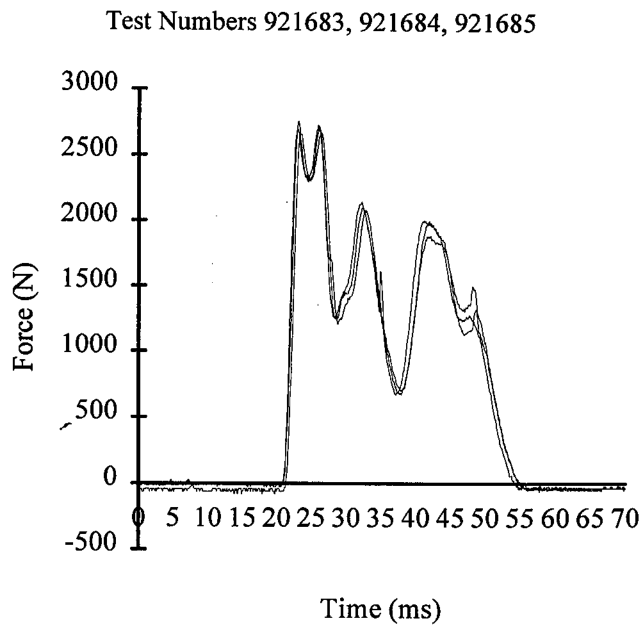

Figure 6. Spoke/Rim Impact using DLSF

COMPARISON OF THE BIOMECHANICAL RESPONSE OF THE DLSF WITH THE HYBRID III

From the results obtained in Stage 1 and Stage 2, a quantitative comparison of the DLSF and standard Hybrid III headforms was made. Figure 7 is the overlay plot for both headforms, illustrating their responses for a steering wheel hub impact. Figure 8 is also an overlay plot depicting the responses for the spoke/rim impact.

Both headform impact responses are shown to be reasonably compatible for the two types of impact, especially for hub impacts. Corresponding peak and trough values range from a 100 to 900N difference. This was an expected result for a number of reasons:

- difference in headform mass (DLSF being 300 grams heavier than Hybrid III),

Table 2 - Repeatability Test Results for DLSF

RUN NUMBER	IMPACT POINT	VELOCITY (km/h)	PEAK DECELERATION (g)	PEAK FORCE (N) **	WHEEL DEFORMATION (mm)	HIC
921680	HUB	23.26	262.2	11208.3	- *	1878.3
921681	HUB	23.09	261.4	11598.6	- *	1839.1
921682	HUB	23.61	258.2	11450.1	- *	1786.1
921683	SPOKE/RIM	23.45	52.9	2755.8	61.0	229.3
921684	SPOKE/RIM	23.61	57.3	2666.2	59.3	231.6
921685	SPOKE/RIM	23.97	56.6	2695.7	58.0	240.0

* hub deformations were impractical to measure
** sum of the load cell readings

Test Numbers 921681, 921512

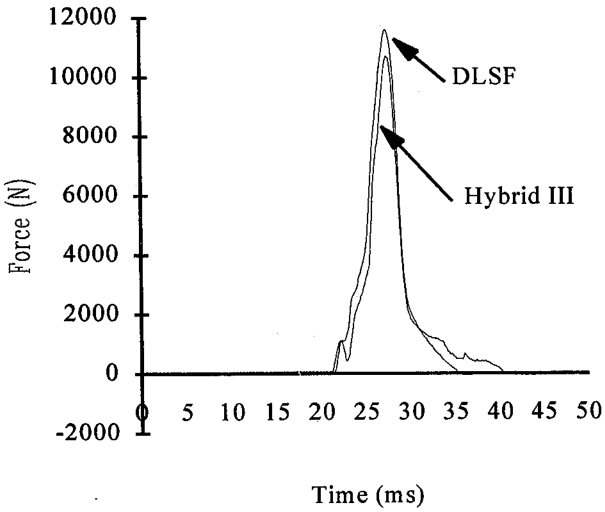

Figure 7. Hub Impact - DLSF vs HYBRID III

Test Numbers 921685, 921515

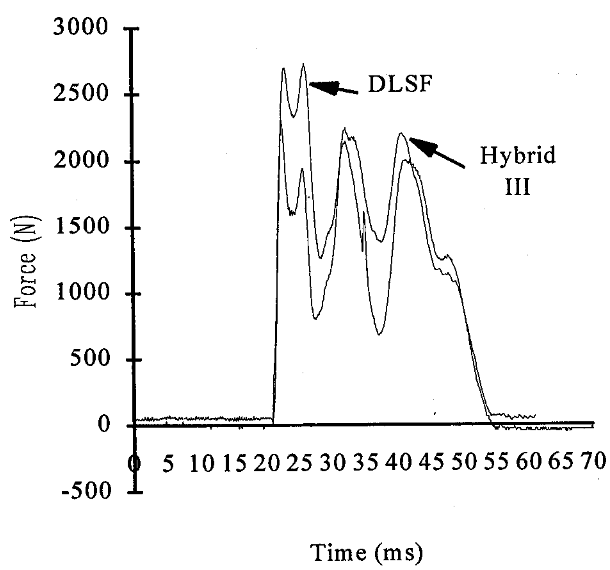

Figure 8. Spoke/Rim Impact - DLSF vs HYBRID III

- the purpose behind the development of the DLSF was because:
  i. the Hybrid III face does not have a crush component that is representative of the human face,
  ii. DLSF detects localized facial forces in laboratory testing which the Hybrid III can not.

It was difficult to assess the significance of the difference between the standard Hybrid III head response and the DLSF response. At the time of this project little information was available with respect to a comparison of the two headforms. Therefore, the calibration procedure necessitates extremely careful adjustment and handling of the calibration device (15), especially with regards to the preload applied to the load washers and the cleanliness of the system.

A common feature that emerges from the biomechanical response results, is that the DLSF gives a higher initial resultant force - time response. For the spoke/rim impact, which occurs for a much longer duration, the Hybrid III response is considerably stiffer in the last two thirds of the impact. The DLSF also yields a higher mean HIC value than the Hybrid III under the same test conditions.

RESULTS - Stage 3

The final stage of the testing program addresses the main aim of the project - to conduct comparative performance tests for energy absorption characteristics for a number of commercially available current model steering wheels.

Four different steering wheels, plus the TRRL wheel, were used in the impact tests in order to evaluate their energy absorbing and injury causing properties. Each wheel was impacted at the hub and spoke/rim junction.

Table 3 summarises the performance of all five steering wheels being investigated. This table shows the variability between current production steering wheels. Impact tests conducted at an average velocity of 6.34 m/s (22.82 km/h) produced peak decelerations ranging from 74.6 to 241.3g for the hub and 47.5 to 107.9g for spoke/rim impacts. Maximum steering wheel deformation ranges from 29.1 to 62.7 mm for hub impacts and 36.2 to 61.7 mm for spoke/rim impacts. The facial contact area at the hub impact site, which ranged from 5030 to 11725 mm^2, had a

Table 3 - Summary of Steering Wheel Performance

TYPE	RUN NUMBER	IMPACT POINT	VELOCITY (km/h)	PEAK DECEL (g)	PEAK FORCE (N)	CONTACT AREA (mm²)	WHEEL DEFORMATION (mm) theory **	exp.	PRESSURE (N/mm²)	STIFFNESS (N/mm)	ENERGY (J)	HIC
A	921511	HUB	22.75	241.3	10533.8	8360	29.1	- *	1.26	1065	49.8	1677.2
B	921730	HUB	- #	258.9	11302.2	5030	36.3	- *	2.25	1015	78.0	1931.6
C	921731	HUB	- #	86.5	3776.1	8810	44.9	- *	0.43	75	47.3	462.4
D	921732	HUB	21.80	119.4	5212.3	7780	33.7	- *	0.67	222	64.8	493.5
E	921733	HUB	22.58	74.6	3256.6	11725	62.7	- *	0.28	73	67.0	368.5
A	921515	SPOKE /RIM	23.10	53.9	2353.0	2280	61.7	56.5	1.03	275	60.3	233.6
B	921747	SPOKE/RIM	22.91	47.5	2073.6	3620	63.6	58.5	0.57	208	43.3	196.2
C	921748	SPOKE/RIM	23.26	48.9	2134.7	2900	66.0	64.0	0.74	110	55.9	192.7
D	921743	SPOKE/RIM	22.76	59.4	2593.1	1860	55.8	49.7	1.39	224	45.9	266.4
E	921745	SPOKE/RIM	23.43	107.9	4710.3	1313	36.2	35.5	3.59	347	78.1	353.6

* hub deformations were impractical to measure
** double integration of acceleration vs time graphs
# value did not register

pressure distribution ranging from 0.43 to 2.25 N/mm², the TRRL safety wheel recording the lowest of the values. It was assumed that there was a constant pressure distribution across the contact area.

From the acquired data it was possible to derive force-deflection characteristics for each steering wheel. The response of the steering wheels, at both impacts sites, depicted non-linear characteristics. The amount of energy absorbed by each wheel was calculated by taking the area under the curve. Due to the non-linear response, the stiffness was determined via the application of a linear function to the loading phase of the curve. This entails a local assessment of the loading portion of the curve at the most linear part of the curve.

DISCUSSION

The simulation of head to steering wheel impacts was accomplished by applying a dynamic load to the steering wheel using the Hybrid III or DLSF headform under guided freefall conditions. The Vertical Drop Impact Test System is a useful setup for this type of experimentation as it reduces the complexity of the impact to be simulated.

With such a system, motion is constrained to a single plane. The direction of travel of the headform is vertically downwards, and on impact the deceleration vector is in the direction of the head centre of gravity. The advantage of using a vertical drop system is that controlled impacts can be performed, allowing for variability of speed and the orientation freedom of the headform.

Stage 1 and Stage 2 results indicate that a repeatable, and relatively inexpensive test procedure has been developed and demonstrated. This procedure is capable of evaluating the performance of steering wheels with respect to their energy absorbing and relative injury causing properties.

In the sample studied, the calculated HIC value ranged from 368.5 to 1931.6 and 192.7 to 353.6, for hub and spoke/rim impacts respectively. The HIC value is used here as a means to compare steering wheels, not to give a direct relationship to the severity of the injury.

From Table 3 it can be seen that the hub is the most significant and likely injury mitigating part of the steering wheel, with peak deceleration values ranging from 74.6 to 258.9g; steering wheel Type B having a peak deceleration almost three and a half times that of Type E. The corresponding HIC values were 1931.6 and 368.5, steering wheel Type B recording a HIC more that five times that of Type E.

From observations of the five types of steering wheels, the reason behind such a large difference was obvious. In a hub impact, such as in Type B, the headform simply hits the rigid end of the steering wheel mounting shaft, offering no yielding of the steering structure or 'ridedown'.

Steering wheels Type C and E performed well when subjected to the same conditions as Types A and B. The significant improvement in response was largely due to the steering shaft end being set well below the surface of the wheel. Shafts supporting steering wheel Type C and E were recessed approximately 55 and 90 mm, respectively from the hub surface, in comparison to 20 mm for Type B. Another factor contributing to its performance was that the hub of Type C was well padded, therefore providing a cushioned impact, and Type E provided an air cushion effect. These simple yet effective design features can result in a very much improved steering wheel hub performance.

The hub area contacted during impact (or area available for contact) is significant and can aid in distributing the force over a larger area thereby becoming less concentrated. The results indicate that a larger contact area together with the above mentioned features can result in a reduced peak deceleration level and HIC value.

The stiffness of the hub was in some cases difficult to determine due to the erratic nature of the curve, and therefore the value stated in the table is only an approximation. In general higher stiffnesses were recorded for the hubs that had poor energy absorbing properties.

Table 3 shows a significant difference in performance between the hub and spoke/rim junction of the steering wheel. Both the peak deceleration and HIC values are less for the spoke/rim impacts. This difference between results is largely attributed to the spoke/rim capability to yield or deform, thereby giving way to the impact. Most of the steering wheel rims were found to be deflected between 50 - 60 mm.

Peak deceleration values for the spoke/rim impacts ranged from 47.5 to 107.9g with HIC values ranging from 192.7 to 353.6. This type of impact did not show such a great variation between values as was discussed with hub impacts. Steering wheel Type B and C produced the best energy absorbing properties, the deep soft padding over the spoke/rim junction and material yielding being the contributing factors. Also, the rim of Type C was set well below the surface of the wheel.

Contact area once again plays a part in reducing the relative injury potential. The general trend mentioned previously for hub impacts is also valid for spoke/rim impacts.

CONCLUSION

Vertical drop impact tests have been carried out to assess the energy absorption characteristics and performance variability between steering wheel types. Stages 1 and 2 demonstrated that the procedure developed can evaluate the performance of steering wheels with respect to their energy absorbing and relative injury causing properties.

Comparative performance tests for the five chosen steering wheels identified features that contribute towards better performance, such as:

- a deep, well padded or air cushioned hub with the steering shaft end set well below the surface of the wheel.
- a well padded spoke/rim area designed to buckle or yield when impacted.
- a large as practical area for contact to distribute the force.

An analysis of the comparative tests confirmed that it is possible to improve the design of steering wheels via simple inexpensive methods, in order to make them less likely to cause serious injury when struck by the occupant.

ACKNOWLEDGEMENTS

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Advanced Injury Criteria and Crash Evaluation Techniques

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United States Department of Transportation
Paper No. 94-S1-O-11

ABSTRACT

The automotive crash environment and the safety systems that operate within it present an extremely complex loading environment to vehicle occupants. Responses of the equally complex human structure to this loading environment determine whether or not an injury hazard is presented to the occupant. As improved, more efficient, and more economical performance is sought from automotive safety systems, the criteria and test devices that evaluate their performance must have greater capabilities. This paper addresses NHTSA's rationale and current research efforts to develop and provide enhanced, mechanically based, injury sensing criteria for the head, thorax, and other body regions. The techniques and processes being developed to allow their application in the physical testing environment are also discussed.

INTRODUCTION

The design, development, and production of an automobile is an extremely complicated, difficult, and competitive process. Not only must good judgments about the design, size, cost, market segment, and many other characteristics of a vehicle be made many years in advance of it's first public appearance, but the many processes that merge these initial decisions and ideas into a viable product must be efficient and functional for a manufacturer to successfully create a product. As the nation's concerns for protecting the environment, conserving natural resources, and improving public safety continue, each of the technologies and processes that direct, develop, and evaluate these various aspects of a vehicle's design should also become more effective, efficient, and timely.

Therefore, as the agency whose mission is to reduce the deaths and injuries that result from crashes, NHTSA must assess the current state of crash safety technology and effect the development and/or advancement of these technologies if deemed necessary. If opportunities exist in the expansion or refinement of evaluation technologies or in their scientific basis, then they should be investigated. To improve the ability of safety technologies to fare in this keen competition with the other various aspects of vehicle design, NHTSA is attempting to improve the science of biomechanics by better understanding the mechanisms of injury peculiar to the automotive crash environment.

It is the contention of the authors that, for the science of impact biomechanics to mature and be applied efficiently, two major deficiencies must be overcome. These areas of needed improvement are (1) a methodology or process about which theoretical bases characterizing the various injury phenomenon can be developed and (2) an experimental or observational capacity capable of documenting, in sufficient detail and accuracy, the causal elements and their effects upon the actual object of interest. Improving the science of impact biomechanics means overcoming the monumental difficulties present when attempting to understand the high speed, short duration interaction between the geometrically and mechanically complex human body and its equally complex impact partner, the automobile. This has caused those attempting the traditional means of developing a theoretical basis using mathematical modeling to either assume rather drastic simplifying assumptions to make their efforts computationally manageable or attempt a level of complexity that extends beyond current solution capabilities. Likewise, experimental efforts have been hampered by having neither the instrumentation capable of measuring directly the parameters of interest, for example rotational acceleration or detailed thoracic deformation, nor possessing the recording capacity necessary to acquire the needed volume of data to truly characterize the event of interest.

GENERAL RESEARCH AGENDA

In light of this situation, the biomechanics research agenda must address several major opportunities. That is, both the theoretical basis of impact biomechanics and the experimental efforts and techniques needed to support and apply the theory must be developed and expanded. Can this be done? Yes. The recent and rapid development of computational capabilities and capacities brought about by explicit finite element codes and parallel computing platforms have created an environment in which the growth of the theoretical basis of impact biomechanics can flourish. This is because, for the first time, the complexities of the automotive crash environment can be encompassed and managed analytically. What is being suggested is that the basic science of impact biomechanics can and should be greatly enhanced by applying this available analytical microscope to understanding and quantifying the injury process. This should result in analytical representations of the human capable of being exposed to the conditions of particular automotive crashes and the extent and severity of expected human injury accurately and reliably predicted.

While developing the analytical capability for evaluating the safety offered by a particular system is valuable, it is also desirable to develop and improve the physical testing capabilities needed for confirmation of a design's ultimate performance. Enhancing the underlying science of biomechanics simplifies this process for several reasons. First, having a clearer understanding of the injury process links injury to the correct, measurable, causal parameters and allows the correct interpretation of the test output to be made. Second, correct knowledge of how the human body reacts to impact allows those pertinent characteristics to be required and embedded within the test device enhancing safety evaluation.

SPECIFIC RESEARCH AGENDA

Since NHTSA is a major contributor and user of the processes that ultimately evaluate the safety of automobiles and has the interest to see that these processes are effective, efficient, and timely, NHTSA has initiated considerable research and development efforts to enhance the knowledge base of impact biomechanics and the technologies that support the development and evaluation of safety systems. The following discussion will detail various research efforts that NHTSA initiated to better understand injury mechanisms in each of the major body areas. Additionally, a short discussion of the form and function that future advanced injury criteria and evaluation techniques may take is also presented.

Head

Two areas of research in head injury are underway: one concentrating on skull fracture and the other, on brain injury. Both are aimed at understanding the injury processes from a fundamental, mechanistic viewpoint and then translating this knowledge into physically realizable detection processes. The skull fracture efforts are based on the premise that the skull fails as a result of the temporal and spatial distribution of forces applied to it during an impact and any fracture detection process must have knowledge of all of these factors. To study the fracture phenomenon, a finite element model of the skull has been developed. Its geometric details have been obtained directly from CT scans of a human head. An exterior view of the model is shown in Figure 1 and a mid-sagittal section of the CT scan from which it was derived is illustrated in Figure 2. The model reflects detailed skull geometry for a specific individual. This model can be exposed to a variety of impact conditions and the magnitude and distribution of stresses and strains within the skull can be calculated. The impact conditions can be prescribed as time-varying pressures applied over prescribed, time varying areas of the skull or, alternatively, as initial conditions of velocity and position between the skull and an impact partner with the resulting interaction forces calculated by the analytical process.

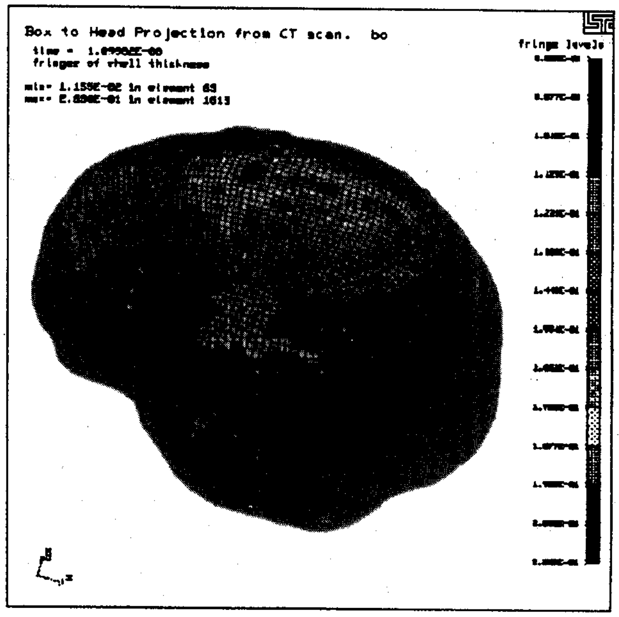

Figure 1. Exterior view of skull.

Experimental validation efforts using human cadaveric specimens are planned to determine if the model possesses those essential characteristics to predict the occurrence of fracture. These tests will use an advanced matrix load cell capable of capturing the spatial and temporal distribution of the impact loads applied to the skull during each impact test. A series of tests with various impact conditions will be conducted and the resulting loads and damage to the skull recorded. After comparisons and necessary adjustments are made to the model, it is expected that the model will be able to predict, with reasonable certainty, the probability of the skull fracture given a specific spatial and temporal loading history.

To apply this technology to the physical testing world, it is anticipated that a head form will be covered over a certain portion of its surface by a matrix load cell like the one used in the experimental studies. An artist's conception of this is shown in Figure 3. This head form could then be propelled into the structure to be evaluated and the force/area/time history recorded. The load history would then be applied to

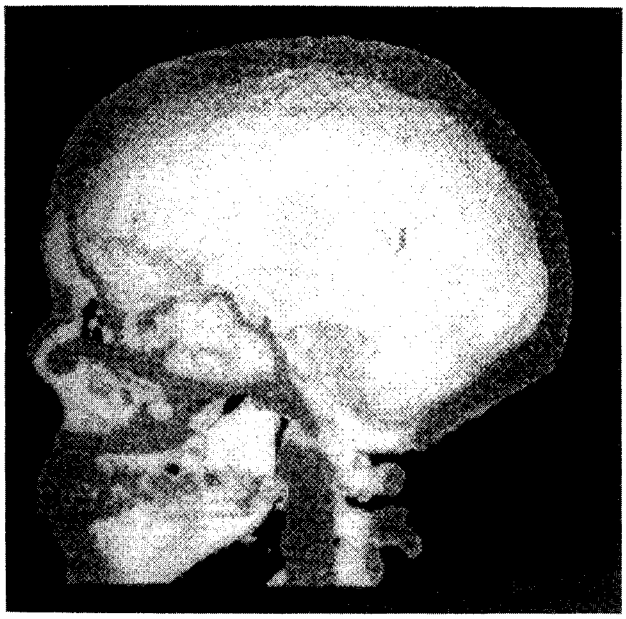

Figure 2. Mid-sagittal section of CT scan.

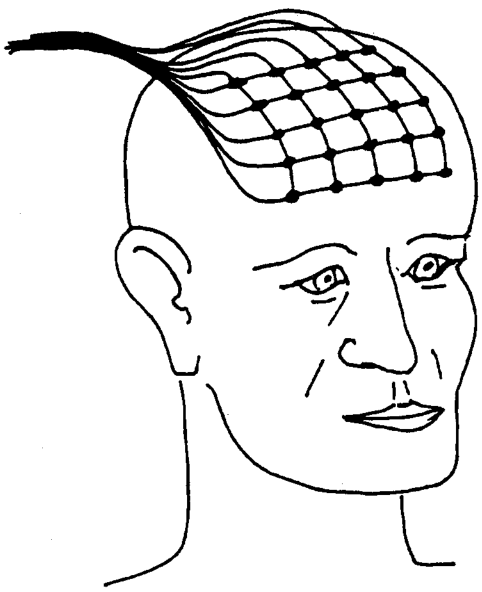

Figure 3. Matrix load cell.

the skull model and its output would determine if fracture conditions prevailed during that specific impact.

Brain injury detection efforts are also proceeding along the same route. That is, a detailed finite element model of the brain within a skull has been developed.[1,2] Its current general configuration is illustrated in Figure 4. This model is being designed with the capabilities to simulate the various mechanical conditions associated with the three primary injury modes most observed in automotive crashes; relative motions between the brain and skull which tear the bridging veins and cause acute subdural hematomas, excessive dilatational stresses within the brain matter which cause focal lesions, and rapid shear deformations of the brain matter that cause diffuse axonal injuries, DAI. That is, dummy instrumentation will capture the translational and rotational motions the head

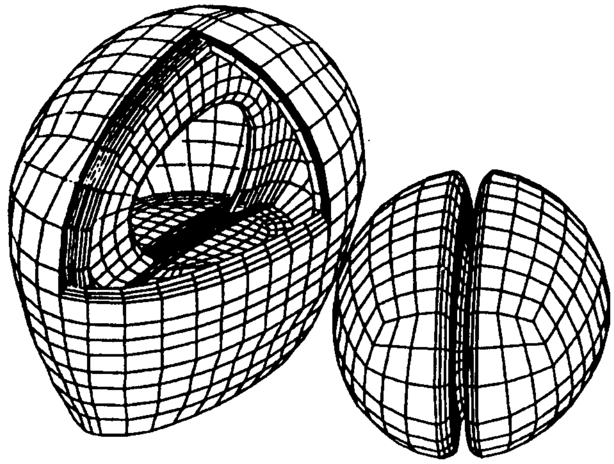

Figure 4. General configuration of brain model.

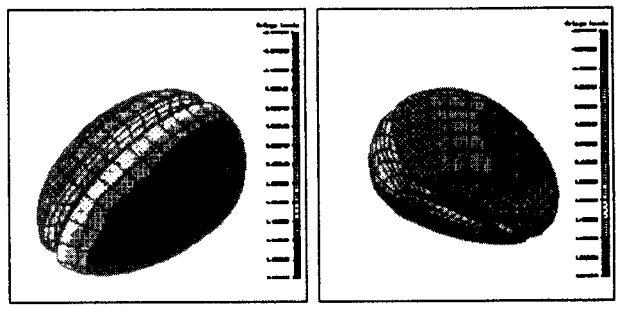

Figure 5. Surface view of predicted DAI.

experiences during an impact. This information will then be translated into appropriate input to cause the brain model to experience the same motions. Then, using the critical level of each of the relevant mechanical parameters associated with the various brain injury mechanisms, the output of the model will be examined to assess the extent and severity of the various injuries.

An example of the current model's capability to predict the extent and severity DAI is illustrated in Figure 5. Here, because neural dysfunction has been experimentally associated with mechanical stretching of axons [3], the severity of DAI is associated with the magnitude of principle strain developed within the brain. The extent of DAI is associated with the volume of the brain experiencing a certain level of principle strain. The brain model has been designed to survey the entire brain volume during the impact and record those areas of the brain that have exceeded specific levels of peak strain. Figure 6 illustrates, across a section of the brain, the spatial distribution of various levels of maximum encountered principle strain and Figure 7 shows the temporal evolution of the maximum encountered principle strain as a percent of total brain volume. It is envisioned that critical volume limits can be specified for various strain levels and even possibly prioritized by anatomical location. Likewise, similar processes could limit the development of focal lesions by monitoring the volume of the brain that exceeds various levels of dilatational stress and limit subdural hematomas by limiting the relative motion between the brain and skull.

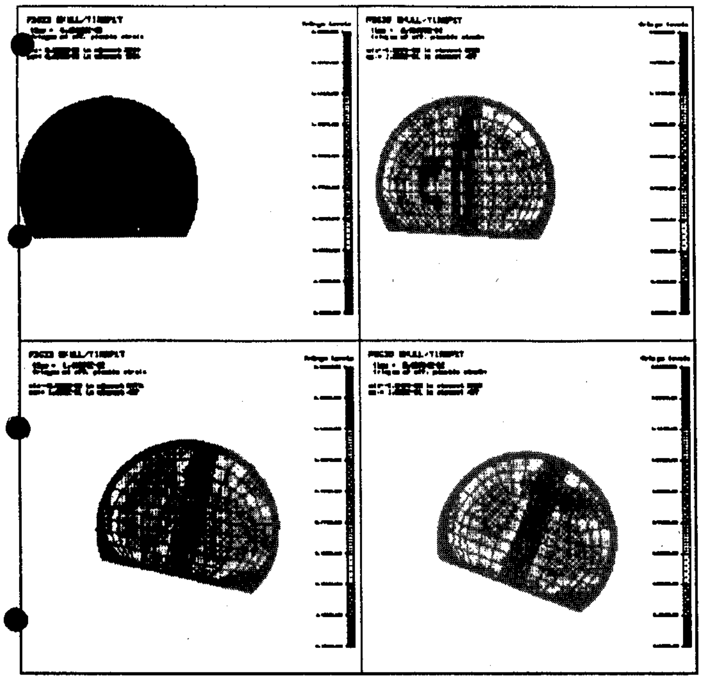

Figure 6. Cross-section of brain showing spatial distribution of maximum strain.

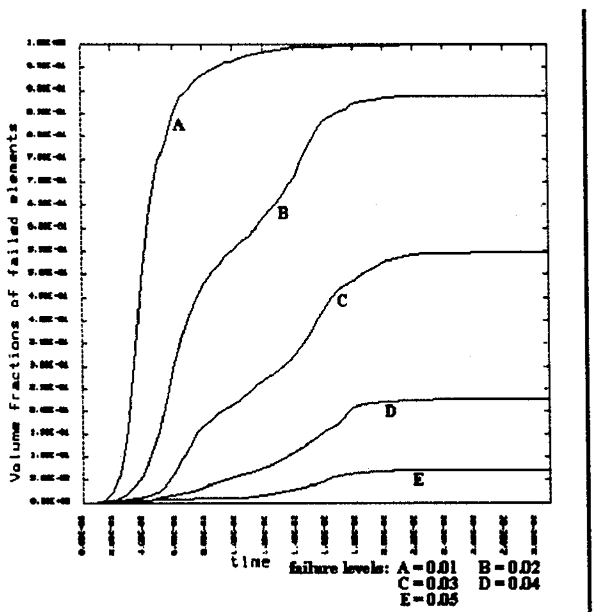

Figure 7. Temporal evolution of maximum principle strain.

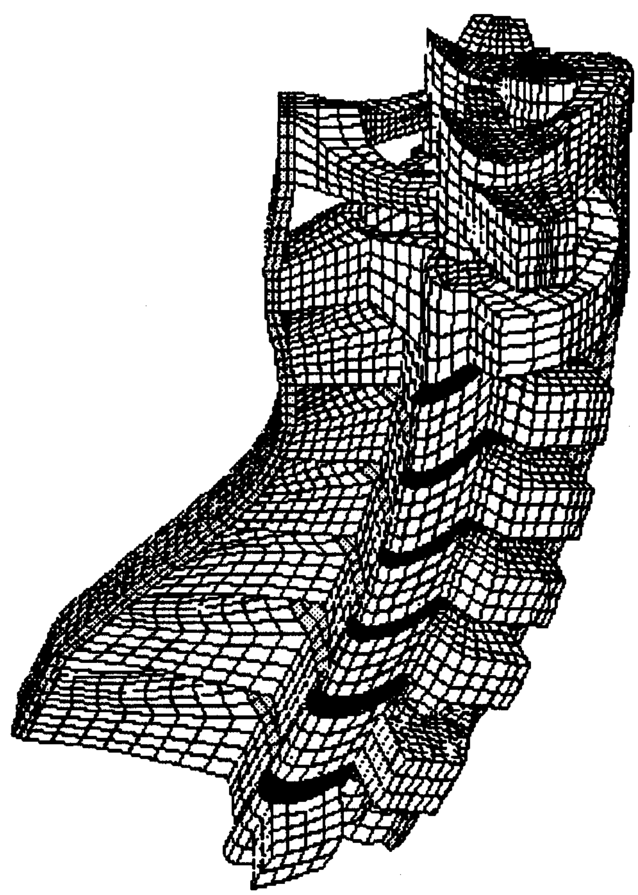

Figure 8a. Current configuration of assembled finite element neck.

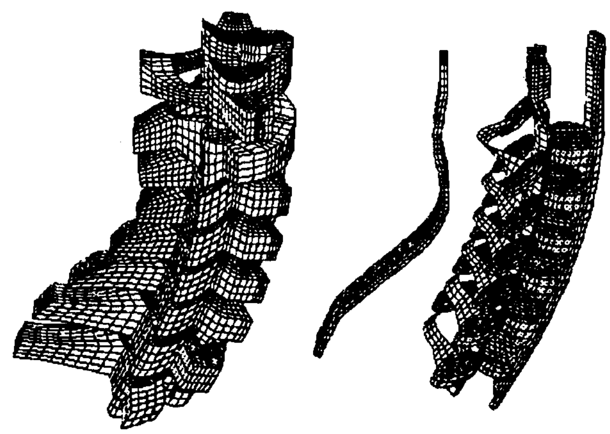

Figure 8b. Exploded view of neck components.

Neck

Neck injury research is also proceeding along dual paths of developing and validating a detailed finite element model of the cervical spine [4] and designing instrumentation and physical representations of the neck to allow efficient evaluations of neck injury risk in testing environments. Figure 8a illustrates the current configuration of the assembled neck model and Figure 8b, an exploded view of the model, clearly illustrates its various components. As can be seen, it has representations of all of the bony structures, all major ligaments, and the intervertebral discs and facets. Again, to gain confidence in the form and predictive capabilities of the model, an experimental effort will subject a series of cadaveric neck specimens to expected automotive crash loading modes and document the forces applied and the resulting motions and failures. The realism and accuracy of the model will be improved through experimental validation until it becomes a reliable predictor of both motion and injury. Whole body tests detailing the in-vivo response will also be conducted to verify the model's ultimate performance.

Enhancements of the agency's physical testing capabilities are centered around the design and development of an improved dummy neck and associated injury sensing instrumentation. This effort has assembled from the available scientific literature, design specifications that characterize the desired response of the new neck in flexion/extension, lateral bending, and axial compression. A prototype concept was first designed as a finite element model, then evaluated, and altered analytically until the desired characteristics were met. This concept was then built and tested. The design has evolved into the form seen in Figure 9. This design has a central column of rubber and aluminum discs representing the neck with cables located front and back, mimicking the human musculature. These cables control the rotational movement of the head relative to the base of the neck. The anticipated kinematic response of this latest design to -Gx accelerations is illustrated in Figure 10 and comparisons of this response with the response derived from human testing is shown in Figure 11. Representative axial compression characteristics have also been achieved by appropriately adjusting the cross-sectional properties of the rubber sections while maintaining their bending properties.

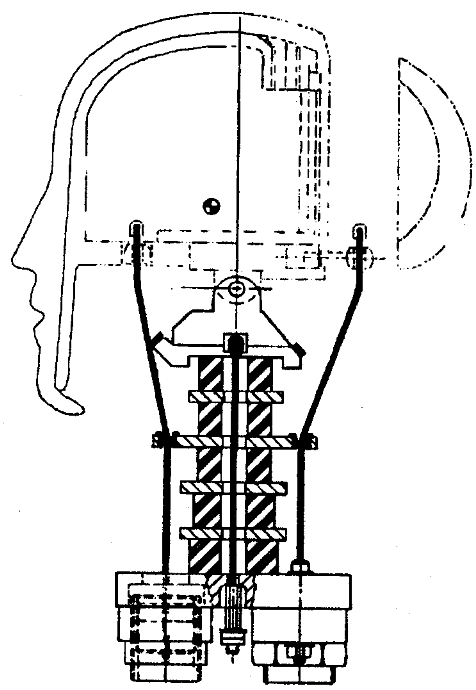

Figure 9. Current configuration of new prototype dummy neck.

Since specific injury criteria have not yet been developed, the instrumentation that is being incorporated in the new neck structure has been designed to provide the complete loading state at any position along the length of the neck. This will be achieved by including, six axis load cells (3 orthogonal forces, 3 moments) at each end of the neck structure as well as an instrument, called the COBRA (Cervical Omnidirectional Bending Response Apparatus), located centrally within the neck which provides information on the instantaneous shape of the neck at any time during an event.

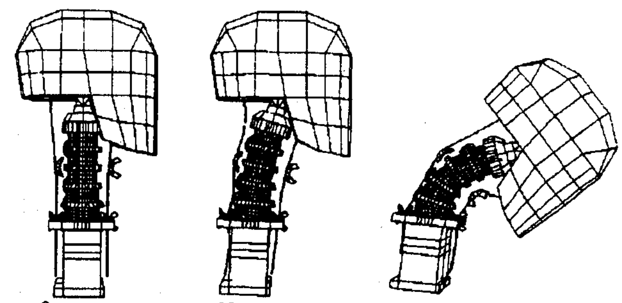

Figure 10. Kinematic response of prototype neck to -Gx acceleration.

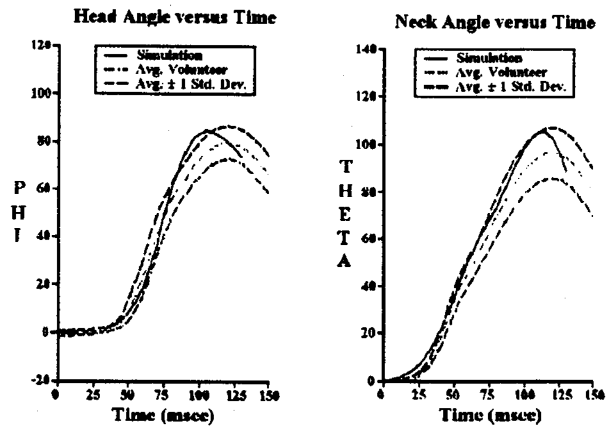

Figure 11. Comparison of prototype neck with human response corridors.

Thorax

Analytical efforts are developing a finite element model of the torso.[5,6] This is a generalized model which incorporates, (1) detailed representations of the thoracic skeleton including the spine, rib cage, and shoulders, (2) appropriate muscles and ligaments, and (3) a simplified representation of the internal organs. Its current configuration is illustrated in Figure 12. The model is capable of interacting with models of typical automotive restraints. Examples of the model interacting with a torso belt (Figure 13a) and an air bag (Figure 13b), illustrate the ultimate potential that this analytical technique offers the bioengineer and restraint designer. Subsequent development efforts will incorporate representations of the head, arms, pelvis, and lower extremities to allow simulation and evaluation of interactions of the complete person with the entire vehicle interior. This will provide a capability for direct analytical evaluation of the human injury risk, rather than providing predictions of dummy responses and then having to evaluate them for projected human injury risk.

The experimental effort is proceeding along a more conventional approach of understanding and quantifying the thoracic injury process by exposing highly instrumented cadaveric specimens to a variety of impact conditions of interest, and documenting both their mechanical responses and injuries. The large volume of data so obtained has been analyzed and several potential injury predictive processes have been developed. One process has used the output from chest

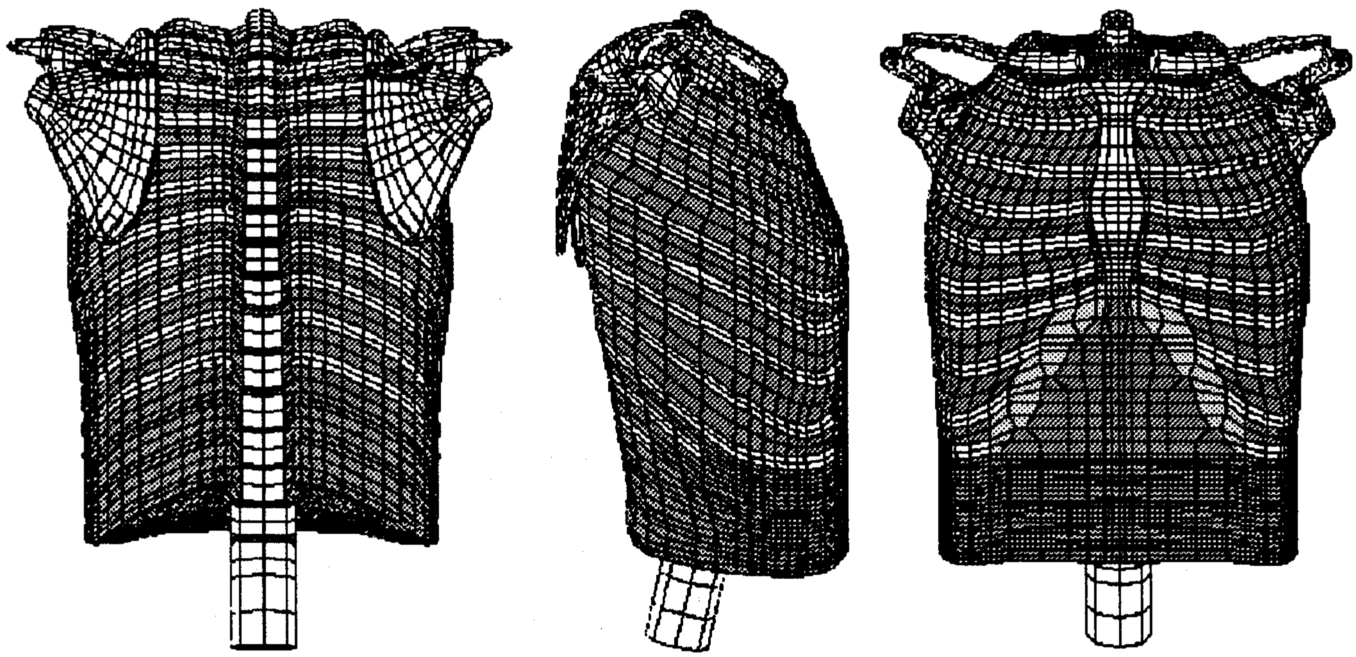

Figure 12. Current configuration of finite element thorax.

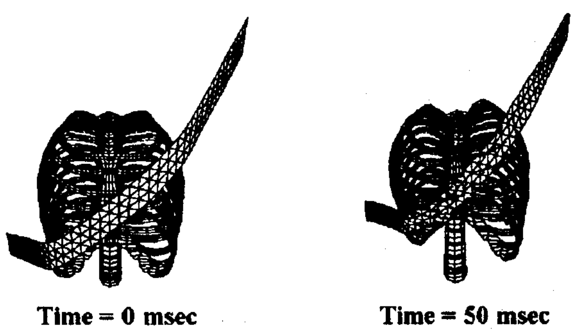

Figure 13a. Finite element thorax interacting with 2-point belt restraint.

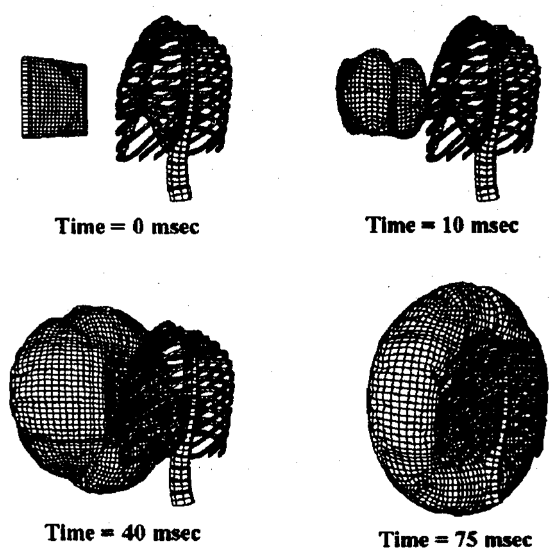

Figure 13b. Finite element thorax interacting with air bag restraint.

bands (instruments that are circumferentially applied to the thorax and provide geometric descriptions of the time varying cross-section) to generate deformation measurements at five points cross-section, to generate deformation measurements at five points on the rig cage, three across the front at the level of the fourth rib and two at the level of the eighth rib. These five locations are shown in Figure 14. These deformations, together with acceleration levels and age, have demonstrated good predictive capability when analyzing responses from subjects for injury level restrained by a various restraint systems. The sequence of operations that this injury predictive process employs is illustrated in Figure 15. It first assembles the measured displacements and accelerations and determines, using an analytical filter, if the deformation response of the thorax resembles the response from a belt or air bag restraint. Then, depending upon the classification, the displacement and acceleration data are parameterized and submitted to either the belt-like or bag-like injury criterion. Of the 55 cadaver tests conducted so far, this injury discrimination process has correctly classified 54 of the 55 tests as to whether their highest thoracic injury is rated at an AIS 3 or greater.

An alternative process, one that uses local change in curvature obtained directly from the chest bands, is also being developed and analyzed. This process has taken on the demanding challenge of predicting, regardless of the restraint being used, the number and location of expected rib fractures resulting from a chest impact. Figure 16 illustrates how well the current function, which uses curvature change, location of the curvature change, and maximum central chest deflection, can distinguish when fracture producing conditions exist. In order to implement this process in a testing environment and not require a full chest band on a dummy, a method that uses only three rib cage deflections to produce estimations of local curvature change has also been developed.

Advanced dummy development activities have been underway for some time and details of the current design's characteristics and performance have been previously reported.[7-9] Efforts have focused on developing a thoracic structure that has more realistic anthropometry, more appropriate articulations, better local impact responses, and increased and improved instrumentation for the prediction of injury (Figure 17). Obviously, if the dummy thorax possesses correct impact response characteristics and is outfitted with the necessary transducers to provide the necessary input to either of the injury criteria discussed previously, it is anticipated that more accurate evaluations of safety performance can be made regardless of the kind and combination of restraints being used.

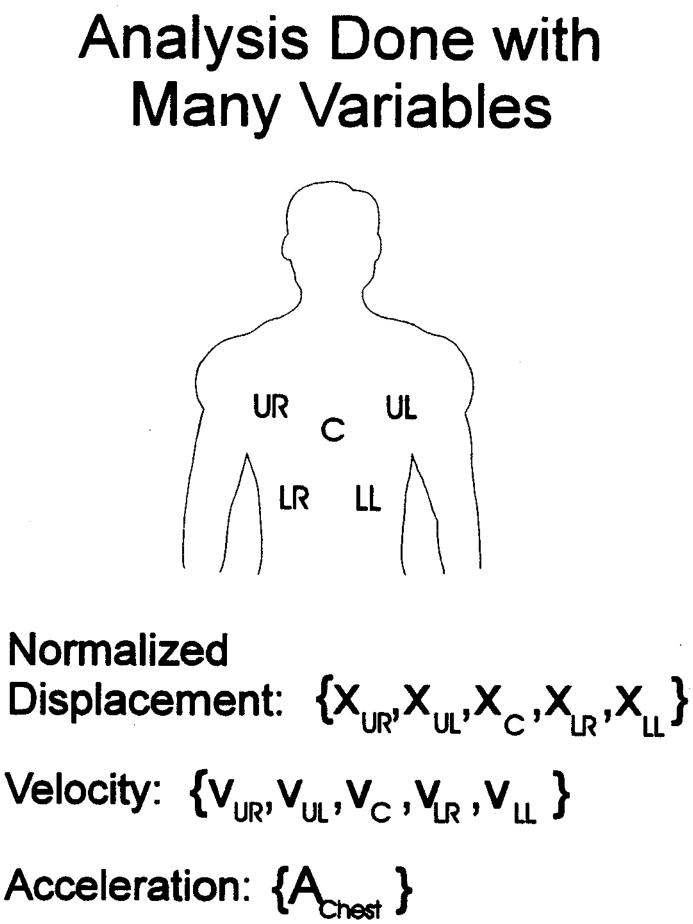

Figure 14. Location of five deformation points used for injury prediction.

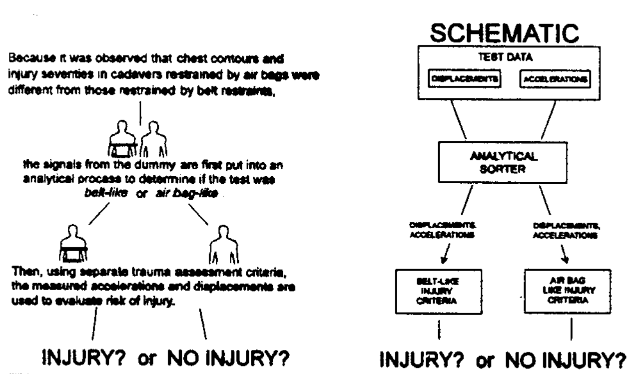

Figure 15. Injury prediction scheme using multiple chest deflections.

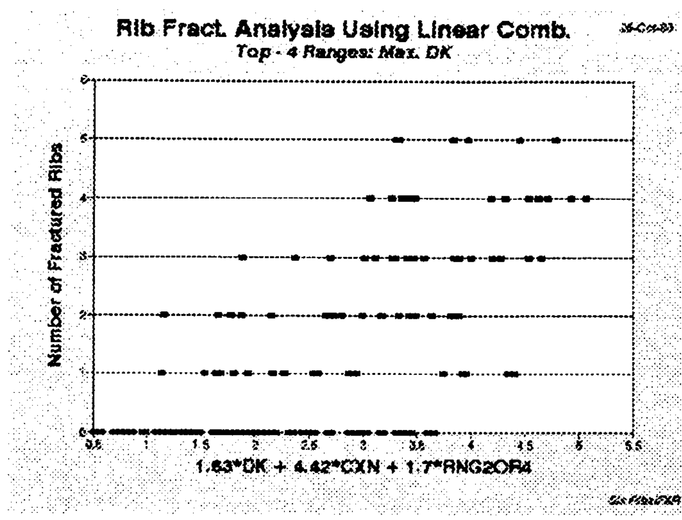

Figure 16. Example of rib fracture prediction using local change in curvature.

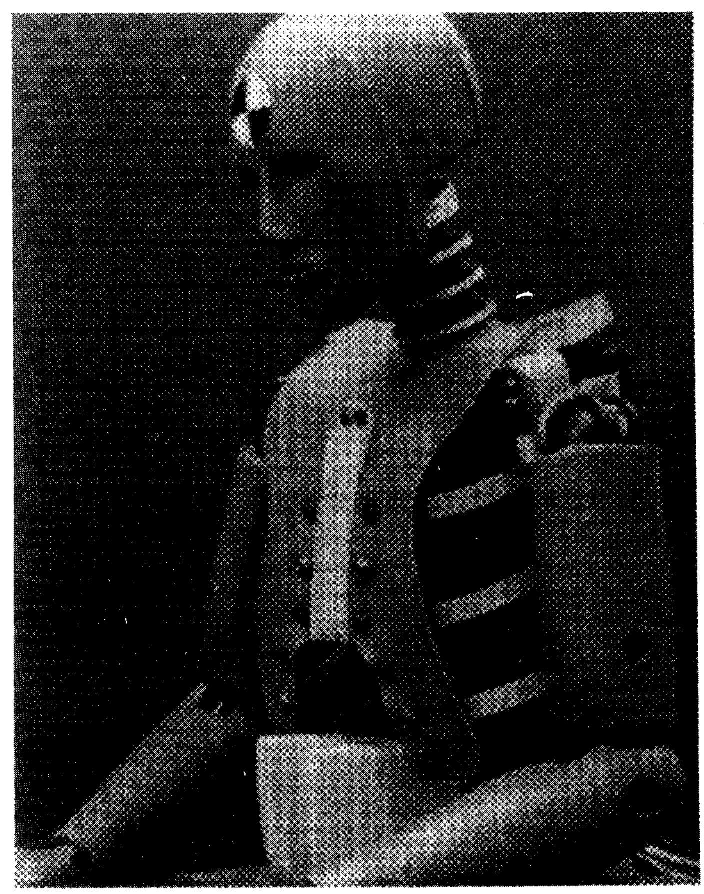

Figure 17. TAD-50M Torso Prototype Assembly with /Hybrid III Head and Neck.

Lower Extremities

As with the other major body areas, finite element modeling activities are also underway in the lower extremity area. An example of a model being developed to understand injury processes in the ankle area is shown in Figure 18. Experimental efforts are also underway that are augmenting the development of the model's capability and understanding of the operative injury processes. Injury modes under study include femoral fractures induced either by axial or bending loads, patellar and ligamentous injuries in the knee area, tibial fracture due to either bending or axial loading, ankle injuries associated with dorsi/planar flexion (toes up or toes down) and inversion or eversion, and rapid caudal-cephalad (toe to head) accelerations. The effects of pre-impact bracing, which can significantly alter the magnitude of the forces applied to and transmitted through the legs during a crash, are also being investigated.

Physical hardware development efforts are incorporating improved dimensional, inertial, and range of motion attributes of human limbs into improved dummy hardware. Figure 19 shows a schematic diagram of the current lower extremity prototype. Additional instrumentation to measure the necessary parameters to detect injurious levels of load for the various injury modes of interest is also being developed and incorporated into the design. The schematic in Figure 20 also shows these various instruments and the injuries that are anticipated to be monitored by them.

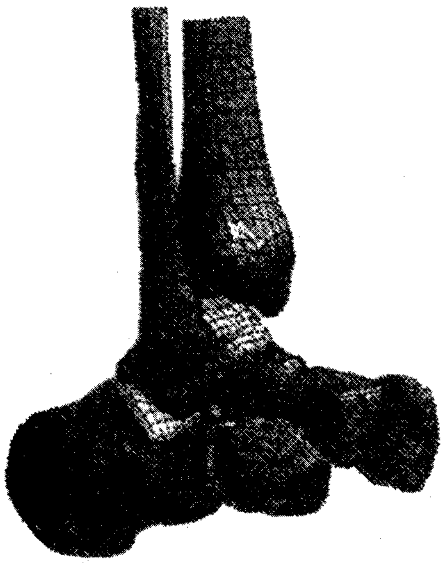

Figure 18. Finite element model of ankle.

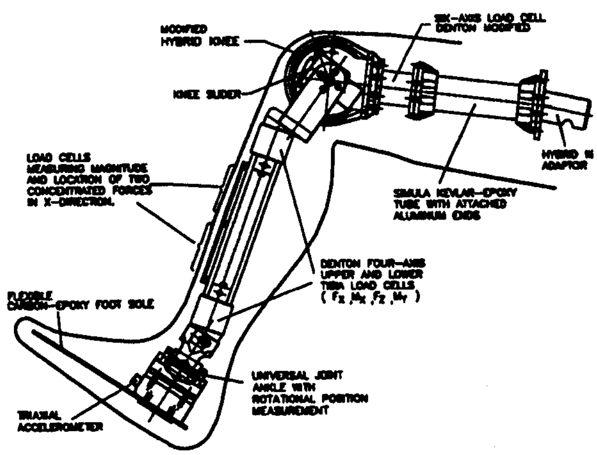

Figure 19. Schematic of current advanced lower extremity.

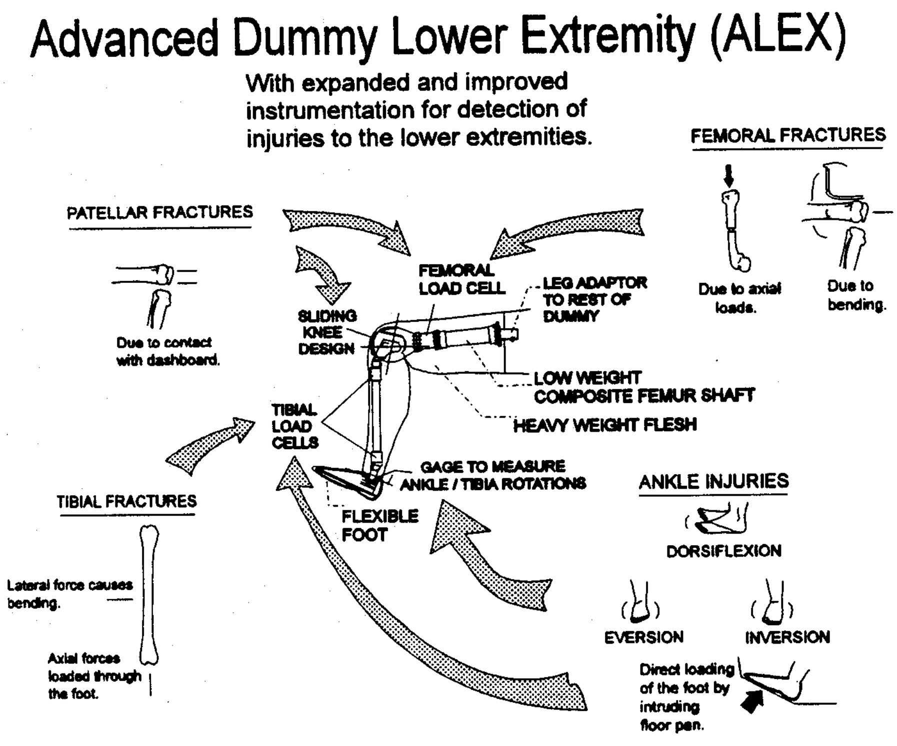

Figure 20. Injury prediction scheme using the advanced lower extremity.

DISCUSSION AND CONCLUSIONS

The inclusion and improvement of automotive safety will remain a priority in the coming years. However, incorporation of safety will not be done in isolation, but will be accomplished by hammering out difficult compromises between many conflicting requirements. How well safety fares, depends, in large part, on how well the injury processes are understood, how accurately and efficiently this understanding can be used to determine the safety of vehicles, and how efficiently and timely safety considerations can be introduced into the design of the vehicle.

Because the current state-of-the-science is somewhat rudimentary, NHTSA's biomechanical research and development efforts are undertaking a broad range of activities in nearly every major body area. These activities range from analytical and experimental efforts that seek to improve the scientific basis of impact biomechanics to the development of physical testing hardware that seeks to embody and use the newly acquired knowledge. Through these efforts, it has become obvious that to raise the state-of-the-science in impact biomechanics, it will require the introduction of additional complexity to both the analytical basis of the science and to the physical test devices that ultimately embody this increased knowledge. However, as the promise of this developing technology becomes a reality, it is believed that the added complexity should be far outweighed by the benefits of providing effective, efficient, and timely crash safety in vehicles in the coming years.

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Development of an Anatomic 3-D-Finite Element Model of the Human Head Utilizing CT-Data

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94-S1-O-12

ABSTRACT

Experimental tests are only able to predict human head injuries to a limited extent. Current occupant simulation models, based on rigid body systems or finite element models of Dummies, are used for the simulation of crash tests. This paper outlines the first stage of development of a three-dimensional finite element model of a human head.

The aim of our research work is to identify injury mechanisms and to develop injury criteria representing the spectrum of significant head injuries. The anatomic head model will be used as a predictive tool for estimating the tolerance threshold in response for dynamic loading.

The geometry of the model based on CT (Computer Tomography) scans and represents the anatomy of a male human skull. A new approach to transform the two-dimensional Computer Tomography data into a three-dimensional finite element input file was developed. The model at its present stage consists of 1.342 solid elements representing the skull bones with 2.874 nodes in 31 layers.

INTRODUCTION

Head injury is the most common type of injury to all seriously injured road users especially car occupants. This remains true even with the introduction of enhanced restraint technology into all new cars and with the high levels of seat belt use achieved by the application of mandatory seat belt laws. The control of head injury risk in the automotive world is attempted through the Federal Motor Vehicle Safety Standards 200 series, notably FMVSS 208. This standard involves a whole system performance test in which a dummy is exposed to 30 mph frontal impact crash.

The risk of head injury is judged by calculating the Head Injury Criterion (HIC) that is unique among the injury criteria in safety regulations because the limit of 1.000 was not based on crash-tests where HIC was measured and corresponding impact loads observed. The HIC is widely used in experimental crash testing since its introduction in the early 1970's. The single-axis translational acceleration basis for HIC has been later replaced by the resultant acceleration (figure 1) of a triaxial accelerometer array that is rigidly mounted near the center of mass of the Dummy headform. The recent change to the HIC definition took place in 1986 when a limit of 36 milliseconds maximum duration was placed on the calculation interval [7, 8, 11].

Several problems concerning the use of the HIC are related to the basic research work for the development of the HIC. The gap between this evolving knowledge on the subtleties of actual injuries on the one hand, and the crude representation of head injury risk by HIC number on the other has been questioned for several reasons. The inadequacy of this procedure has become increasingly apparent in recent years as epidemiological, experimental and clinical work has illustrated the complexity of actual skull and brain trauma.

$$HIC = \max \left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a_{res}\, dt \right]^{2,5} (t_2 - t_1)$$

Figure 1. Calculation of the Head Injury Criterion (HIC)

Discussions on the most appropriate tolerance level for the head injury criterion implicitly accept the validity of the HIC as a measure of injury risk. There is much evidence that a deeper understanding of the injury-producing mechanisms is needed and a more realistic biomechanical injury criterion is necessary [2, 10].

The development of anthropomorphic Dummies over the years has resulted in closer approximations to the human body in many respects. The headform still consists of a hollow cast aluminium shell, shaped like the human head, covered with a soft plastic flesh simulation, and adjusted to weight the same as its average human counterpart. The impact response of a human head is obviously completely different from that of the rigid body response of the aluminium skull.

Test Results - Distributions of dummy response results from FMVSS 208 and NCAP tests of passenger cars from model year 1987 trough 1991 are shown in figure 2. Over 90 percent of the Drivers HIC and Passengers HIC are below 800 and 710 in the FMVSS 208 tests. In NCAP, only 58 percent of the HICDs and 72 percent of the HICPs are below 1.000 [3]. The FMVSS 208 data indicate no significant head injury risk for the majority of passenger cars.

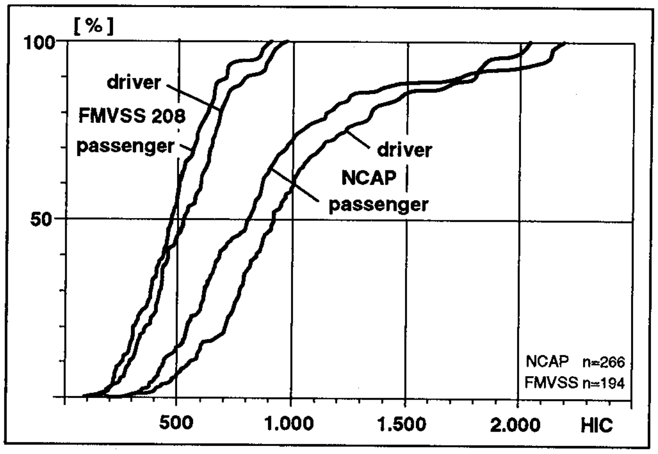

Figure 2. Cumulative frequency of HIC for Driver and Passenger Dummy in FMVSS 208 test and NCAP test

Accident analysis data - In contrast to these experimental crash test results real world accident research reveals that head injury is the most common severe type of injuries. To clear up the importance of head injury in real traffic accidents a statistical analysis of accident data of the Medizinische Hochschule Hannover (MHH) was carried out. Table 1 shows the distribution of injury severity of different body regions and the particular significance of head injuries in traffic accidents for all involved persons (7.060 single injuries in total).

Table 1
Distribution and frequencies of injured body regions

	AIS ≤ 3		AIS > 3	
head	1.598	23,7 %	103	49,3 %
neck	379	5,6 %	19	9,1 %
thorax	977	14,5 %	44	21,1 %
abdomen	208	3,1 %	34	16,3 %
pelvis	398	5,9 %	3	1,4 %
extremities	3.191	47,3 %	6	2,9 %
total	6.751	100 %	209	100 %

The sample consists of 3.330 injured persons with 1.701 head injuries. 90 % of the injured persons suffered injuries coded with AIS 1 and AIS 2. The injuries mainly responsible for fatalities are distributed according to body regions as: 50 % head, 19 % thorax, 6 % spine. These data really show that HIC is not strongly correlated with the risk of head injuries in real world accidents and that HIC is not an adequate biomechanical prediction for injury risk. The lack of correlation is understandable when the wide variety of head impacts, restraint systems, car designs and different injuries are viewed with the expectation that a single measure of head dynamics should be related to all outcomes.

BIOMECHANICAL ENGINEERING

At the moment, involvement and efforts in detailed finite element modelling are concerned with finite element models of current mechanical Dummy models. In these "third generation" Dummy models, mechanisms of the deformable parts are modelled in their structural detail via finite elements, which leads to potentially high precision response for arbitrary loading. There is now a rising interest in models of isolated parts of the human body to obtain more realistic information about their response in crash events as valuable additional results to conventional readings [4].

Finite element modelling of human parts can be used to analyse and assess various impact conditions. The finite element model approach necessarily requires both, skull geometry and constituent material properties to determine reliable and reproducible mechanical response of the head.

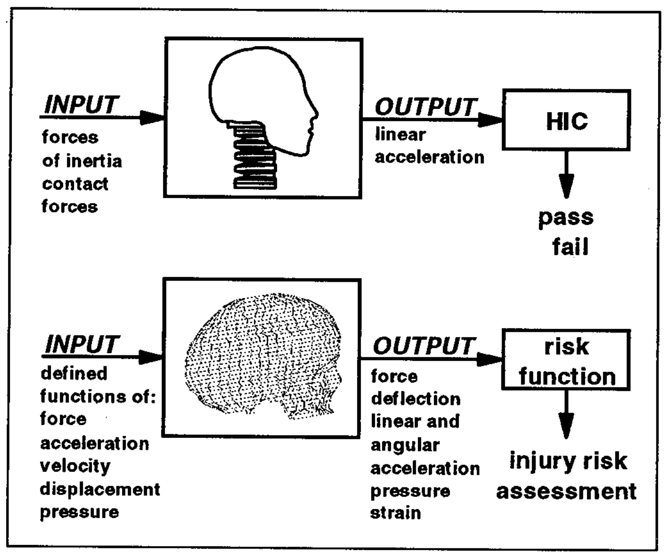

Figure 3. Comparison of experimental and numerical injury assessment

Several models of the human head have been carried out in the past as two-dimensional models of the mid-sagittal or coronal plane. Limitations of finite element modelling efforts in head injury were questioned by Khalil and Viano in the early 1980's caused by the assumptions and approximations made at that time [5]. Most were caused by restriction in CPU capacity and insufficient finite element program codes. However, it is now widely accepted that the finite element modelling is the only comprehensive method to approach head injury mechanisms.

Recently two three-dimensional models of the human brain and skull have been published. The former consists of an approximated anatomical geometry of the human brain without skull structures [1]. The latter based on the geometrical proportions of the HYBRID III headform with additional anatomical features [12]. A recent review of finite element modelling of head impact was published by Sauren and Claessens [13]. They also draw the conclusion that finite element analysis seems to be the most appropriate analytical technique for analysing the relationship between input parameters and local loading of complex biomechanical structures (figure 3).

Application of finite element modelling to biomechanics - For this purpose, a new method of designing a model with accurate geometry and material properties was required. The finite element simulation is generally subdivided into three different parts (figure 4):

- Development of geometrical models and determination of material properties and boundary conditions (pre-processing)
- Numerical solution with finite element program code (main processing)
- Visualisation and analytical interpretation of results (post-processing)

CAD data were converted into finite element data by mesh generator programs. The material data used in automotive development are well known and described by analytical material formulations. The main-processing part provides information that can be interpreted by post-processors. These results were directly used as guidelines for the automotive engineering process.

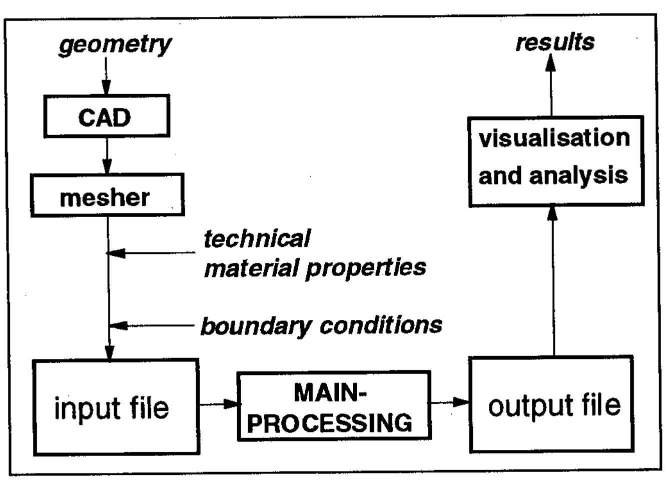

Figure 4. Finite element modelling in automotive development

Compared with the automotive development, geometry data from most of the human parts are not available. Furthermore biological material properties must be converted into numerical material properties, suitable for the finite element program code. Calculated mechanical output parameters must be converted into parameters that provide a biomechanical description of the consequences of impacts and which can be used for the assessment of injury risk (figure 5).

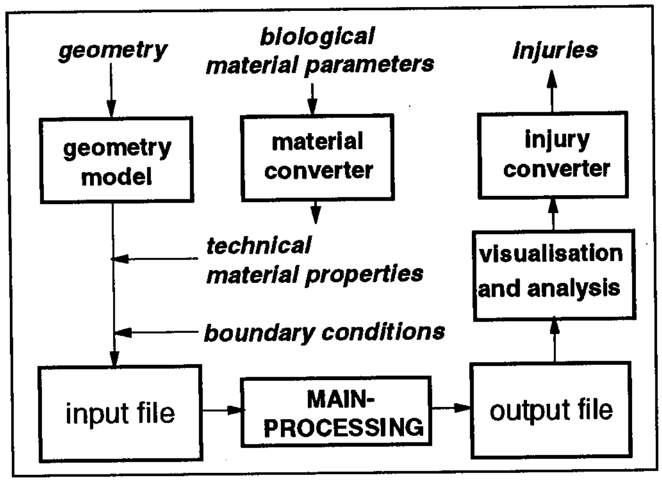

Figure 5. Finite element modelling in biomechanics

Considering the requirements to a finite element program code for biomechanical analysis we decided to apply the finite element code PAM-CRASH - commonly used in the automotive industry for dynamic crash simulation - which provides the following features [9]:

- ▷ dynamic, non-linear large deformations
- ▷ three-dimensional different shaped solid elements
- ▷ pressure simulation on solid surfaces
- ▷ viscoelastic-plastic and hydrodynamic material characteristics
- ▷ contact algorithms for sliding and sticking
- ▷ adjustable force-deflection characteristics for joints and constraints.

METHOD

The different head injuries resulting from various types of loading and linear and angular accelerations require a three-dimensional model. The geometrical data of the head are the essential parameters to describe a model. For the generation of the finite element model it is desirable to obtain geometrical information from computed data like CAD data in automotive development. With the help of a special purpose computer program, solid elements of the skull, based on Computer Tomography (CT) pictures (figure 6) were generated and an input file for the finite element code PAM-CRASH was created.

The two-dimensional Computer Tomography (CT) pictures of parallel horizontal slices of a human skull were transformed into computer graphics format. A three-dimensional mesh and an input file were created with PEGAM, a PC based pre-processor program for interactive graphical development of three-dimensional finite element geometry models, including the generation and preparation of program code related finite element input files.

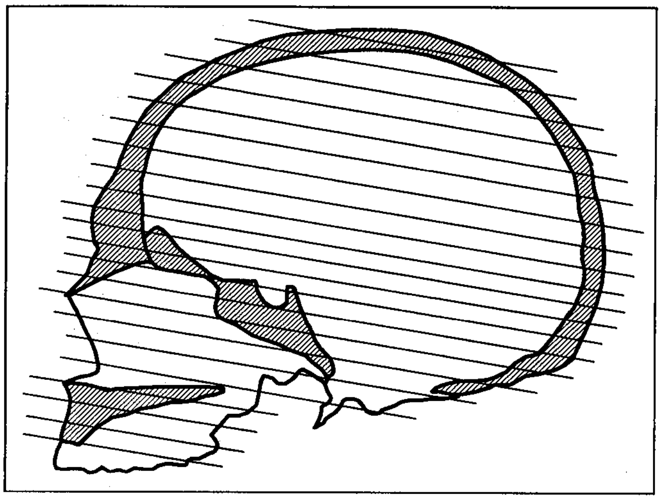

Figure 6. Scheme of Computer Tomography scans

The user is able to control the number and density of nodes interactive on the screen via mouse. Variable dimensions and distribution of elements allow the development of models with higher accuracy in particular regions with increased node density. The generated finite element mesh of different layers is directly visible on the screen as a wire frame model, which permits to control the order of the elements immediately (figure 7).

The automatic mesh generation of a three-dimensional finite element model is inappropriate since no CAD data are provided. In addition to that, the transformation of the complex geometrical structures into discrete nodes, joined together as solid elements, can only be realised by sophisticated numerical algorithms, which are hardly available in commercial computer programs up to now.

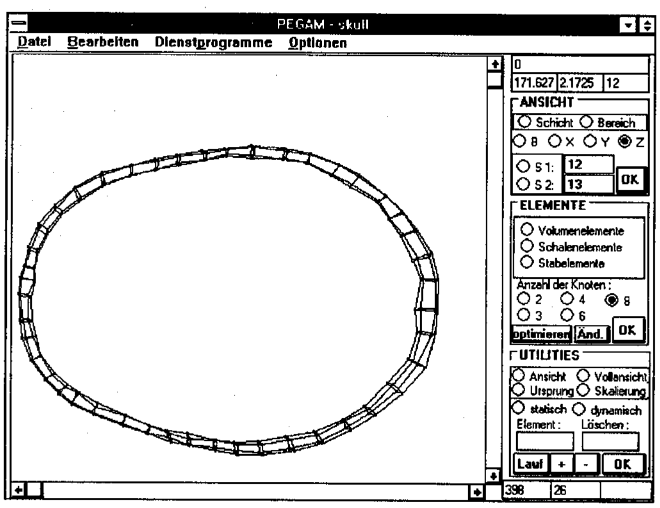

Figure 7. PEGAM user interface with modelled solids, linking two layers

Modelling procedure - At first the scanned CT pictures were scaled and assigned to an origin to provide the accurate 3D geometry. The nodes were created via mouse click on the screen. The positions of the last adjacent layer nodes are displayed as reference points for the positions and distances of the following nodes. The nodes of two adjacent layers are linked together as solid elements. The order of element nodes is stored in an element data file.

The program provides 8-, 6- and 4-node elements that are necessary to assure a realistic mechanical force distribution. The user is able to choose the node input order. The program will create the adequate order of node numbering (right-handed system) within the element data file. The option to modify or erase elements at any time of the modelling is advantageous. The mesh of single layers can be printed out. Figure 8 shows the generation of a finite element model input file with the pre-processor program PEGAM.

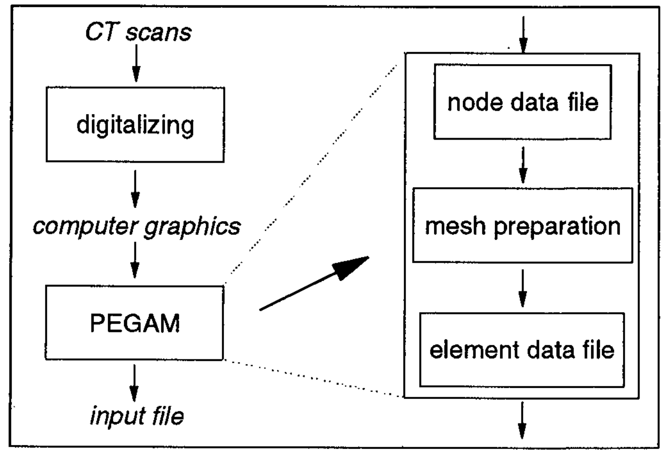

Figure 8. Generation of a finite element model input file with the pre-processor program PEGAM using CT scans

After generating and modifying the mesh, an input file with basic values for material and boundary conditions was created which allows to start a PAM-CRASH session and the graphical output of the mesh with DAISY, the ESI post-processor. The basic values were substituted by concrete material and boundary conditions to calculate the results for particular impact simulation of the human skull. Our program is not only capable of modelling the human skull but for any complex three-dimensional structures.

HUMAN HEAD MODEL

The human head model consists of 1.342 solid elements (8-, 6- and 4-node) with 2.874 nodes in 31 layers and represents the bony structures of a human skull without mandible structures. The element extent is dependent on the scan distance (5 mm). The skull bones were generated as one layer solids. Three-layered material characteristics will be provided through the material models. Element sizes and numbers are different for both sides because of natural differences in the shape of the skull bones. The figures from 9 to 12 show different views of the three-dimensional human head model.

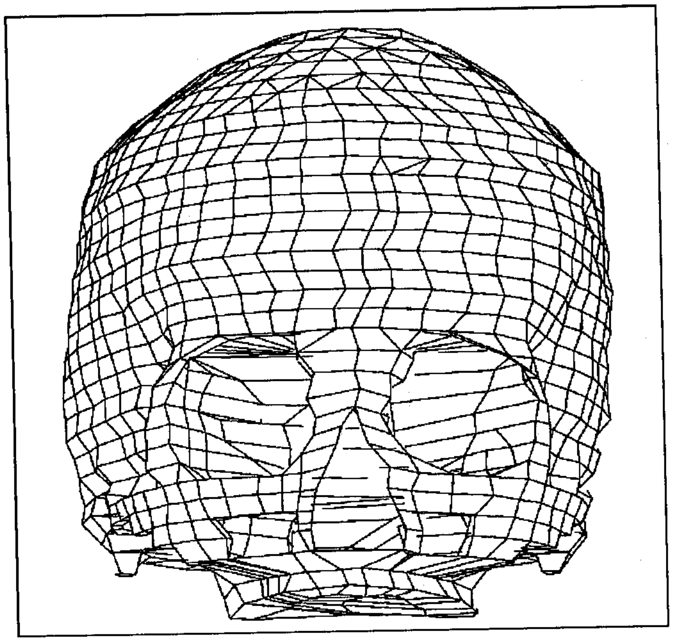

Figure 9. Frontal view of the human skull model

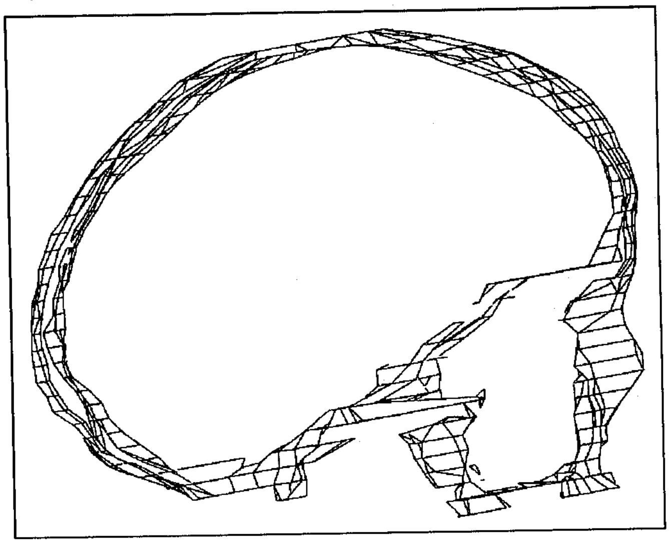

Figure 10. Mid-sagittal view showing the cranial cavity

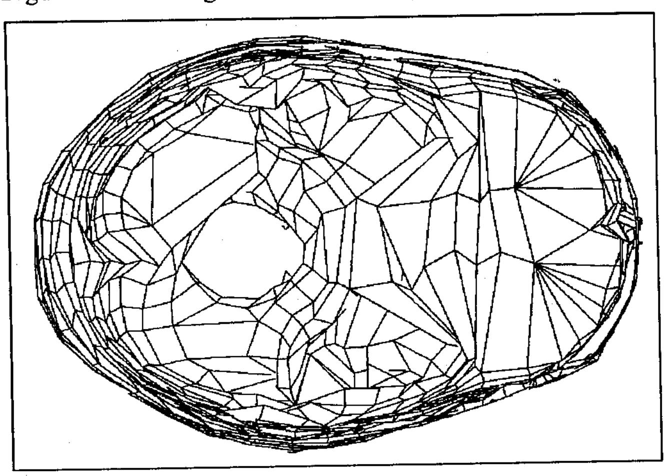

Figure 11. Inferior view of the human head model showing the base of the skull with the foramen magnum

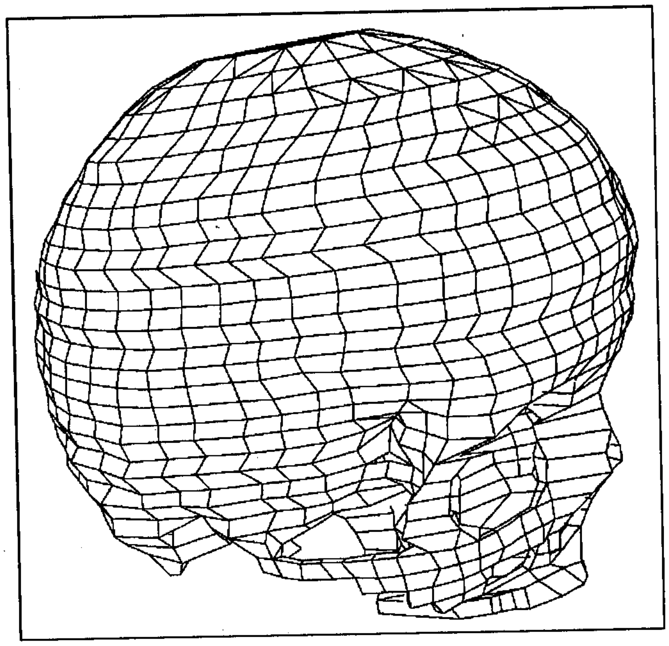

Figure 12. Lateral view of the human skull model

OUTLOOK

Future extensions of the finite element model of the human head include the addition of an anatomic brain model, the tissues and the cerebral spinal fluid (CSF). The geometric features will be gained from Magnetic Resonance Images data. Further validation of the model and the integration of additional material properties are needed. First material parameters were gained by performing special material tests by experiments and finite element simulations and by comparison of the test results [6]. After validating the subsystems by adjusting boundary conditions the complete head model will be validated by comparison with laboratory experiments.

Once validated, this human head model could furnish more accurate data about the true risk of head injuries in a crash event, otherwise difficult to achieve experimentally. The model will provide the determination and assessment of various initial parameters concerning different loads and the biomechanical limits of the human head to develop enhanced injury and protection criteria.

The ultimate objective is to use the head model in conjunction with a model of the human cervical spine for achieving a maximum of local biofidelity of the head-neck complex. In the future numerical models of the human body will replace and reduce laboratory experiments with human cadavers.

SUMMARY AND CONCLUSIONS

Head injury represents the mayor part of the severe injuries in almost all types of traffic accidents. Head injury mechanisms are difficult to study experimentally due to the great amount of variables involved and ethical problems using human cadavers and animals as surrogates of the living human. Finite element modelling is the widely accepted comprehensive method to study the degree of human tolerance to head impact and to define injury probability thresholds.

The three-dimensional human head model presented in this paper represents anatomical features of an adult human head. Two-dimensional Computer Tomography images were used to visualise the complex three-dimensional geometry of the anatomical structure of a human head. The CT scans were transformed with a self-developed pre-processor program PEGAM into a finite element model that comprises of 1.342 solid elements with 2.874 nodes in 31 layers. The model is implemented into the finite element code PAM-CRASH and will be used for simulating head impacts.

ACKNOWLEDGEMENTS

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Biofidelity Improvements to the Hybrid III Neck

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ABSTRACT

This paper describes the steps taken to improve the biomechanical fidelity of the neck of what is now the standard frontal impact test dummy, the Hybrid III, to make it more suitable for motorcycle crash testing.

On the basis of volunteer and cadaver studies, several refinements have been made to the Hybrid III neck. These include changes to the range of motion of the head/neck joint and its means of static adjustment, a change in the neck stiffness in flexion/extension and the improvement of torsional biofidelity.

The purpose of these modifications is to improve the response characteristics of the neck, to allow the dummy to be used in a larger range of postures than the standard and to make the neck and head respond more realistically during the testing of current motorcycle safety systems.

INTRODUCTION

Background

St-Laurent et al (1989), described the design and basic features of an anthropometric test device (ATD) specifically designed for the motorcycle test environment. The motorcycle crash environment is relatively unconstrained (in comparison to that of a vehicle occupant), with many individual events occurring during the period of the collision. Keeping the motion of the surrogate true to that of a human is vital to the assessment of injury potential.

This motorcyclist ATD was based on the "pedestrian" version of the Hybrid III and was modified to be more suitable for motorcycle testing, Gibson et al (1992).

Injury monitoring was improved by replacing the standard steel tibia and femur of the Hybrid III with frangible composite units whose strength and stiffness characteristics more closely matched those of a human. The knee complex was redesigned to allow simulation of ligament rupture at the appropriate biomechanical levels. The ATD also had additional modifications to the head and neck interface to allow fitting of a helmet. Hands which were able to grip the motorcycle handle bars were also used. Finally, it contained an onboard data acquisition system in the chest cavity.

This version of the motorcyclist ATD, MATD 1, was used in a crash test series aimed at evaluating the potential of motorcycle leg protectors, Newman et al (1991). This series of tests was one part of a major study combining analysis of accident data bases, Pedder et al (1989), crash victim simulation, Zellner et al (1991), and an injury cost model, Newman et al (1992), to allow realistic evaluation of the effect of the use of leg protectors on motorcycles. This study led to the establishment of an International Organization for Standardization (ISO) working group, (ISO 1994), whose purpose was: "...to define common research methods and a means for making an overall evaluation of the effect that devices which are fitted to motorcycles and intended for crash protection of riders have on injuries when based over a range of impact conditions based on accident data."

Interest in other possible motorcycle safety devices has been growing. In parallel with developments in automobile crash safety, the feasibility of using airbag restraint systems for motorcycle riders was the subject of several exploratory studies but many of the issues involved were yet to be addressed. Further work was required to investigate the feasibility of motorcycle airbag systems, Zellner et al (1994). Particular areas of concern with the ATD airbag interaction included the effect of the airbag on an out of position rider, the stability of the airbag in the motorcycle crash environment and the interaction of the helmet and airbag during inflation. On the basis of a review of available literature, Biokinetics and Associates Ltd. (1990a), a set of requirements for an interim dummy for use with airbag motorcycles was drawn up, Biokinetics and Associates Ltd. (1990b).

The requirements reflected that the available ATDs had been developed to represent vehicle occupants in direct frontal or lateral impacts. These ATDs were not appropriate for use with the large unrestrained motions of a motorcycle crash test environment. Specifically, the Hybrid III dummy needed modifications in those areas likely to contact the airbag. The position and orientation of the head was critical in determining the interaction with the airbag. The possibility of airbag/helmet interaction also had to be accounted for.

Based on this review and the experience gained with MATD 1, a further series of refinements to the pedestrian Hybrid III were proposed in addition to those incorporated in the MATD 1. The new dummy was designated the MATD 2. Changes to the onboard data acquisition system now allowed the thorax to retain the characteristics of the Hybrid III thorax, but with a revised and more comprehensive chest deformation sensing capability. An injury monitoring abdomen was included along with some changes to the lumbar spine. Finally, a modified neck was developed.

In what follows, this paper will discuss in more detail the design guidelines of this modified neck. The modifications to the neck of the MATD will be described and results of testing will be presented.

DESIGN OBJECTIVES

The design of the new neck was to meet three main requirements.

The first requirement was to improve the anthropometry of the head to thorax junction of the dummy. Several considerations were important:

- The MATD 2 had to allow the use of a motorcycle helmet;
- The dummy had to be able to assume the full range of seated postures of a rider on a variety of motorcycles types; and
- The shape of the neck area must not cause any interaction problems with the airbag such as snagging.

Secondly, the neck responses must maintain a high level of biofidelity to ensure that the position and phasing of the head and neck remained consistent with that of a human leading up to the airbag interaction. This consistency of position and phase needed to be maintained in both frontal and lateral impact conditions.

Finally, the neck required biofidelic torsional compliance as this had been shown to be a problem in the first series of accident reconstructions with the standard Hybrid III neck, Zellner et al (1994).

BIOMECHANICAL REQUIREMENTS

Early efforts at establishing response corridors were conducted by Mertz and Patrick (1971) and Mertz et al (1973), in which a volunteer and several cadavers were subjected to non-injurious and injurious levels respectively. Test subjects were restrained with the torso reclined 15° from vertical and exposed to fore-aft deceleration pulses exhibiting peak accelerations up to approximately 10g for the volunteers and up to 14g for cadavers. Performance requirements were based on the relationship between the torque at the occipital condyles and the angular position of the head relative to the torso for flexion and extension, Figures 1 and 2. Kinematic characterizations (displacement, velocity, acceleration) of the head and neck were not presented due to the lack of a unique relationship between the head angle relative to the torso and the position of the head centre of gravity. The study developed neck-injury indices for automotive occupants in frontal impacts and established performance requirements for the development of the Hybrid III automotive ATD.

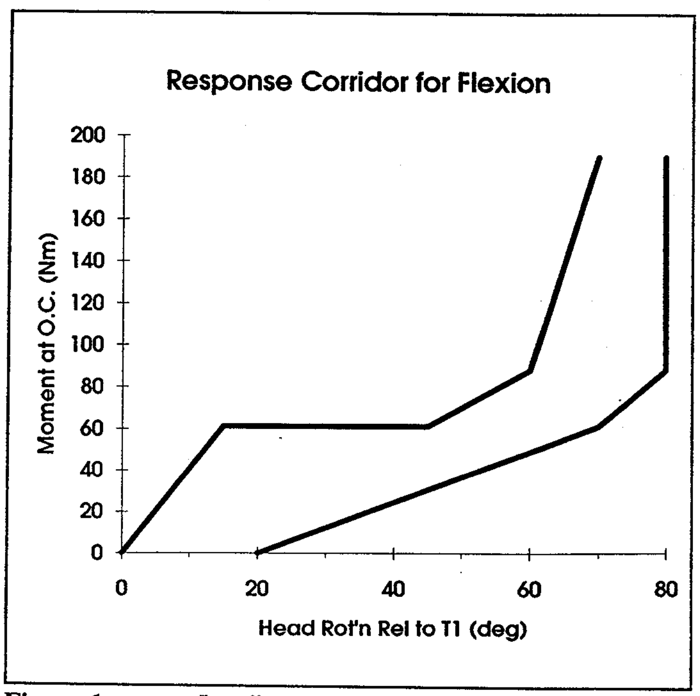

Figure 1: Loading corridor for neck flexion (forward bending) based on Mertz et al (1973).

Lateral performance requirements were presented later by Patrick and Chou (1976).

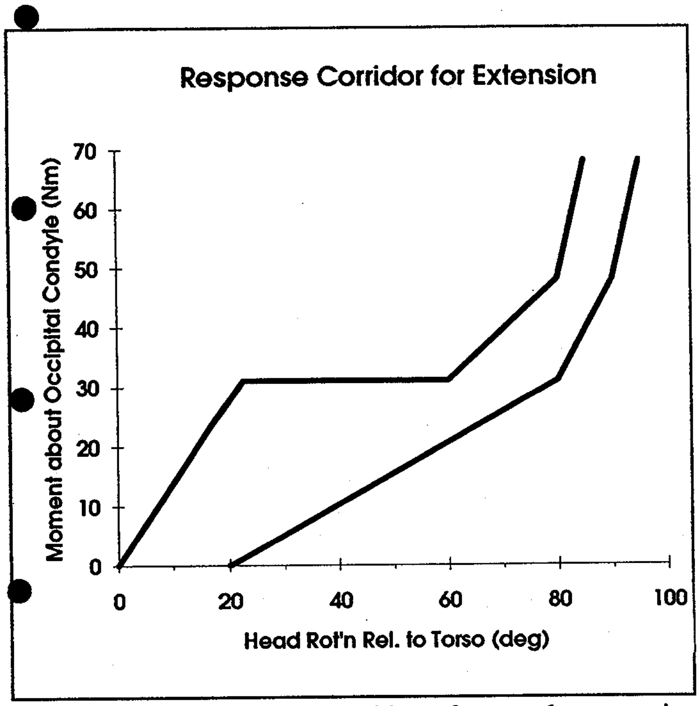

Figure 2: Loading corridor for neck extension (rearward bending) based on Mertz et al (1973).

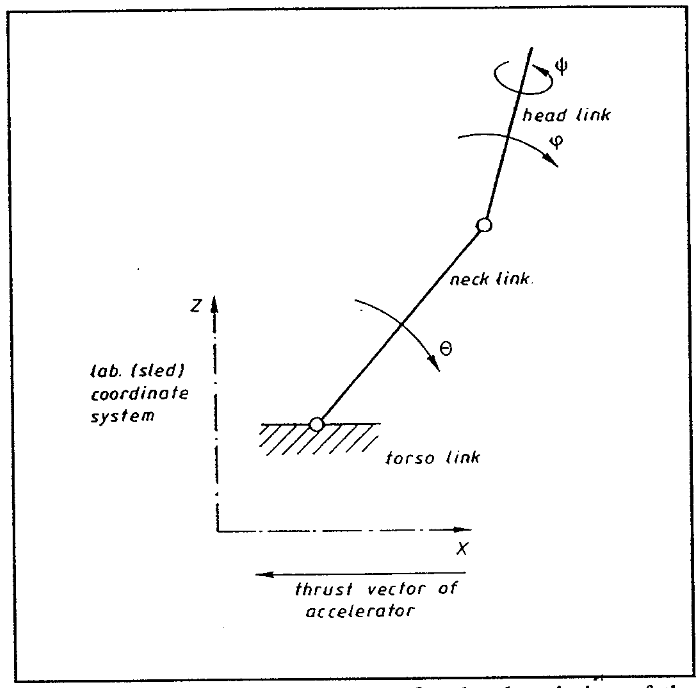

Figure 3: Analogue system for the description of the relative head motions, proposed by Wismans et al (1986).

This data was noted by Mertz et al (1973), and Wismans and Spenny (1983), as necessary, but not sufficient conditions for fully describing the performance of the head and neck complex. Wismans et al (1983, 1984, 1986, 1987) proposed a series of kinematic and joint torque performance requirements for frontal, oblique and lateral directions. The requirements were based on an extensive analysis of volunteers sled tests conducted by the Naval Biodynamics Research Laboratory (NBDL). The seated upright volunteers were restrained and tensed prior to being exposed to low severity levels (greater than 5g) with the most severe peak sled acceleration level of 15g and sled velocity change of 17 m/s. Photographic targets and accelerometer instrumentation totalling 0.53kg were mounted on the head for determination of head and neck kinematics.

Analysis of the head centre of gravity and occipital condyle trajectory revealed circular arcs which led to the development of a mechanical analogue system consisting of two linkages and three degrees of freedom, Figure 3. The general curvilinear motion of the volunteers exhibited similar trends for all impact vectors and resulted in an analogue system for each vector to account for varying link lengths and joint locations. The motion of the head relative to the neck was characterized by three phases. The typical test data, shown in Figure 4, illustrate a lagging of the head link relative to the neck during the initial stages of motion **(1)**. The upper neck joint torques were very small in this phase. This was followed by a greater rotation of the head relative to the neck **(2)**, and then an in-phase rotation of both links before rebound **(3)**. Both lateral and oblique tests resulted in similar but less pronounced trends and involved some head rotation about the vertical axis of the head due to the offset of the head centre of gravity from the occipital condyles.

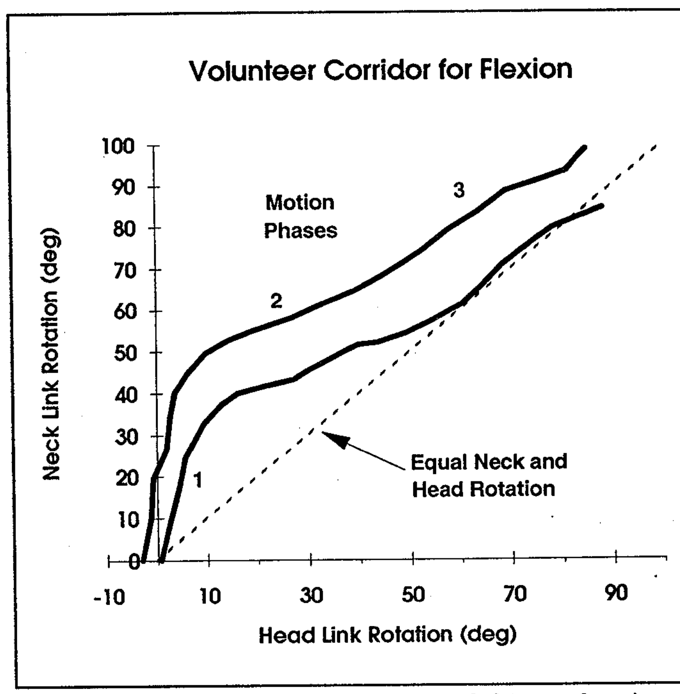

Figure 4: The neck link rotation (θ-θ_0) as a function of head flexion (φ-φ_0) corridor derived from human volunteer tests, Wismans et al (1986).

The linkage model was used to derive joint stiffnesses for the lower and upper pivots and head rotation. These were based on dynamic analysis of the head and neck system. Assumptions made in the analysis, included the location of the occipital condyles, the lack of involvement of the neck's inertia, and treating as minor the effects of translation and rotation of the first thoracic vertebrae referenced in the laboratory coordinate system.

Several points were noted in developing guidelines for the design of the MATD 2 neck. These included:

1. The mean values for peak rotations of all the joint pivots were strongly dependent on impact severity and direction, however, the prescribed trajectory remained unchanged.

2. The mean peak head relative to neck rotations were strongly dependent on impact direction as well as impact severity.

3. The head exhibits a free range of motion during the initial stages of flexion for all impact directions and this may be perceived as simple translation.

4. The joint torques for the analogue system remain constant for all impact severities.

The proposed flexion response specifications to be used in the development of the MATD 2 neck were head relative to neck angle rotation, head link rotation as a function of time, and head centre of gravity trajectory. These ensure that the proper location and orientation of the head relative to the thoracic spine are maintained. The specifications are limited to low impact severities for tensed volunteers, restrained in the upright seated position.

The mean head torsional response developed by Wismans and Spenny (1983), was also used in the performance specifications for the MATD 2 neck to provide biofidelity in the lateral direction (due to oblique impacts from air bags, for example).

The data presented in Figure 5 was derived from two sources. Tensed volunteers, restrained in the upright position who were exposed to sled accelerations between 5g to 10g, with additional dynamic torsional response data presented by Myers et al (1989), to provide response to failure. Myers performed dynamic torsional failure tests on five ligamentous cervical spine specimens (CO-T1). The tests were performed at a loading rate of 500 degrees per second in pure torsion without any end constraints.

The loading rates were similar to those experienced by volunteers in the Wisman and Spenny (1983) study with a mean value of 600 degrees per second. The response data in Figure 5 for the cervical spine reflect the passive effects of ligamentous tissue and not the effects of musculature as seen by Wismans and Spenny. The initial free range of motion is consistent with ligament slackness and is consistent with static torsional tests on cervical spine specimens conducted by Geol et al (1984, 1988), Panjabi et al (1988), and Winterbottom et al (1989). The torsional stiffness, however, is greater than in the static tests and is consistent with the strain rate dependency of ligamentous tissue (Viidik, 1987).

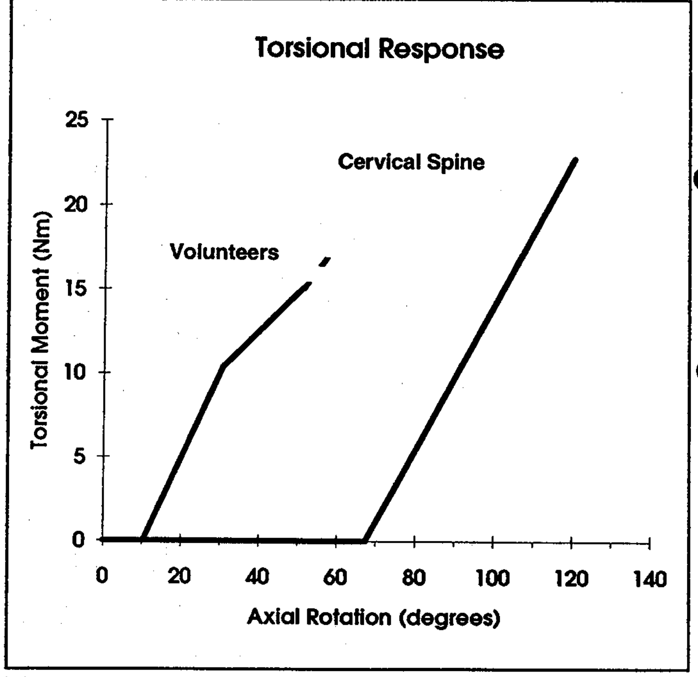

Figure 5: Dynamic torsional response data from Wismans and Spenny (1983) combined with cervical spine torsional failure data from Myers et al (1989).

Based on the two response corridors, a new performance specification was developed by the superposition of the mean muscular and ligamentous response curves, Figure 6. The wide performance corridor is based on the standard deviations from each study. A linear response curve was proposed for the MATD 2 neck to simplify its design, Biokinetics and Associates Ltd. (1992).

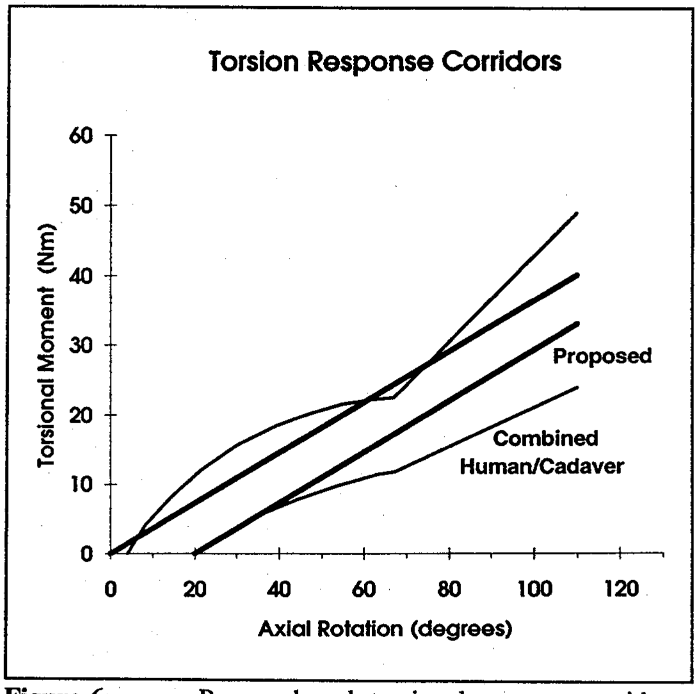

Figure 6: Proposed neck torsional response corridors.

NECK DESIGN

Helmet Fitting

Enabling a helmet to be fitted to the Hybrid III head required the design of extensions to the nape and chin area of the headskins, Figure 7. These extensions were required to support the chin strap and nape area of the helmet to ensure realistic helmet stability during the crash.

Flexion Response

Initial design efforts of the MATD neck were aimed at replicating the kinematic performance requirements for frontal flexion in terms of the head trajectory and orientation to provide realistic contact points with airbags and external objects. The occipital condyle torque specifications for flexion were also adhered to for injurious levels. Biofidelity for non-injurious torque levels was of secondary concern.

The Hybrid III ATD head and neck structure was chosen for the basis of the design as it possessed some biofidelity in flexion and extension and provided the required repeatability and durability for the motorcycle crash environment. The kinematic response of the neck was overly stiff, Wismans and Spenny (1984). Preliminary modelling with the crash victim simulation program (MADYMO), indicated the need to reduce the lower neck stiffness in flexion, increase the range of motion of the occipital condyle joint in flexion and extension, and to reduce the stiffness of the occipital condyle joint in extension. The modified neck, Figure 7, was subjected to frontal impact sled tests replicating the more severe volunteer tests analyzed by Wismans and Spenny (1984), including the initial head and neck orientation. The extended range of motion was incorporated into a torsion element mounted between the top of the modified neck and the Hybrid III head. The element had a mass of 0.84kg and increased the neck length by 12mm. A comparison of the dynamic neck performance with the standard Hybrid III neck is presented in Figure 8, with reference to the Mertz et al (1973) volunteer corridor and peak cadaver response reported by Wismans et al (1987).

The kinematic rotational response is presented in Figure 9 along with that for the standard Hybrid III neck and the Wismans et al (1987) performance corridor. It can be seen that the characteristic phases of head relative to neck rotation has been substantially achieved along with greater flexibility resulting in a larger more realistic head excursion. This is shown more graphically in Figure 10. The prescribed trajectory of the head center of gravity also complies with the specifications from Wismans et al (1987), Figure 11. The effect of the added mass and increase in neck length by the torsional element was investigated in conjunction with the neck skin extensions by conducting standard Hybrid III neck calibration tests with the torsional element mounted on a modified neck. The test gives a nominal 7m/s, 25g pulse to the head-neck system by means of a downwardly swinging pendulum. The peak moment about the occipital condyle remained unchanged, however a 9% increase in absolute head rotation was observed.

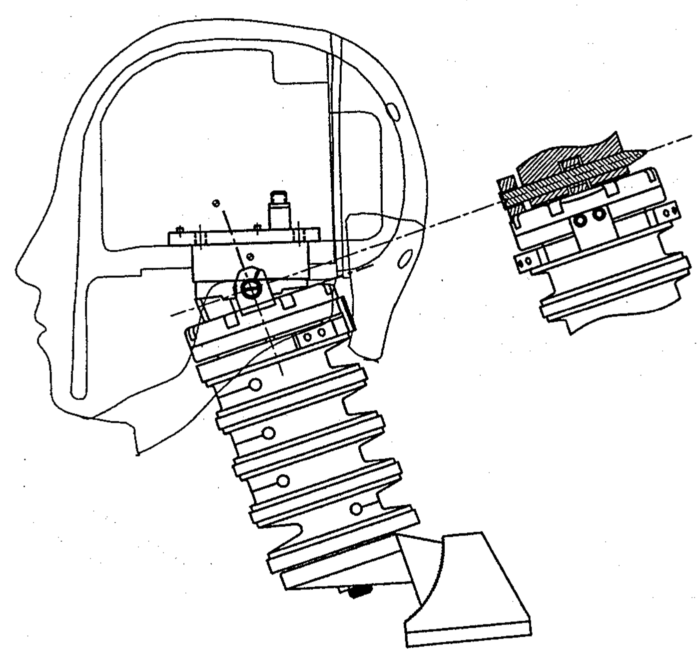

Figure 7: Assembly drawing of the modified neck showing the initial position adjustment clamp and the torsion element on top of the neck.

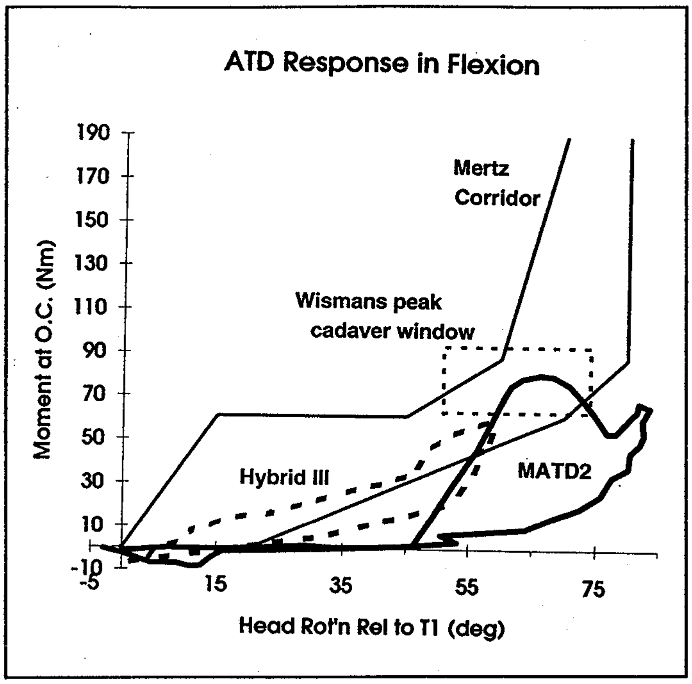

Figure 8: A comparison of the MATD 2 and Hybrid III dynamic response to frontal loading, Mertz et al (1973) and Wismans et al (1987).

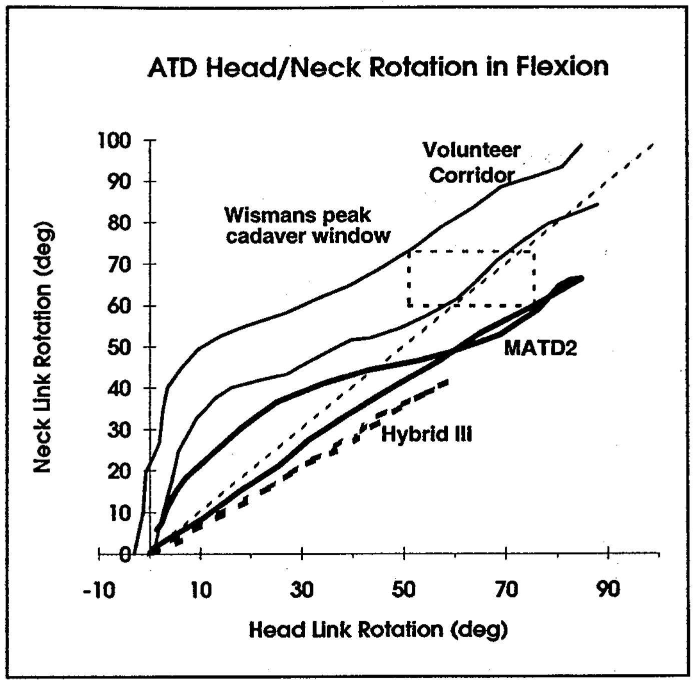

Figure 9: A comparison of the MATD 2 and Hybrid III neck/head kinematic response, Wismans et al (1987).

Torsional Performance

Performance of the torsional element in rotation about the longitudinal axis of the neck was evaluated by imparting a pure dynamic torsional load to the neck assembly, similar to the method used by Myers et al (1989). Figure 12 illustrates the performance of the standard Hybrid III neck and MATD 2 neck in relation to the proposed corridors. The Hybrid III neck exhibits a high initial stiffness followed by a lower stiffness equal to the slope of the corridors. The torsion element introduces a low stiffness torsional spring in series with the neck, reducing the initial stiffness for the first 40° of rotation.

Head and Neck Orientation

During the initial development of MATD 1 it became apparent that a greater range of adjustment of the head and neck static position was required to allow proper head attitude for a rider seated in a variety of positions, between upright and prone, on a motorcycle, Figure 13. The range of adjustment afforded by the Hybrid III was not sufficient and modifications were made to the lower neck bracket and upper neck joint to better approximate the lordotic curvature of the cervical spine and to maintain a level head orientation.

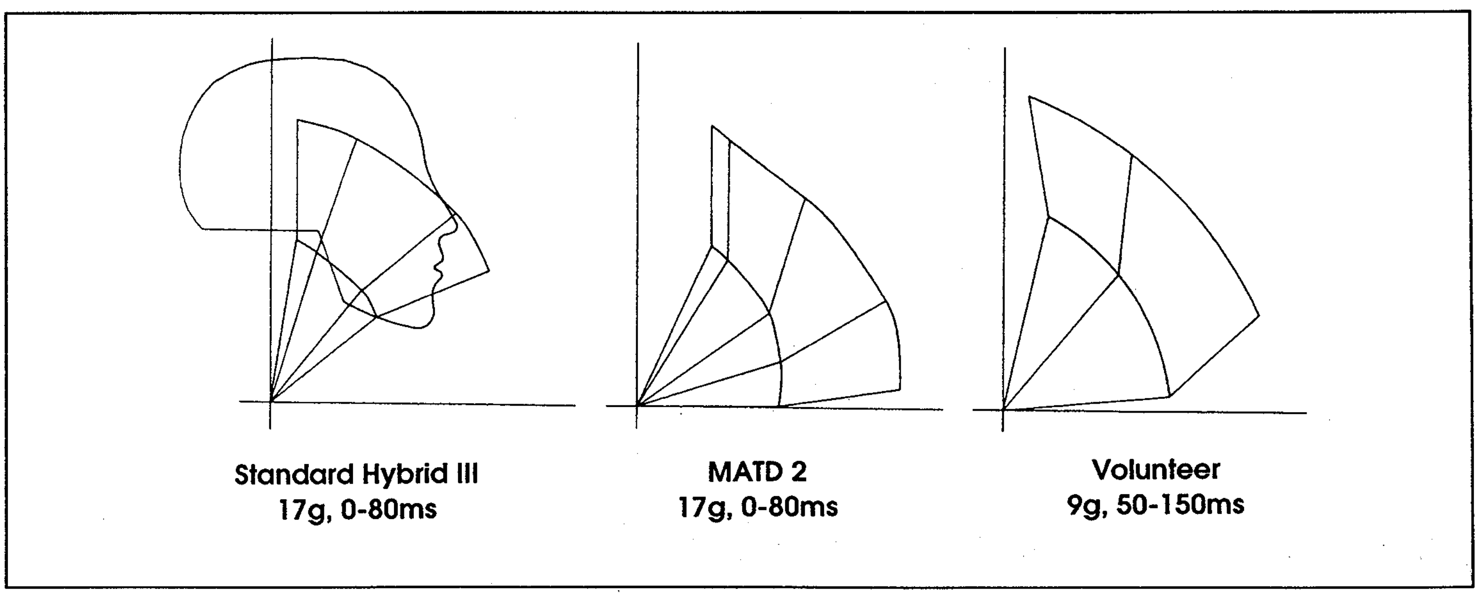

Figure 10: Absolute head and neck position of Hybrid III, the MATD 2, and a volunteer during a frontal impact.

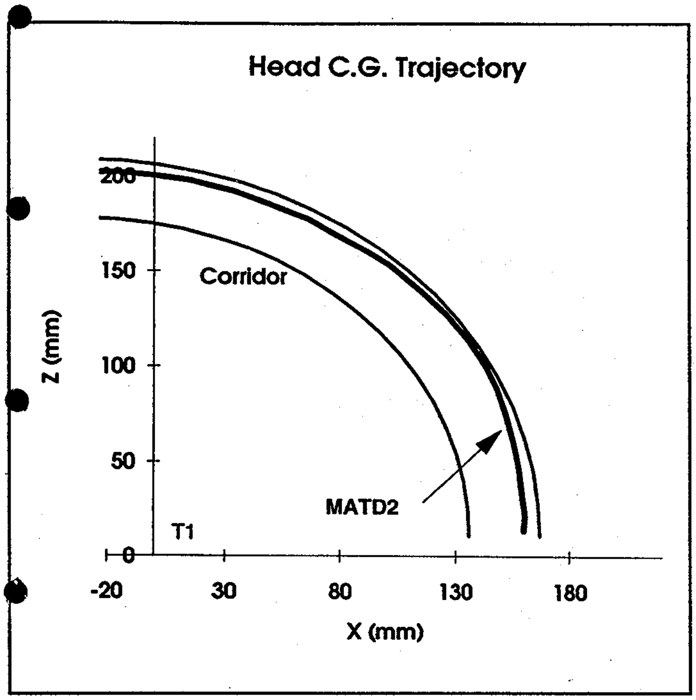

Figure 11: Trajectory of the CofG of the MATD 2 head.

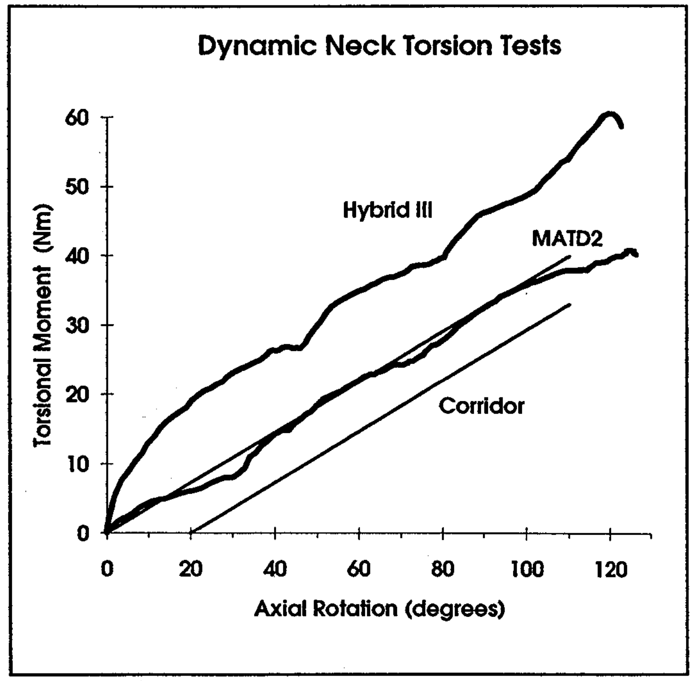

Figure 12: Dynamic torsion response of the Hybrid III and MATD 2 necks in relation to the proposed corridors.

The MATD 2 has incorporated an extended range of motion in the lower neck bracket of the Hybrid III dummy allowing approximately 7 degrees of flexion and 14 degrees of extension. The occipital condyle joint accommodated nodding joint blocks of a fixed geometry to preset the head in different orientation dependent on the orientation of the dummy and neck.

Experience with this arrangement during testing led to an alternative design being incorporated, which allowed a constant 1 G torque to be applied to the head. This allowed the helmeted head to have an initial position anywhere within the limits of motion of the joint, Figure 7.

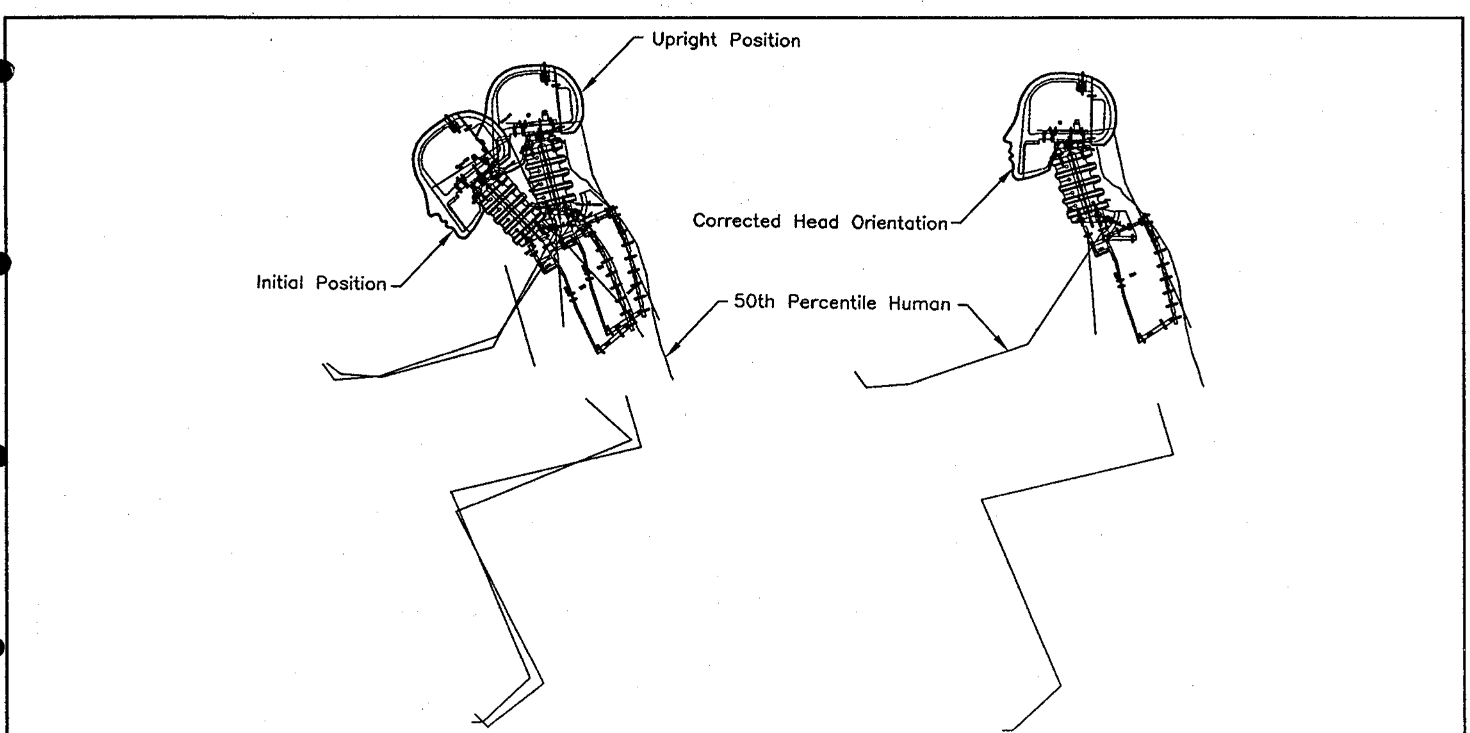

Figure 13: Comparison of Hybrid III seated posture with that for a 50th percentile human subject.

Airbag Neck Shroud

The MATD 2 dummy neck was fitted with a custom neck shroud to prevent unrealistic interactions with inflating airbags. The shroud comprised of a low density foam collar wrapped circumferentially about the neck which filled all interspacial gaps between the mandible and flesh skin of the upper thorax. The low flexural resistance of the shroud permitted the head to be fully flexed and partially extended without creating any gaps. The full scale tests did not reveal any airbag interaction problems with the arrangement.

MATD 2 TESTING

Static Tests

Four cadaver tests were conducted by the Institut National de Recherches sur Les Transports et leur Securité (INRETS), Ramet et al (1994). The test results were useful in helping to verify the whole dummy response in out-of-position stationary airbag deployments.

Briefly, the test consisted of placing the cadaver as a rider in prone or semi- prone position on a stationary motorcycle equipped with a car type airbag on the steering head. In the first test the thoracic spine was at about 65° from the vertical. Potentially fatal neck injuries, including fracture to the base of the skull and C1 with cord damage occurred.

Cadaver Test 1 was reproduced using the MATD 2 with the increased flexion-extension capability of the neck. The data from this test indicated potentially fatal neck injuries with high neck loads in tension and shear and a high extension moment recorded by the neck transducer. For this test an acceptable level of agreement was obtained with the overall motions of the dummy and the cadaver.

Full Scale Moving Tests

Eight full scale moving motorcycle tests were staged using the MATD 2. These involved three different test configurations, Zellner et al (1994). The motorcycle, moving at 48 km/hr impacted the mid side of:

1. a stationary car at 90°;
2. a 24 km/hr car at 90°; and
3. a 15 km/hr car at 135°.

In the first three tests, the MATD 2 was fitted with a neck having the extended flexion/extension response. For the last five tests the modified torsion response element was fitted as well.

Further verification tests of the neck performance under conditions similar to the NBDL volunteer tests have been planned at TNO and VRTC.

SUMMARY

The motorcycle crash test environment is significantly different to that for a vehicle occupant. Some modifications have been found necessary to make the Hybrid III ATD suitable for use in this environment.

This paper outlines the design requirements for a motorcyclist ATD neck for use in evaluating the safety performance of motorcycles equipped with airbags. An outline of the biomechanical requirements for such neck is presented.

The Hybrid III neck was chosen as a basis for the MATD 2 neck because of its repeatability and durability. The modifications were made to achieve the following:

- to allow the use of a helmet;
- to allow the ATD to maintain a human like posture;
- to improve the phasing of the head and neck motion;
- to introduce torsional compliance to the neck; and
- to ensure no snagging of the neck structure occurred when used with an airbag.

A limited test series was run to verify the effectiveness of the modifications. Further testing is planned.

ACKNOWLEDGEMENTS

The authors would like to express their gratitude for the support received from their colleagues at Dynamic Research Incorporated, California.

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ACEA Investigations Regarding Hybrid III Chest Deflection

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Introduction

Since its introduction in 1986 by NHTSA, the Hybrid III test dummy was subjected to various evaluations dealing with its response characteristics such as biofidelity, durability, sensitivity, calibration aspects and as well as instrumentation behaviour. The use of this dummy in Europe and the USA for research and development and/or certification purposes allowed a significant experience to be obtained by many manufacturers, research loboratories and regulation authorities.

In 1991, ACEA Task Force on Dummies conducted a study with the aim to summarize experiences in the utilisation of the Hybrid III within ACEA member companies. Two major points were identified in this study, which would need further investigations:

- The chest deflection measurement device, which may give unreliable results in some types of chest loading by the shoulder belt,
- the foot-ankle-tibia angular motion, which was found by a Ford study to be lower and stiffer than that of the PMHS.

Abstract

In line with agreements with SAE experts a research program aiming at the evaluation of these improvements was conducted by ACEA. It consisted of dummy preparation, static and pendulum tests involving the chest, and sled tests with driver and passenger dummies for different sled deceleration pulses and occupant restraints (three-point belt system or a combination with an airbag).

The objective of this paper is to highlight the chest deflection measurement approach that was implemented in the Hybrid III dummy and to present detailed results which were obtained in this program.

During the static and pendulum tests, when the loadings to the chest have been moderate, the standard rod and the string potentiometers appeared to function without any obvious faults. However in sled tests some problems were observed: while the string potentiometers seemed to function well, the rod potentiometer has failed in a few cases, due to disengagement of the rod from the groove in the sternum plate.

A general observation from all tests is, that the rod potentiometer in the large majority of cases shows an about 10 mm higher displacement than the one measured at the ends of the ribs. This is explained by the "hinge and lever effect", permitting the sternum plate to move progressively much closer to the spine than the ends of the ribs do.

As concerns reliability, the data obtained in this study support the string potentiometer approach for chest deflection measurement on the Hybrid III dummy.

Different locations show different deflection values, so a complete chest deformation description would require more than one single measurement. Comparison of the rod potentiometer and a string potentiometer using the same installation was impossible for obvious reasons. Even attached to the ribs, with more variations in load transfer, the string potentiometer showed acceptable repeatability.

In order to solve the chest deflection issue, it is proposed to replace the standard rod potentiometer by a string potentiometer, using identical mounting position.

1. Objectives of the present study

The key problem linked with the Hybrid III chest deflection instrumentation is, that it shows erratic readings on some occasions, when the chest is exposed to violent or non-central loadings. In extreme cases, the rod might even get disengaged from the groove in the sternum front plate. This problem was found by various laboratories in Europe [1] and USA [2]. ACEA's Task Force on Dummies decided, at a meeting in December 1992, to undertake the following actions in order to examine this problem:

- Equip the Hybrid III chest with three additional string potentiometers,
- evaluation of such equipped chest in static tests and pendulum tests,
- evaluation of this approach through sled tests using different restraint systems, dummy locations and sled pulses,
- discussion of the main findings within ISO and with SAE Dummy Working Group.

The main goal of this ACEA work was to evaluate an appropriate and simple solution for the important issue of chest deflection on Hybrid III dummy.

2. Chosen instrumentation for the chest

Because it was decided to keep the rod for reference purposes, it was agreed to add the additional potentiometers in the neighbourhood of the rod system in order to possibly find out a location allowing to replace the rod system which, as said before, was found to be unreliable.

Placing three potentiometers on the spine was judged to be sufficient to give enough information about the movement of the sternum plate. To increase the information, more potentiometers could have been used, but at a penalty of increased complexity and cost.

The free end of the potentiometer string could be attached to the sternum plate or to the end of the rib. Since one of the goals for the study was to see the difference (if any) between the standard rod potentiometer response and the actual rib movements, it was decided to attach the string to the ribs.

The selected potentiometer positions are described in **Figure 1**.

String potentiometers intended for the measurement of dynamic displacements require a low inertia moving system and a high tension force in the string. If this requirement is not met, the potentiometer system will not cope with rapid changes (accelerations) in the displacement studied. Depending on the sign of the acceleration, the result might be slack or breakage of the string. For the present study, the potentiometer type used in the Biosid chest instrumentation has suitable characteristics in this aspect and was consequently selected for this study.

3. Static and pendulum tests

Two test series with two chests were performed: six static and five dynamic test series.

3.1 Static tests

The two chests were subjected to compression in six different modes as described in **Table 1**.

configu-ration	load application	location	loading device
1	whole chest	front	stiff plate, 600 x 600 mm
2	transverse top	between rib 1 and 2	cylinder , 155 mm diameter
3	transverse mid	between rib 3 and 4	cylinder , 155 mm diameter
4	transverse bottom	between rib 5 and 6	cylinder , 155 mm diameter
5	lateral 40 mm offset	right from mid chest	cylinder , 155 mm diameter
6	lateral 40 mm offset	left from mid chest	cylinder , 155 mm diameter

Table 1: Test configurations of static tests

In these tests only the chest was used; the arms, neck and lumbar joints were disconnected. The bib was present, but no vest was fitted. A compression rig designed for Hybrid II abdomen calibration tests was employed.

The first test was performed by placing the chest with the sternum downwards against a horizontal plate and applying a compression force to the spine. For five tests a horizontal cylinder, 330 mm long and with 155 mm diameter, as shown in **Figure 2**, was used to compress the chest with centralized or offset loadings.

Schematic illustration of these loadings are found in **Figure 3**. With the moving cylinder transverse to the chest, the cylinder contacts with the chest were between rib 1 and 2, between rib 3 and 4 and between rib 5 and 6. With the moving cylinder parallel to the spine, the contacts were 40 mm offset from the median plane, i.e. on the left and right line of the screws joining the ribs and the sternum front plate.

Recordings were made of the travel of the moving cylinder, the standard chest potentiometer and the added three string potentiometers.

Diagrams in **Figure 3** present displacement data from all transducers and all tests. The displacement data are read when the cylinder has moved inwards 50 mm after its first contact with the chest.

3.2 Dynamic tests

The two chests were then subjected to five dynamic tests in different modes, as shown in **Table 2.**

In these test series the chests were installed in a complete Hybrid III dummy. An impact pendulum rig designed for Hybrid III chest calibration tests was employed. The tests were performed like the usual 6,7 m/s impactor tests for certifying the Hybrid III dummy.

configuration	load application	location
1	standard	13 mm below center of rib 3
2	upper	55 mm upwards from standard
3	lower	55 mm downwards from standard
4	left	55 mm to the left from standard
5	right	55 mm to the right from standard

Table 2: Test configurations of the pendulum tests

One of the tests had the pendulum to impact the chest as standardized, i.e. 13 mm below the horizontal centerline of rib number 3. Four other tests had the same alignment but with the pendulum impacting the chest with offsets 55 mm upwards, downwards and sideways from the standard center position.

Records were made of the signals from the standard chest potentiometer and the added three string potentiometers.

Figures 4 and **5** illustrate the loadings as well as the recorded peak displacement data from all tranducers and all tests. It can be seen that, apart from the magnitude of the signals, the displacement curves are of very similar shape. Therefore the string potentiometer system appears to accurately record the movement of the chest.

3.3 Data analysis

The reason for seeking an alternative string transducer to replace the standard rod transducer, stems from actual use of the dummy in severe test conditions which occur during full scale impacts. Under these conditions the rod potentiometer has exhibited erratic or faulty behaviour.

During the static and standard dynamic tests with the installed potentiometers the loadings to the chest have been moderate, and the standard rod potentiometer as well as the string potentiometers appeared to function as expected without any obvious faults.

A general observation from all data is that the rod potentiometer in the large majority of cases shows a higher displacement than the one measured with the string potentiometer at the rib ends. The difference is on the order of 10 mm. This effect can be explained with reference to **Figure 6**, which shows how the sternum plate moves more rearwards than the rib ends do. The bib urethane sheet joining the rib ends and the sternum plate acts as a soft hinge.

During tests with offset loadings, large differences between the rod potentiometer and the string potentiometer responses are readily observed. Differences up to 30 mm occur depending on the offset loading. The sternum plate, and more so the rod potentiometer, is obviously unreliable as an indicator of the movement of the ribs.

The more offset the load is (sideways or downwards) from the center of the chest cage the more disputable is the reading of the rod potentiometer compared with the actual rib movement. This is best seen in the static test **Figure 3**, bottom right, where the load is on the lower chest.

The dynamic low impact case does not show this so clearly because of a larger impact surface and a higher force application point compared to the static case.

4. Sled Tests

Both modified dummy chests were installed in two 50th percentile Hybrid III dummies and subjected to sled tests simulating severe impact conditions in different test configurations with different restraint systems and different dummy locations in a representative modern European vehicle.

4.1 Test matrix

For this purpose an Opel Astra car body was used in nine sled tests. That means three test configurations as shown in **Table 3**, which were performed three times each to include also analysis of the repeatability.

In these tests different restraint systems were employed, starting with the classic three-point belt system up to future supplemental systems such as the airbag .

Sled pulse derived from actual crash tests representing 0° 50 km/h and future 30° ASD tests.

test series	1	2	3
sled pulse	0° barrier test, Opel Astra, 50 km/h	0° barrier test, Opel Astra, 50 km/h	30° ASD* barrier test, Opel Astra, 50 km/h
car body to sled fixation	longitudinal, 0°	longitudinal, 0°	longitudinal, 13° turned to the right
dummy	driver only	driver + passenger	driver + passenger
restraint system driver passenger	 belt --	 belt + airbag belt	 belt + airbag belt

* ASD = Anti Slide Devices

Table 3: Sled test matrix

Reinforcement at several points such as the belt fixations, the B-pillars and the floor at the seat rail fixations, enabled the car body to withstand the test series without being damaged. In each test new belts, seats and steering wheel were used.

The dummies were settled in the mid seating position, in accordance with FMVSS 208. After each test they were checked and again calibrated after each test series. Both dummies were fully equipped with measurement instrumentation at head, neck, chest, spine, pelvis, femurs, knees and lower legs. About 60 measurements per dummy were recorded.

Some photographs of the sled tests and the modified chests with the added string potentiometers are to be found in the **Annex**.

4.2 Test results

As results of the sled tests a lot of data are available. For simplicity reasons only the most important measurements are taken into account here and especially those which are related to the behaviour of the chest.

Table 4 contains mean values and the standard deviation of all three test series measured at the driver and passenger dummy.

As can be seen, the repeatability of the measurements can be considered very good in general.

test series			1		2		3	
sled pulse			0°, 50 km/h		0° , 50 km/h		30° ASD , 50 km/h	
restraint system driver			belt		belt + airbag		belt + airbag	
restraint system passenger			–		belt		belt	
			mean value	standard deviation	mean value	standard deviation	mean value	standard deviation
sled speed		km/h	53,5	0,1	52,2	0,2	52,1	0,8
sled acceleration		g	33,9	0,5	34,5	0,1	31,4	0,5

1. DRIVER

measure	meas. variable	unit	driver		driver		driver	
head load	HIC 36 ms	-	1096	58,1	607	14,9	533	39,2
chest acceleration(T4)	a res 3ms	g	49,0	0,2	50,2	3,3	49,3	1,2
sternum acceleration	a upper max	g	51,7	2,2	59,0	8,1	52,7	4,7
	a lower max	g	43,6	0,4	51,6	2,7	38,6	2,1
chest deflection	s rod max	mm	55,9	2,6	59,9	0,6	51,9	0,5
	s string upper max	mm	31,9	3,2	44,6	2,1	35,0	2,0
	s string mid max	mm	46,2	3,1	41,9	3,0	42,3	3,8
	s string lower max	mm	18,4	3,5	38,6	0,7	24,6	3,0
shoulder belt load	F max	kN	10,2	0,3	9,5	0,3	9,8	0,4
lap belt load	F max	kN	10,1	0,3	10,2	0,0	8,9	0,4
spine acceleration(T12)	a res 3ms	g	51,9	1,3	51,0	1,7	47,6	1,1

2. PASSENGER

measure	meas. variable	unit	no passenger		passenger		passenger	
head load	HIC 36 ms	-	-	-	688	32,8	520	39,0
chest acceleration(T4)	a res 3ms	g	-	-	52,5	1,8	44,5	1,4
sternum acceleration	a upper max	g	-	-	57,4	2,1	54,3	12,0
	a lower max	g	-	-	65,5	3,1	60,5	9,1
chest deflection	s rod max	mm	-	-	39,0 *	-	51,0	2,4
	s string upper max	mm	-	-	49,9	1,8	36,9	2,1
	s string mid max	mm	-	-	17,4	10,5	35,0	4,1
	s string lower max	mm	-	-	49,8	2,1	41,2	1,3
shoulder belt load	F max	kN	-	-	10,2	0,1	10,2	0,0
lap belt load	F max	kN	-	-	9,5	0,3	9,5	0,3
spine acceleration(T12)	a res 3ms	g	-	-	43,7	1,1	40,8	2,7

*** only one value available**

Table 4: Results of sled tests with Hybrid III dummies

4.3 Driver chest response

Good repeatability and very small deviations appeared in *test series 1* at the chest and lower sternum acceleration values of the driver.

In *test series 2* the driver chest loading was slightly higher than in the previous series because of the effect of simultaneous restraining forces of the belt and airbag.
As a result of the shoulder belt force on the driver dummy greater values were always measured at the upper sternum compared with the lower sternum.

With the rod potentiometer greater driver's chest deflections were always noticed than with the string potentiometers.

In *test series 1*, in line with the belt's pattern on the drivers chest, there were much greater values measured with the mid and upper string potentiometer, which are loaded by the shoulder belt. The difference "rod potentiometer - mid string potentiometer" was about 10 mm.

The driver's chest deflections in *test series 2* were more regular due to the additional airbag. The difference between the maximum value of the string potentiometer (upper) and the rod potentiometer was about 15 mm.

The behaviour of the driver's chest in *test series 3* was more complex compared to *test series 1 and 2*. The belt load influence was greater than in the second test series, because of the oblique forward motion of the driver and the smaller support of the airbag seen by the greater shoulder belt force. The difference between the maximum value of the string potentiometer (mid) and the rod potentiometer was about 10 mm.

In **Figures 7 -18** the chest deflection time histories of the four potentiometers are presented for the driver in all test configurations.

The magnitude of the curves for *test series 1* in **Figures 7 - 10** are very different, depending on the placement of the potentiometers. Time histories for all curves are similar. The maximum value is always reached nearly at the same time at about 80 ms. Although having a lower level, the mid string potentiometer curve fits best to the rod potentiometer measurement in this test series.

The greatest rod measurement occurs however in *test 1.1*, whereas for the mid string potentiometer the smallest result is noticed there.

In **Figures 11 -14** only few differences between the curves of *test series 2* are observed. Time histories are again very similar and with the maximum at about 80 ms. Also the rod potentiometer values are again greater than the string potentiometer measurements. As an effect of the airbag, the chest loading is regularly and all string potentiometer measurements are on about the same level.

In *test series 3* (**Figures 15 - 18**) the time histories differ more. All curves of *test 3.1* have a time shift of about 10 ms compared with both others tests. Because of the more flat and longer duration of the sled pulse the maximum occurs between 90 and 105 ms. The upper string potentiometer failed after 74 ms, when the signal cable was damaged. The mid string potentiometer curve fits best to the rod potentiometer's, although it is again smaller.

A quick overview of the relations between the chest deflection measurement with the standard rod potentiometer and the three string potentiometers is given by the mean time histories calculated from the single curves in each test series. For the driver they are shown in **Figures 19 - 21**.

In all test series the upper string potentiometer measurement is slightly earlier than the mid string and the rod potentiometer measurement. The last one is always the lower string potentiometer. Again the smaller differences are seen between the three string potentiometers in *test series 2* compared with *series 1 and 3* and also the later occuring maximum in *test series 3*.

4.4 Passenger chest response

As seen in **Table 4**, only one value measured with the standard rod potentiometer for the passenger's chest deflection was available in *test series 2* because of problems

5. Summary

The reason for seeking an alternative transducer to replace the standard rod potentiometer, stems from the actual use of the Hybrid III dummy in severe test situations, where the potentiometer has exhibited erratic or faulty behaviour.

Within the framework of the ACEA's evaluation program on Hybrid III dummy two chests were equipped with additional string potentiometers.These chests have been evaluated in static, pendulum and sled tests. The responses of the rod and string potentiometers were compared in these tests.

During the static and standard dynamic tests, the loadings to the chests have been moderate, and the standard rod potentiometer as well as the string potentiometers appeared to function without any obvious faults.

However in sled tests, some problems were observed: although the string potentiometers seemed to function well, the rod potentiometer apparently has failed in a few cases, due to disengagement of the rod from the groove in the sternum plate.

A general observation from all tests is, that the rod potentiometer in the large majority of cases shows a higher displacement than the one measured at the ends of the ribs. The difference is in the order of 10 mm. This is explained by the "hinge and lever effect", permitting the sternum plate to move progressively much closer to the spine than the ends of the ribs do.

During the static and pendulum tests with offset loadings, larger differences between the rod and the string potentiometer responses are readily observed.

6. Conclusions

The data obtained in this study support, as concerns reliability, the string potentiometer approach for chest deflection measurement on the Hybrid III dummy.

In none of the tests there were disconnections of the strings as were observed with the rod potentiometer (disengagement of the rod from the sternum plate).

It was impossible to compare in this study, in a direct manner, the rod potentiometer and a string potentiometer using the same installation (in the same chest) for obvious reasons.

Even attached to the ribs - with more variations in load transfer - the string potentiometers showed acceptable repeatability.

When the chest loading results from belt and airbag combination the chest deflection pattern is more regular than with a belt only restraint.

In order to solve the chest deflection issue on the Hybrid III dummy, ACEA, TF.D proposes to replace the standard (and unreliable) rod potentiometer by one string potentiometer, fitted inside the upper part of the spine. The string should be horizontal and its free end be attached to the sternum plate at about the level of the third rib.

with the measurement equipment. Even that value appears unreliable as explained below.The string potentiometers showed more deflection on the left side of the sternum (upper and lower) than on the right side (mid). The maximum value measured with the rod potentiometer was here 11 mm smaller than that one measured with the string potentiometers (upper and lower).

Due to the oblique impact situation the chest in *test series 3* was more regularly deformed. The string potentiometers measured maximum deflections between 35 - 41 mm. Measurement with the rod potentiometer resulted in an about 10 mm greater value.

In **Figures 22 - 29** the chest deflection versus time curves of the four potentiometers are presented for the passenger in all test configurations.

Only one curve from the rod potentiometer is available in *test series 2* (**Figures 22 - 25**). In *test 2.1* the shape of the rod potentiometer response indicates a malfunction, possibly caused by rod disengagement at about 60 - 70 ms. In *test 2.2* the signal cable was damaged, in *test 2.3* a problem in the measuring module occurred. After *test 2.3* it was noticed that the rod was disengaged from the groove in the sternum front plate!

Time histories of the upper and lower string potentiometers differ only slightly, but for the mid string potentiometer very much. The maximum is at about 75 - 80 ms for all curves. The upper and lower string potentiometer's curve fits best to the rod potentiometer's. In this test series the greatest values are not measured at the rod, but at the upper and lower string potentiometer.

In *test series 3* (**Figures 26 - 29**) the same time shift of 10 ms as at the driver's side occurred in *test 3.2* with all potentiometers. The other deviations in the time histories were not significant. The maximum for all curves was between 90 and 100 ms.

A problem in the measuring module after 65 ms was noticed in *test 3.3* at the lower string potentiometer. The curve of the lower string potentiometer fits best to the rod potentiometer measurement, but is again smaller.

For a quick overview **Figures 30** and **31** show the mean time histories of the passenger's chest deflection, measured with the standard rod potentiometer and the added three string potentiometers. These mean curves were calculated from the single curves in each test series.

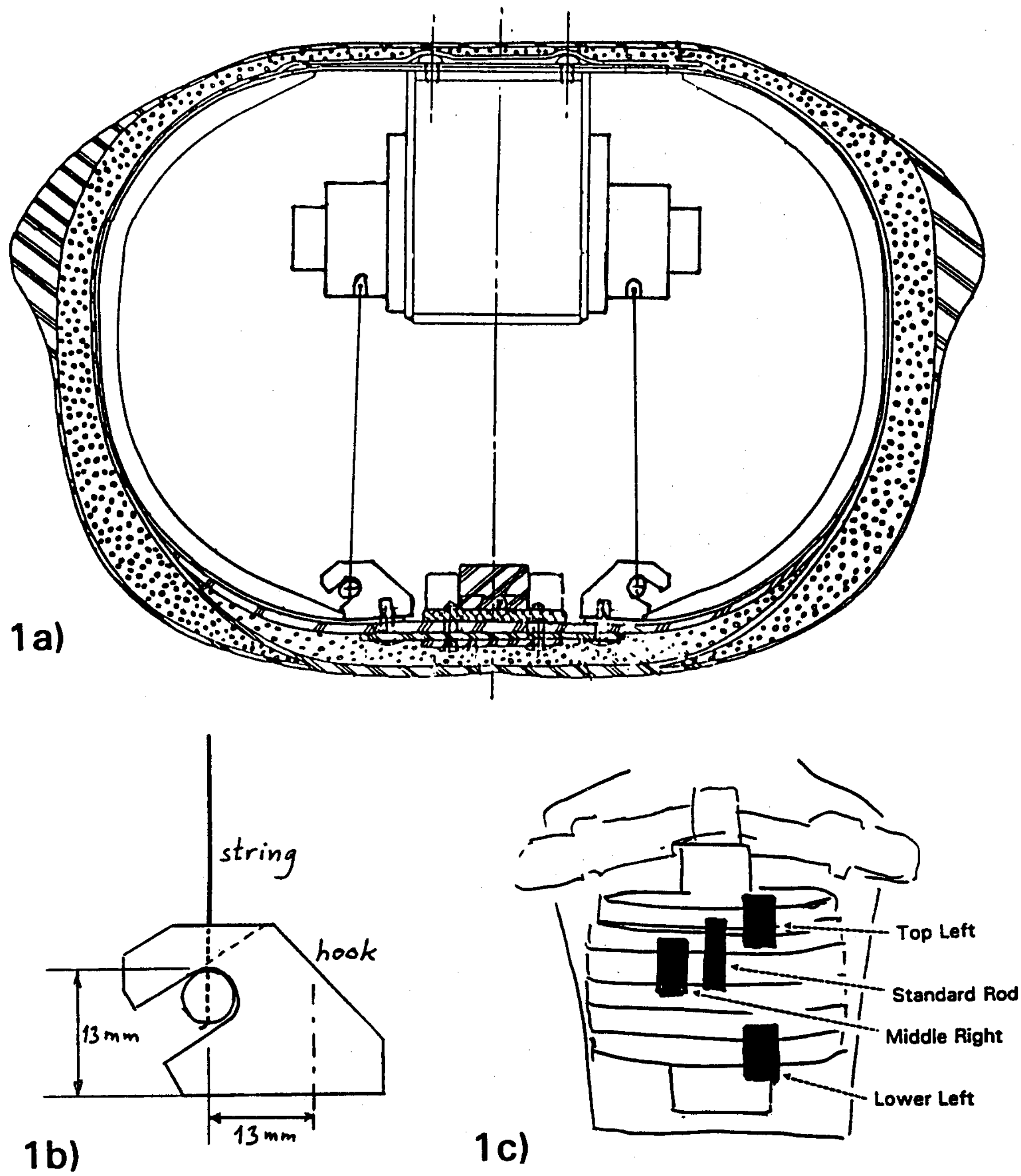
In *test series 2* the rod potentiometer measured a smaller deflection than the upper and lower string potentiometer.

As result of the later maximum of the sled pulse in *test series 3* also the passenger's maximum chest deflection occurred later.

References:

[1] ACEA Working Document: Hybrid III Experiences, Mai 1992, WG.D/11/92, ISO/TC22/SC12/WG5 , Doc. N341

[2] Draft Report 27th Meeting, December 1992, ISO/TC/SC12/WG5, Doc. N357

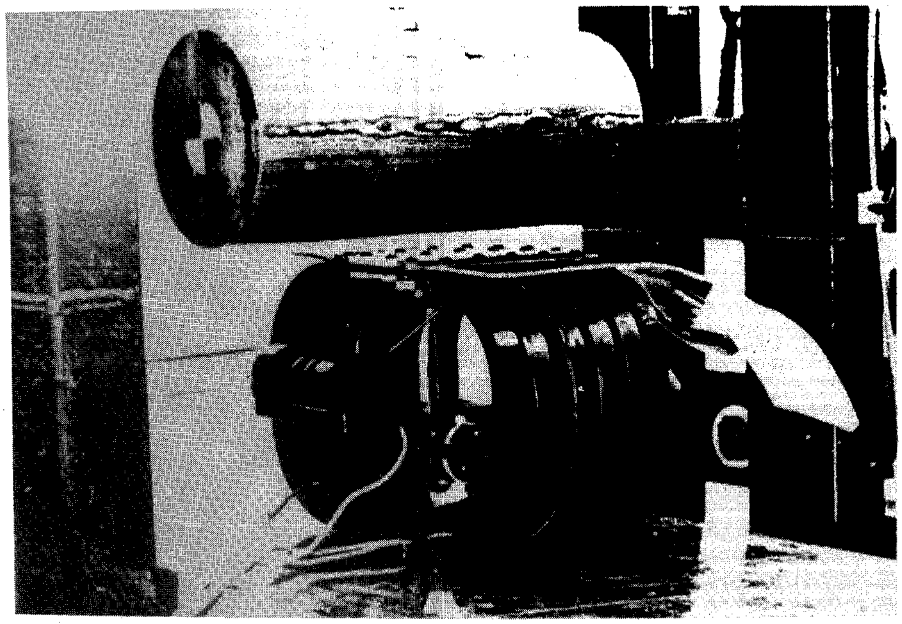


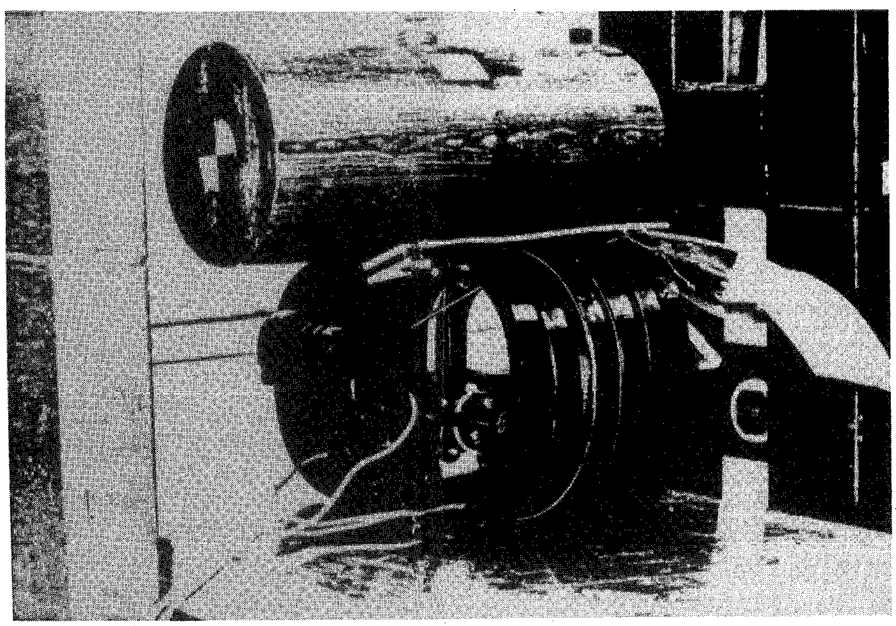
1 a) Top view of chest and potentiometers

1 b) Detail view of the hook connecting the string wire to the end of the rib. The hook is fastened to the rib at the existing hole at the end of the rib.

1 c) Frontal view of the locations and designations of the displacement transducers. The strings were attached to ribs number 1, 3 and 6 counted from the top.

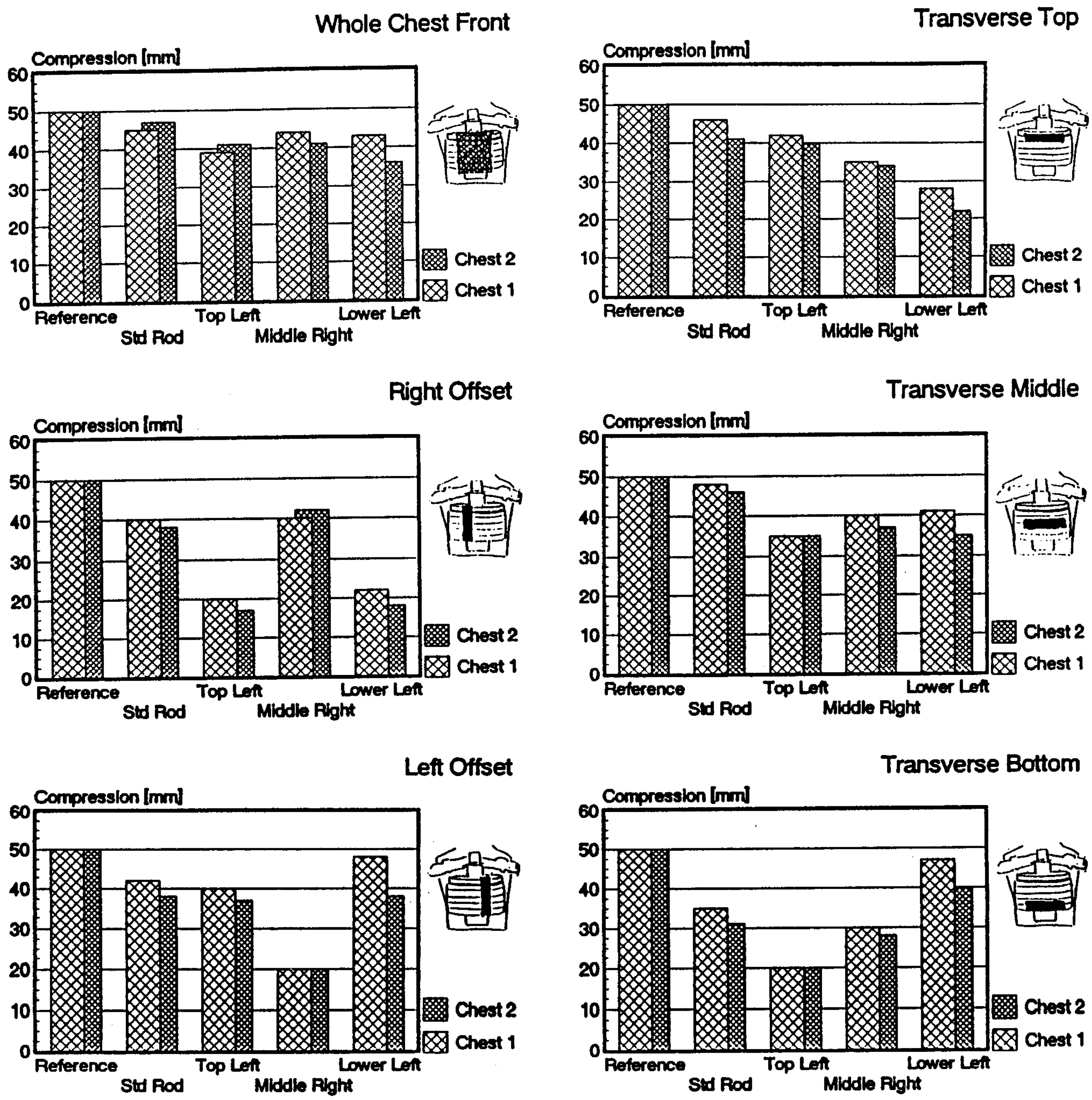
Figure 1: Installation of the string potentiometers





The bottom picture shows how the horizontal cylinder compresses the right side of the chest leaving the left side little deformed.

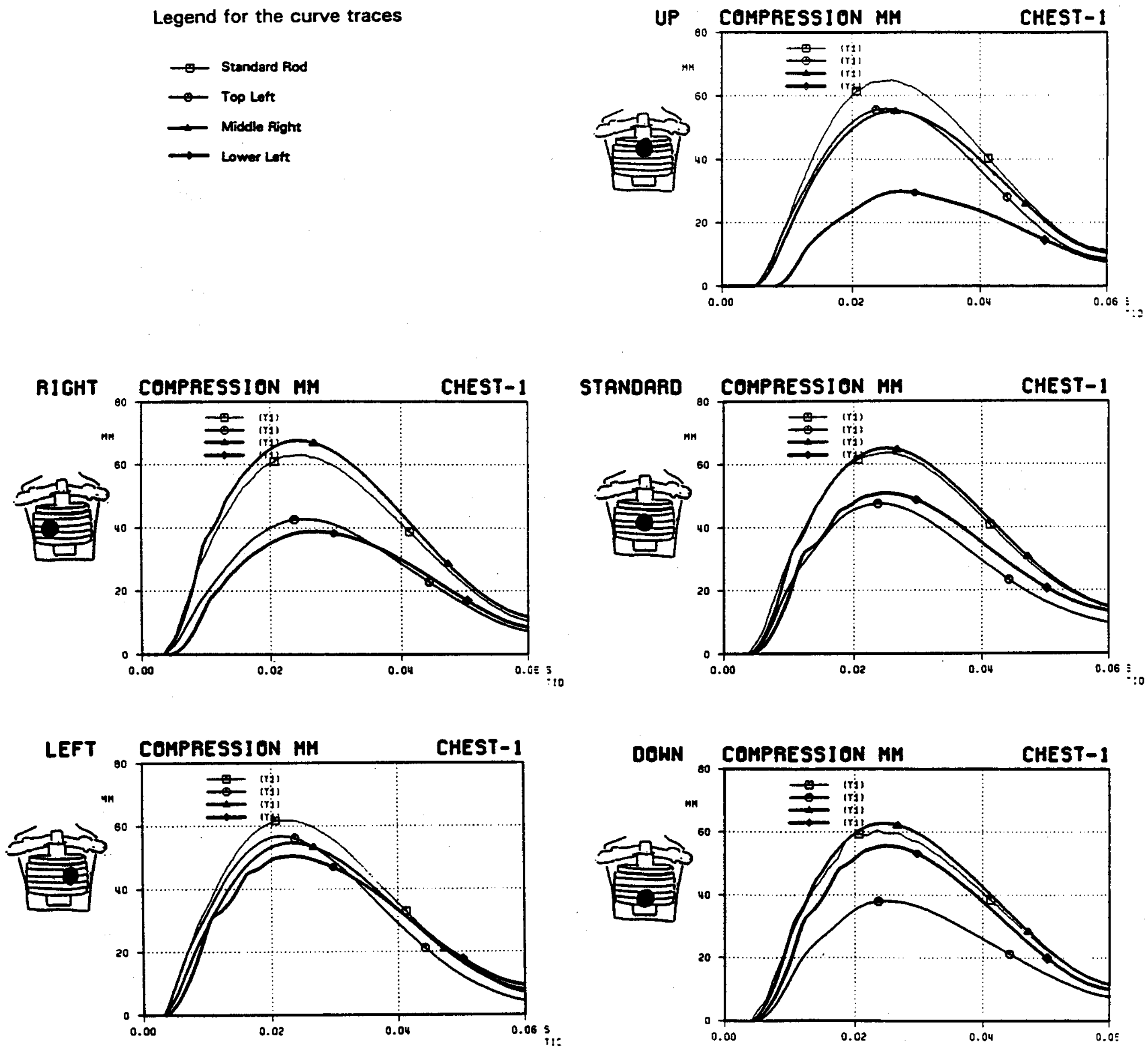
Figure 2: Static compression test



The diagrams show the recorded compressions for the different transducers and the different loading cases.

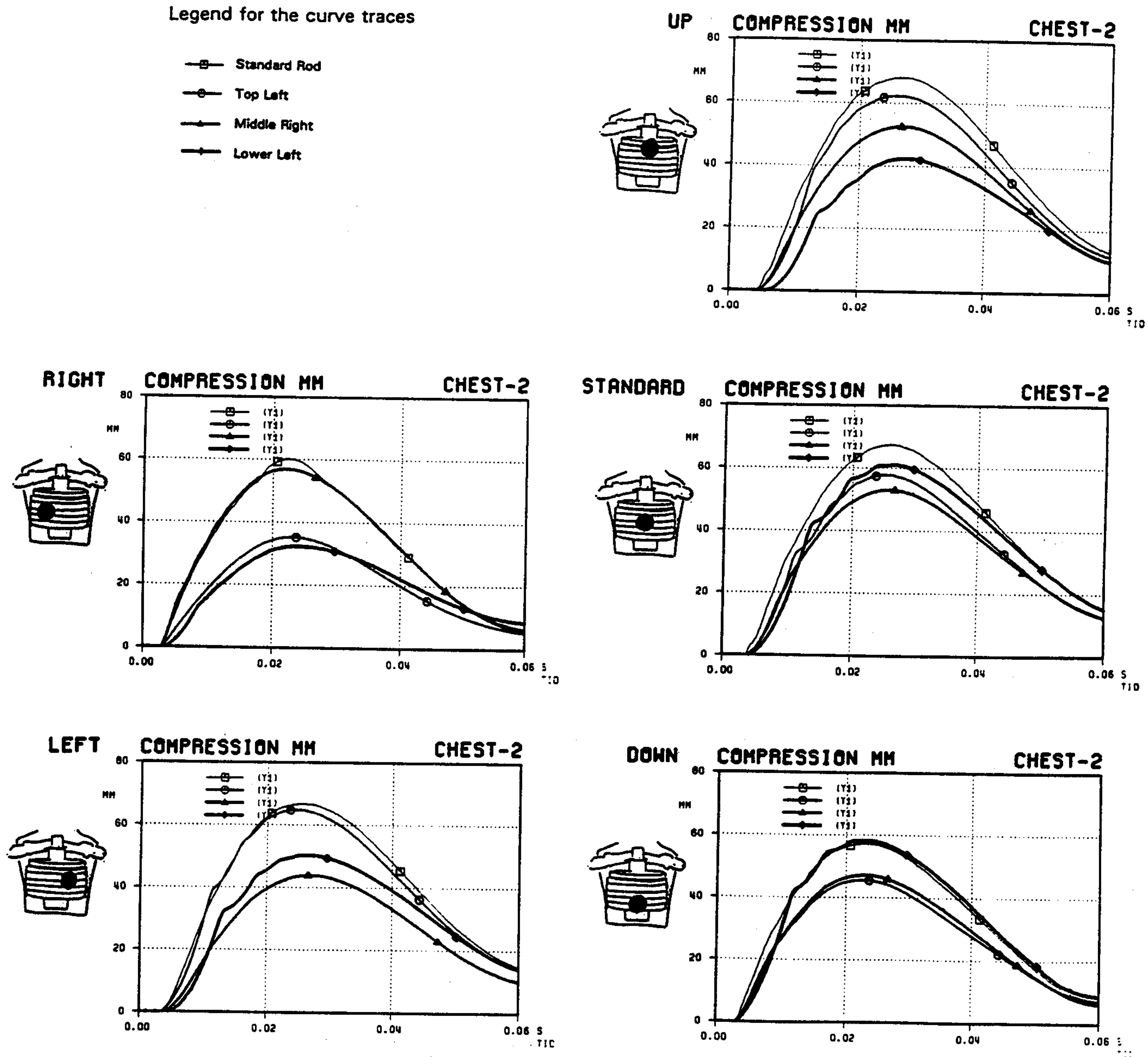
See **Figure 1** for locations and designations. A reference transducer was installed on the compression rig. It measured the actual travel of the loading cylinder.

Figure 3: Results of static compression tests



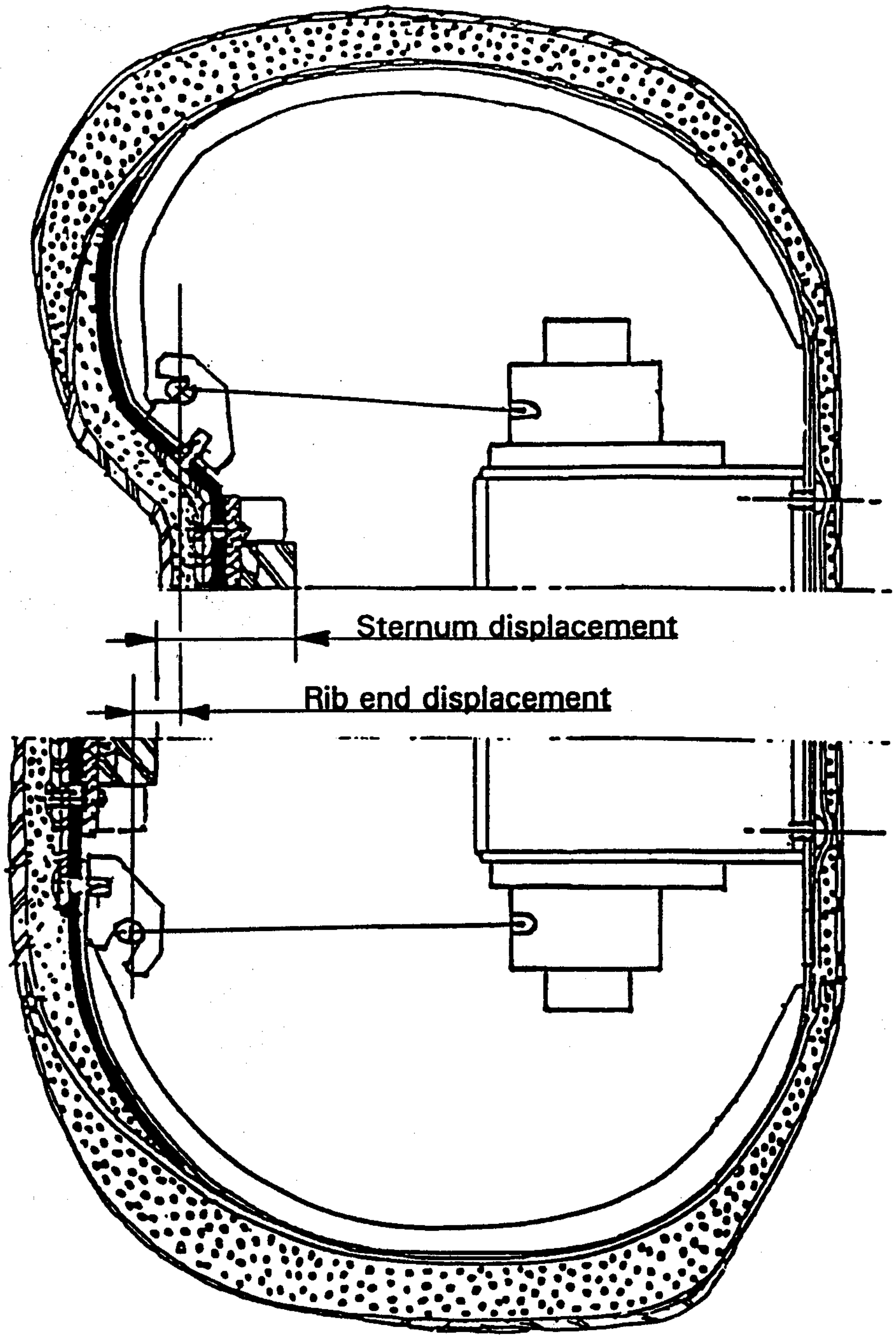
Each diagram shows the four recorded compressions in each loading case as indicated.

Figure 4: Results of dynamic tests on chest No.1



Each diagram shows the four recorded compressions in each loading case as indicated.

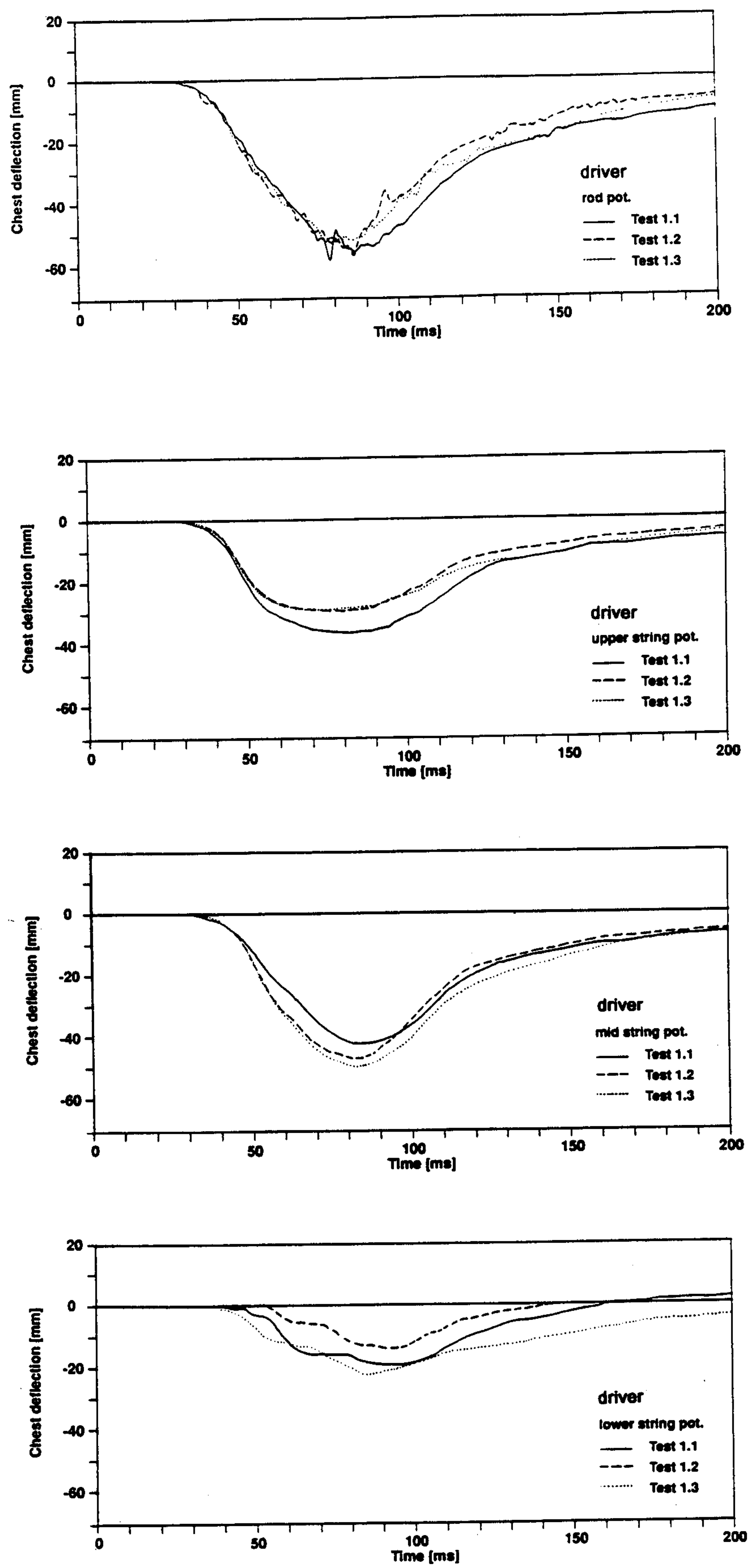
Figure 5: Results of dynamic test on chest No.2



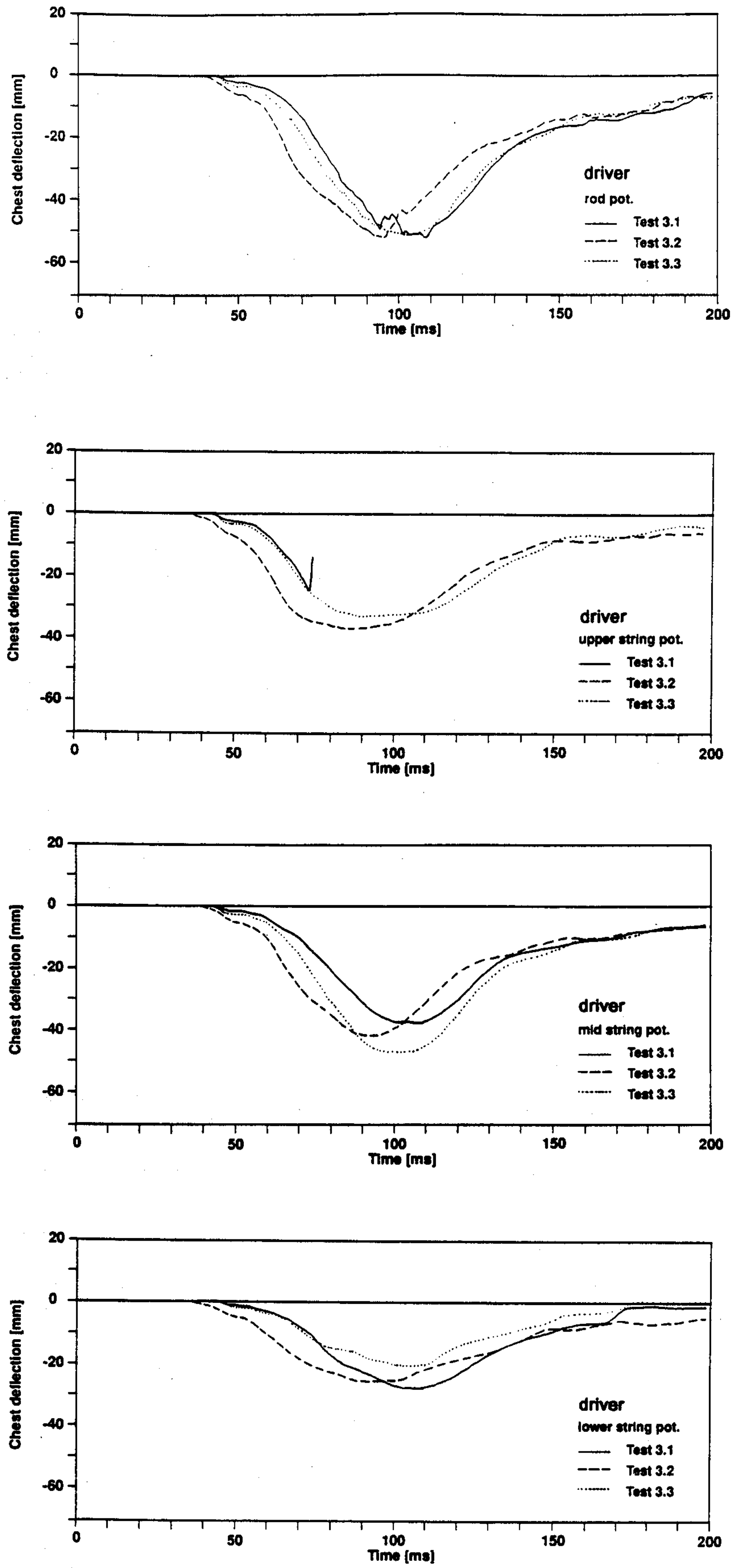
The drawing intends to illustrate how a "hinge and lever" action of the bib permits the rib ends to "dip inward" and let the sternum plate move progressively much closer to the spine than the actual rib movement would indicate. The effect may be generated by the comparatively soft urethane bib joining the rib ends and the sternum plate.

The urethane bib is seen as the thick black line in the drawing.

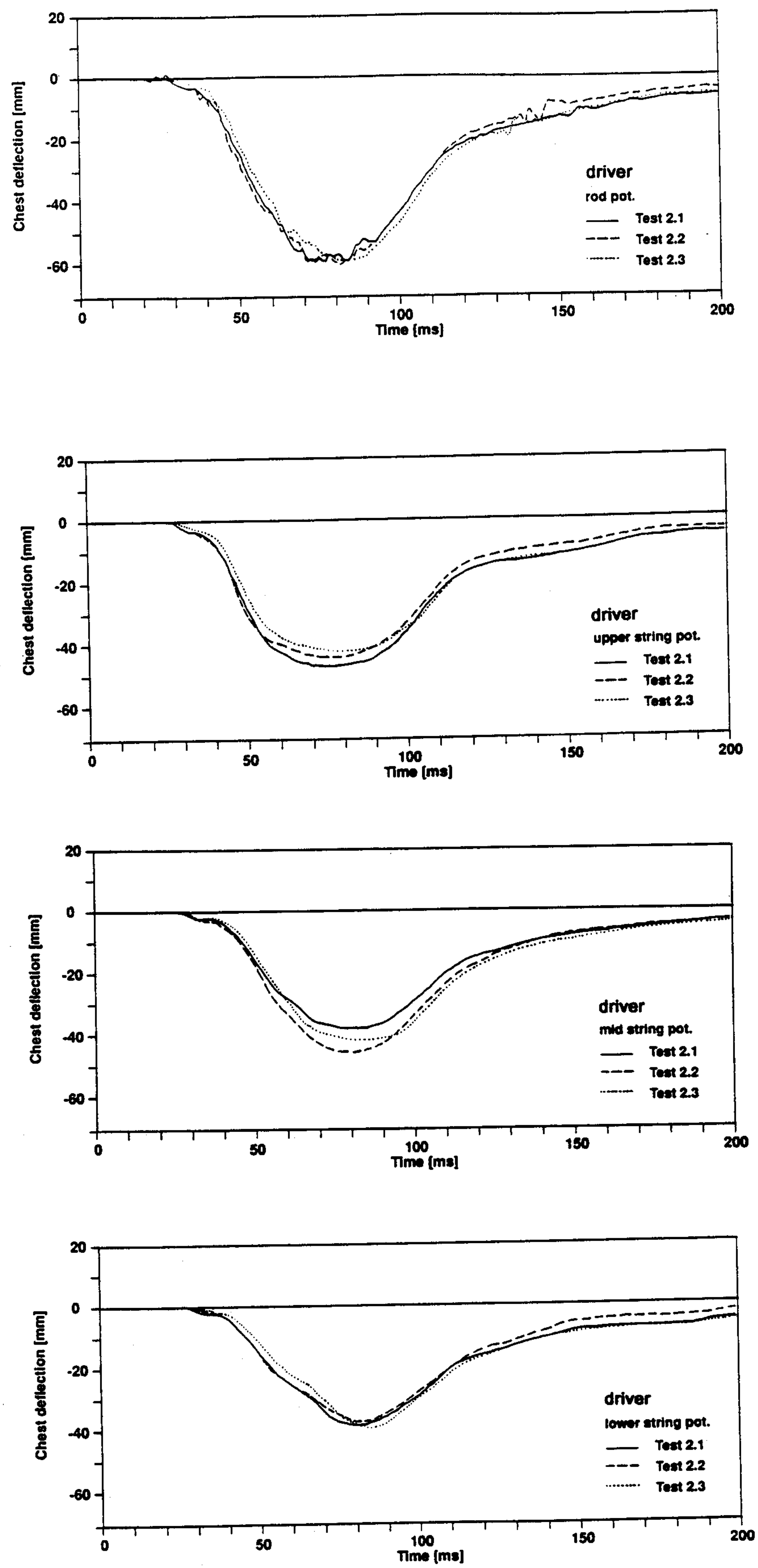
Figure 6: Discrepancy between sternum and rib movement



Figures 7 - 10: Driver chest deflection in test series 1



Figures 15 - 18: Driver chest deflection in test series 3



Figures 11 - 14: Driver chest deflection in test series 2

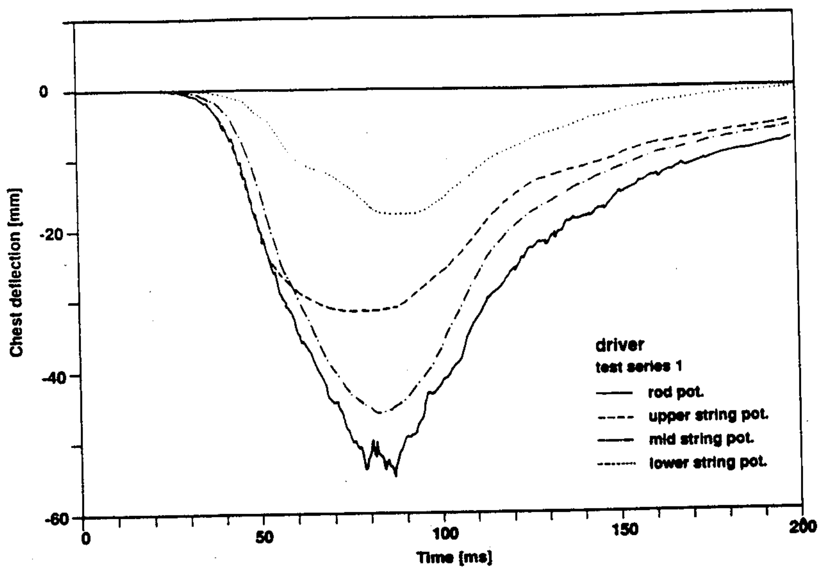


Figure 19: Driver chest deflection mean curves of test series 1

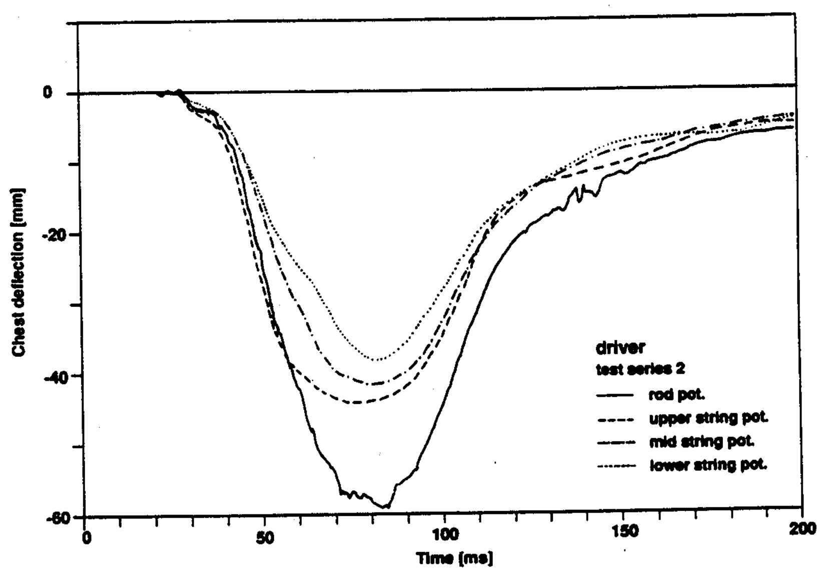


Figure 20: Driver chest deflection mean curves of test series 2

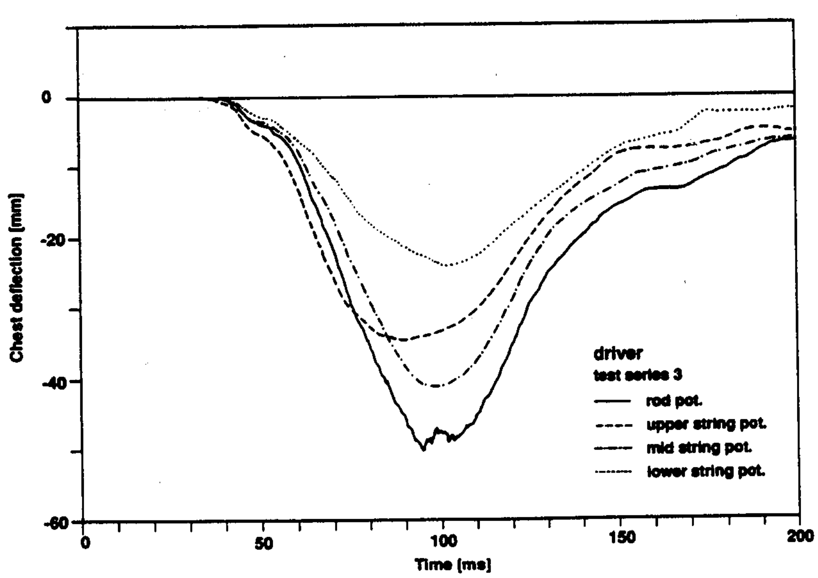
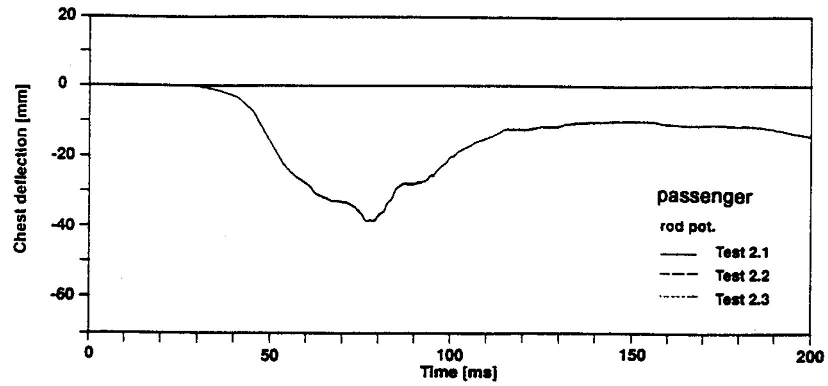
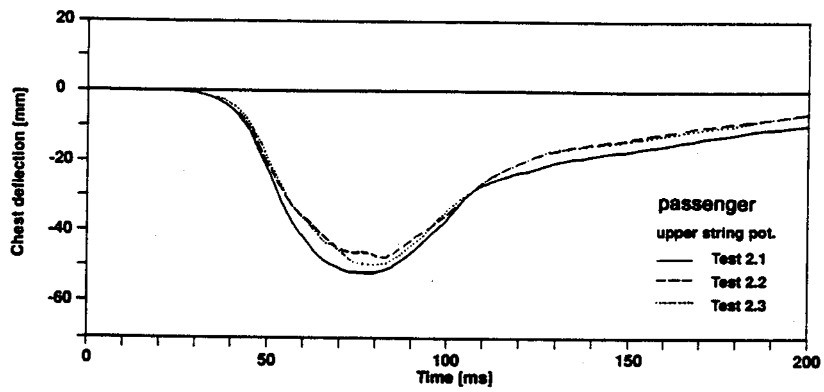
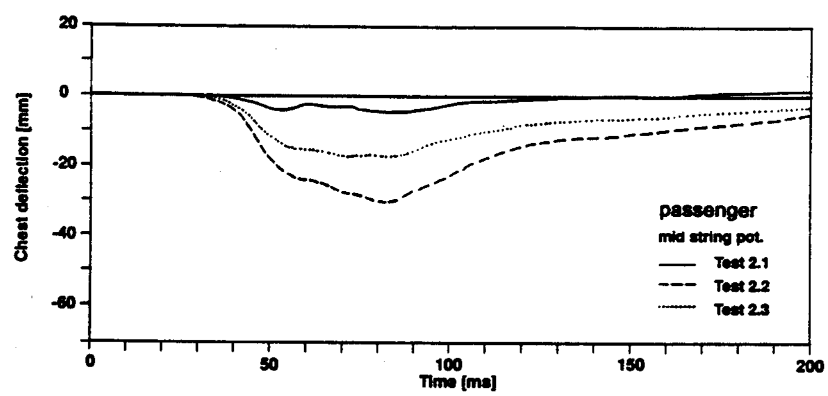
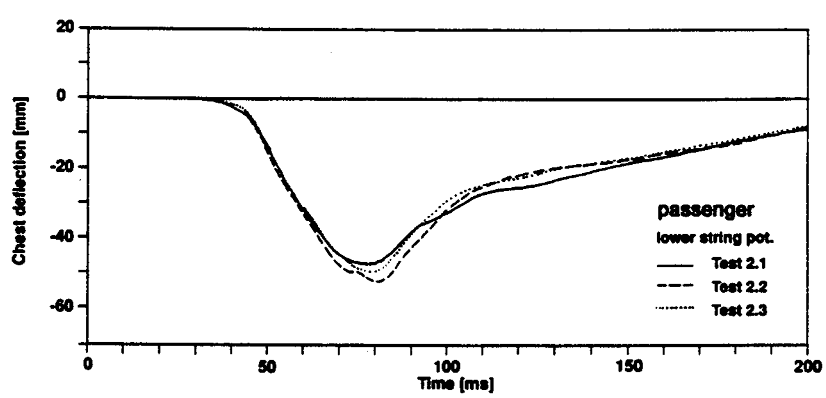


Figure 21: Driver chest deflection mean curves of test series 3

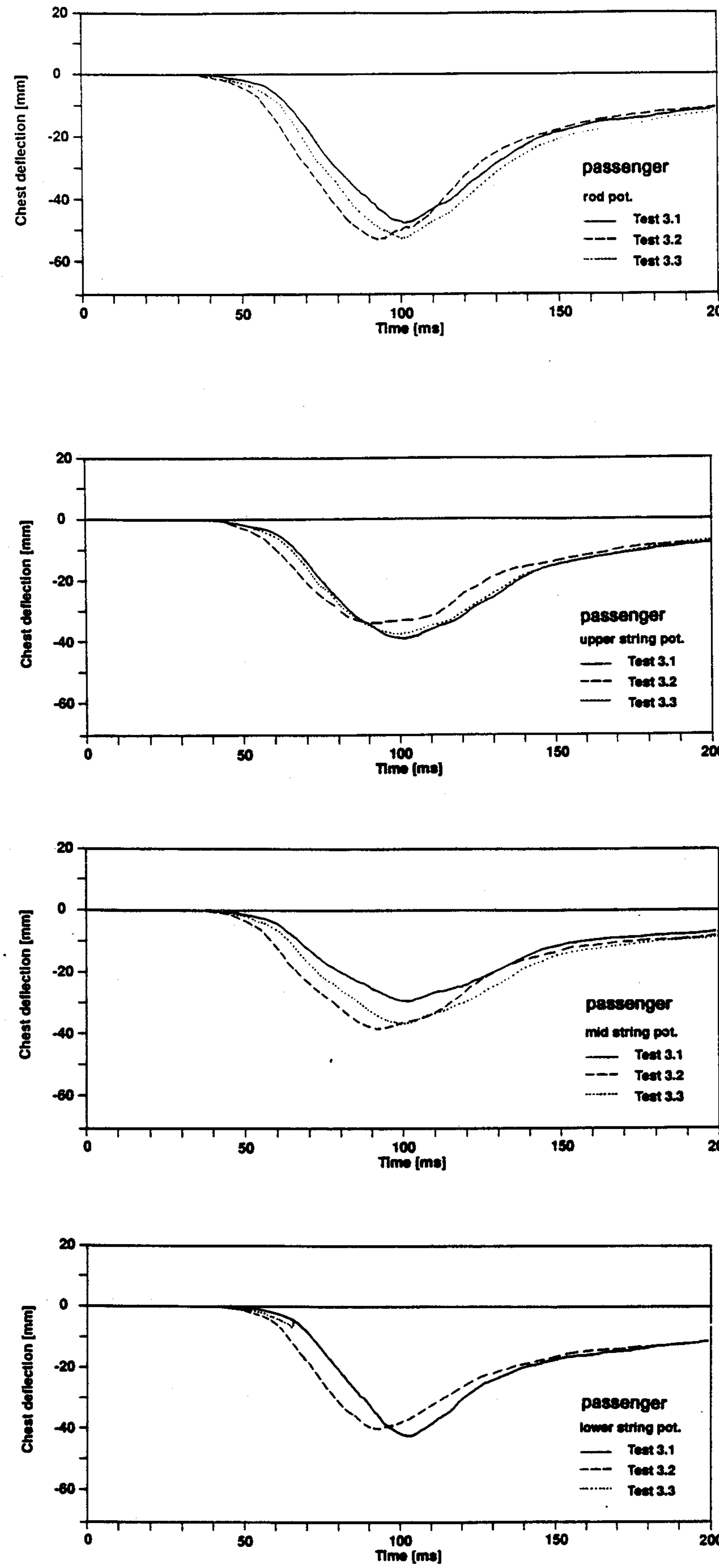








Figures 22 - 25: Passenger chest deflection in test series 2



Figures 26 - 29: Passenger chest deflection in test series 3

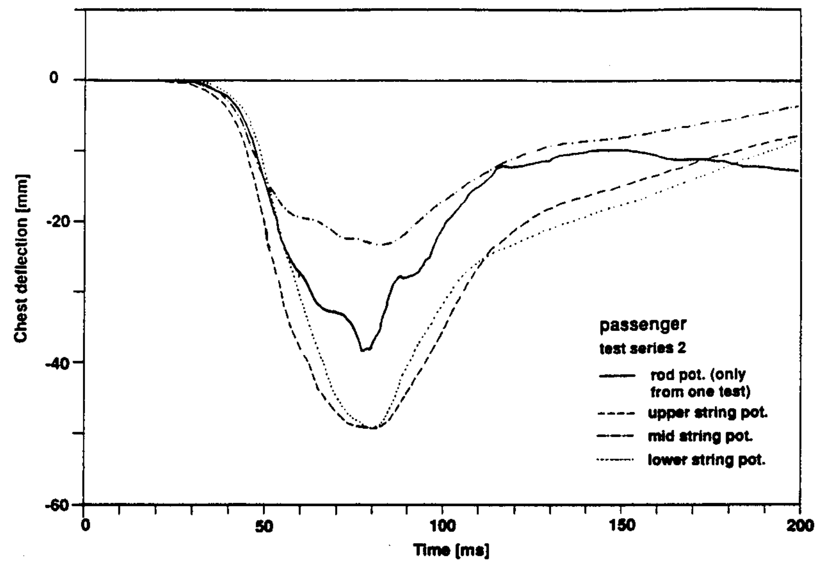


Figure 30: Passenger chest deflection mean curves of test series 2

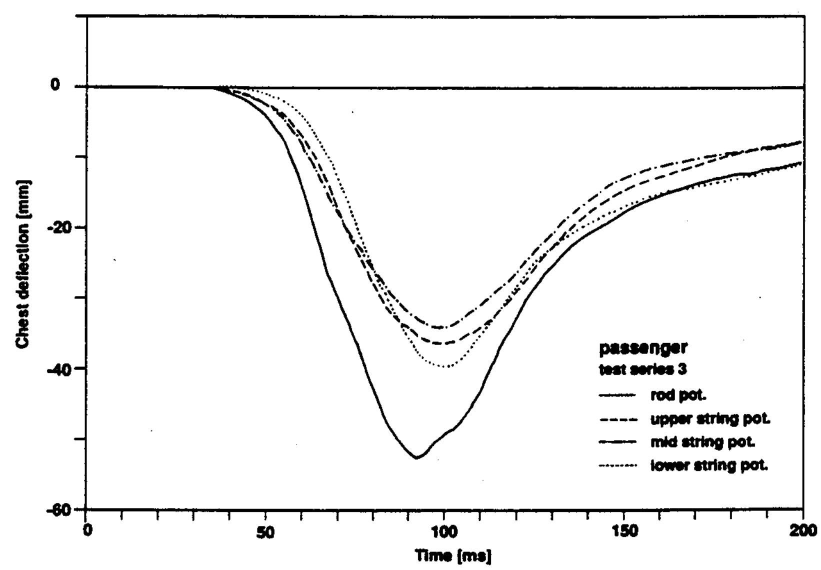


Figure 31: Passenger chest deflection mean curves of test series 3

ANNEX

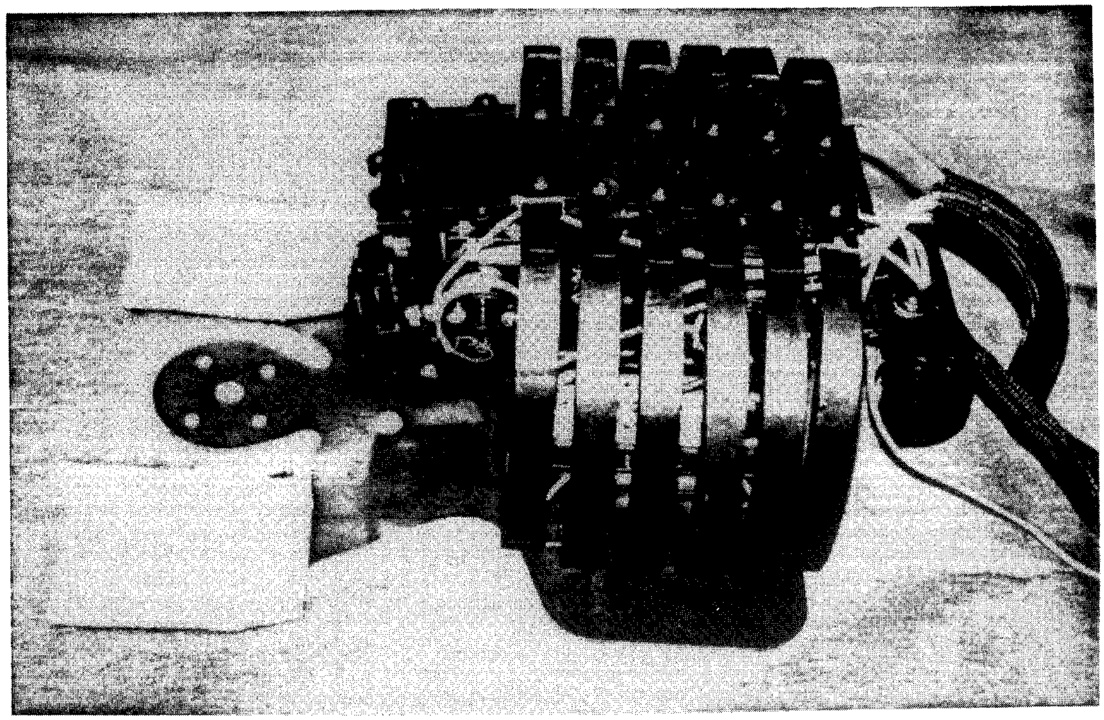


Figure A1: Modified H III chest, left rear view

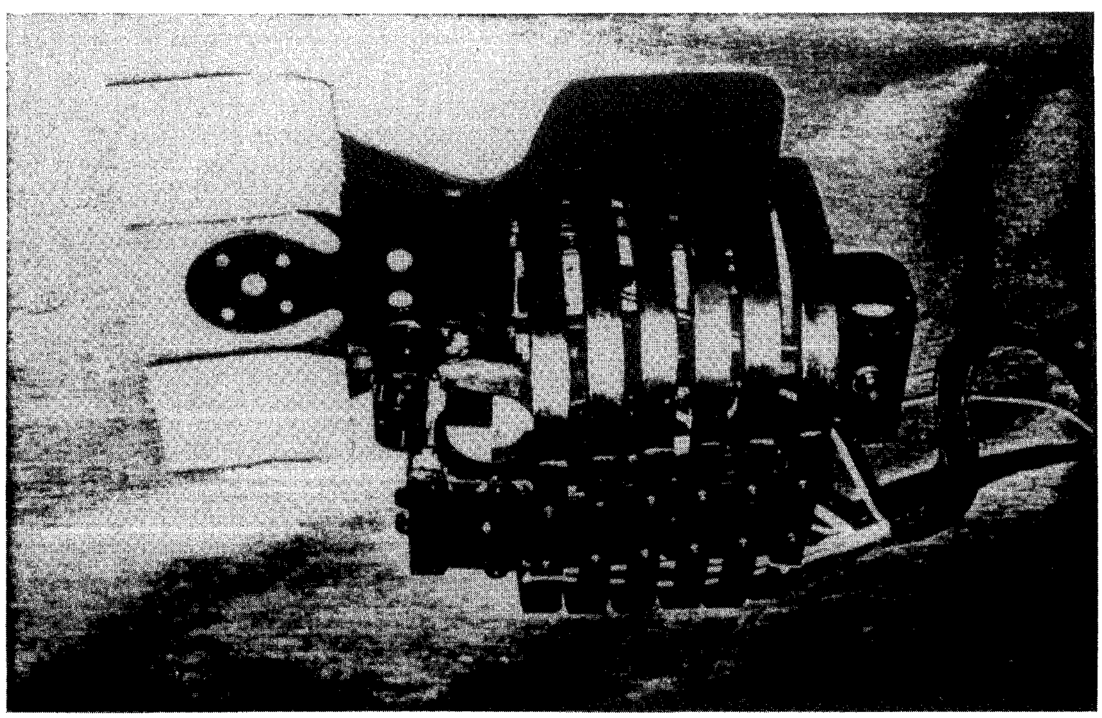


Figure A2: Modified H III chest, right rear view

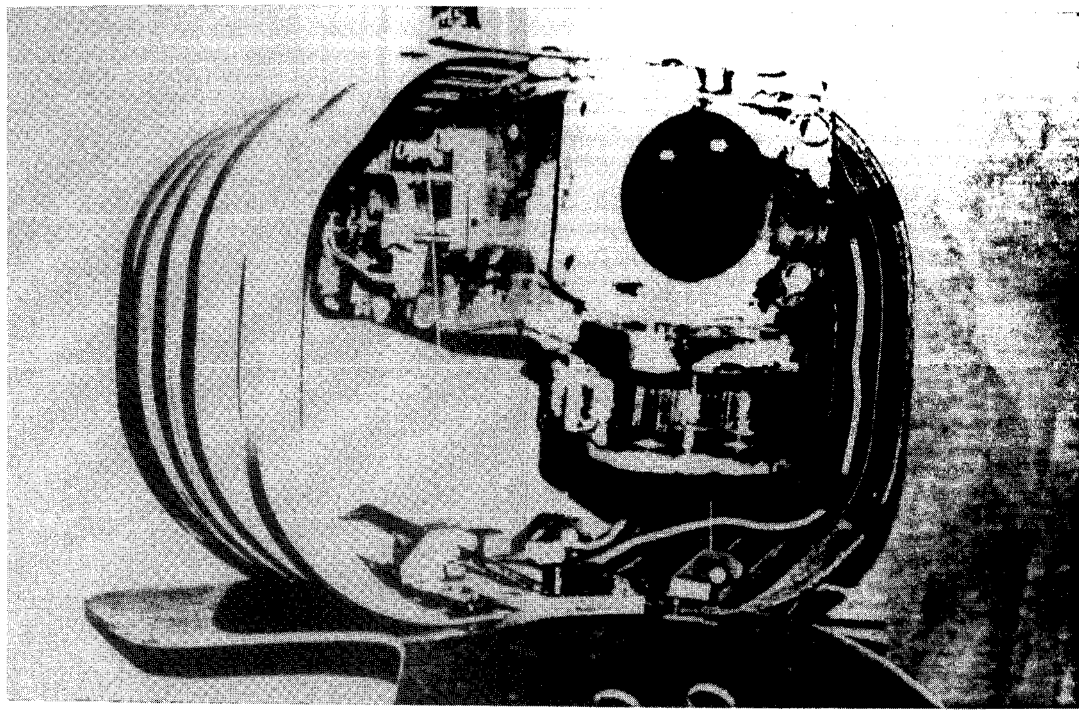


Figure A3: Modified H III chest, right top view

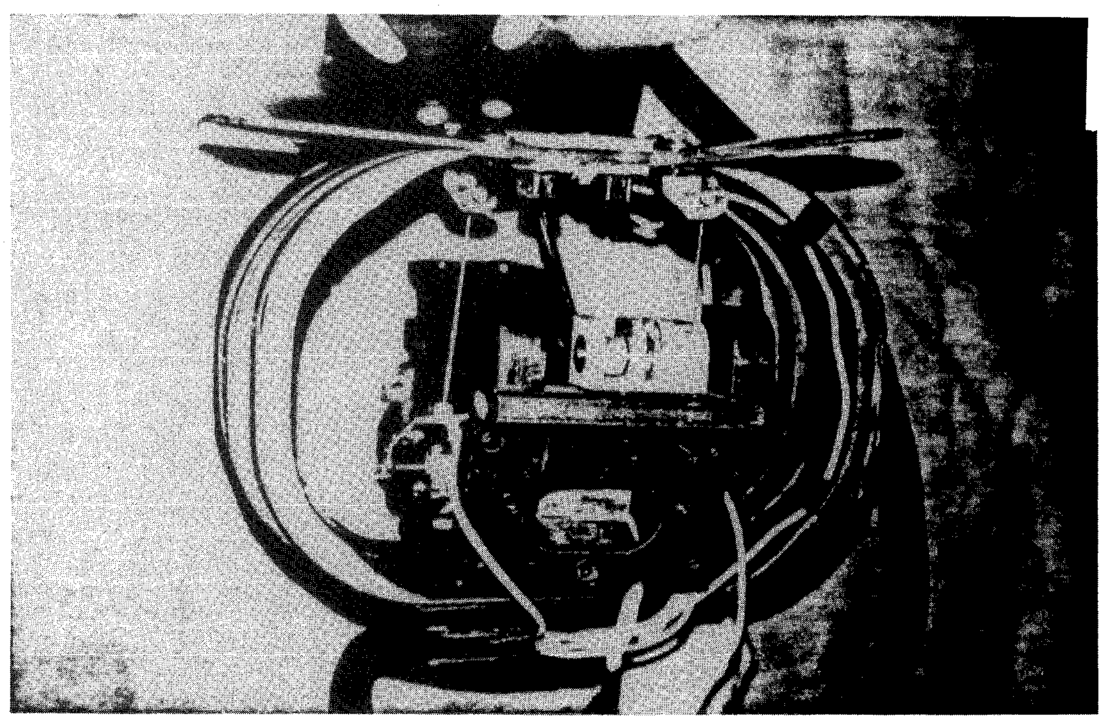


Figure A4: Modified H III chest, right bottom view

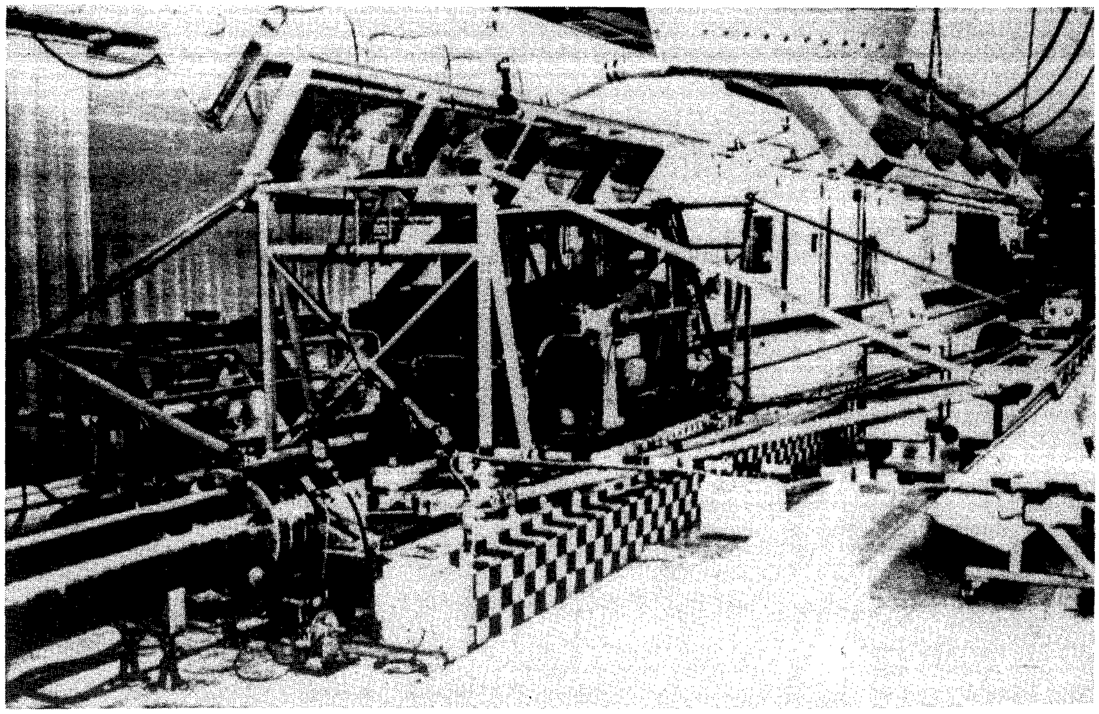


Figure A5: Opel Astra passenger compartment on Porsche Hyge Sled

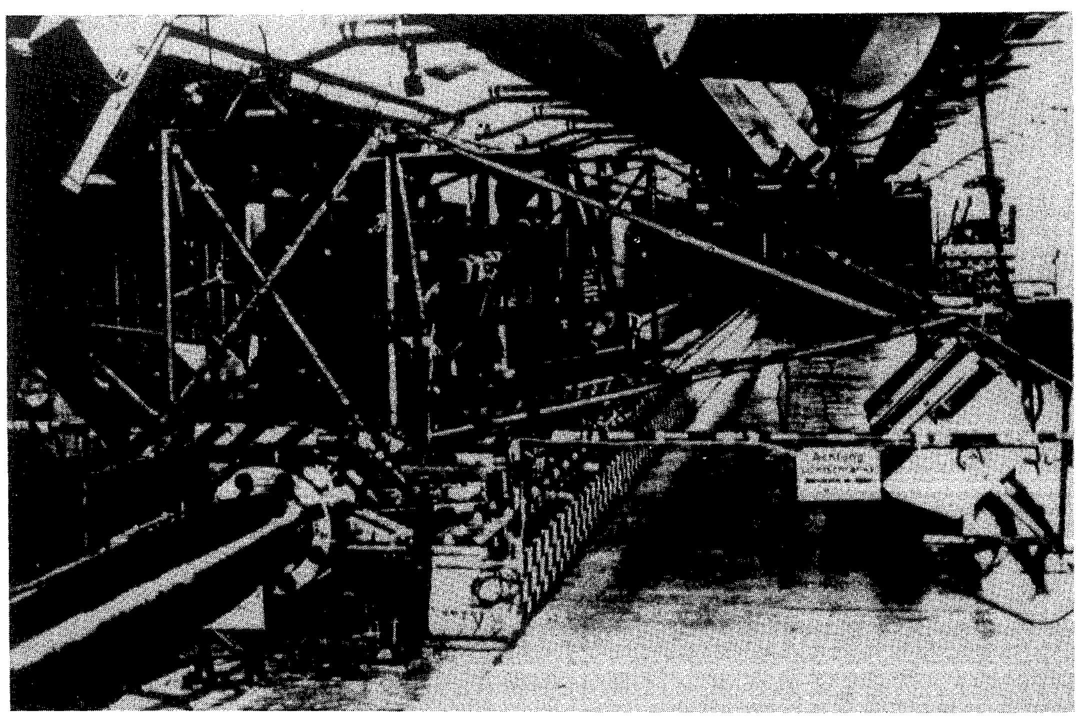


Figure A6: Oblique test set-up with Opel Astra in test series 3

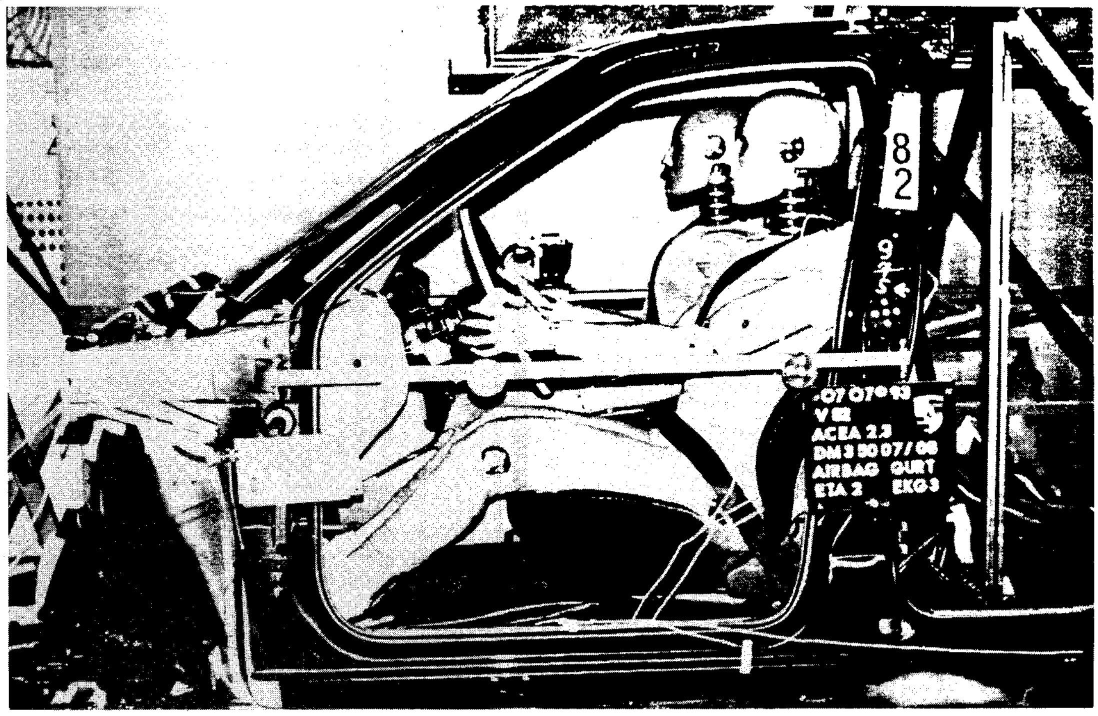


Figure A7: Dummy position before test (test series 2)

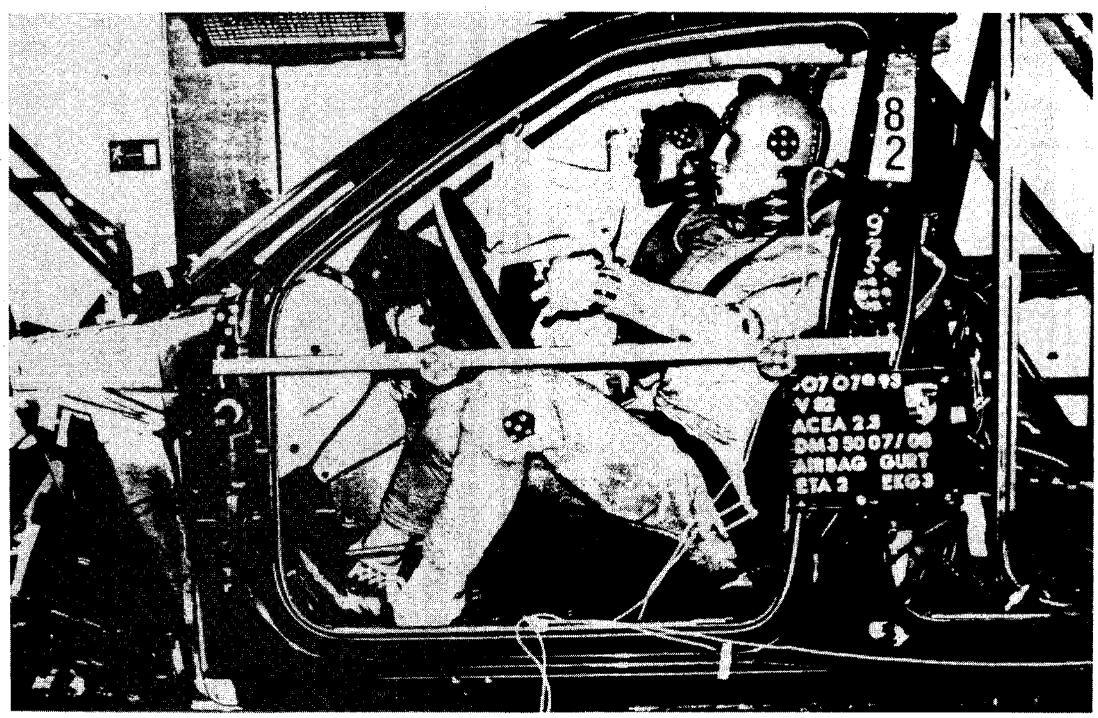


Figure A8: Dummy position after test (test series 2)

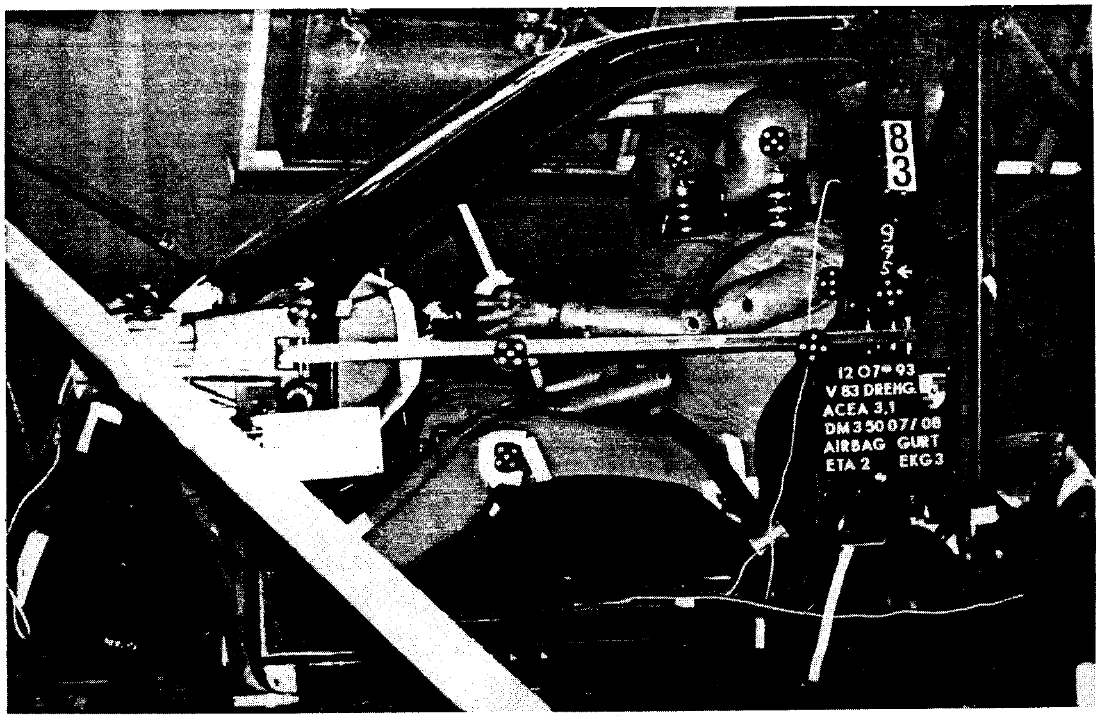


Figure A9: Dummy position before test (test series 3)

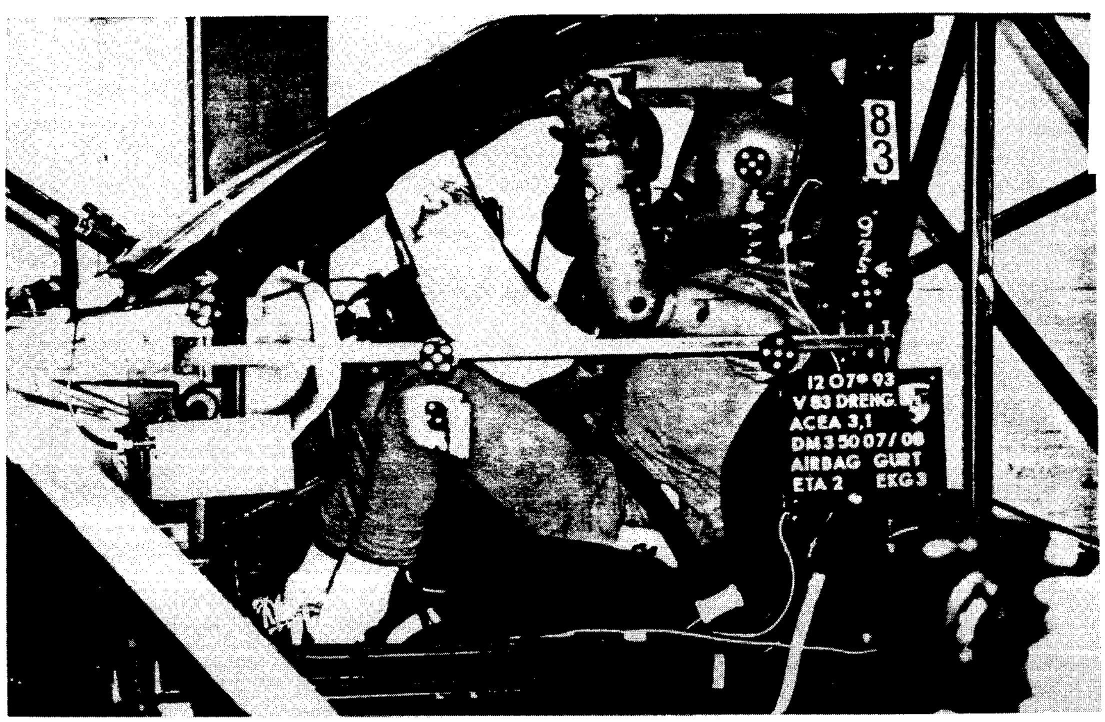


Figure A10: Dummy position after test (test series 3)

A Finite Element Model of the Pedestrian Leg in Lateral Impact

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INRETS, Institut National de Recherche sur les Transports et leur Securité
France
Paper N° 94-S1-O-15

ABSTRACT

In car/pedestrian accident mathematical simulations, it is desirable to extend existing rigid body human model towards deformable finite element models. Thereby a wider range of front car structure/pedestrian interactions can be covered. Even though some injuries to pedestrian are due to contact with the ground, research concerning the severity of injuries due to the car contact, related to the bumper and the bonnet height and stiffness, and to the speed of the vehicle, are being carried out.

In a previous study a finite element model of the pedestrian knee-joint in lateral impact was expanded. This paper presents a modelling of a human leg in lateral impact for use in an explicit finite element code. The articulation between each condyle of the femur and the corresponding tuberosity of the tibia is mainly described. The bones entering into the formation of the knee-joint are the condyles of the femur above, the head of the tibia below. The bones are connected together by ligaments, some of which are placed on the exterior (e. g. ; lateral and medial collateral...) of the joint, while others occupy its interior (e. g. ; anterior and posterior crucial...).

This model will be impacted to estimate the severity of leg lesions and to predict the risk of leg injuries in car/pedestrian accidents. The effect of the impactor stiffness, velocity and height will be evaluated.

Experimental results from static tests and impact tests, to characterise the mechanical behaviour of each part, like the ligaments or the bones, and the whole kinematics of the knee, serve as a basis for the validation of the model.

INTRODUCTION

In this paper, statistical analyses for pedestrians accidents, the description of the car/pedestrian accidents, an overview of the functional anatomy of the lower limb, the main car/pedestrian leg injuries and the majority crash simulation are showed. Then the methodology for the modelling, the validation of the human leg model and results are presented. The code used for the mathematical simulations is the three dimensional non-linear explicit Finite Element code PAM-CRASH developed by ESI (Engineering Systems International S.A., France).

Statistical analyses for pedestrians accidents

Every year thousands of pedestrians are killed or injured in road traffic accidents in the world. The number of people injured in Europe, USA and Japan decreased from 33,000 in 1970 to 18,000 in 1986 (Vallée et al, 1989). Since then, the number of pedestrian fatalities in traffic accidents has been almost stable. 500 pedestrians fatalities (Retting, 1993) occurred annually in crashes that involved trucks during the period from 1986 to 1990 in the USA.

The number of killed pedestrians compared to the total number of killed road users varied from 13 percent in the Netherlands (EEVC/CEVE, 1982) to 15 percent in the USA, to 18 percent in Europe (Vallée et al, 1989), to 30 percent in Japan (Ishikawa et al, 1991) and 45 percent in Dehli in India (Sarin et al, 1990). The percentage of pedestrians killed in all road accidents is higher in less motorised countries than in highly motorised countries (Malini et al, 1990). 35-45 percent of all road accident casualties were pedestrians in the less motorised countries, and these accidents were particularly common in the urban areas.

Two main age groups are significantly represented in Europe (Vallée et al, 1989) :

- children under 16 whose percentage as compared to the number of pedestrians killed decreased from 21 percent in 1976 to 15 percent in 1986,
- adults over 64 whose percentage increased from 13 percent to 14 percent for the same period.

In France each year, 7500 children are injured among which 1800 are seriously injured and 120 are killed (MAIF, 1994). Half of those accidents happened on the way home/school.

Description of the car/pedestrian accident

Pedestrians often cross a street in a more or less perpendicular direction when they are hit from the side by the front structure of a car.

Car/pedestrian accident could be described firstly by the impacts against the front of the car, bumper and the bonnet edge for the lower body region, mainly for the leg ; secondly the impacts against the bonnet or the windscreen for the head. Finally there is the contact with the ground for the whole body.

The shape of the front of the car has an influence on the pedestrian kinematics, not only on its trajectory but also on the velocity of each body segment. The kinematics of a pedestrian is a major factor in determining the location, the occurrence of contacts between the different body segments against a vehicle, the ground (Grösch, 1989), and also the impact velocity of these contacts (EEVC, 1982).

Car/pedestrian accident assumptions

Then some years ago INRETS decided to go further and try to understand the question of pedestrian and leg injuries. A program has been started with different cars, impacting cadavers and dummies. This program has proceeded step by step. The first step was a full scale cadaver test in which the deformation of the leg at the time of the impact was observed from high speed films. What was interesting was that when this deformation of the leg occurred around the front of the car, the upper part of the body, which was free and not suspended at that time, did not move. It moved later. So the leg injuries can be considered quite separately from those to other body parts.

Also, due to the complexity of car/pedestrian accident description, in this paper we focus only on the first part of the car/pedestrian accident which is the contact between the front of the car and the pedestrian leg.

Functional anatomy of the leg (Gray, 1977)

<u>Leg Bones</u> -The skeleton of the leg (lower limb) consists mainly of two parts : the upper leg (thigh) and the lower leg.

The thigh is that portion of the lower extremity which is situated between the pelvis and the knee.

The femur is the longest, and strongest bone in the skeleton, and almost perfectly cylindrical in the greater part of its extent. The femur is divisible into a shaft and two extremities. The shaft of the femur is a cylinder of compact tissue, hollowed by a large medullary canal. The cylinder is of great thickness and density in the middle third of the shaft, where the bone is narrowest and the medullary canal well formed ; but above and below this the cylinder gradually becomes thinner, owing to a separation of the layers of the bone into cancelli, which project into the medullary canal and finally obliterate it, so that the upper and lower ends of the shaft, and the articular extremities more especially, consist of cancelled tissue invested by a thin, compact layer.

The skeleton of the lower leg consists of three bones : the patella, the tibia and the fibula.

The patella is a flat triangular bone, situated at the anterior part of the knee-joint.

The tibia is situated at the front and inner side of the leg, and, excepting the femur, is the longest and largest bone in the skeleton. It is prismoid in form, expanded above, where it enters into the knee-joint, more slightly enlarged below. It presents a shaft and two extremities and its structure is like that of the femur.

The fibula is situated at the outer side of the leg. It is the smaller of the two bones of the lower leg, and, in proportion to its length, the most slender of all the long bones : it is placed on the outer side of the tibia, with which it is connected above and below. Its upper extremity is small, placed toward the back of the head of the tibia and below the level of the knee-joint, and excluded from its formation : the lower extremity inclines a little forward, so as to be on a plane anterior to that of the upper end, projects below the tibia, and forms the outer ankle. Is also presents a shaft and two extremities and its structure is like of the femur.

Knee joint - The knee-joint must be regarded as consisting of three articulations in one : one between each condyle of the femur and the corresponding tuberosity of the tibia, and one between the patella and the femur.

The bones entering into the formation of the knee-joint are the condyles of the femur above, the head of the tibia below. The bones are connected together by ligaments, some which are placed on the exterior of the joint, while others occupy its interior.

The main ligaments in the knee joint are : the External Ligaments are the Lateral Collateral Ligament and the Medial Collateral Ligament ; which are stressed when the leg is stretched and relaxed when the knee is flexed ; the Interior ligaments are the Anterior Crucial Ligament and the Posterior Crucial Ligament ; which are always stressed.

Muscles - The main muscles around the knee-joint are : in front and at the sides, the Quadriceps extensor ; on the outer side, the tendons of the Biceps and the Popliteus ; on the inner side, the Sartorius, Gracilis, Semitendinosus and Semimembranosus ; behind, an expansion from the tendon of the Semimembranosus.

Meniscus - The meniscus are two crescentic lamellae which serve to deepen the surface of the head of the tibia, for articulation with the condyles of the femur. The circumference of each cartilage is thick, convex, and attached to inside the capsule of the knee.

Car/pedestrian lower limb injuries

In car/pedestrian accident, injuries are caused by the impacts against the front of the car, bumper and the bonnet edge for the lower body region, mainly for the leg ; and the impacts against the bonnet or the windscreen for the head. Others injuries are also due to the contact with the ground.

The severity of injuries due to the car contact are related to the bumper and the bonnet height and stiffness, and the speed of the car. All these injuries were not fatal, but they led to very severe disabilities and impairments generally for a long duration. In some cases, they demonstrated an irreversible character, especially when the speed of the involved vehicle was higher than 30 km/h. The main injuries observed in adults (Manoli, 1986) relate to bone segment fractures, femur-tibia or fibula, articular troubles especially at the knee ligament level and soft tissues of the whole leg.

Oftentimes the tibia and/or fibula are the site of initial contact between the automobile and the pedestrian. The effect of bumper heights on the location of the fracture has been well summarized (Ashton et al, 1983). The injuries to the bones themselves may be severe. The skin and muscle tissue surrounding them are frequently damaged severely as well. Knee injuries consist of either injuries to the knee ligaments and soft tissues, or to the bones contributing to the articulation, or to both.

Knee ligament are the results of a bending force applied to the joint. In automobile-pedestrian interactions, valgus stress may tear the medial structure. A valgus stress injury may result in injury to the medial collateral ligament of the knee and medial knee cartilage. These ligament tears may be incomplete or complete, with total disruption of the fibres. Also commonly associated is the injury to the anterior crucial ligament and, on rare occasions, the posterior crucial ligament as well. If all of these structures and the capsule of the joint are also torn, a knee dislocation may result.

Severe injuries (complete tears) of the ligaments are best treated surgically with repair of the ligaments by direct suture after the initial evaluation is completed. The anterior crucial ligament is frequently difficult to repair as it is often torn in the mid-substance of its fibres.

Fractures of the joint may also occur with or without ligament injury. Valgus stress injury may result in fracture to the lateral tibial condyle. In general, if there is displacement, these are operated on and open reduction and internal fixation is performed.

It should be stressed that the knee ligament and bone articulation fractures are extremely severe injuries. Furthermore, because of their long term consequences, even if they are not very frequent, ligament injuries must be considered very carefully.

Majority crash simulation

There are many ways of pedestrian accident simulation ; the full-scale tests in which a vehicle hits a dummy or a cadaver, the rig tests in which an impactor simulating a segment of human body hits a chosen area of a vehicle or an impactor simulating a chosen area of a vehicle hits a segment of human body, subsystem test methods to evaluate Pedestrian protection, and, mathematical modelling of a vehicle hitting a pedestrian.

Mechanical models - For the evaluation of car-front aggressiveness to pedestrians in a car/pedestrian collision, subsystems and full pedestrian dummies have been considered for a leg-to-bumper impact test.

The Rotationally Symmetrical Pedestrian Dummy (RSPD), developed at Department of Injury Prevention, Chalmers University of Technology in Sweden and INRETS in France, is a pedestrian dummy equipped with a system for measuring the moments and forces in the lower extremities, especially at the knee joint (Aldman et al, 1985).

A mechanical representation of the lower limb in form of an impactor with deformable knee joint developed by INRETS is representative of a subsystem (Cesari et al, 1991).

Four mechanical substitutes of a pedestrian were used to test the influence of different car-front shapes and dummy parameters on the results ; the leg of the Rotationally Symmetrical Pedestrian Dummy (RSPD), a Hybrid-II pedestrian dummy, a modified Hybrid-II pedestrian dummy equipped with a steel bar serving as knee joint, and a RSPD - Hybrid-IIP combined dummy in which the lower part of the RSPD and the upper part of the Hybrid-IIP were connected by a joint in such a way that the movements of the upper part were similar to those in cadaver tests (Ishikawa et al, 1992).

Mathematical models - A 2D mathematical simulations of the pedestrian leg in lateral impact were conducted by INRETS (Bermond et al, 1992) with the rigid body program Madymo (TNO). Results of this model were compared with those obtained with the instrumented mechanical leg, developed by INRETS.

A 3D pedestrian knee joint model was developed as a first step in a new description of the whole pedestrian body for computer simulations (Yang et al, 1992) with Madymo. The new developed model was verified with results from tests with biological material previously performed at the Department of Injury Prevention, Chalmers University of Technology in Sweden.

A mathematical breakable leg model was developed and implemented into the pedestrian lower extremity model (Yang et al, 1993). The leg model, described with Madymo (TNO) consists of two rigid-body elements connected by a fracturable joint. The results showed that the modified model gave a higher biofidelity than did the previous model with the undeformable representation of the leg segments.

A pedestrian model was created to be used with the Crash Victim Simulation (CVS). The model consists of fifteen segments connected by fourteen joints. The geometry and the characteristics of the body segments, and the mechanical properties of the joints are bases on available anthropometrical and biomechanical data. Results were compared with cadaver tests (Ishikawa et al, 1993).

A 2D dynamic anatomical model of the human knee joint (Rahman et al, 1993) simulate its response under impact. The knee joint is modeled as two rigid bodies, representing a fixed femur and a moving tibia, connected by 10 non-linear springs. Two springs represented the anterior and the posterior fibers of each of the anterior and the posterior crucial ligament, four springs represented the medial collateral ligament, and one spring represented each of the lateral collateral ligament and the posterior part of the capsule. Knee response was determined under sudden rectangular pulsing posterior forces applied to the tibia and having different amplitudes and durations. It is hard to compare this model calculation with other data beause of the limited amount of experimental data available in the literature.

A three body segment dynamic model of the human knee (Tümer et al, 1993) includes tibio-femoral and patello-femoral articulations, and anterior crucial, posterior crucial, medial collateral, lateral collateral, and patellar ligaments. A specially developed human knee animation program is utilized in order to fine tune some model parameters. Numerical results are presented for knee extension under the impulsive action of the quadriceps femoris muscle group to simulate a vigorous lower limb activity such as kicking. The results are discussed and compared with limited data reported in the literature.

These car/pedestrian accident mathematical simulations were carried out with the rigid body program Madymo or CVS. A significant shortcoming of such an approach, however, is the need to provide experimental force deflection data as input for the contact models. In addition the geometry is met only poor, e.g. by ellipsoids. Finite Element models, on the other hand, can potentially cover a much wider range of loading situations. As the level of modelling is fundamentally different, such models are based essentially on material properties and the geometry of the surrogate to be discretized.

A finite element model of the pedestrian knee-joint in lateral impact (Bermond et al, 1993) was compared with cadaver tests (Kajzer, 1990).

In this paper this study was expanded to the lower limb.

METHODOLOGY

Lower limb model assumptions

To analyse the complexity of the problem several assumptions are made to simulate the behaviour of the lower limb in lateral impact :

- only the two bones are taken into account, the femur and the tibia. Only the cortical bone is described, because the spongy tissue is less stiff. The patella and the fibula do not influence significantly the response.
- only the joint of the knee is described with the posterior and anterior crucial ligament, and the medial and lateral collateral ligament.

The others ligaments and tendons and muscles are not described. At the beginning of the impact however the muscles are stressed, we suppose they do not change the response a lot, because they are less stiff than the four ligaments we have chosen.

The meniscus are not yet represented, because mechanical properties data are not easily available.

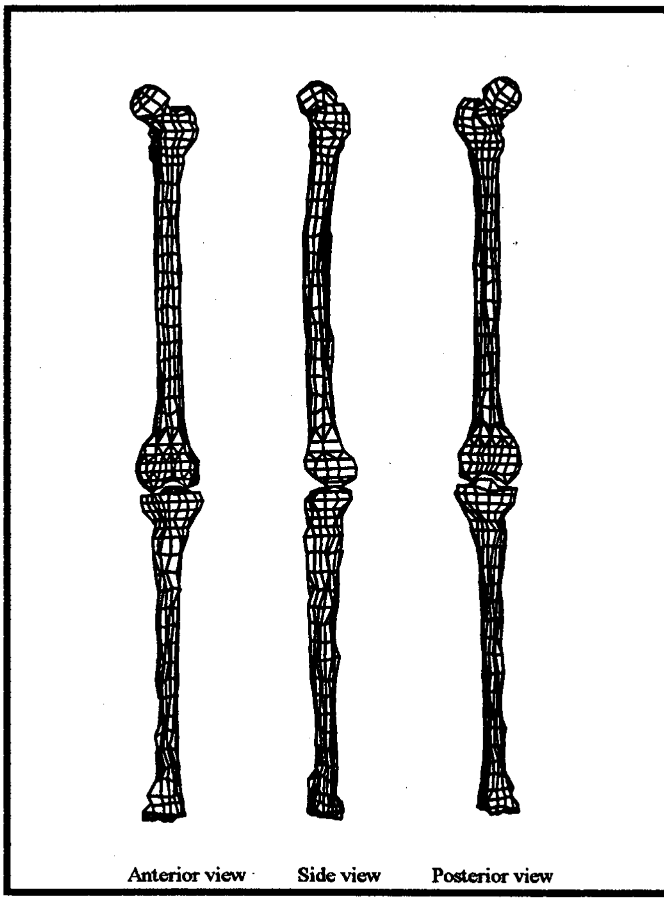
Geometry of the lower limb model

The bones are described in 3D space. The shape of the shaft the femur and the tibia is reconstructed from human leg X-ray scanner. The geometry is discretized with shell elements. The mesh of the two extremities of the femur and the tibia are obtained with an ultrasonic device (GP8 3D from Science Accessories Corporation). A mesh is drawn by hand on real bones and nodes are reached with the stylet which gives on a file the three dimensional coordinates of the node. The femur mesh is discretized with around 600 nodes and 650 elements, and the tibia mesh is discretized with 500 nodes and 550 elements.

The ligaments are described as a 1D linkage element with non-linear behaviour.

The figure 1 shows the human lower limb model in anterior view, side view and posterior view.

Figure 1
Human lower limb model.



Material properties of the lower limb model components

The material properties of the lower limb model components are found in the literature (Viano, 1986 and Skalak, 1987).

<u>Mechanical properties of bones</u> - The characteristic of the bone (Burstein et al, 1976, Keaveny et al, 1993) (table 1) is viscoelastic quality. Cortical bone is similar in properties to other fibrous materials such as wood, and has substantially more compliance than engineering materials such as metals, but more rigidity than spongy bone. Bone is one of the most rigid biological materials in the body and has a significantly greater stress carrying capacity than soft tissues which are frequently used to link long bones through joints or cover the musculoskeletal system.

Table 1
Mechanical properties of bones.

Cortical bone	Femur	Tibia
Density : kg/m^3	1900	1900
Elastic modulus : N/m^2	$17.6\ 10^9$	$18.4\ 10^9$
Plastic modulus : N/m^2	$0.754\ 10^9$	$1.2\ 10^9$
Yield stress : N/m^2	$0.12\ 10^9$	$0.13\ 10^9$
Ultimate stress : N/m^2	$0.14\ 10^9$	$0.15\ 10^9$
Poisson's ratio	0.326	0.326

<u>**Mechanical properties of the ligament**</u> - The main function of ligament (Herzberg et al, 1981, Race et al, 1993, and Woo et al, 1993) (table 2 and table 3) is to provide stability to joints and limit their range of motion and is to resist tensile loading either due to muscular contraction or loads tending to displace the joint.

Mechanical properties of ligament have mainly been determined by tensile testing of isolated tissues.

Table 2
Mechanical properties of the collateral ligaments.

Ligament	Lateral collateral	Medial collateral
Elastic modulus : N/m^2	$15\ 10^6$	$15\ 10^6$
Ultimate stress : N/m^2	$400\ 10^6$	$200\ 10^6$
Rupture force : N	3000	3000
Ultimate Strain at rupture : %	30	40
Density : kg/m^3	1000	1000
Poisson's ratio	0.3	0.3

Table 3
Mechanical properties of the crucial ligaments.

Ligament	Anterior Crucial	Posterior Crucial
Elastic modulus : N/m^2	$30\ 10^6$	$35\ 10^6$
Ultimate stress : N/m^2	$200\ 10^6$	$100\ 10^6$
Rupture force : N	6000	6000
Ultimate Strain at rupture : %	60	60
Density : kg/m^3	1000	1000
Poisson's ratio	0.3	0.3

Impactor assumptions

The form of the impactor is a half cylinder. It represents an approach of the bumper shape. The geometry is discretized with shell elements. The material properties of the iron are chosen. The impactor weights 16 kg.

MODEL VALIDATION

Experimental results from static tests and impact tests, to characterise, the mechanical behaviour of each part, like the ligaments or the bones, and the whole kinematics of the lower limb, will serve as a basis for the validation of the model. Two INRETS laboratories (Laboratory of Impacts and Biomechanics (L.C.B.) at Bron and the Applied Biomechanics Laboratory (L.B.A.) of Marseille) and a laboratory at Chalmers University (Department of Injury Prevention (D.I.P.) at Göteborg) are linked by a programme. This project was to analyse the effects of shearing loads (Kajzer, 1990) and bending moment (Kajzer, 1993) applied laterally to the human knee joint.

This experimental study was carried out at L.B.A. (INRETS University of Aix/Marseille-II Associated Research Unit) at the North Faculty of Medicine of Marseille. To determine the ultimate resistance to shear force or bending moment of the human knee, it was desirable to make separate experiments, where only one of those two parameters affects the biological material at the time.

Effect of shearing loads

Nineteen tests with lower limbs from cadavers were carried out : nine for an impact speed of 15 km/h and 10 at 20 km/h.

Dynamic testing of the leg was made using an impactor which was propelled by sandows. A specially designed impact arm for doing shearing load, equipped with force transducers was mounted in front of the impactor. Figure 2 shows the initial of the tests procedure.

Effect of bending moment

Seventeen test were carried out under dynamic conditions : seven at a velocity of 16 km/h and ten at 20 km/h.

A specially designed impact face for doing bending moment was used. Initial test conditions are showed in figure 3.

Figure 2
Human leg in lateral impact (Kajzer, 1990), Shearing load test.

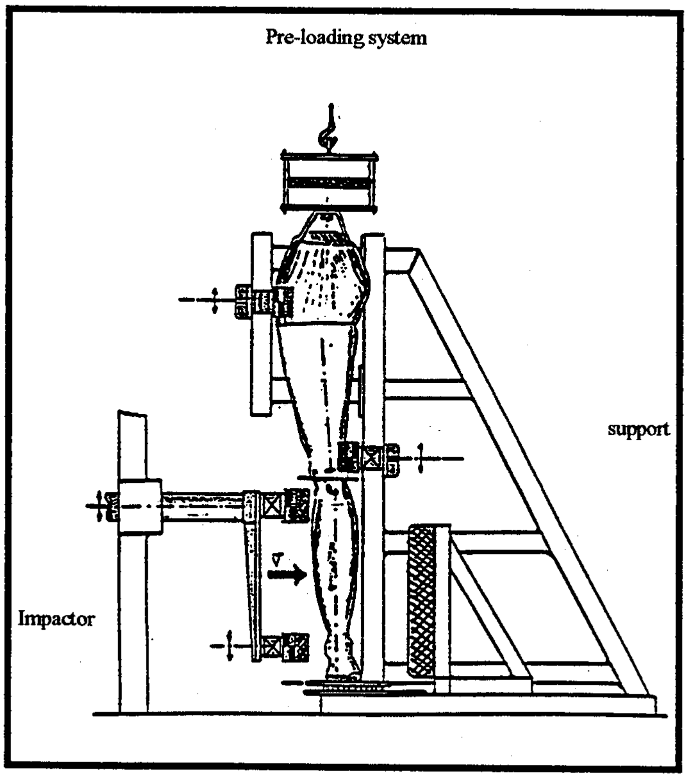
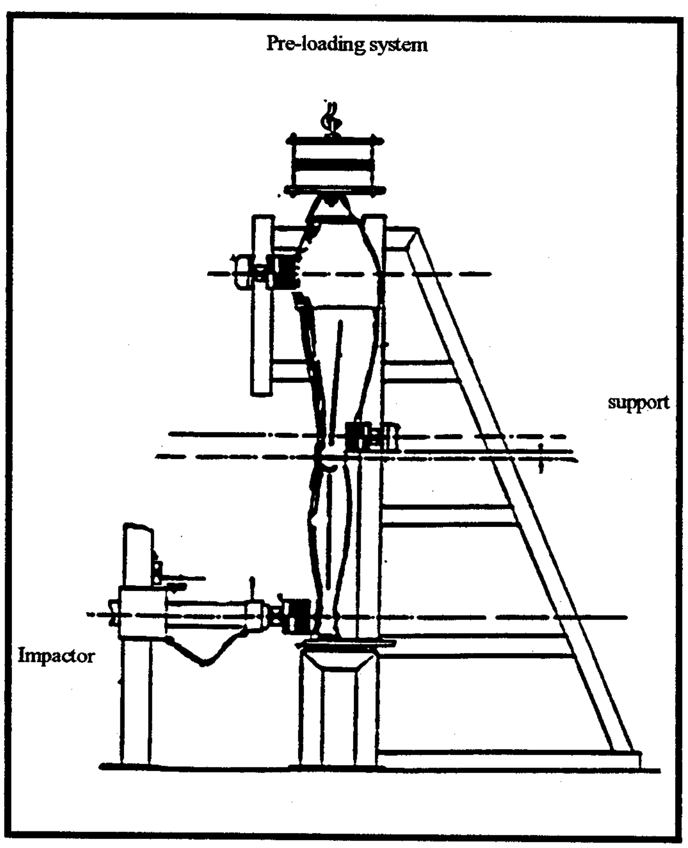


Figure 3
Human leg in lateral impact (Kajzer, 1993), Bending moment test.



Tests

To perform analysis of every test, two high speed cameras (1000 frames/s) were used during the tests and six targets were fixed on femur and tibia to permit high speed films to give the information about the kinematics of the leg. The dynamic response was measured with several force transducers.

Validation

To validated our model we compare the results from the tests with those from our model without forgotten our lower limb joint model assumptions.

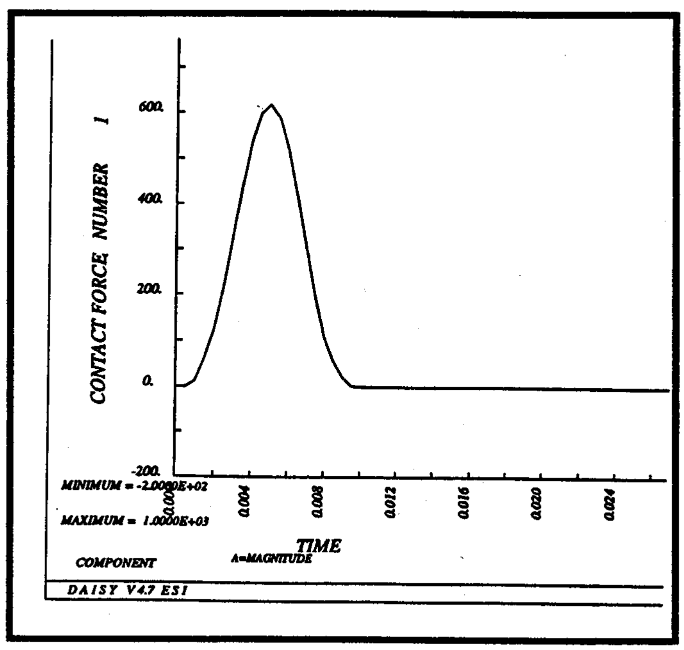
RESULTS FROM THE LEG MODEL

The results from the computer simulations are shown in figure 4 to 8, with the units from the System International.

The upper part and the external side of the tibia is impacted at 2.33 m/s.

On the figure 4 the contact force magnitude between the impactor and the tibia is maximum at around 0.005 s.

Figure 4
Contact force, between impactor and tibia.



The initial position of the human lower limb model with the impactor model is presented at figure 5. On the same figure the deformed shapes of the leg model are showed at 0.005 s, 0.0055 s, 0.006 s and 0.0065 s.

Figure 5
Lower leg impact test, kinematics.

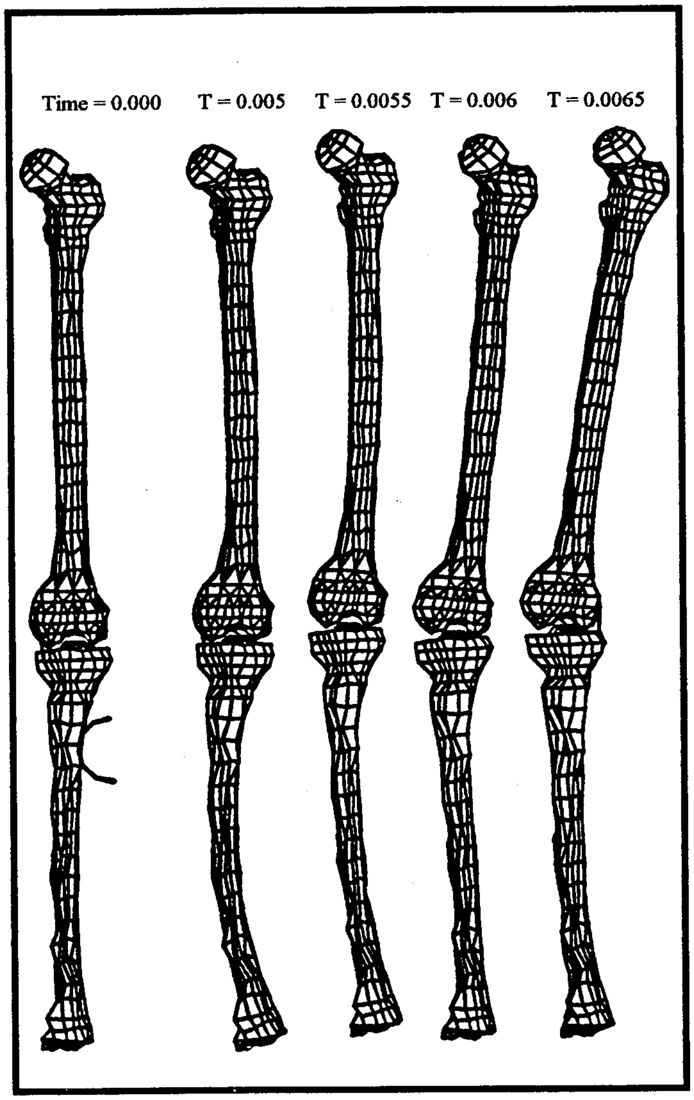
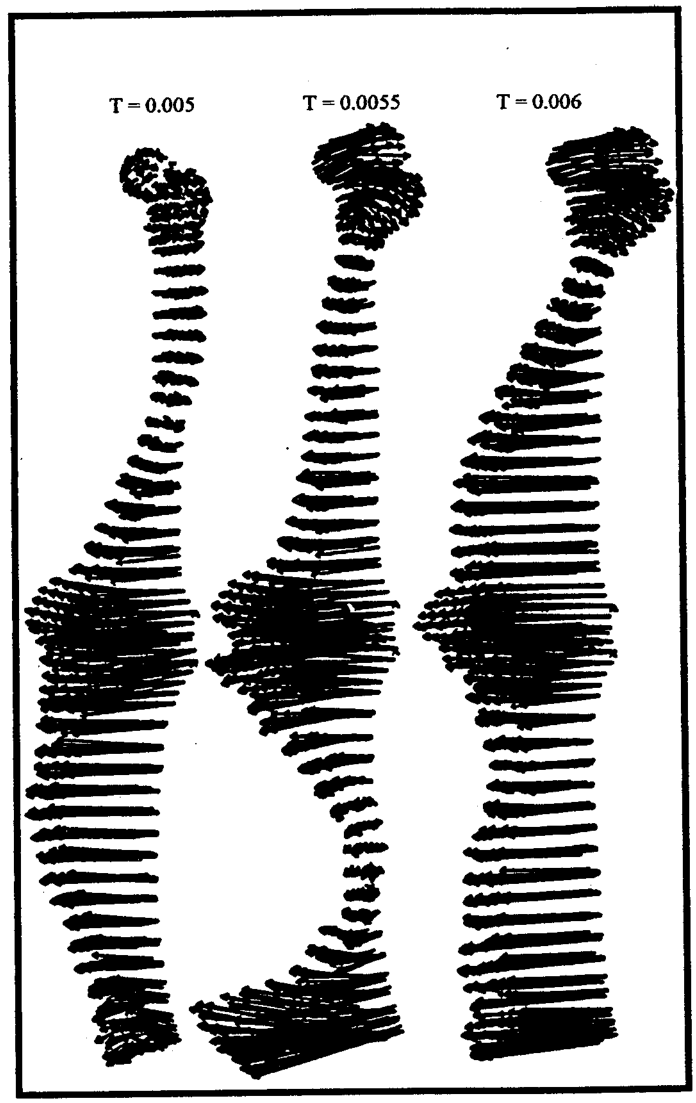


Figure 6
Velocity vector.



For each direction x, y and z, the displacement, the velocity and the acceleration curves for each node of the model are calculated and also the magnitude. Theses curves are filtered using SAE channel class from 1000 Hz to 60 Hz. There are peak values corresponding at the impact. The maximum effective surface stress and the Von Mises stress are also calculated for each element. The maximum effective surface stress is concentrated around the area of the impact at 0.004 s and after near the ligament insertion at 0.008 s.

On figure 6 the velocity vectors are plotted at 0.005 s, 0.0055 s and 0.006 s. The velocity vector field, at 0.005 s, is quite well regular distributed for all the lower leg. Then, at 0.0055 s, it is concentrated on the bottom of the tibia and at the knee. After at 0.006 s, it is quite regular distributed for all the lower limb.

The figure 7 shows the internal energy (due to the strain of the material), the kinetic energy (due to the displacement of the material), of the tibia, the femur and the ligaments. The ligaments accumulate more internal energy than kinetic energy, and the opposite appear for the bones. The tibia accumulate more kinetic energy and internal energy than the femur.

The axial force in the ligaments are shown on figure 8 and are filtered using SAE channel. During the first 0.01 s, the medial collateral ligament are more stressed in tension than the anterior crucial ligament, and the lateral collateral ligament are more stressed in compression than the posterior crucial ligament. After, from 0.01 s until 0.016 s the posterior and the lateral collateral ligament is stressed in tension, and the anterior and the medial collateral ligament is stressed in compression.

Figure 7
Energies of material,
Material No. 2 : femur, material No. 5 : tibia, material No. 8 : ligaments.

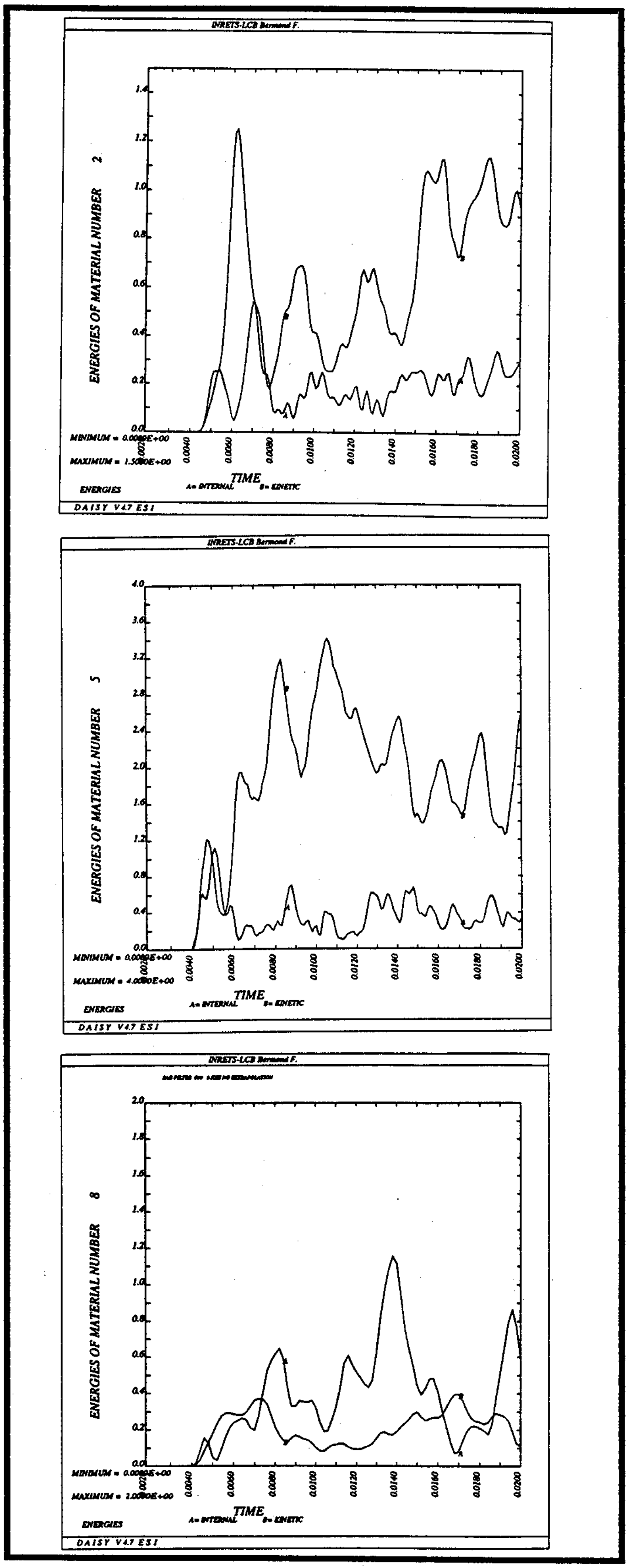
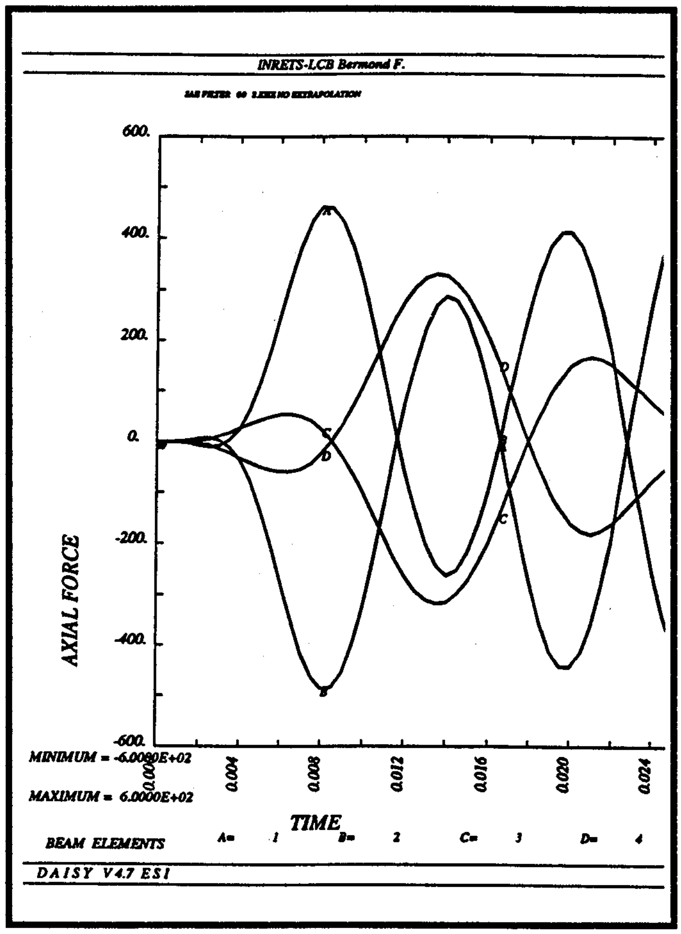


Figure 8
Axial force in the ligament,
No. 1 : medial collateral, No. 2 : lateral collateral,
No. 3 : anterior crucial, No. 4 : posterior crucial.



CONCLUSIONS

The aim of this paper was to create a second step for a human lower limb model in lateral impact. The first step in a previous study concerned the human knee joint model. This approach with Finite Element Method gives information about the internal mechanical behaviour, the kinematics, the displacement, the velocity, the acceleration, the maximum effective surface stress, the Von Mises stress and the contact force between the impactor and the tibia.

The model is not very well validated, and we will reduce several assumptions such as the response of the soft tissue and the muscle, or the whole shape of the leg. The mesh will be improved.

We still have to simulate other use conditions of the model as a function of the stiffness, the height the speed or the energy of the impactor.

Both aspects of modelling and experimental approach still require a lot of tests.

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Finite Element Modeling and Analysis of Thorax/Restraint System Interaction

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ABSTRACT

Various modeling techniques are playing an increasingly important role as a cost effective means of supplementing crashworthiness data for gaining a better understanding of the injury mechanisms associated with automotive crashes. The interaction of a geometrically accurate (50th percentile male) finite element model of the human thorax, and finite element models of a seat belt restraint system and an airbag are examined. Optimization of the thorax model under frontal impact conditions as well as the development of an improved shoulder structure are discussed. Using LSDYNA3D, the three-dimensional finite element structural analysis code, stress fields within the thorax model are examined and the results, using each restraint system in a comparable impact environment, are presented.

INTRODUCTION

A geometrically accurate, finite element model of the human thorax has been developed and exercised using LSDYNA3D, a finite element solver from Livermore Software Technology Corporation (LSTC). Figure 1 illustrates the baseline mesh for this model. The model is represented by a segmented spinal column consisting of twelve thoracic and five lumbar vertebrae and the associated intervertebral disks, twelve ribs, back, abdominal and intercostal muscles, homogeneous viscera and concentrated masses representing the head, arms and lower torso. Also shown in the figure is a rigid body impactor that was used to determine force/deflection characteristics of the model. The model has been validated and optimized by subjecting it to impact conditions specified in Title 49, Part 572 of the Code of Federal Regulations (CFR) which prescribes an impactor weight of 51.5 pounds, with an initial velocity of 22 feet/second. The results of this impact are compared to force/deflection data that has been gathered on cadavers[1-3] and scaled to a 50th percentile male[4].

MESH DEVELOPMENT

In earlier work[5], mesh generation was accomplished with INGRID, the mesh generating software that accompanies DYNA3D[6], the dynamic solver provided by Lawrence Livermore Laboratories (LLL). Early development of the mesh for the geometrically accurate thorax[7] was accomplished primarily with DISPLAY, mesh generating software from the Engineering Mechanics Research Corporation. Current mesh generation and model manipulation are being performed with PATRAN from PDA Engineering. The dynamic solver used in earlier work was DYNA3D from LLL while LSDYNA3D from LSTC is being used for the current work. The geometry used in the current model was based primarily on data published by Roberts and Chen[8], other available anthropometry[9,10] and cross-sectional anatomy[11]. The model was then scaled to represent a 50th percentile male. All elements in the thorax model are eight-node solids.

MATERIAL PROPERTIES

An accurate representation of the properties of biological materials presents the biggest challenge to the modeler of human body parts. There is ample information on the properties of stiff materials like bone that are relatively easy to characterize in the laboratory. On the other hand, for soft biological materials, there is little or, in many cases, no information available that is directly applicable for use in

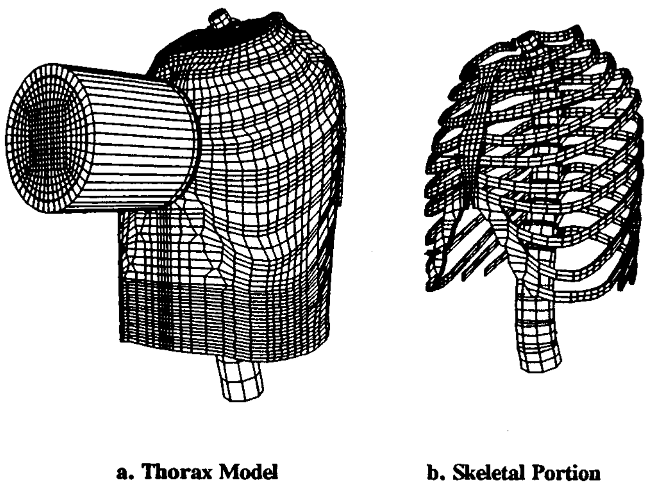


Figure 1. Baseline Thorax Model

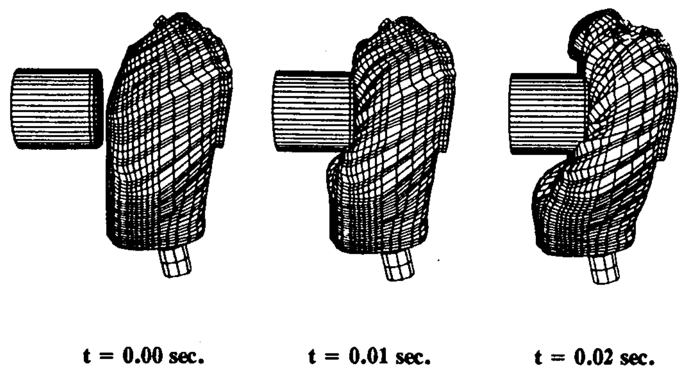


Figure 2. Baseline Model Under Part 572 Impact Side View

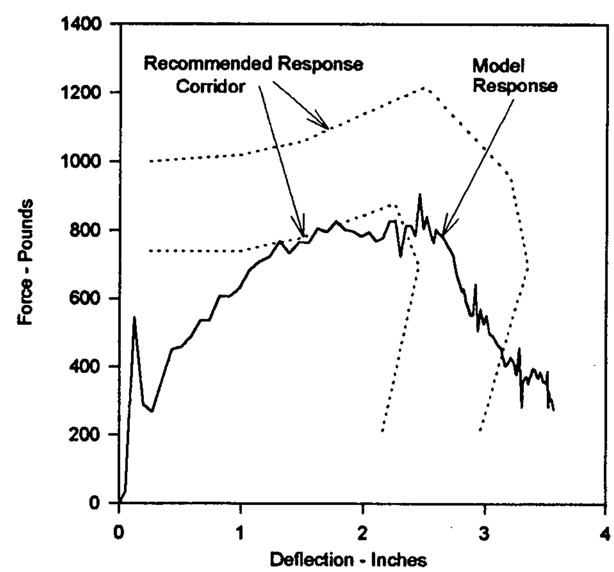


Figure 3. Force/Deflection Characteristics (Baseline Model - Impactor Initial Velocity = 22 feet/sec.)

finite element analysis. For the models developed in the current work, material properties have been taken from the literature[12-17]. The bone, cartilage, and ligaments have been represented by linear elastic materials while the interior thoracic volume and some of the muscle elements have been represented by a viscoelastic property defined by the following equation for the shear modulus G.

$$G(t) = G_L + (G_S - G_L)\varepsilon^{-\beta t}$$

where:

G_S = short term shear modulus
G_L = long term shear modulus
β = decay constant

RESULTS AND DISCUSSION

BASELINE MODEL

Figure 2 is an illustration of the baseline model subjected to impact conditions specified in Part 572 of the CFR. It can be seen at t = 0.02 sec. in Figure 2 that there is significant extrusion of the softer interior material at the top and excessive spreading of the ribs, both of which contribute to excessive compliance of the model. Figure 3 illustrates the force/deflection characteristics of this impact. In addition to the model response, Figure 3 shows the recommended response corridor based upon data gathered in the field on cadavers[1-4]. The results confirm that this model was too compliant, that is, there was too much deflection along the impactor center line and force levels did not attain values that were acceptable. This was somewhat anticipated as the material properties used were obtained from an earlier 7-rib model[5] with a geometry that was considerably stiffer to frontal impact than the present configuration.

BASELINE MODEL OPTIMIZATION

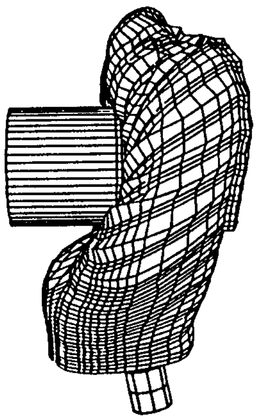
Several things were done to optimize the response of the current model including capping the top with a layer of relatively stiff elements, stiffening the intercostal muscle elements, adjusting the shear modulus G of the interior material and modifying the sternal mass.

Capping Interior Material

As seen in Figure 2, under impact, the interior material is extruded up through the top in a way that is not observed in actual testing due to the presence of additional structure (clavicle, head and neck). To eliminate this problem, the top layer of elements was given an elastic modulus of $E = 1.5x10^3$. The effect on the response is shown in Figure 4. It can be seen that the interior material no longer extrudes from the top but the spreading of the ribs has become more exaggerated, especially between the upper ribs. The force/deflection characteristics are shown in Figure 5. Although the interior material no longer extrudes from the top, it can be seen that the response characteristics did not change significantly.

Intercostal Muscle Modification

It can also be seen in Figure 2 that in addition to excessive spreading of the ribs in the model, the intercostal muscles bulge unrealistically. The material properties used



t = 0.02 sec.

Figure 4. Baseline Model Under Part 572 Impact Capped Interior Material (Side View) (Impactor Initial Velocity = 22 feet/sec.)

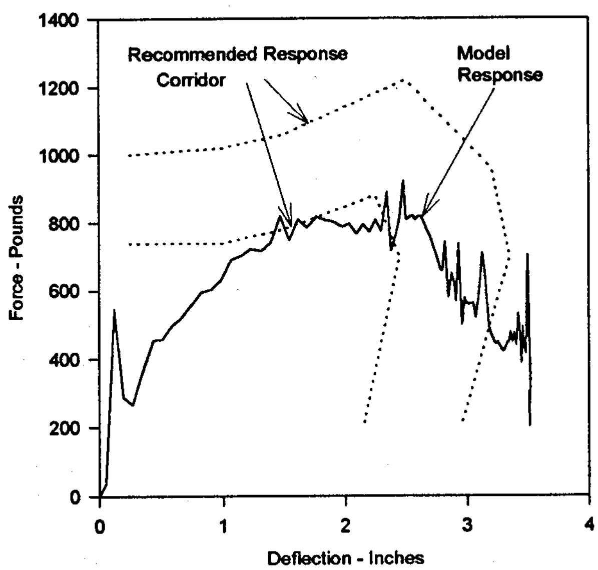
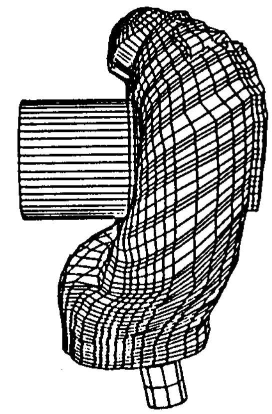


Figure 5. Force/Deflection Characteristics (Baseline Model - Capped Interior Material) (Impactor Initial Velocity = 22 feet/sec.)

for the intercostal muscles were based on laboratory data from samples of isolated muscle tissue. Intercostal tissue actually contains numerous other materials (nerves, fascia, blood vessels) that tend to give it a much stiffer characteristic. The intercostal muscles were given an elastic modulus of $E = 1.5x10^3$ and the resulting response is shown in Figure 6. It is apparent from the figure that the ribs no longer spread and the intercostal muscles no longer bulge as they did previously but the interior material now extrudes even more dramatically from the top. Figure 7 illustrates that this modification had a greater effect on the force/deflection characteristics than capping the interior material.

The impact response of the model when applying both of the above modifications (cap and stiffened intercostal muscles) is shown in Figure 8. There is no longer spreading



t = 0.02 sec.

Figure 6. Baseline Model Under Part 572 Impact Modified Intercostal Muscles (Side View) (Impactor Initial Velocity = 22 feet/sec.)

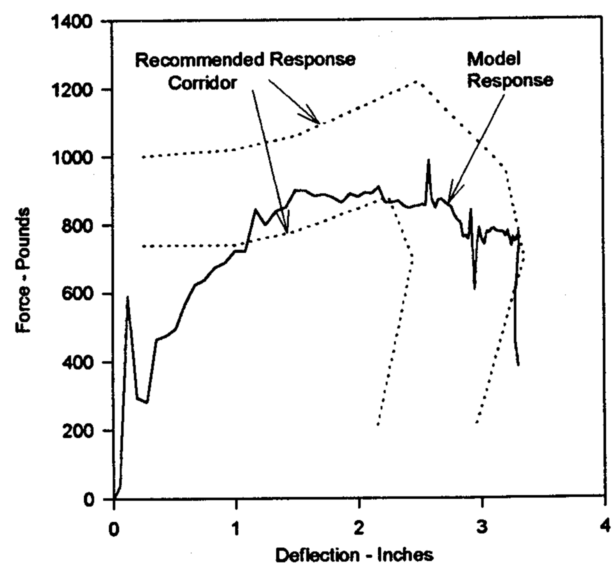


Figure 7. Force/Deflection Characteristics (Baseline Model - Modified Intercostal Muscles) (Impactor Initial Velocity = 22 feet/sec.)

of the ribs or extrusion of softer interior material and the abdomen is seen to protrude in a manner similar to what is seen in actual tests. The resulting force/deflection characteristics can be seen in Figure 9 where further improvement is noted. The maximum deflection observed is now within the recommended corridor. An adequate force level has still not been achieved however, and additional modifications were required.

Shear Modulus Modification

A parameter that was of great importance in the current model was the shear modulus G of the interior material. There is very little data in the literature for this parameter. In many cases however, the long term shear modulus G_L can be inferred from static measures of elastic modulus which are more commonly reported. The short term shear modulus G_S

which, as will be seen, has a large effect on the dynamic response of the model, is not well documented for most biological materials. In earlier work[5], modification of the shear modulus of the interior material had little effect on the force/deflection characteristics of the model. In that model, which was not an anthropometrically accurate representation,

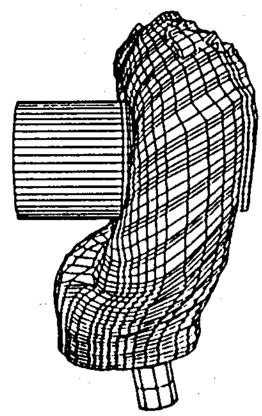


Figure 8. Baseline Model Under Part 572 Impact Cap and Modified Intercostal Muscles (Side View) (Impactor Initial Velocity = 22 feet/sec.)

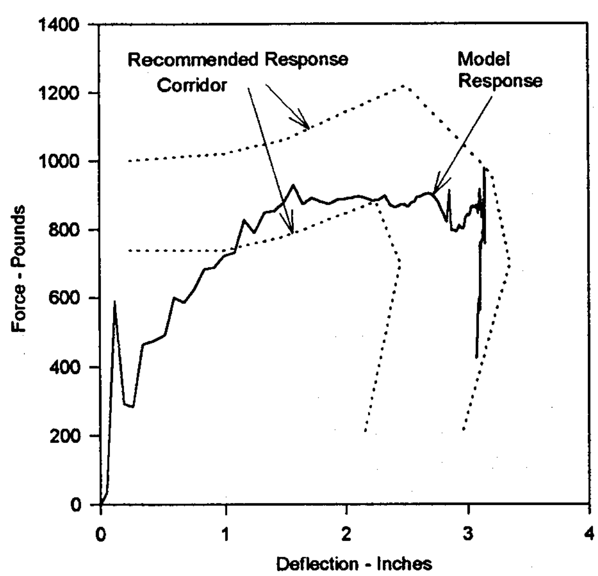


Figure 9. Force/Deflection Characteristics (Baseline Model - Cap and Modified Intercostal Muscles) (Impactor Initial Velocity = 22 feet/sec.)

the impact response was dominated by the rib geometry. While yielding an acceptable global force/deflection characteristic, individual ribs did not exhibit appropriate bending characteristics. The current model exhibits much more sensitivity to changes in shear modulus. The short term shear modulus was increased and applied in combination with the two modifications discussed above. The results are shown in Figure 10.

As seen in the figure, a short term shear modulus of G_S = 8.57 psi results in most of the impact response falling within the recommended corridor. This value of G_S was used in all subsequent testing. At this point, the only unsatisfactory aspect of the response was the initial rise, which was not within the recommended corridor.

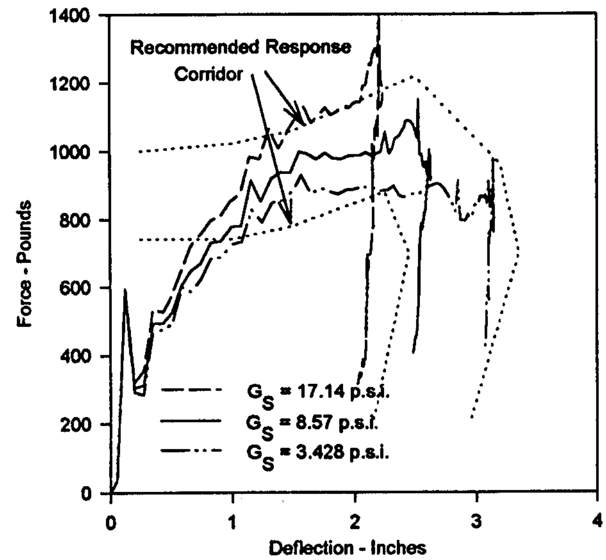


Figure 10. Force/Deflection Characteristics (Baseline Model - Modified Shear Modulus) (Impactor Initial Velocity = 22 feet/sec.)

Sternal Mass Modification

In an effort to improve the initial rise in the force/deflection characteristics, the sternal mass was increased slightly (1/2 pound) and the results are shown in Figure 11. There is reasonable argument for making such a change as the baseline model contains no musculature at the front. The muscles were omitted to avoid the extreme crushing of soft tissue that would occur between the impactor and the skeletal structure of the thorax. This extreme crushing would likely lead to element inversion and a program crash. It can be seen from the figure that the initial rise has improved but that the response again falls below the corridor following the initial rise. It is likely that the response could be further improved by adding mass just behind the sternum in such a way that the impactor encounters the additional mass in an incremental fashion. Without a well founded physical argument for making such a change, this issue was not pursued further. It was also felt that development of discrete organs in the future may have a significant effect on the initial rise of the force/deflection response of the model. The current configuration then, was considered to be a reasonable representation and as good as could be achieved at this time. The material characteristics that were used in this model are summarized in Table 1. This configuration was used in the development of contact surface models.

CONTACT SURFACE DEVELOPMENT

The thorax model has been tested with two contact surface models; a diagonal driver side seat belt and an airbag. The input pulse to both models was a ramp velocity of 0 to 264 inches per second (15 mph) from 0 to 100 milliseconds and then maintained at 264 inches per second for another 100 milliseconds.

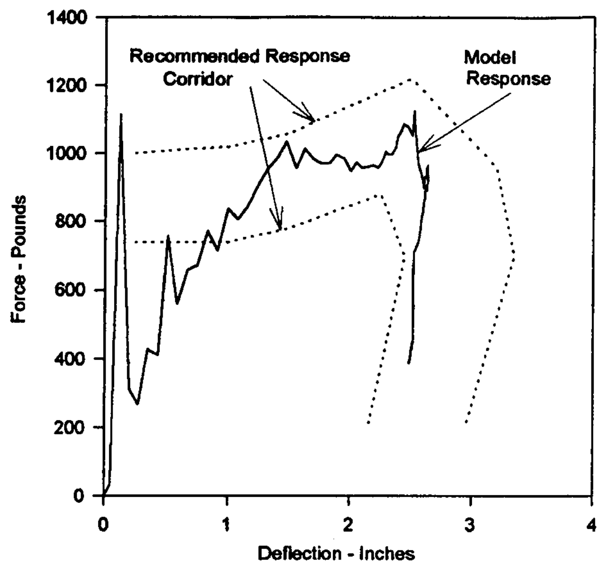


Figure 11. Force/Deflection Characteristics Sternal Mass Modification (Impactor Initial Velocity = 22 feet/sec.)

Table 1
Model Material Properties
for the Thorax Model
(Units are in pounds, inches and seconds)

Bone $E = 1.75 \times 10^6$ Poisson's Ratio = .3 Density = 1.73×10^{-4}	Intervertebral Disks $E = 1.5 \times 10^3$ Poisson's Ratio = .2 Density = 1.0×10^{-4}
Viscoelastic Interior K = 41.7 $G_S = 8.570$ $G_L = .3428$ Density = 1.0×10^{-4} $\beta = 100$	Intercostal Muscles $E = 1.5 \times 10^3$ Poisson's Ratio = .3 Density = 1.0×10^{-4}
Cartilaginous Elements $E = 3.00 \times 10^{-3}$ Poisson's Ratio = .46 Density = 1×10^{-4}	Abdominal Muscles K = 66.6 $G_S = 10.170$ $G_L = 3.390$ Density = 1.0×10^{-4} $\beta = 100$
Ligamentous Elements $E = 1.74 \times 10^{-3}$ Poisson's Ratio = .42 Density = 1.0×10^{-4}	Back Muscles K = 33.3 $G_S = 10.350$ $G_L = 3.448$ Density = 1.0×10^{-4} $\beta = 100$

Seat Belt Model

The seat belt model (Figure 12) consisted of triangular shell elements. The belt was two inches wide and was represented as a linear elastic material with $E = 5.0 \times 10^4$ psi., resulting in a elongation of 20 percent under a tension of 2,500 pounds. The ramp input velocity described above was applied in a rearward direction at each end of the belt and the thorax itself was free to move in any direction. The contact interface had a coefficient of friction of .5. In an earlier implementation of the seatbelt, four-node shell

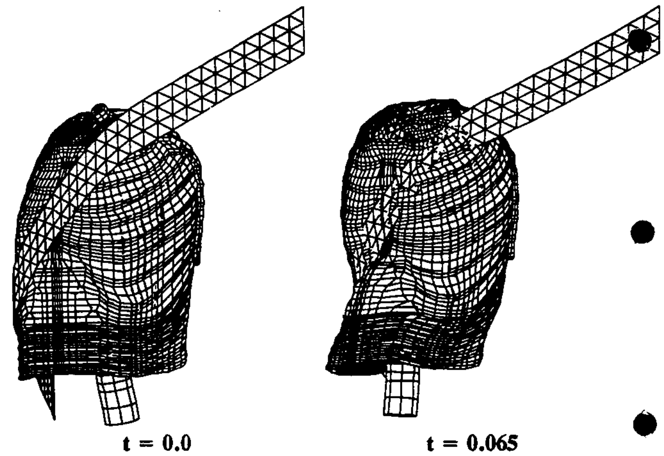


Figure 12. Thorax/Seatbelt Configuration

elements were used and significant hourglassing was experienced with these elements. Hourglassing is not possible with triangular elements and the current seat belt model performed well. In Figure 12, significant deformation of the thorax is noted at t = 0.065 seconds.

Figure 13 illustrates the thorax/seatbelt model under severe impact. Only the skeletal portion of the model is shown as an examination of the stress in the ribs is desired. Of particular interest in this figure is the stress distribution away from the belt. A high stress region is noted in the ribs in the upper right quadrant. The darkest portions of the illustration represent areas where the stress exceeds 7,000 psi. In recent belt tests with cadavers performed for the NHTSA, rib fracture was noted in the upper right quadrant.

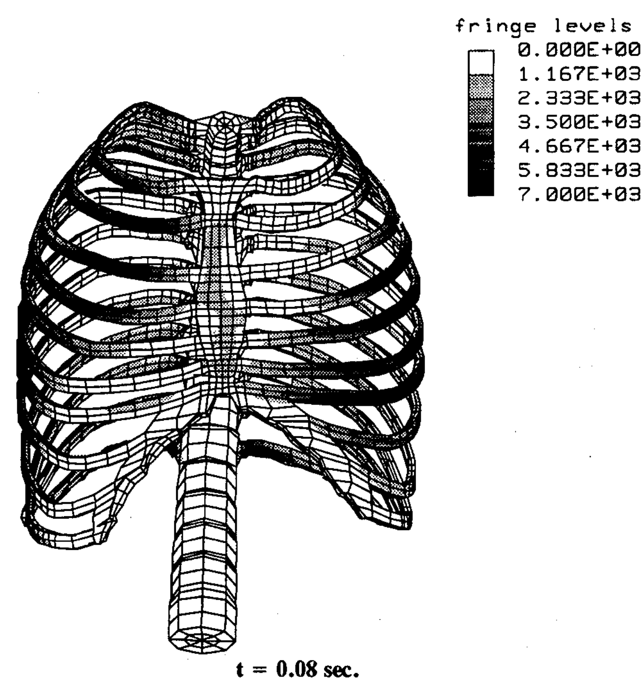


Figure 13. Stress Contours Under Severe Impact (Thorax/Seatbelt Model)

under severe impact conditions. The thorax/seatbelt model in Figure 13 confirms the potential for this fracture.

Airbag Model

The airbag model provided by LSTC consists for the most part of four-node membrane elements. Developed in cooperation with Imperial Chemical Industries, the bag is a folded fabric model, employing a single surface contact algorithm. The material model used has an elastic modulus of 1.2 x 10^5 psi making it relatively stiff in distension. The bag is vented toward the rear at two locations with holes that are 2.98 in^2 in area. The inflation of the bag is based on a model[18] developed for incorporation into the CAL3D[19] occupant dynamics simulation program. A stonewall definition is placed at the rear of the airbag model as a reaction surface. The ramp velocity is imparted to the airbag by applying the velocity to the stonewall definition. A coefficient of friction of .5 is used at the stonewall/airbag interface and the airbag/thorax interface. The deployment of the airbag is illustrated in Figure 14.

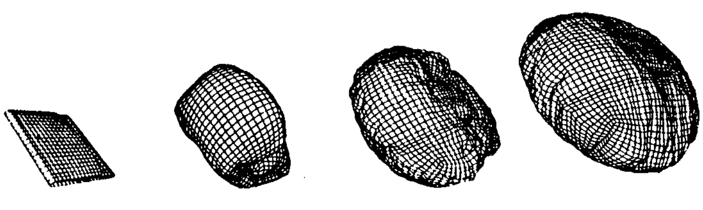


Figure 14. Airbag Model Deployment

Since the mesh of the thorax model was developed with DISPLAY and PATRAN while the mesh of the airbag model was developed with INGRID, merger at the mesh generation stage was impractical. Instead, the airbag model was incorporated into the LSDYNA3D input deck of the thorax model. The contact interface was implemented by use of the automatic contact input generation provided with LSDYNA3D. Computational overhead during deployment of the airbag was reduced by designating the entire thorax model as a rigid body and delaying initiation of the thorax/airbag contact interface calculations (computationally intense) until just before contact is made. At this point, the elements of the thorax are switched back to deformable materials. Initial problems with penetration of the thorax model thorough the shell elements were corrected with modification of the contact algorithm at LSTC. Currently there is very little penetration of the interfaces observed, until extremely severe impact conditions are encountered. The thorax/airbag interaction is illustrated in Figure 15.

Airbag pressure (gage) during deployment is shown in Figure 16. A peak pressure of .8 atmospheres is seen early in the inflation process at 11 milliseconds and the bag is fully inflated at 30 milliseconds. It is then undisturbed and deflating through the vent holes until the thorax makes contact around 66 milliseconds and the pressure again begins to rise soon after this contact. The pressure continued to rise until the test was terminated at 120 milliseconds when an element of the interior viscoelastic material became unstable.

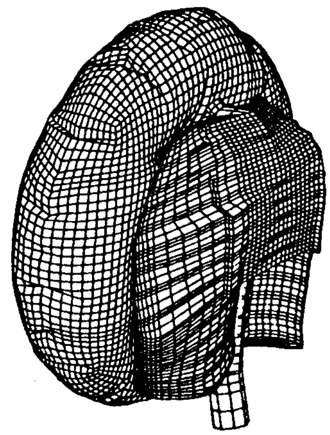


Figure 15. Thorax/Airbag Interaction

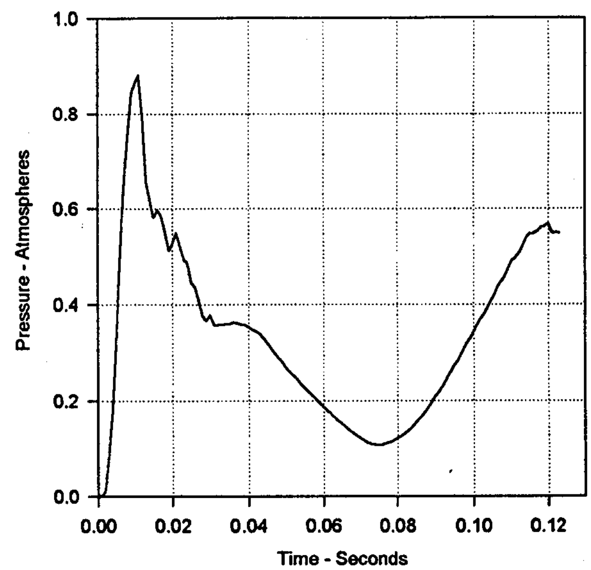


Figure 16. Airbag Pressure (gage) During Deployment

Seatbelt - Airbag Comparison

Early in the contact surface model development, problems were encountered with instability of viscoelastic elements under severe impact. To insure element survival in seatbelt/airbag comparison tests, it was required to increase the bulk modulus of these materials by an order of magnitude. In addition, Poisson's ratio for the intercostal muscles was increased from .3 to .499. With the currently available material models this is often necessary in cases of very large deformation. The thorax model with these changes was used to measure relative performance of the seatbelt and airbag models.

To compare the performance of the seat belt and airbag, thorax deflection, spine velocity and acceleration at the level of the impactor in the Part 572 tests have been observed for both restraint system models. Figure 17 illustrates the mid-line deflection of the thorax model as it encounters each

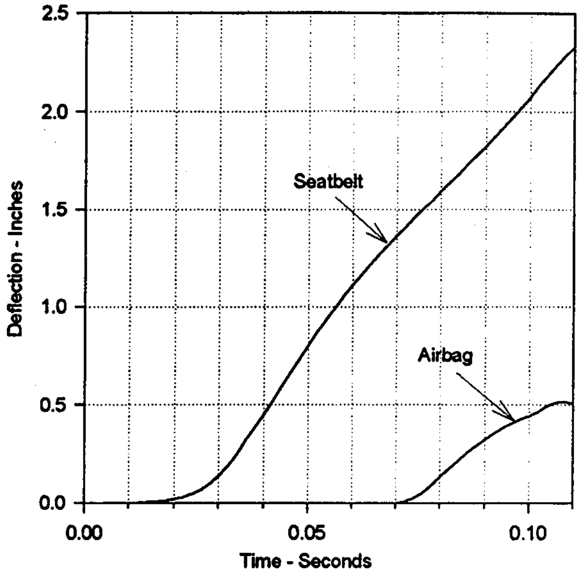


Figure 17. Thorax Deflection

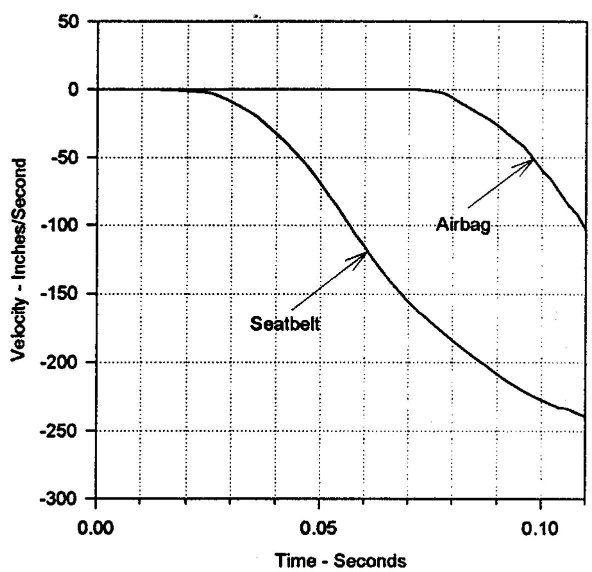


Figure 18. Spine Velocity

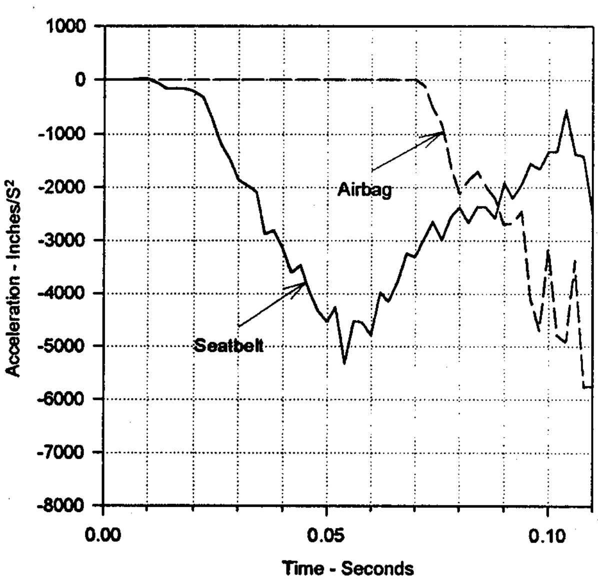


Figure 19. Spine Acceleration

restraint system. Mid-line deflection is defined as the reduction in distance between two nodes in the thorax along the centerline of the impactor. One node is on the posterior surface of the sternum and the other is on the anterior surface of a vertebra. Thorax deflection when contacting the airbag occurs much later than in the seatbelt case and the deflection itself is considerably less. Figure 18 illustrates the spine velocity for each of the restraint system models and Figure 19 illustrates the accelerations experienced with each restraint system at that same point. Velocity and acceleration have been measured at the above mentioned node on the spine.

As can be seen in Figures 17, 18 and 19, the two tests are considerably out of phase, that is, the thorax makes contact with the seat belt almost immediately while, in the airbag case, contact is made after approximately 66 milliseconds. It is helpful to normalize the data by plotting time histories after the initial contact with the restraint system. Initial contact is assumed to have occurred when there is a perceptible deflection of the thorax. This happens at t = .008 seconds with the seatbelt model and at t = .066 seconds with the airbag model. Normalized representations of deflection, velocity and acceleration are shown in Figures 20, 21 and 22.

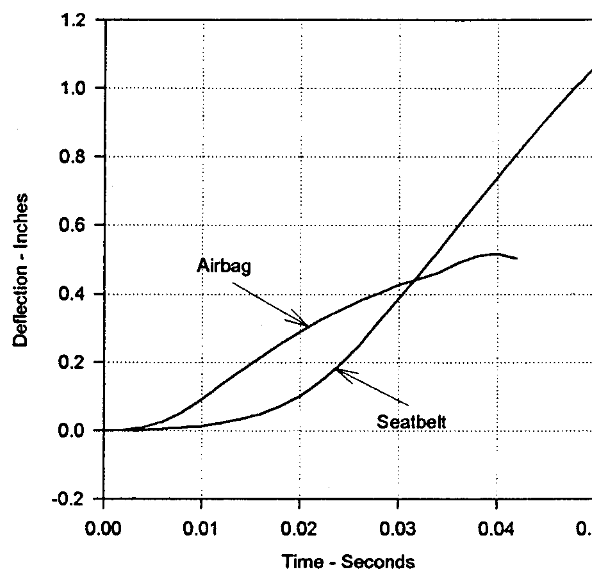


Figure 20. Thorax Deflection After Initial Restraint System Contact

The difference in the dynamic response of the thorax in the two cases shown is significant. Figure 20 indicates that after initial contact the thorax deflection due to the airbag is greater than that due to the seatbelt until about 32 milliseconds when deflection due to the seatbelt becomes greater. Figures 21 and 22 show remarkable similarities between the two cases in the shape of the time histories of velocity and acceleration with a slight phase difference implying a more rapid onset of both parameters for the airbag model.

A better performance comparison can be made by observing the critical parameters as a function of the change in velocity of the thorax. Figure 23 illustrates the mid-line deflection for the two models as a function of velocity. It can be seen that after a common change in velocity of 105 inches/second (approximately 6 miles/hour), the mid-line deflection for the thorax/seat belt model is approximately 1.04 inches while that for the thorax/airbag model is only .5 inches, a significant difference.

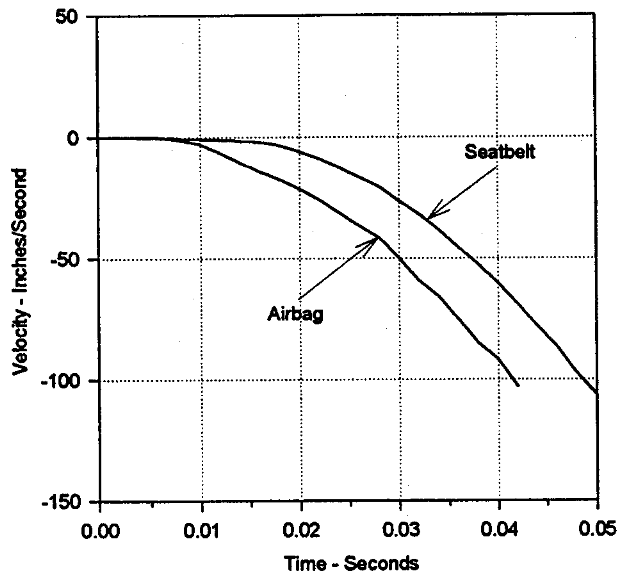


Figure 21. Spine Velocity After Initial Restraint System Contact

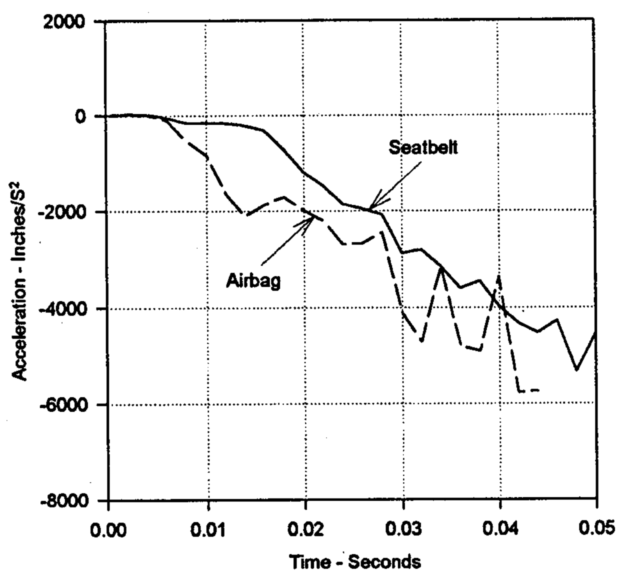


Figure 22. Spine Acceleration After Initial Restraint System Contact

Figure 24 is an illustration of the bony structure of the thorax after a velocity change of 105 inches/second for the seatbelt model and Figure 25 illustrates the airbag model at the same change in velocity. It can be seen that there is a difference in the stress distribution for each case as would be expected.

In the seatbelt case there is significant asymmetry as would be expected. The stress distribution is determined by the course of the belt, and maximum stresses appear to occur where bending moments in the ribs are greatest. In this case the maximum stress observed was 14,970 psi. The darkest portions of the ribs in Figure 24 are areas that exceeded a stress of 5,000 psi.

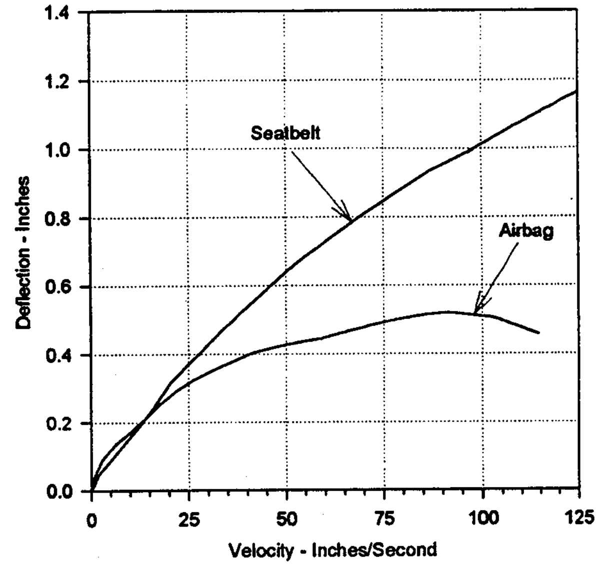
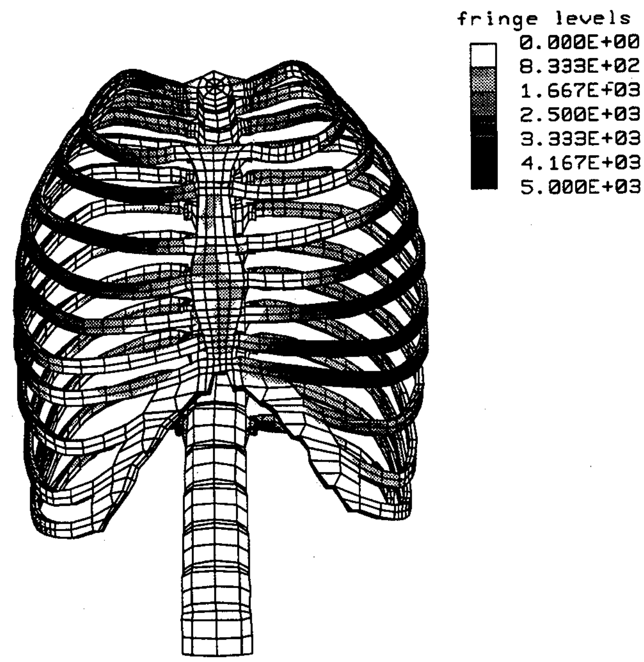


Figure 23. Spine Velocity vs. Deflection



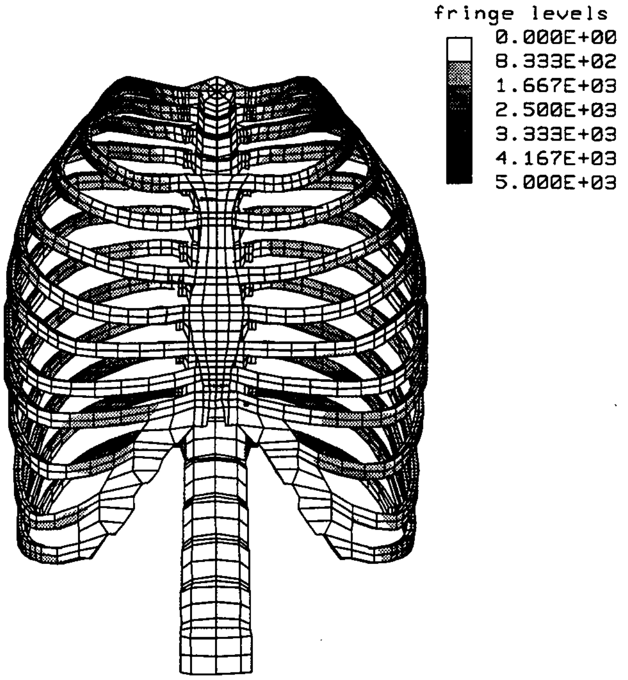
Seatbelt Model

Figure 24. Stress Contours at ΔV = 105 Inches/Second (Maximum Principal Stress)

In the airbag case (Figure 25), the stress distribution is symmetrical with maximum stress equally distributed along the lateral margins of the ribs on both sides. The maximum stress observed in this case was 12,665 psi.

IMPROVED SHOULDER STRUCTURE

Surface geometry data from Viewpoint, Inc. was imported into PATRAN and used to construct a finite element model of the shoulder girdle consisting of a scapula, clavicle and



Airbag Model

Figure 25. Stress Contours at ΔV = 105 Inches/Second (Maximum Principal Stress)

the ligaments connecting the two (Figure 26). The shape of the structure was adjusted slightly to fit the current thorax model.

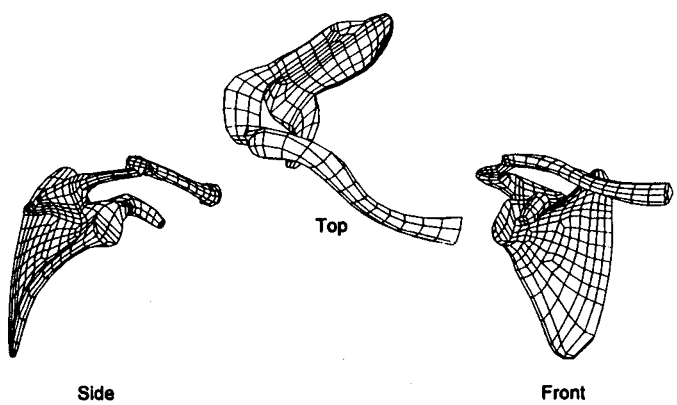
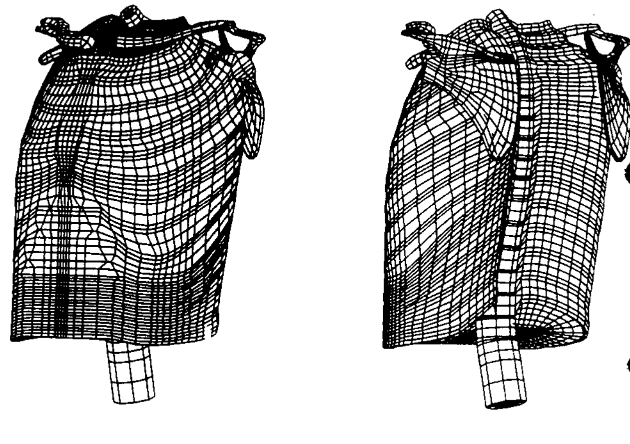


Figure 26. Scapula/Clavicle Structure

Maintaining an accurate shape of the shoulder structure made it difficult to connect the structure to the existing thorax model. Tying the two with muscle elements by equivalencing of nodes was virtually impossible and the surfaces will be connected as tied interfaces in LSDYNA3D.

Figure 27 illustrates the bony portion of the shoulder girdle as it appears incorporated into the thorax model. This model will be tested under PART 572 conditions to determine if the shoulder structure has any effect on the response to frontal impact. It is anticipated that there will be changes in the response using a seatbelt as the belt will pass over the shoulder structure.



a. front oblique b. rear oblique

Figure 27. Thorax/Shoulder Complex

FUTURE WORK

Work planned for the future will include additional restraint system analyses with a complete thorax/shoulder girdle complex, the development of rigid body extremities, side impact testing and the development of discrete intrathoracic organs.

CONCLUSIONS

The current geometrically accurate finite element model of the human thorax represents a useful tool for the analysis of frontal impact. The model will be of great use in the optimization of contact surfaces such as seatbelts, airbags, steering wheels and other interior structures. The current thorax/seatbelt model successfully confirmed the potential for rib fracture in the upper right quadrant of the thorax away from the belt line, a phenomenon that had been experienced in the field under similar impact conditions. An improved shoulder structure promises to result in more reliable testing of restraint system models, especially seat belts and will play an important role in side impact tests.

Regarding the comparison of airbag and seatbelt performance, several tentative conclusions may be drawn. Under comparable impact conditions (i.e. after a common change in velocity), mid-line deflection of the thorax is significantly less with an airbag restraint system than with a diagonal seatbelt restraint system. In addition, rib stress is less with the airbag model than with the seatbelt model. Lateral stress symmetry is observed in the airbag case, distributing the load more uniformly.

There remain several issues that are of significant importance. Among these is the lack of information on the material properties of intercostal muscles. Until this information is available, there will remain uncertainty in the combined effect of intercostal muscle stiffness and short term shear modulus on thoracic force/deflection characteristics.

The limited availability of appropriate material models for anatomical simulations in LSDYNA3D or public domain DYNA3D presents another problem. A very useful model for biological materials would incorporate both hyperelastic and viscoelastic properties. With improved material models, there will be an opportunity for modeling thoracic contents and examining strain distribution within the thoracic cavity.

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Mathematical Model of Pedestrian Lower Extremity

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ABSTRACT

Injuries to the lower extremity accounted for a major proportion of the casualties in vehicle-pedestrian accidents. Impact injuries to this body region are rarely fatal, but they often result in a relatively high social costs due to the consequence of impairment and disability as well as workloss. A pedestrian protection should therefore be given priority. In the paper the mechanisms of injury and the injury tolerances of the lower extremity in car-pedestrian accidents are described and analyzed. Based on the analyses of injury mechanisms, a 3D mathematical model of lower extremity with human-like knee joint and breakable leg elements was developed. The model of the knee joint includes the articular surfaces, ligaments and capsule represented by the ellipsoid and plane elements as well as the spring-damping elements. The leg is represented by two rigid-body elements connected by a joint in which the leg deformation under lateral impact is defined. The mechanical properties of the model are based on available biomechanical data.

Validation of the new developed model was made with results from previously performed experiments with biological specimens. The computer simulations of these experiments were carried out with the model using the MADYMO 3D program. The bumper impact force the leg acceleration, the condyle interface forces, the ligament forces and the ligament relative elongation were calculated and compared with the results from experiments with biological specimens. The calculated values from simulations correspond in general to measured parameters in experiments.

The model showed a higher biofidelity than the traditional MADYMO model of the lower extremity with a cardan knee joint and an undeformable representation of the leg. The model can be used to investigate impact response of the lower extremity under varying impact conditions. The injury risk of the lower extremity in car-pedestrian accidents can also be predicted by the model.

BACKGROUND

Each year about half a million people are killed and thirty-five million injured in road traffic accidents worldwide (Evans, 1991). Huge economic losses and serious consequences result from these traffic accidents. It is a common target for those who work in the traffic safety field to reduce the number of traffic accidents and minimize the consequences of accidents. Accident analyses and impact biomechanics research play an important role in the work to improve the understanding of what happens to the victims and to propose countermeasures.

Epidemiology of Lower Extremity Injuries in Vehicle-Pedestrian Accidents

Traffic accident investigations around the world have indicated that the proportion of pedestrian fatalities to all killed road users varied from roughly 14% in the France (ACEA, 1992) and in the United States (NHTSA, 1992) to 30% in Japan (Ishikawa et al., 1991), 33% in the United Kingdom (ACEA, 1992), and 45% in Delhi in India (Sarin et al., 1990).

The distribution of pedestrian victims by age shows that elderly people (over 65 years of age) are most frequently involved in fatal accidents (EEVC/CEVE, 1982), and the frequency of injured children (under 15 years of age) is much higher than that of elderly adults.

During the past two decades significant reductions in pedestrian fatalities have been achieved in Europe (ACEA, 1992) and the United States (NHTSA, 1992). In the United States, the pedestrian fatalities in 1992 was 29% lower than in 1981. Moreover a decrease in the proportion of killed pedestrians with respect to total traffic fatalities was observed. In Germany in 1970, about 32% of all traffic fatalities were pedestrians. In 1990 their proportion decreased to about 19%. In France a reduction from 21% to 14% and in the United Kingdom from 38% to 33% was observed. This tendency was discussed internationally, and it seems that mainly the education, traffic planning and new aerodynamic design of cars influenced this trend. Unfortunately, non-fatal accidents were not analyzed in these studies. Analyses of accidents with pedestrians show that two body segments are overrepresented in the injury statistics, the lower limbs and the head. Ashton and Mackay (1979) reported that leg injuries represented about 60% of the non-fatal cases.

It is relatively common that injuries to the lower extremities among pedestrians are one of the main causes of impairment and disability (EEVC/CEVE, 1982). The impact injuries to this body region are rarely fatal (Ashton et al., 1977), with a rating grade of only 1 - 3 according to the Abbreviated Injury Scale (AIS). However the AIS scale mainly measures risk of fatality (threat to life) (AAAM, 1990), and does not consider social costs of the injuries and long-term consequences, such as disabilities. Injuries to the lower extremities require long periods of hospitalization and lead to many lost working days (Joynt, 1986).

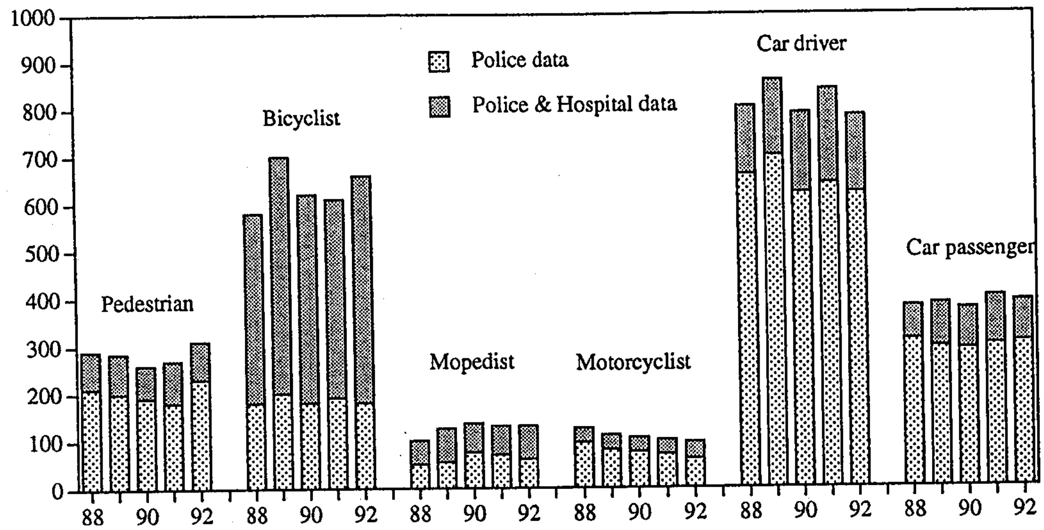

Figure 1. Killed and injured persons in traffic accidents in Gothenburg from 1988 to 1992.

Most epidemiological studies are only based on police-reported accidents. But in a Swedish study performed by TTA (1992), it was shown that in Gothenburg in cases of the pedestrian and the bicyclist about 25% to 60 % of all accidents are not reported to the police (Figure 1). In epidemiological studies more effort should be made to analyze hospital-based data, considering the long-term consequences and the social costs of the non-fatal injuries to the lower extremity. Further efforts are needed not only to reduce the number of accidents but also to minimize the risk of injuries to the lower extremity and its consequences. It is necessary to choose and implement efficient safety measures in such a way that they offer as good protection as possible.

Injuries and Injury Mechanisms

A schematic representation of major injuries to the lower extremity in a car-pedestrian lateral collision is shown in Figure 2. A large lateral impact force, combined with probable axial loading of the leg, results in multiple injuries. The following modes of injury to the lower extremity are most common in car-pedestrian accidents (Ashton et al., 1979; Backaitis et al., 1983): tibia/fibula fracture, knee injuries (including femoral condyle and tibial condyle fractures, knee ligament tearing and rupture), patella fracture, femur fracture and ankle/foot dislocation and fracture.

Determination of the cause of injuries to pedestrians is complicated, as the body parts could come into contact with the vehicle and/or the ground. Lower extremity injuries most likely result from vehicle-front contact (Ashton et al., 1977). The impact with the car front and the subsequent acceleration of the pedestrian's lower extremities result in complex injury mechanisms. There are various mechanisms of lower extremity injuries in pedestrian accidents due to complexity and uncertainty of the accidents. The injuries of the lower extremity may occur in relation to one mechanism or a combination of several mechanisms.

Thigh - Femur fracture in car-pedestrian collisions may result from hood edge - thigh contact (Ashton et al., 1977). A lateral impact to the thigh causes a concentrated load and bending load on the femur. When the stress exceeds the yield limit the femur fractures.

Leg - Contact with bumper generates a risk of tibia shaft fractures (Ashton et al., 1977; Bunketorp, 1983). These fractures occur when a concentrated stress exceeds the tolerance level at the impact area or of the tibia shaft. The stress results from a concentrated load and high level of bending moment due to a direct bumper impact.

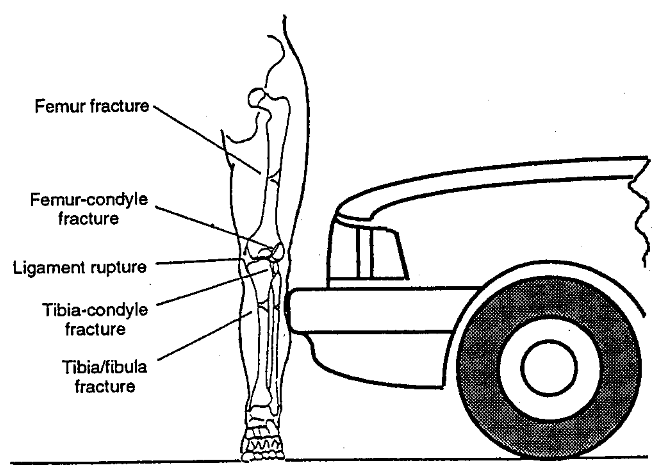

Figure 2. Major injuries to the lower extremity in a lateral impact.

Knee - The knee joint can be regarded as the biomechanical link between the thigh and the leg. When impact occurs close to the knee joint, it generally leads to forces that turn the leg outward around an assumed axis corresponding to the course of the impacting car front. The first consequence of these forces is injuries in the contact area as well as extra-articular injuries (Figure 3). Due to the forces transmitted through the knee joint, a transverse dislocation between the leg and the thigh occurs. This leads to a luxation of the knee joint accompanied by the over-stressing and over-stretching of all affected parts of the ligamentous structures. The consequence of this luxation is intra-articular injuries of the knee joint.

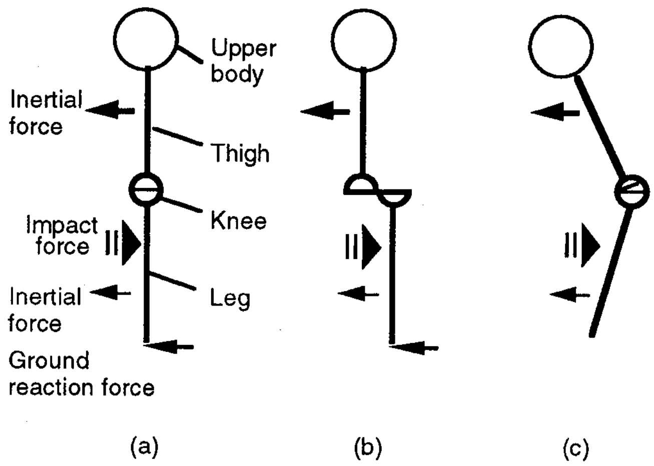

Figure 3. Injury Mechanisms of the leg and the knee joint: (a) contact injury; (b) shearing injury; (c) bending injury.

Another obvious effect of the impact of the car bumper on the lateral aspect of the knee is that the lower extremities bend laterally. This lateral bending results in tensile forces on the medial side of the knee and compressive forces in the lateral condyles. Usually the medial collateral ligament is most frequently injured as the ligament tensile strains exceed the yield limit and may be torn from one of its attachment areas. These forces often also result in compression fractures of the lateral condyle of the tibia. These fractures usually extend into the knee joint. The inertia of the foot causes the leg to rotate about its longitudinal axis, resulting in shear in the soft tissues at contact with the bumper and possibly also torque which is transmitted to the knee region. The worst case in car-pedestrian accidents seems to be when the bumper impacts the one lower extremity that at that moment supports the body and when this impact occurs close to the extended knee joint (Kajzer, 1989).

Ankle - Lateral impact on the leg leads to an external rotation of the ankle joint, resulting in ankle dislocation and fracture due to shearing and bending forces, which are attributable to bumper impact combined with a reaction force between the foot and the ground (Bunketorp, 1983). Injuries to the ankle joint are not common in car-pedestrian accidents, but may be a problem with the decrease of the bumper level to protect the knee from injury.

Tolerance Levels

The tolerance levels of the lower extremity have been extensively studied in experiments with human subjects under impact loading associated with traffic accidents (Powell et al., 1975; Melvin and Nusholtz, 1980; Cesari et al., 1982; Nyquist et al., 1985). It is considered that the tolerance level is related to many factors such as sex, age, body size, health condition, loading and constraint conditions. In car-pedestrian accidents, direct impact by the car bumper will result in "free flight" of lower extremities. In car-to-car impacts, an occupant restrained by a seat belt is hit by car-interior structures in the seated position. Impact injuries to the lower extremity of a vehicle occupant are different from impact injuries to a pedestrian, due to the different impact configurations.

There are a lot of data that can be used to establish the injury tolerance level of the human body regions in terms of loading conditions. However most data concerning tolerance levels of the lower extremity have been obtained in experiments regarding vehicle occupant injuries corresponding to vehicle frontal impact. The injury tolerance of pedestrian lower extremity has only been investigated in a few studies. Based on a literature study, injury tolerance levels of the femur, tibia, knee joint and ankle joint are described, which can be applicable in mathematical modeling of the lower extremity of pedestrian.

Femur - During the last two decades, a large number of studies have been performed to investigate the fracture tolerance level of the femur to axial impact forces, primarily as a result of research concerning car occupant safety in frontal impacts (Powell et al., 1975). Based on dynamic experiments, a femur injury criterion (FIC) was developed by Viano (1977):

$$F(kN) = 23.14 - 0.71\ T(ms) \text{ for } T<20 \text{ ms}$$

$$F(kN) = 8.9 \text{ for } T\geq 20 \text{ ms}$$

where F is the axial compressive force, and T the primary load pulse duration. In this criterion the force to produce fracture is a function of load pulse duration. Unfortunately these tolerance levels are related to femur fractures that are generated by injury mechanisms that are not realistic in pedestrian accidents. However the methodology used to define the FIC can be applied to define dynamic characteristics of long bones in the lateral impact. Gibson et al., (1986) proposed the tolerance level to fracture the femur of 7.5 kN as a suitable value for mathematical modeling of pedestrian lower extremity.

Tibia - The dynamic bending strength of the tibia has been studied with unembalmed tibias by Nyquist et al. (1985). The bending moment to produce a tibia fracture was found to be 320 Nm for males and 280 Nm for females. Hoefs and Heinz (1987) proposed that the bumper impact force in contact with tibia should be below 4 kN.

Knee - Limited data are available for injury to the knee joint at lateral impact loads. Bunketorp (1983) performed a series of experiments with human lower extremity specimens at lateral impact loading associated with car-pedestrian collisions. In this study, condylar bone fractures were observed at peak impact forces from 3 kN to 8 kN in the experiments at an impact speed of 31 km/h.

Kajzer et al., (1990 and 1993) determined the injury tolerances of the knee under lateral shearing and bending load of the extended lower extremity. The peak value of the knee shearing force associated with the knee injury was about 2.6 kN at an impact speed of 15 km/h and about 3.2 kN at an impact speed of 20 km/h. The mean peak value of the knee bending moment associated with the injuries was 101 Nm at an impact velocity of 16 km/h and 123 Nm at an impact velocity of 20 km/h. The peak load value increased with a higher loading speed. This finding confirmed that the response of the knee joint depends on the loading rate, due to the viscoplastic property of biomaterials.

The tolerances of knee ligaments are described widely in the medical literature (Girgis et al. 1975, Trent et al. 1976 and Andriacchi et al. 1983). Unfortunately these data are based on static or quasi static experiments.

Protection countermeasures

Analyses of traffic accidents and research into injury mechanisms help us develop guidelines to improve vehicle safety. The passenger car is the vehicle most frequently involved in vehicle-pedestrian accidents in all highly motorized countries, and it is therefore appropriate to give priority to the study of car-pedestrian collisions. Many safety improvements have been made in cars for occupant protection, including common use of the occupant restraint systems, the air bag, reinforcement and padding of side panels, and reinforcement of the footwell area. So far very little has been done for pedestrian protection.

Lowering the bumper level and increasing the compliance of the bumper system was proposed to reduce the risk of knee and leg injuries, as a lower and more compliant bumper system can reduce the bumper impact force upon impact with leg and minimize the shearing force and the bending moment in the knee joint and leg segment (Bunketorp, 1983; Aldman et al., 1986). Double bumper systems has been suggested to lower the contact point on the pedestrian leg (Kajzer et al., 1989; Grösch and Heiss, 1989). The principle of this solution was to keep the standard bumper and attach a structure below the bumper to reduce the bending moment at the knee level.

The difficulty of protecting the pedestrian lies in the complexity of the problem particularly with regard to the different sizes and ages of the victims (children, elderly people) and different injury types (the most frequent of which are those to the lower extremities and to the head). Lowering of the bumper level may reduce the severity of the injury to the leg, but the potential risk of fracturing the ankle joint then becomes greater. Possible measures to improve the car in this aspects are the use of energy-absorbing materials in the front structures of the vehicle, removing sharp edges and increasing the distance between the hood and engine components.

MATHEMATICAL MODEL OF THE LOWER EXTREMITY

During the past two decades research on pedestrian protection has been widely done with biological models and mechanical models. Biological models have been used to study the impact tolerance of lower extremity. Biological models and mechanical models were used to investigate the aggressiveness of car front structure.

Mathematical simulations of the pedestrian impacts were performed by Wijk et al., (1983) and Janssen et al., (1986). In these studies pedestrian body was described by slightly modified characteristics of the Part 572 crash dummy. Analysis of results from these computer simulations of pedestrian impacts shows that the standard description of the pedestrian model in the MADYMO based on Part 572 crash dummy is not fully comparable with the experiments performed with biological specimens. The deficiencies are the limited lateral flexibility in the pedestrian model and the undeformable elements. In these computer simulations, the impact response of the knee appeared excessively stiff, compared with the impact response of a biological specimen. Knee and leg injuries cannot be properly predicted in simulations with this pedestrian model. As the mathematical models derived from the crash dummies are not adequately representative of the lower extremities, it is necessary to develop a mathematical model based on the available biomechanical data from human subject experiments. Such a model should comply with the human body as closely as possible.

Study of injury mechanisms of the lower extremity indicated that the knee injuries are influenced by the leg bone deformation and fracture. The response of the knee joint is strongly dependent on whether the leg was fractured or not (Yang and Kajzer, 1992). The dynamic response of the knee and the leg during a lateral impact could not be properly predicted by the simulations with the standard cardan joint and the rigid element that are commonly used in traditional multibody models. For the reason mentioned above a 3D human-like knee joint model and a breakable leg model were developed to obtain a mathematical model with good biofidelity.

The aims of this study were the follwing:

- to develop a 3D mathematical model of the lower extremity, with special emphasis on the biofidelity of the knee joint and the leg,

- to validate the developed model with available results from human subject experiments.

The validated model should be usable to predict the risk of injury to the lower extremities upon lateral impact loading, to evaluate the frontal structures of vehicles and to introduce a guideline for safety component design of automobiles in conjunction with a sub-system test procedure of vehicle aggressiveness.

Knee Joint Model

Three dimensional knee joint model - The knee joint is the largest joint in the human body. It is a very complex system and many mechanical aspects of the joint functions are not yet completely understood. The behavior of the knee at impact depends mostly on its geometry and the stiffness characteristics of the ligament structures. In modeling of the knee, it is therefore necessary to describe the articular surfaces, the ligaments and the capsule. In this study, the knee joint model was limited to take into account the femoral and tibial condyles, the ligaments and the posterior part of the capsule. All the relevant elements of the knee which are mainly responsible for the transfer of forces acting on the knee joint are taken into account for development of the knee model. For simplification purposes, some anatomic structures, such as the menisci, are not included in the present knee model.

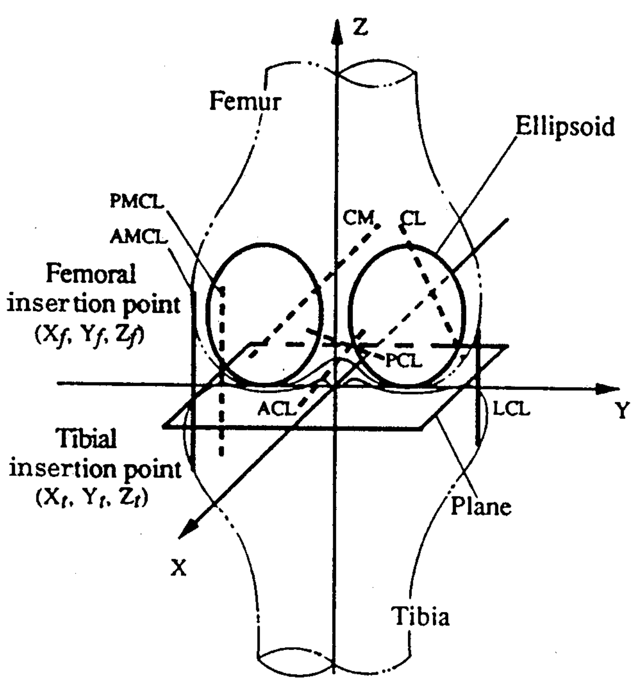

Figure 4. Configuration of the 3D knee joint model and the coordinate system. For simplification the attachment point of the LCL is placed on the tibia.

Geometrical configuration of the model of the knee joint - In the mathematical knee model the skeletal parts, ligaments and the capsule are represented. The skeletal parts of the knee joint, including the femoral and the tibial condyles, has been described mathematically by ellipsoid and plane elements (Figure 4). The soft tissue structures as the major ligaments and the joint capsule were decided to be represented by a set of spring elements: the anterior cruciate ligament (ACL), posterior cruciate ligament (PCL) and lateral collateral ligament (LCL) by one spring each, the medial collateral ligament (MCL) by two springs, one for the anterior part (AMCL) and one for the posterior part (PMCL). The posterior part of the capsule was decided to be represented by two springs, one for the posterior medial part (CM) and one for the posterior lateral part (CL). The mechanical properties of the knee joint structure were based on available biomechanical data.

The dimensions of all the simulated elements are based on available data measured on specimens of the human knee joint. The data from such measurements show large differences between specimens. Since approximate ligament dimensions are necessary in the computer simulation, an average value for the length of the ligaments has to be chosen. Table 1 shows the length of ligaments derived from Girgis et al. (1975), Trent et al. (1976) and Andriacchi et al. (1983). The coordinate system is shown in Figure 4. The width of the medial-lateral femoral condyles is taken as 80 mm, the distance between the ellipsoid (condyle) centers is 50 mm.

Table 1
Length of the knee ligaments

Ligaments	Length (mm)
ACL	35
PCL	38
AMCL	73
PMCL	73
LCL	50
CM	55
CL	45

Ligament strength and contact stiffness - Studies of the ligament strength and elongation have been carried out by many researchers (Noyes et al., 1974; Girgis et al., 1975; Trent et al., 1976; Kennedy et al.,1976; Noyes and Grood, 1976). Typical force deflection characteristics for the ligaments were measured by Trent et al. (1976). They reported the average force per unit strain and the average rupture force for the different ligaments. The spring force deflection characteristics of the ligaments used in our model are based on Wismans (1985). The representations of the stiffness of the spring element are illustrated in Figure 5.

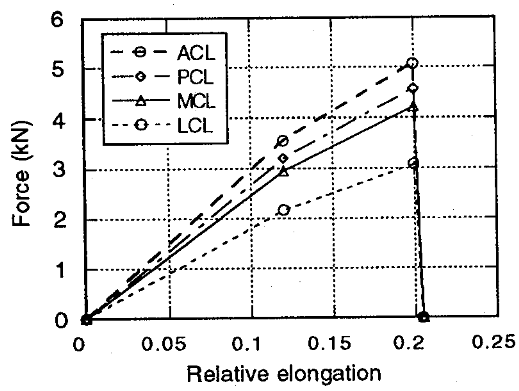

Figure 5. Force deflection characteristics of the ligament springs in the knee model.

Butler et al. (1986) proposed 13% to 15% of the ligament strain as an appropriate value for the failure of the ligament. The first sign of partial rupture of the ligaments was defined in our simulations to occur at 12% of the corresponding strain. At 20% strain it is assumed that the rupture is total. Table 2 shows a correlation of ligament strain calculated in computer simulation to the AIS (Abbreviated Injury Scale) severity classification of the ligament injuries used in the experiments with biological material. The AIS system has been widely used since 1971 to describe the risk of death from different injuries, and gives a code number, in a scale from 1 to 6, for injury severity classification. This correlation made it possible to compare results from the computer simulations with injuries found in the previously performed experiments with biological material.

Table 2
Correlation of the ligament strain with severity classification of the ligament damage

Ligament strain ε (%)	AIS code
$\varepsilon \geq 20$	3
$15 < \varepsilon < 20$	3 -
$12 \leq \varepsilon \leq 15$	2
$\varepsilon < 12$	0 - 1

Data according contact stiffness of the femur and tibia condyles from static experiments have been chosen in our model. Walker and Hajek (1972) made an experiment with four cadaver knee joints and measured the compression of the joints in axial static loading of 1500 N. It was found that the compression of the knee joint was 1 mm after 5 seconds of loading, and that it was virtually stable at 2 mm after 30 minutes of loading duration. In another study, a linear force deformation characteristic of 750 N/mm was proposed by Wismans (1985) in a 2D model of the human knee joint. This linear force deformation characteristic for each condyle interface was used in the knee model. The friction at the interface of the condyles was assumed to be zero in the knee model, since the friction coefficient is small due to the synovial fluid lubrication.

Leg Model

Instead of one rigid element, as in the original MADYMO model, the pedestrian breakable leg model consists of two rigid body elements connected by a "frangible joint" with characteristics described by a user subroutine. The "frangible joint" is located and variable at the bumper impact level and defined by a cardan joint. The geometry and mass characteristics of the leg model are calculated to achieve properties consistent with the one element model of the leg (Figure 6). The user subroutine in the MADYMO 3D (TNO, 1992) was used to describe the "frangible joint".

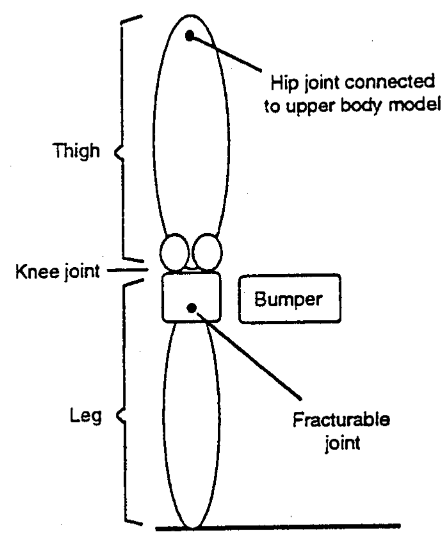

Figure 6. The lower extremity model with breakable leg.

The characteristics of the "frangible joint" are shown in Figure 7a and 7b where ϕ, θ, ψ are the rotation angles in the cardan joint, T_ϕ, T_θ, T_ψ are the torques acting on the joint, and α is an undimensional coefficient. As long as the criterion of fracture initiation is not fulfilled, the coefficient $\alpha = 1$ (Figure 7b) and the "frangible joint" will convey components of the moment according to the typical characteristic (Figure 7a), which has been introduced to the MADYMO 3D program in a standard way using the input data file.

The process from the beginning of the fracture to the total fracture of the bone is characterized by a sudden decrease in rigidity in the "frangible joint". In the adopted model it is assumed that the decrease is a linear function of time (Figure 7b). The whole process ends after time interval ΔT, when the value of moment conveyed by that artificial joint decreases to the level in which only damping and friction is remaining.

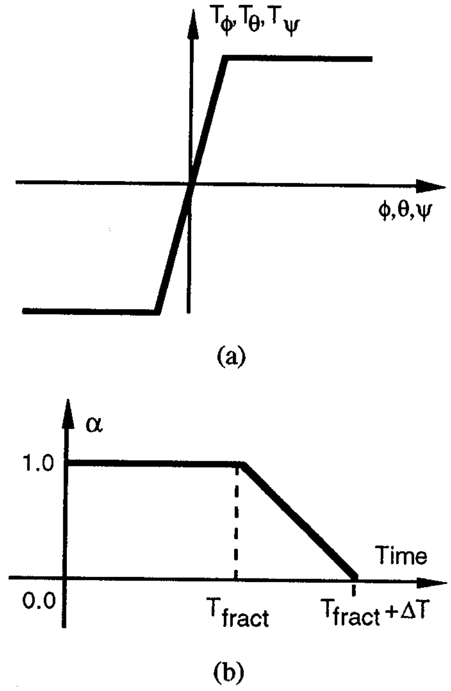

Figure 7. Components of moment-deformation characteristics of "frangible joint".

The bone material as all biological materials has viscoelastic properties. It is known from experiments (Viano, 1977; Lowne, 1982) with cadaver specimens that the force value that initiates the bone fracture process depends on the duration of a load pulse in the way shown in Figure 8, as well as on a loading rate.

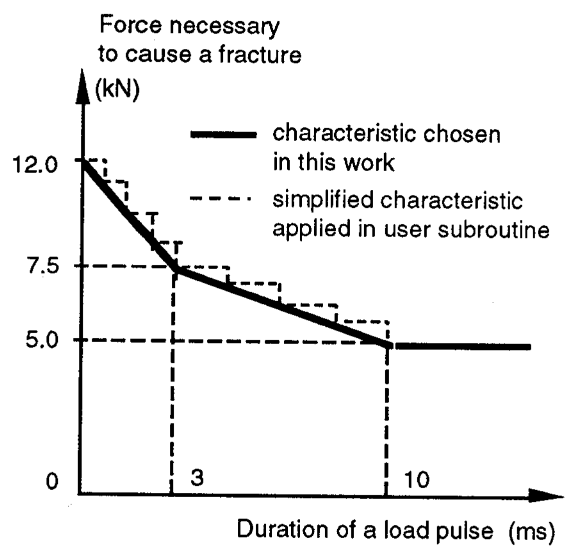

Figure 8. Dependence between the duration of the load pulse and the force value in fracture of a long bone: characteristic used in the presented study.

The tibia fracture process represented by the "frangible joint" was simulated by means of the user subroutines which describe the dynamic response of the tibia to the various impact load pulses (Figure 8). The input data for the "frangible joint" model originate from available biological specimen experiments. Figure 9 presents a detailed scheme of implementation of the "frangible joint" model in MADYMO.

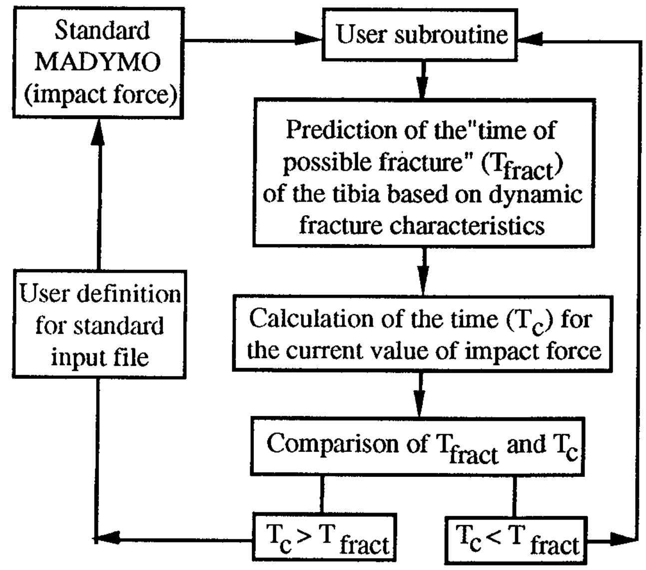

Figure 9. Flow chart of the user defined subroutine for "frangible joint" model in the MADYMO 3D system.

In case of impact, the value of a load pulse changes very rapidly. Thus, to predict whether a fracture will occur, it is necessary to check the time history of the impact force between a bone and an impactor on-line during simulation. The impact force is calculated for each time step of the simulation.

During the modeling, the program calculates the impact force step by step. At the same time the user subroutine predicts the "time of the possible fracture" (T_{fract}) based on the fracture characteristics, and calculates the time (T_c) for the current value of impact force. Thus, a comparison is made between T_c and T_{fract}. If the duration of the current impact force is less than the predicted T_{fract}, the user subroutine goes on the prediction of the tibia fracture. If the duration of the current impact force is greater than predicted T_{fract}, a fracture is initiated, and a new user definition of the standard MADYMO input file is used henceforth in the calculation.

Validation of the Mathematical Model of the lower extremity

The new models of the knee joint and the breakable leg were implemented in the pedestraian model and were validated against the previously performed human subject experiments (Bunketorp, 1983 and Aldman et al., 1986). In a series of simulations, the pedestrian model was hit by a bumper below the knee joint at impact speeds of 31 km/h. The height of the bumpers was chosen to be 450 mm and 325 mm above the ground. Different bumper's characteristics were used to simulate the same test conditions as in the previous experiments with biological subjects. The impact force, the condyle interface forces, the ligament tensile forces, the ligament relative elongation and the leg acceleration were calculated and compared with outcomes from human subject experiments.

RESULTS AND DISCUSSION

The results from the computer simulations with human-like knee joint and the breakable leg model for the four configurations at an impact speed of 31 km/h are presented and compared with the results (mean values) from the biological specimen experiments.

Impact forces and accelerations - The bumper impact forces and the leg accelerations at impact level from the computer simulations and the human subject experiments are presented in Table 3. The peak bumper impact forces and the peak accelerations of the leg at impact level changed with the different parameters for bumper compliance and bumper level. The impact forces varied between 2.2 kN and 7.2 kN for the simulation series with the breakable leg model, which was in accordance with the specimen experiments. The accelerations of the leg at impact level varied from 80 g to 520 g. The peak accelerations in the simulations were higher than the results from the biological specimen experiments.

A comparison between the results of the simulations with the breakable leg model and those of earlier biological specimen experiments showed that the peak values of the bumper impact force in the simulations agree with the results (mean values) from the biological specimen experiments (Table 3). The input parameters of the simulation set-up were based on mean values and therefore such a system cannot give a good correlation with each single experiment with a human leg specimen, but the same tendency of peak impact forces as in biological specimen experiments can be predicted very well by simulations. The calculated impact force on the bumper tends to increase with increased stiffness of the bumper system.

Table 3 shows the accelerations of the leg at impact level in the mathematical simulations and in the biological specimen experiments. If we make a comparison between results from the simulation and the experiment of each individual configuration, a difference will be found. An important reason for this is that the measurement method in the specimen experiments was completely different from the calculations in the simulations. In the experiments, the accelerometer strapped to the leg soft tissue at the opposite side of the impact area was unstable. The signal from the accelerometer was registered by a mechanical device that could not catch the high frequency signal. The mechanical recording device thus worked as a filter, and the high frequency signal was cut off. Therefore, it was anticipated that the results from such a measurement would be much lower than from the simulations. Another reason for this difference is probably variations in active mass of biological specimens in the previous experiments. Even though the higher accelerations were obtained in simulations rather than in experiments, a similar tendency of peak accelerations can clearly be seen for all configurations in the simulations with the breakable leg model and in the biological specimen experiments. It is shown that the breakable leg model is sensitive to changes in car-front parameters, such as bumper stiffness.

It is necessary to point out that an impact phenomenon lasts for a very short time (milliseconds). Thus, there is a need to apply standard filtering procedures for experimental experiments as well as for computer simulations. Without such procedures any accurate comparisons between experimental and calculated results would be very difficult or even impossible, in particular if the results have been obtained by different research teams and not all the experiment conditions are reported.

Condyle contact forces - In the computer simulations with the breakable leg model, the condyle contact forces varied between 1.9 kN and 9.8 kN for the lateral condyle, and between 0.15 kN and 0.20 kN for the medial condyle (Table 4). In the human leg specimen experiments, a transverse fracture below the tibial condyle

Table 3
Peak impact forces and leg accelerations at impact level from the computer simulations and specimen experiments at an impact speed of 31 km/h (Experiment results are based on Bunketorp, 1983 and Aldman et al., 1986)

configuration	Specimen Experiment mean value (N=5)		Computer Simulation	
	impact force (kN)	acceleration (g)	impact force (kN)	acceleration (g)
Rigid-high	7.4	263	7.2	520
Less rigid-high	2.4	87	2.5	125
Soft-high	2.6	68	2.2	80
Less rigid-lower	2.2	93	2.5	120

at the impact level and/or a split-depression fracture of the lateral tibial condyle could be observed in experiment 1 and 4 in the configuration of "soft" - high level bumper. The highest AIS for the condyle damage was 3 in the experiments.

Table 4
Condyle contact force from simulations and condyle damage from biological specimen experiments at an impact speed of 31 km/h
(Experiment results are based on Bunketorp, 1983 and Aldman et al., 1986)

configuration	Condyle damage* from experiments		Condyle force from simulations	
	MC**	LC**	MC (kN)	LC (kN)
Rigid-high	0	0 to 3-	0.20	6.0
Less rigid-high	0	0 to 3	0.20	9.8
Soft-high	0	0 to 3	0.15	9.1
Less rigid-lower	0	0	0.15	1.9

* AIS code
** MC = Medial condyle, LC = Lateral condyle

In all simulations with the high level bumper (Table 4), the calculated value of contact force for the lateral condyle ranged from 6.0 kN to 9.8 kN, and from 0.15 kN to 0.20 kN for the medial condyle. In the corresponding experiment with the human leg specimen, damage of AIS 3 to the lateral condyle could be observed but there was no damage to the medial condyle. In the case of the "less rigid" - lower bumper, the condyle contact forces were lower for the lateral condyle (1.9 kN). The condyle contact force from the simulations indicated that a good prediction of impact response of the knee was achieved with the breakable leg model.

In a study with cadaver specimens, Powell et al. (1975) reported that condyle fractures were observed when the peak impact force varied from 7 kN to 10 kN. This experimental result is not directly comparable with results from our simulations due to differences in test conditions, but we noticed that a very close force level (6 kN to 10 kN) was obtained in our simulations. The condyle fractures were observed in 40% of the experiments with biological specimens, except for "less rigid" - lower bumper configuration where no condyle fracture was observed. In the mathematical simulation of this configuration the condyle contact force was low. The calculated condyle force can be used to predict the risk of condyle fracture.

Ligament strains - The ligament strains varied between 6% and >20% for MCL, 3% to 17% for ACL and 2% to 11% for PCL in the simulations with the breakable leg model (Table 5). The ligament strains in these simulations indicated that the MCL experienced greater tension than did other ligaments. Ligament strains exceeding 20% mean that complete rupture of the ligament occurs. Typically, the results from experiments with the "rigid bumper" - high level configuration show that MCL ligament damage was AIS 3 in all five experiments. In experiment number 4 for the same configuration, the impact response was also mainly connected to all ligament damage of AIS 3.

In all computer simulations the largest relative elongation appeared for MCL and can be seen in Table 5. The risk of damage to the MCL was high in the biological specimen experiments. In these experiments it corresponded to AIS 3 and AIS 2 damage of MCL. The mechanism of damage to the knee joint in the experiment with human leg specimens is very complicated, and many structures cooperate in the energy absorption. In the mathematical simulation we cannot analyze the value of each output parameter separately. It can be noticed that in experiments with biological specimens, fractures of the tibia and the

Table 5
Ligament strain from simulations and ligament damage from biological specimen experiments at an impact speed of 31 km/h
(Experiment results are based on Bunketorp, 1983 and Aldman et al., 1986)

configuration	Ligament damage* from experiments			Ligament strain (%) from simulations			Bone damage*
	MCL	ACL	PCL	MCL	ACL	PCL	
Rigid-high	3	0 to 3	0 to 3	>20	17	11	
Less rigid-high	0 to 3	0 to 2	0 to 3-	19	6	4	[3] (3)
Soft-high	3	0 to 3	0 to 3	17	5	4	
Less rigid-lower	2 to 3-	0	0	6	3	2	

* AIS code
[3] = Tibial fracture, (3) = Lateral condyle fracture

lateral condyle were observed in this configuration. These fractures may have protected the knee ligaments from damage in experiments. In the "less rigid" - lower bumper configuration, the relative elongation (6%) of MCL was underestimated in the simulation.

The second largest relative elongation for all ACL can be calculated. In the simulations, the values of the ACL relative elongation varied from 3% to 17%. In the "rigid" - high level bumper configuration, the ACL relative elongation was high (17%), and a high risk of ACL damage could be seen in the experiments. In the "less rigid" - lower level bumper configuration, the relative elongation of the ACL was low, and no damage to the ACL was noted in the experiments.

The calculated relative elongation of all PCL was smaller than that of MCL and ACL in the same configuration. The results of PCL relative elongation from the simulations ranged from 2% to 11%. A similar tendency of relative elongation and damage for the PCL was observed in the simulations and experiments. In our mathematical model the tibial and femoral condyles were represented by rigid elements. The characteristics of condyle fractures were not improved in the model. Even though the fracture of the condyle cannot be simulated, the mathematical model can adequately predict the risk of ligament damage.

Time histories - A comparison of the time histories of the bumper impact forces and the leg accelerations at impact level for all configurations are illustrated in Figure 10 and 11. In the simulations, it is important to obtain an impact response corresponding to biological specimen experiment. The time histories of bumper impact force show that the response time of peak value from the simulation was consistent with result from corresponding specimen experiment. The wave forms are similar between the simulations and experiments. The response time and wave forms of leg accelerations at impact level are also comparable between simulations and experiments. However, in the configuration with less rigid bumper, the response time of peak value is different between simulation and experiment. This difference seems to be influenced by the resultant stiffness at the impact-contact area.

It was shown that impact response of the knee could generally be predicted by the condyle contact force and ligament strain calculated in the model. These forces and strains might correlate to injuries to the knee observed in experiments and real accidents. In the current study, with a human-like knee joint and a breakable leg model, the condyle contact forces and the ligament strains appeared more reasonable. The model is more sensitive to changes of impact parameters.

The calculated value of impact force in simulations is less influenced by ligament strength. However, the impact response of the knee joint is significantly influenced by the ligament strength characteristics in the simulations. The lateral condyle contact forces increase and ligament elongation decreases with the increase of ligament strength. The effect of the biological material property is important for the calculation of the ligament force and elongation.

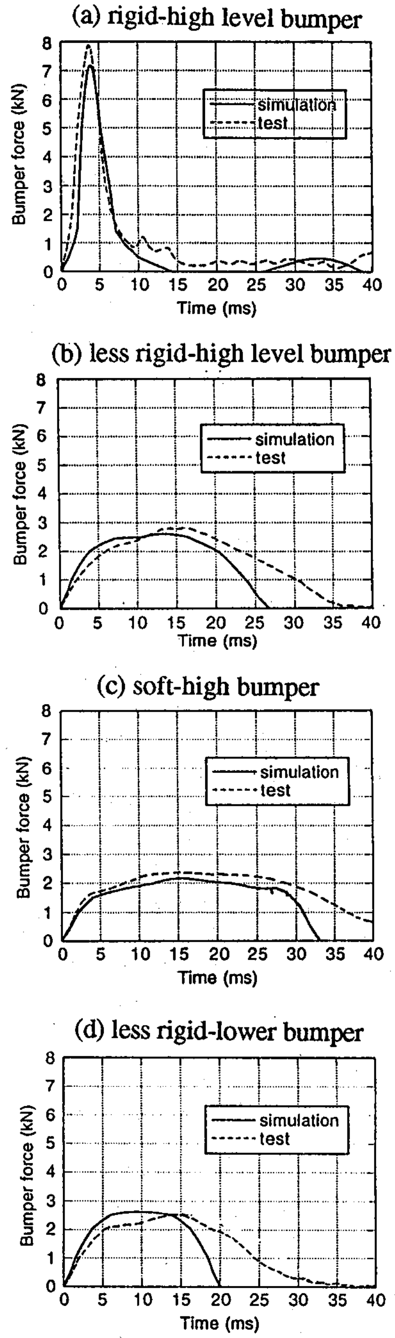

Figure 10. The time histories of bumper impact forces from the simulations and the typical experiments.

The ligament is sensitive to the loading rate due to its viscoelasticity. In case of lateral impact to the leg, the knee joint ligaments are exposed to a high loading speed. At present the available data of ligament load-deformation are based on experiments with lower loading speeds. For instance, Kennedy et al. (1976) reported an almost 50% increase in the load to failure when the loading speed was increased fourfold from 12.5 cm/min. to 50 cm/min. during tensile testing of the knee joint ligaments. In the current simulations, the estimated values of ligament strength for dynamic response, are based on a study presented by Wismans (1985) (Figure 5). The results indicated that the selected values for ligament strength are acceptable for this velocity range.

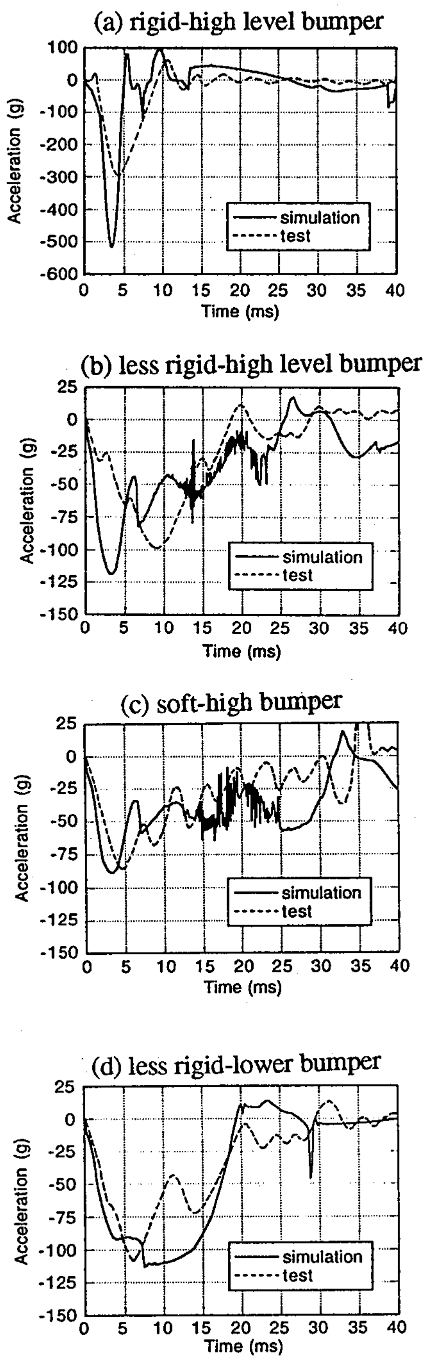

Figure 11. The time histories of leg acceleration at impact level from the simulations and the typical experiments.

CONCLUSIONS

There is an increasing need of various mathematical models with good biofidelity in simulation studies of crash accidents. Mathematical models provide a very cost-effective and versatile method for analyzing dynamic responses of complex systems, such as human body responses.

The developed lower extremity mathematical model, with human-like knee joint and breakable leg elements, has been implemented using the MADYMO program in a configuration of car front-pedestrian impact. Good correlation between results from the computer simulations and the human leg specimen experiments has been achieved. The output parameters from this model could show the potential of crash analysis using the mathematical model. Some physical quantities, difficult to measure in laboratory crash experiments, can be calculated using the mathematical model, such as calculation of the knee ligament strain and the contact force of the articular interface. It can fill the gap of laboratory crash experiments.

Validation of the mathematical model showed that the model allows prediction of the risk of knee ligament failure and long bone fracture. It can also be used to analyze the injury mechanism of the knee and fracture of the leg after lateral impact to the pedestrian leg under various impact conditions. The validated model is therefore expected to be useful for parameter studies of car-pedestrian crash accidents.

Sub-routines defined by the user in the MADYMO 3D system are useful tools in biomechanical modeling, allowing simulation of some physical phenomena, such as the viscoelastic property of the long bone fracture that cannot be described by the present MBS program. The method for modeling of long bone viscoelastic properties proposed in this work can also be applied to modeling of ligaments and condyles of the knee joint as well as other structures of the human body.

The mathematical model of the lower extremity with the human-like knee joint and breakable leg can be used instead of a sub-system impact test proposed for evaluation of car-front aggressiveness against pedestrians.

The model was only validated for the pedestrian lower extremity. It can be used in other configurations, for instance, for car occupants, but in this case the input data must then be adjusted and validation of the model should be carried out for this new configuration.

Some differences were observed between the computer simulations and the biological specimen experiments. They are most likely due to the limited availability of data about biomaterial properties for the simulations and the simplified geometry of the bone structures.

Despite relative simplicity of rigid multibody models, their versatility can provide relevant and acceptable information about human reactions to impact loading with a shorter calculation time than the FEM models. But the reliability of the MBS models strongly depends on the availability of experimental data about the various components. To improve the calculation results, it is necessary to carry out extensive experimental investigations that can provide proper dynamic data about car components as well as human body segments for both hard and soft tissues. The behavior of the human body, such as the size, mass and moment of inertia of body segments, can be derived from a potential of the GEBOD program. However the fundamental shortcoming of a rigid multibody model is that contact surfaces are restricted to ellipsoid and plane shapes. Finite element models, on the other hand, are essentially based on consistent material properties and accurate geometry, so that deformation of body regions can be simulated in a more realistic way. Thus, both techniques of the multibody system and finite element method should be applied to modeling of the human body by taking advantages of each algorithm.

There are needs for future research work to focus on:

- development and validation of a realistic human body model, which will be based on the present study;
- development and validation of a FEM model of body segments which will allow calculations of the stress and strain distribution within body segments, and facilitates a good understanding of injury mechanisms at the level of stress analysis;
- parameter studies of the impact biomechanics of body segments, with the emphasis on the lower extremities, especially the knee joint and leg bone;
- assessment of car front aggressiveness against pedestrian with a verified mathematical model.

ACKNOWLEDGMENT

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Development and Design of a New 18-Month-Old Child Dummy

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ABSTRACT

During 1993, an ad-hoc working group of the GRSP, addressing ECE Regulation 44 (Child Restraint Systems), decided to propose the addition of a 'Group 0+' to this regulation. This group of restraints concerns the maximum size/age/weight of children to be carried in a rearward facing child restraint system that can be held by a conventional 3-point belt system in front passenger car seats. The working group decided that for the evaluation of these type of CRSs, an 18-month-old dummy was needed. On this basis, the TNO Crash-Safety Research Centre, together with Ogle Design Ltd., started to work on a new child dummy: the TNO P1½.

In this paper, the development and the design of this new prototype 18-month-old dummy are presented and the rationales behind its design are discussed. Based on regulatory and research applications of the P1½, performance specifications are set up.

The most important specifications concern the anthropometry and biofidelity of the new dummy. In addition other characteristics (repeatability, reproducibility, durability, etc.) have been taken into account during the design process. Using the latest anthropometry data available, incorporating enhanced instrumentation and applying new materials to improve biofidelity, have provided an advanced child dummy design.

INTRODUCTION

The first child dummy used in Europe to evaluate child restraint systems (CRSs), mainly served to determine the strength of these protective devices. This dummy, called Pinocchio, was of very simple and basic design and was developed by TNO in the mid sixties. Its main body parts were made of wood and leather and its joints incorporated steel elements (Figure 1).

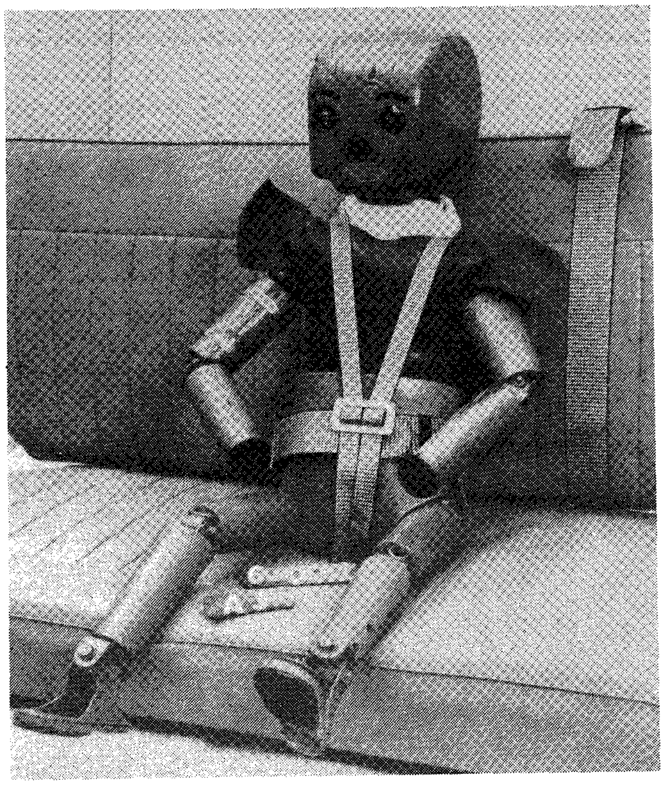

Figure 1. Pinocchio [1].

Though of simple design, Pinocchio provided first insights into child occupant protection and child dummy development. Representing a child of approximately 4 years old, this dummy was used in a comparative test programme on child restraints [1].*

This test programme indicated, amongst other things, the need to improve protection of the child when transported in (passenger) cars and initiated enhanced safety at regulatory level. In the mid seventies, the United Nation's group of experts on passive safety (GRSP) started to work on requirements for CRSs, which have been layed down in a regulation which is known as ECE Regulation 44 [2] (further referred to as ECE R.44). An ad hoc group within the GRSP was asked to develop a series of child dummies needed for this regulation. This series is known as the TNO P-series of child dummies, incorporating the P0 (newborn), P ¾ (9 months), P3 (3 years), P6 (6 years) and P10 (10 years) [3,4]; the 'P' still referring to Pinocchio. The P-series of child dummies is shown in Figure 2.

Enhancements in CRS development and improved knowledge of occupant protection have led to a rather extensive amendment of ECE R.44 [5,6]. In September 1993, the GRSP has decided that a new dummy is required, representing an 18-month-old child The new (03) series of amendments to ECE R.44 have recently been approved by the United Nations Working Party 29.

* Numbers between brackets designate the references at the end of this paper.

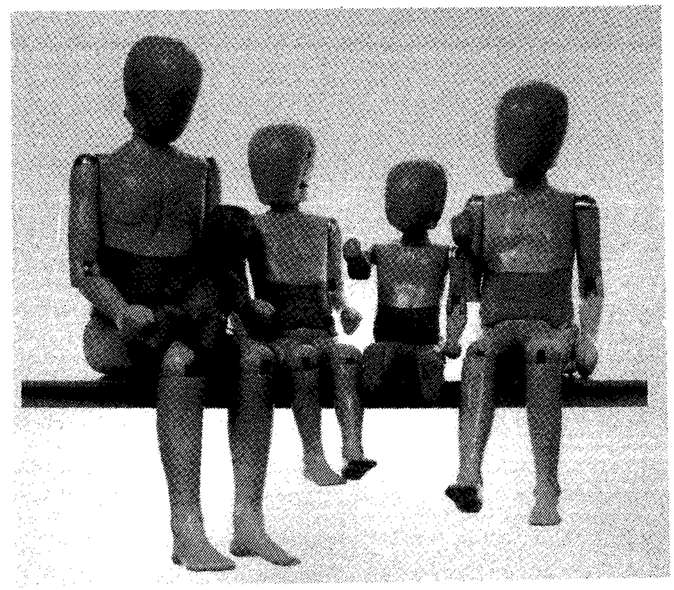

Figure 2. TNO P-Series of Child Dummies (from left to right: P10, P0, P3, P ¾ and P6).

In parallel to these regulatory activities, the TNO Crash-Safety Research Centre performed an extensive review study on child dummy development. Starting in 1991, fundamental knowledge has been gathered on injury biomechanics of children, child anthropometry and on general dummy characteristics, such as repeatability, reproducibility, instrumentation, sensitivity, handling, etc. [7,8,9,10]. This review study has nearly reached completion and provides a kind of 'state-of-the-art' that can be used for future child dummy development.

Putting the GRSP and TNO developments together, the TNO Crash-Safety Research Centre has decided to develop, together with Ogle Design Ltd (UK), a new 18-month-old dummy for ECE R.44. This new dummy completes the TNO series of child dummies for this regulation.

The objective of this paper is to present the development and design of the prototype 18-month-old dummy and the rationales behind its design.

In this paper, first the applications of the new dummy are described. Combining these applications with information on existing child dummy designs, the configuration of the new 18-month-old dummy is defined. This configuration provides a general impression on the dummy's complexity: it explains which body parts and joints have been modelled.

Second, design and general performance specifications are given, which have been used throughout the design process. Main attention is given to anthropometry and biofidelity but also other characteristics (repeatability, reproducibility, sensitivity, durability, etc.) have been taken into account and are discussed in this paper.

Third, the design of the prototype dummy is presented per body part and as a full assembly. In this part of the paper, also the measurement capabilities of the dummy are shown.

Fourth and final, conclusions of the design process are presented and attention is given to future activities of the development of the new 18-month-old dummy.

APPLICATIONS

The first step in the design process of any crash dummy is to determine what the applications of the dummy are or may be. On the basis of the applications and knowledge on existing child dummy designs, the configuration of the dummy is defined.

ECE R.44 Group 0+

In the current version of ECE Regulation 44 (including the 02 series of amendments), CRSs are classified in 4 mass groups [2]:

- Group 0: for children of mass less than 10 kg;
- Group I: for children of mass from 9 kg to 18 kg;
- Group II: for children of mass from 15 kg to 25 kg;
- Group III: for children of mass from 22 kg to 36 kg.

To evaluate CRSs according to ECE R.44, the TNO P-series of child dummies are specified (see Figure 2). The protective performance of CRSs has to be evaluated using 2 dummies per group: one at the top end (weight) and one at the low end (weight); e.g. a Group 0 type CRS has to be tested using the P0 (3.4 kg) and the P¾ (9 kg).

The new series of amendments (03) to ECE R.44, provides the opportunity to extend the weight, and thus age, of children to be carried rearward facing by adding a Group 0+ ('zeroplus') [5]. Group 0+ type CRSs can be used rearward facing only, in the front passenger seat held by a conventional 3-point belt system. This group concerns children up to 13 kg which is approximately the 95th percentile weight of an 18-month-old child. Considering the limited space available when using a 3-point belt, however, the maximum child dimensions approximate that of a 50th percentile 18-month-old child. The GRSP therefore requested a dummy representing a 50th percentile 18-month-old child for the top end evaluation of Group 0+ type CRSs.

Particularly the dynamic sled tests included in ECE R.44 determine the functional requirements of the dummy. A frontal impact sled test should be conducted at 50 km/h with a maximum trolley deceleration between 20g and 28g. Also, a rear impact sled test should be conducted at 30 km/h with a maximum trolley deceleration between 14g and 21g. The principle of the test set-up for Group 0+ CRS, not leaning against the dashboard/instrument panel is shown in Figure 3.

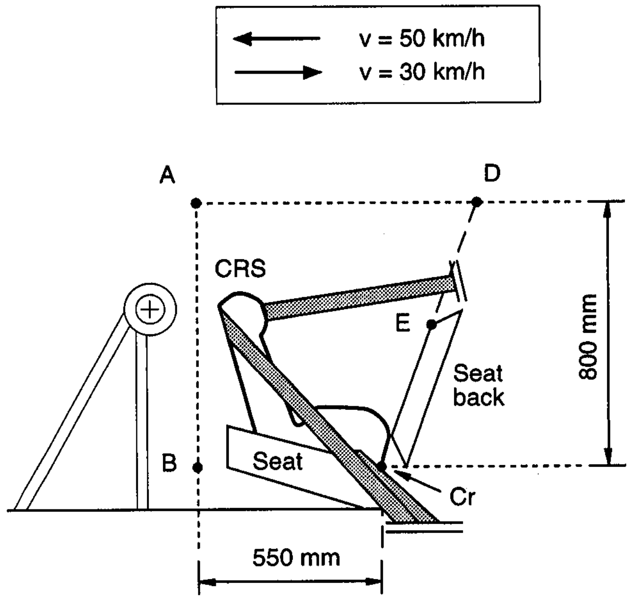

Figure 3. ECE R.44 sled test set-up; Group 0+ rearward facing CRS not leaning against the dashboard.

The dummy performance criteria for ECE R.44 Group 0+ type CRSs, in both front and rear impact, are:

- The resultant chest acceleration may not exceed 55g for longer than 3 ms cumulatively;
- The vertical component of the chest acceleration, from the abdomen to the head, may not exceed 30g for longer than 3 ms cumulatively;
- Considerable abdominal penetration is not allowed;
- No excessive stresses may occur at weak body parts (abdomen, crotch, etc.), neither as a result of direct contact nor as a result of inertial loading;
- The head should not pass the planes AB, AD and DE shown in Figure 3;
- The head shall not contact any parts of the vehicle interior with a velocity exceeding 24 km/h and the part contacted shall meet the requirements of the energy absorption test of ECE Regulation 21, Annex 4.

Other Applications

The use of the new 18-month-old dummy will probably not be restricted to rearward facing CRSs in ECE R.44 test conditions only. Most obvious extensions of the application of the new dummy are forward facing CRS loading conditions, airbag-CRS interaction and restraint mis-use. These (research) applications have also been taken into account in the development of the new dummy, particularly requiring enhanced instrumentation, improved durability and an even more human-like design of the dummy, compared to its regulatory use.

Configuration of the 18-Month-Old Dummy

The complexity or simplicity of a dummy is a reflection of the minimum level of assessment required by the applications. The European regulation only requires quantitative assessment of the kinematics of the dummy. No high level of detail of the various body parts is required for this but all principle body parts and joints have to be incorporated in the new dummy. This also accounts for other forms of CRS evaluation. A dummy configuration is therefore chosen similar to the current P-dummies (not P0), including:

- a head;
- a flexible neck;
- a torso consisting of a thorax, a compressible abdomen, a flexible lumbar spine and a pelvis;
- shoulder joints;
- hip joints;
- upper extremities consisting of an upper arm, elbow joint and lower arm which includes the hand (no wrist joint);
- lower extremities consisting of an upper leg, knee joint and lower leg which includes the foot (no ankle joint).

Because this configuration is similar to the existing series of P-dummies, the new 18-month-old dummy is given the name 'P1½'; the 'P' referring to Pinocchio and '1½' referring to the child's age (in years) it represents.

DESIGN AND PERFORMANCE SPECIFICATIONS

Detailed design and performance specifications for the P1½ have been established for anthropometry and biofidelity. Only general specifications have been defined for other dummy characteristics.

Anthropometry

The quantitative performance criteria of ECE R.44 are mainly of a kinematic nature. The anthropometry (geometry, inertia and ranges of motion) of the dummy is thus very important: the dummy should particularly reflect the motion of an 18-month-old child. Furthermore, the loading condition is (nearly) in a sagittal plane of the dummy. Correct sagittal ranges of motion of the joints are thus more important than those in other directions.

The anthropometry of the P1½ dummy is entirely derived from the TNO Child Anthropometry Database 'CANDAT' [9,10], which is set up from anthropometry surveys and growth regression formulas from longitudinal growth studies. CANDAT includes anthropometry data from the USA and Western Europe, obtained in the period 1970-1992, and includes over 90 dimensions. From this database a large number of parameters have been determined, specifying a 50th percentile 18-month-old child.

Four types of anthropometric data have been considered:

- external and internal dimensions;
- body segment masses;
- moments of inertia and positions of the body segment centres of gravity; and
- joint ranges of motion.

The most important ***dimensions*** are contained in Table 1 but more have been used in the design process. Figure 4 provides an illustration of the definition of some of these dimensions. Table 1 contains both the value for a 50th percentile 18-month-old child as well as the actual value of the prototype P1½.

Table 1.
Dimensions of a 50th percentile 18-month-old child and the P1½ [10]

CANDAT No.	dimension (description)	18-m-child value (mm)	P1½ value (mm)[1]
	torso		
p3	sitting height (to top of head)	507	507
p5	shoulder height sitting	309	305
p8	biacromial distance	209	210
p9	shoulder width (maximum)	223	224
	hip/pelvis		
p31	trochanter height	366	360
p33	hip width seated	174	174
	thigh		
p34	thigh height (sitting)	65	66
p37	buttock-knee length	240	239
p38	buttock-politeus length	202	201
p39	buttock-foot (leg stretched)	416	412
	lower leg		
p40	knee height	220	214
p41	popliteal height	175	173
p42	tibial height	196	193
	arm		
p51	shoulder-elbow distance	154	157
p54	elbow width	248	250
p55	upper arm bone length	140	142
	lower arm and hand		
p56	lower arm and hand length	209	206
p59	lower arm bone length	116	118
	head and neck		
p66	head length	169	160
p67	head width	126	124
p68	head circumference	480	468
p69	menton-vertex	163	163
p74	neck width	68	70
p76	menton - back of the head	196	187
p77	menton - back of head circumference	533	510
p94	shoulder to vertex	196	195

1: values are ± 3 mm.

Regression equations have been used to establish segment masses, position of the centres of gravity and moments of inertia [11,12,13,14,15]. In those studies longitudinal growth of children is described by linear or quadratic equations. Jensen uses one parameter (age) as independent parameter. Schneider and Zernicke use age, body mass, segment length and circumference as parameters. The values from CANDAT have been used as input. The total body mass is directly contained in CANDAT. Table 2 contains both the ***total body mass as well as the segment masses*** for a 50th percentile 18-month-old child and the P1½.

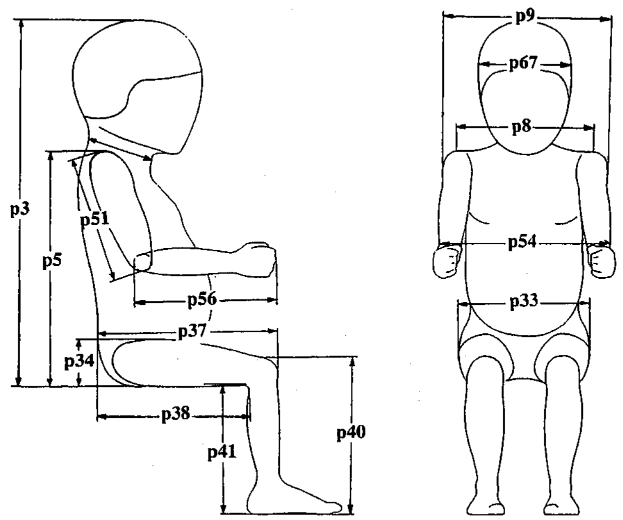

Figure 4. Illustration of child anthropometry dimensions.

Table 2
Segment masses and total body mass [10]

segment (description)	18-month-old child value (kg)	P 1½ value[1] (kg)
head and neck	2.73	2.73
torso	5.06	5.06
upper arm (2)	0.27	0.27
lower arm and hand (2)	0.25	0.25
upper leg (2)	0.61	0.61
lower leg and foot (2)	0.48	0.48
total body mass	11.01	11.01

[1]: values are ± 0.05 kg, except for total body mass which is ± 0.1 kg

The ***position of the centres of gravity and the moments of inertia*** for all segments have been calculated and used in the design process but are not presented here.

The ***joint ranges of motion*** are presented per joint in the section 'design of the P 1½' of this paper.

Biofidelity

The achievable level of biofidelity of a crash dummy strongly depends on the availability of human response data. Currently, no biofidelity requirements exist for child dummies based on actual child responses, except perhaps for some kinematic requirements and material properties [8,16,17,18].

Some biofidelity response requirements for child dummies have been established by scaling adult data. Using a simple technique, developed by GM [19,20], biofidelity targets for the head, neck and lumbar spine of child dummies have been established [21]. A more advanced scaling method has been applied to the 'Kroell adult thorax response corridors' [22,23], using the validated Lobdell model of the human thorax [24]. This method provided force-deflection response corridors for an 18-month-old child dummy [25].

The scaled biofidelity requirements will be used in the evaluation of the prototype P 1½ and is not discussed extensively here. Some comments on body part biofidelity are included in the section 'design of the P 1½' in this paper, particularly concerning the stiffness of various body parts and what affect this has on their design.

Other Characteristics

Many characteristics determine the performance of a crash dummy besides its anthropometry and biofidelity. Some general specifications are presented here that have been taken into account during the development of the P 1½.

General requirements for crash dummy repeatability and reproducibility are that the coefficient of variation of the dummy responses should be below 10% to be acceptable and below 5% to be good [26,27]. This implies two design characteristics: firstly materials should be applied that show limited variation in their properties and secondly it should be possible to certify the dummy. Certification of the P 1½ will particularly address joint characteristics (related to the dummy's kinematics) and body part stiffness (related to the interaction with the CRS). For economic as well as practical reasons, certification of the P 1½ is kept to a minimum but sufficient level for use in ECE R.44.

A correct interaction with the CRS implies generally correct body shape and stiffness. Quite some attention has been given to modelling of the skeleton of the dummy. These -stiffer- parts have been given anatomical shapes, especially at those areas where contact with a CRS is obvious. For the -softer- flesh system surrounding the skeleton, durability has been the main characteristic taken into account.

ECE R.44 only requires to assess the resultant and vertical acceleration at the thorax centre of gravity. Research applications, however, require enhanced measurement capabilities of child dummies, particularly addressing spine loads. The P 1½ has been designed such that load transducers can be incorporated into the spinal column. Also additional acceleration transducers can be incorporated into the dummy to study its kinematics.

DESIGN OF THE P 1½

The Head and Neck

Overall size, weight and weight distribution are important for the ***head*** but no details of the facial structure are considered necessary. Head contact will occur with the CRS and even head contact with the vehicle interior is allowed, provided that the vehicle interior provides sufficient shock absorption. Head stiffness should thus be generally correct.

The design of the head of the P 1½ is shown in Figure 5. The head incorporates a durable head-skin and a semi-rigid skull. The skull consists of an upper and lower part and is provided with a cavity to accomodate instrumentation. This cavity also contains a metal balast weight to obtain the correct head mass and moments of inertia. The facial part is left featureless for reasons of repeatability and durability.

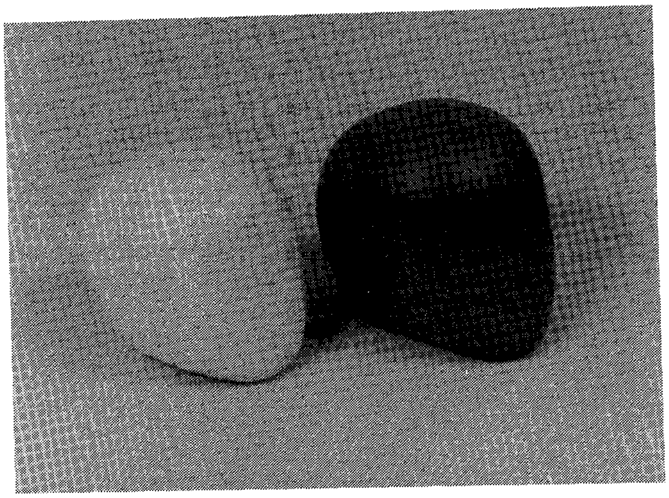

Figure 5. Semi-rigid skull (left) and total head assembly of the P 1½.

The motion of the head is very much controlled by the ***neck***. A child's neck is known to be weaker than that of an adult because the muscles and ligaments, bridging the actual joints of the neck and the OC (occipital condyles) joint, are not yet fully developed [28,29]. At the age of 18 months, a child is already able to keep its head upright [24] thus implying that the neck assembly of the P1½ should provide sufficient stability to keep the head upright under normal (non-impact) conditions.

ECE R.44 includes requirements for the maximum head excursion during impact. The neck and OC joint should be correct in allowing the head motion. The ranges of motion are considered the most important biofidelity requirements for the neck and OC joint. Not all degrees of freedom are equally important for the P1½: the main direction of the load will be in the sagittal plane of the dummy. Sagittal flexion and extension (fore-aft bending) biofidelity of the neck is more important than torsion, shear and compression, however, the design of the neck should allow all these modes of deformation.

Table 3 shows the anatomical ranges of motion of the head-neck system and the design targets used for the P1½ OC joint and neck. The relatively large range of motion at the upper neck (OC and C1-C2 joints) is assigned to the OC joint in the P 1½; the rest of the range of motion of the neck is assigned to the actual neck of the P1½. Thus, similar to the other P-dummies (except the P0), the P 1½ incorporates a separate OC joint.

Table 3.
Neck and OC-joint anatomical ranges of motion and P 1½ design targets [10]

joint	anatomical range of motion	P 1½ neck design
OC	15 degrees[1]	30 degrees[1]
C1-C2	15 degrees[1]	
C2-C3	8 degrees[1]	
C3-C4	12 degrees[1]	Total neck flexion and extension designed for 60 to 70 degrees
C4-C5	18 degrees[1]	
C5-C6	17 degrees[1]	
C7-T1	9 degrees[1]	
OC torsion	unknown	none
total neck torsion	unknown	20-45 degrees
total neck shear	21 mm	20 ± 3 mm

[1]: applies to both flexion and extension

The design of the neck of the P1½ is presented in Figure 6. The OC joint is represented by a hinge joint which behaviour is friction adjusted. The lower neck part incorporates a spherical screw which, together with the OC-joint, allows shearing type of deformation of the neck. The central part of the neck is made of rubber allowing bending, torsion and compression.

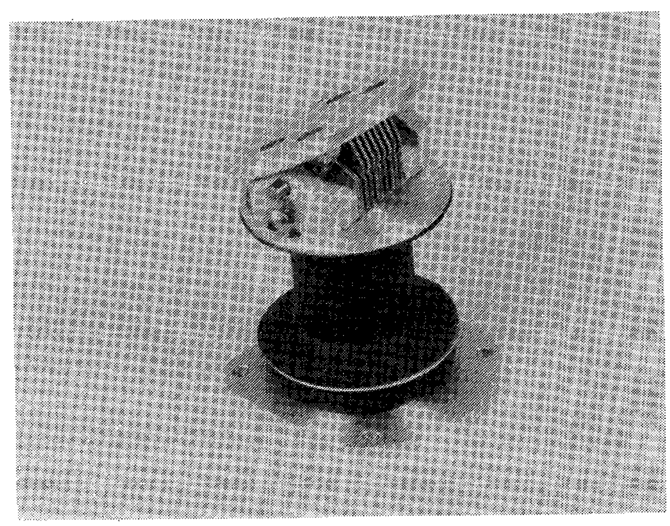

Figure 6. Neck of the P 1½.

The Torso

The torso comprises the thorax, abdomen, lumbar spine and pelvis. For the thorax region, particularly the clavicle and sternal area as well as the back of the dummy have been considered in the design process because of the interaction with the CRS. For the thorax back, a anthropomorphic concave shape with a smooth surface and without protruding parts or large cavities is required. The back should have a resilient flesh-skin covering on a rather stiff structure representing the spine and the ribcage.

Figure 6 shows the semi-rigid skeleton of the ***thorax*** of the P 1½ including the structural replacement for the lower neck transducer. The thoracic skeleton connects the neck, lumbar spine and shoulder joints. The central part of the thoracic skeleton contains a cavity to accomodate instrumentation. In front of the thoracic skeleton, a deformable insert is placed to provide the correct stiffness. The complete torso is covered by a polymer skin-flesh system.

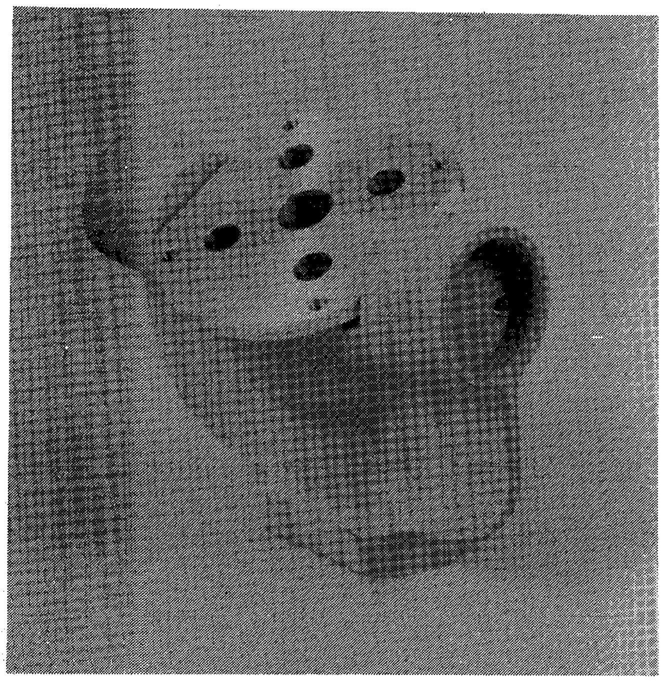

Figure 7. Thoracic skeleton of the P1½ with (metal) structural replacement of the lower neck transducer.

Large deformations of the ***abdomen*** can occur due to belt loading or contact with the restraint or vehicle interior. The abdomen should thus be able to sustain considerable loads and large deformations.

The abdomen of the P 1½ is designed as a one part deformable element, similar to the other P-dummies. This element can be removed from the cavity in the torso to allow access to the thorax insert, lumbar spine and pelvis skeleton. At the front, the abdomen smoothly follows the thorax and pelvis contours. Figure 8 shows the torso assembly of the P1½, clearly showing the transitions between the thorax, abdomen and pelvis.

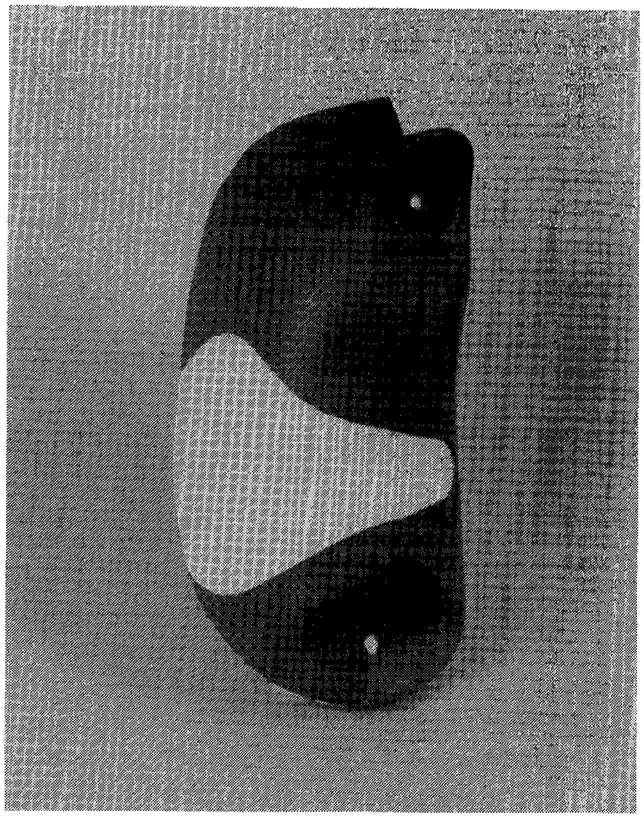

Figure 8. Torso of the P 1½ (white part is the abdomen).

The human ***lumbar spine*** area reveals both a considerable range of motion as well as support for the upper part of the body. Sagittal flexion of 90 degrees and lateral flexion of 60 degrees are reported in literature but these are approximate values only. The stability of the upper part of the body, provided by the lumbar spine is a result of the spinal structure, the abdominal stiffness and muscular activity in this area. No muscular activity is, however, present in a dummy.

The lumbar spine of the P 1½ has been designed as an axially symmetric rubber structure, providing sufficient flexibility. This structure also provides sufficient stability to the upper part of the dummy, without relying on the abdominal stiffness. This because considerable deformation of the abdomen is required. A central (metal) spine cable is incorporated into the lumbar spine for two reasons: first to enhance durability and second to be able to pre-set the spinal stiffness. The design of the lumbar spine of the P1½ is shown in Figure 9.

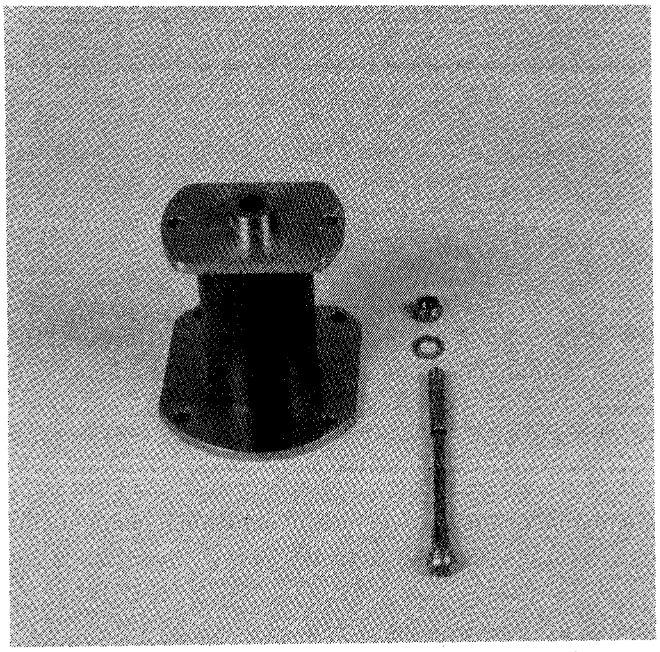

Figure 9. Lumbar spine of the P1½ (spine cable is disassembled).

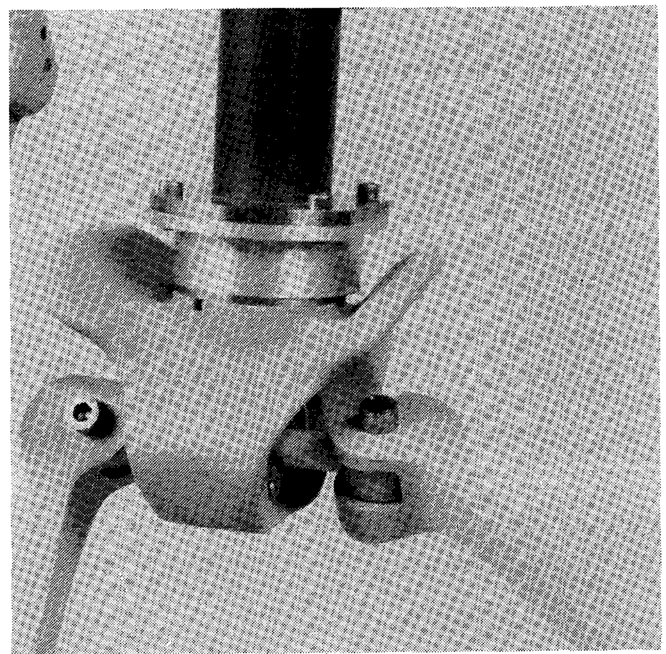

Figure 10. Pelvis area of the skeleton of the P1½.

Interaction with a belt system or shield of a CRS requires a anthropomorphic shape of the ***pelvis***, particularly of the anterior superior iliac spines. The shape of the buttocks and the rear of the iliac wings is important for contact with the seat and back of the CRS. The shape of the pelvis is based on anthropometric data and photographs of skeletons of children from 0 to 11 years. From the photographs it was concluded that the shape of the pelvis is similar at all ages and that the iliac spines are present even at an early age.

For the P1½, the iliac wings and the sacrum have been modelled as one element. The flesh around the pelvis and upper legs is shaped in such a way that the possibility for a belt to slip into any opening between the pelvis and the upper leg is reduced whilst achieving the desired ranges of motion in the hip joint. Figure 10 shows the pelvis area of the skeleton of the P1½. The sacrum part incorporates a cavity to accomodate instrumentation. The metal part between the lumbar spine and the sacrum is a structural replacement for a lower spine load transducer.

The Shoulder Joints and Upper Extremities

The term ***shoulder*** is generally used to describe the complex mechanism connecting the thorax clavicle, scapula and humerus (upper arm). In the P1½ dummy, a glenohumeral joint is implemented (connecting the upper arm to the thorax skeleton) which will further be referred to as the shoulder. The clavicle and scapula are designed as integral parts of the thorax skeleton.

The human shoulder has 3 rotational degrees of freedom. For the current dummy, a 2-dimensional movement is acceptable allowing forward and lateral flexion. Axial rotation of the upper arm is not required for the current application and is not implemented for reasons of repeatability. The anatomical and designed ranges of motion for the shoulder are given in Table 4.

Table 4.
Shoulder anatomical ranges of motion and P1½ design targets [10]

motion	anatomical range of motion (degrees)	P 1½ shoulder design (degrees)
flexion (forward)[1]	168	360
extension (backward)[1]	68	
abduction (lateral)[1]	185	90
horizontal flexion[2]	141	90
horizontal extension[2]	47	90
inward rotation	60	0
outward rotation	45	0

1: In the neutral position, the upper arm is **vertical** along the body for flexion/extension and for abduction.

2: In the neutral position, the upper arm is **horizontal** along the lateral axis of the shoulder for horizontal flexion/extension.

The shoulder joint of the P 1½ has been designed such that it can sustain large tension forces along the upper arm axis as occurring during violent stretching of the arm. Click stops are provided to improve repeatability, such that the upper arm can be placed along the torso (position 0 degrees) and at 40 degrees forward of the torso. Figure 11 shows the principal parts of the shoulder joint, mounted onto the thorax skeleton.

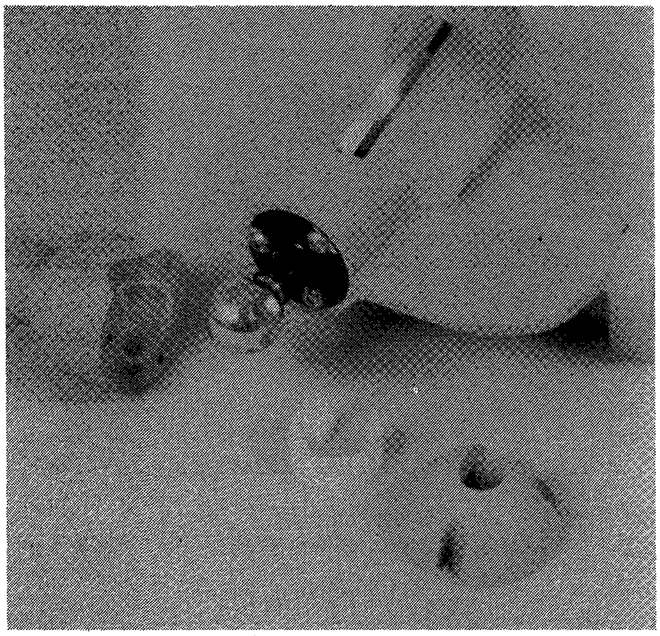

Figure 11. Principal parts of the shoulder joint of the P 1½ (shown together with the thorax skeleton).

The hand is designed as an integral part of the lower ***arm*** (with somewhat closed fingers). The elbow joint has only one degree of freedom (flexion/extension). The ranges of motion for the elbow are given in Table 5. Click stops are incorporated for two preferred positions: the lower arm can be set at 90 degrees to the upper arm or at 130 degrees. These positions have been selected such that the lower arm can be positioned perpendicular to the torso if the shoulder is in one of its preferred positions. A full arm assembly is shown in Figure 12.

Table 5.
Elbow anatomical ranges of motion and P1½ design targets

motion	anatomical range of motion (degrees)	P 1½ elbow design (degrees)
flexion	145	145
extension	0	0

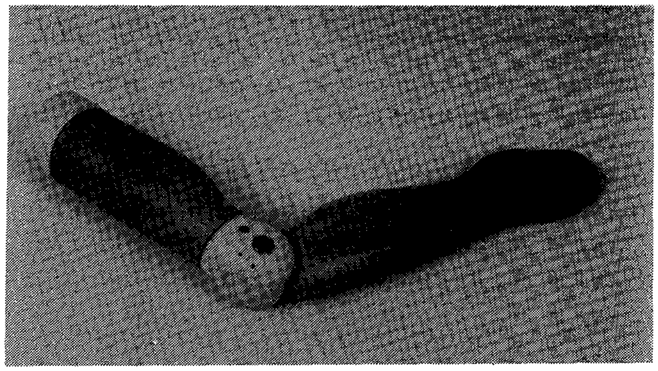

Figure 12. (Right) Arm of the P 1½.

The Hip Joints and Lower Extremities

The human ***hip*** joint is a ball and socket joint with three degrees of freedom. In the P1½ dummy, the main movement of the hip is flexion and extension but adduction and abduction are possible as well. Flexion/extension of the hip is achieved by rotation around an axis through the pelvis. The upper leg is attached to this axis using a gimbal type joint. The hip joint can be adjusted by means of friction in both axes: the one axis directly connected to the pelvis skelton and the axis of the gimbal. This type of adjustment allows the legs to be stabilized in any required initial position, depending on the CRS design. Table 6 provides the information on the ranges of motion for the hip joints. Figure 10 shows the femur connected to the pelvis by the 2-axes gimbal hip joint. The flesh system surrounding the hip joint is an integral part of the pelvis and upper legs of the P 1½.

Table 6.
Hip anatomical ranges of motion and P1½ design targets [10]

motion	anatomical range of motion (degrees)	P 1½ hip design (degrees)
flexion	123	90
extension	7	70
abduction	51	90
adduction	28	5
inward rotation	50	0
outward rotation	50	0

The upper legs will generally be in contact with belts of a CRS. This requires a human-like ***leg*** shape near the hip joint. The leg shape is according to a sitting position where the flesh is deformed by gravity. The upper legs consist of a skeletal part with a flesh system, which has been shaped in a way that minimizes interference of belts with the hip joints.

The knee joint has only one principal degree of freedom (flexion/extension). During impact, violent extension of the lower leg can occur. Lower leg movement is damped at the end of the ranges of motion to avoid unnatural acceleration peaks. The knee ranges of motion are contained in Table 7.

Table 7.
Knee anatomical ranges of motion and P1½ design targets [10]

motion	anatomical range of motion (degrees)	P1½ knee design (degrees)
flexion	145	145
extension	0	0

The knee joint is designed as a friction adjustable hinge, allowing the lower leg to be set in any required initial position (similar to the hip joint). The foot is designed as an integral part of the lower leg. The foot is oriented such that the sole is orthogonal to the lower leg axis. Full assembly of the leg of the P1½ is shown in Figure 13.

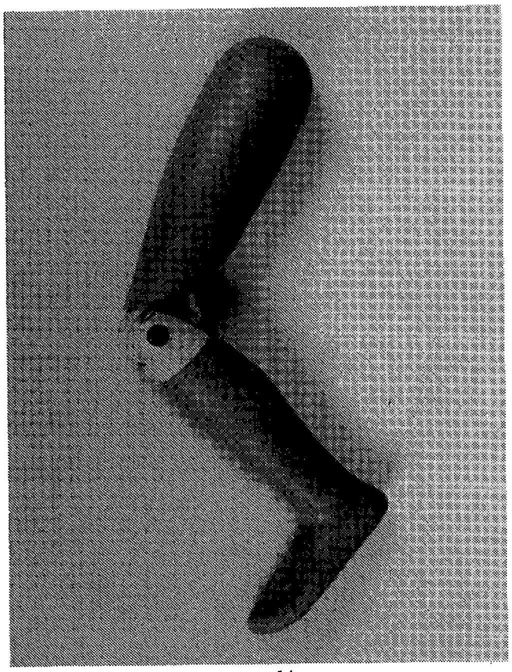

Figure 13. (Left) Leg of the P1½.

TNO P1½ Full Assembly and Instrumentation

The measurement capabilities of the P1½ are summarized in Table 8. Head, thorax and pelvis accelerations, upper and lower neck loads and lumbar spine loads can be assessed with this dummy; in total 27 channels.

The dummy is not standard equipped with all these transducers but structural replacements are provided. The 6-channel load transducers in the spine (or their structural replacements) form an integral part of the dummy's skeleton. The acceleration transducers do not form an integral part of the dummy. All transducers have been accounted for in the body segment masses and thus also in the total dummy mass. The structural replacements have equal mass as the respective transducers.

The locations of the load transducers are illustrated on the skeleton of the dummy, which is shown without the upper part of the skull in (left) side view and front view in Figure 14. The metal cilindrical elements at the top and bottom of the neck and below the lumbar spine, are structural replacements for the 6-channel load transducers, indicated by the arrows. Not shown are the acceleration transducers which are located at the head, thorax and pelvis centres of gravity (c.g.).

Finally, the complete structure of the P1½, in upright sitting position, is shown in transparent view in Figure 15.

Table 8.
Measurement capabilities of the P1½.

body part	assessment	direction	number of channels
head			
	linear acceleration at head c.g.	x, y, z	3
neck			
upper neck	forces and moments at OC-head	x, y, z	6
lower neck	forces and moments at C7-T1	x, y, z	6
thorax			
	linear acceleration at thorax c.g.	x, y, z	3
lumbar spine			
	forces and moments at L5-S1	x, y, z	6
pelvis			
	linear accelerations at pelvis c.g.	x, y, z	3
total			27

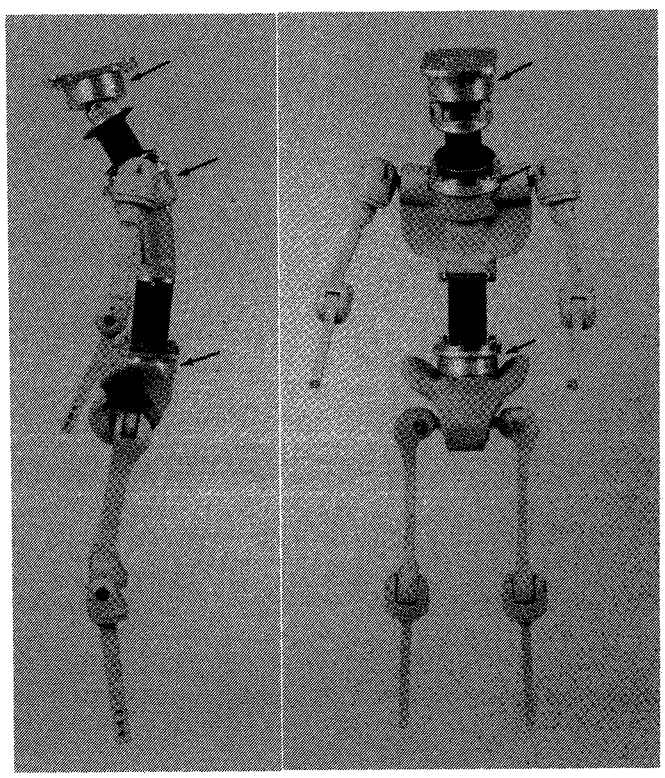

Figure 14. (Left) side view and front view of the skeleton of the P1½ (excluding the upper part of the skull).

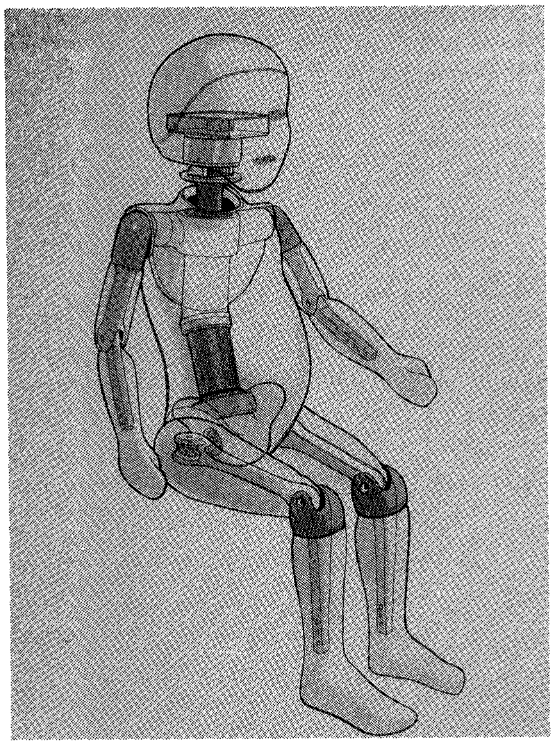

Figure 15. Design drawing of the TNO-P 1½ in upright sitting position.

DISCUSSION AND CONCLUSIONS

This paper describes the development and design of a new prototype 18-month-old child dummy: the TNO P 1½. Amendments to ECE R.44 and an extensive review study on child dummy development, have been the bases for developing this dummy. Next to the regulatory use (ECE R.44) also research applications have been taken into account during the design process. Like all other dummies, the design of the P1½ is a compromise between required and desired assessments, available biomechanical knowledge, measurement technology and manufacturing possibilities.

The external and internal shape as well as inertia of the dummy are specified based on the latest anthropometry data available. Furthermore, realistic ranges of motion have been specified for (and designed into) the P 1½. The design thus certainly will be suitable to evaluate the kinematics of a 50th percentile 18-month-old child.

General requirements for the dynamic performance of the dummy have been specified, but these require further evaluation. Three design features resulting from these requirements have already been taken into account:

- materials have been applied knowing to have good recovery after impact: over 90% of the dummy is made of (durable) polymers which also provide a good weight distribution;
- enhanced instrumentation has been incorporated into the dummy that allows a wider application of the dummy than just 'Group 0+';
- joints have been incorporated that allow easy adjustment and repeatable positioning of the dummy.

As for the current series of TNO child dummies, the name of the new 18-month-old dummy still refers to Pinocchio. The TNO P 1½ has a configuration based on existing child dummies and incorporates existing instrumentation. Particularly using the latest anthropometry data available, incorporating enhanced instrumentation and applying new materials to improve biofidelity, have provided an advanced child dummy design for the P 1½, which reflects the current state-of-the-art on child dummy development.

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Test Procedures for Evaluating Out-of-Position Vehicle Occupant Interactions with Deployed Airbags

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ABSTRACT

The ISO/TC22/SC10/WG3 is currently discussing the standardization of test procedures for out-of-position occupants of vehicles furnished with airbags. The purpose of the present experiments was to contribute to this ISO activities by testing the major out-of- position items proposed in the draft ISO Technical Report, "Guidelines for Evaluating Out-of-Position Vehicle Occupant Interactions with Deploying Airbags,"[1] which was formally recognized as a draft at the ISO/TC22/SC10/WG3 meeting in April 1990. Consequently, we discussed prospective test procedures that will enable us to properly evaluate the occupant's out-of-position behavior in relation to airbag deployment.

Among the 212 cases of out-of-position tests provided in the ISO Technical Report, this report will deal with the results of 30 cases that we experimented with from 1990 to 1992, using a Hybrid III (AM50) dummy and an airbag three-year-old child dummy with driver and/or passenger airbags. The test results indicated the importance of the degree of dummy setting and the injury rating indicated by dummy responses; therefore, the dummy positions of the 30 cases were studied, leading to the selection of the eight most recommendable dummy positions.

INTRODUCTION

Airbags were invented during the second half of the 1960s as a vehicle occupant protection device in the case of frontal collisions. It was in the mid-1970s that airbags were first furnished with airbags for the driver and adjacent passenger in mass-produced vehicles[2]. Today, airbags are widely regarded as an effective protective system, provided the occupant is seated in the correct position. If seated out of position, however, the occupant may suffer an injury more serious in an airbag-equipped vehicle than in a vehicle without an airbag, due to its inflation force.

Research into interactions between out-of-position occupants and airbags began in the early 1970s, with the goal of determining the effects of the inflation force of the driver airbag and of the changed position of the occupant caused by rapid braking. Hybrid III (AM50) dummies, body blocks, etc. were used in earlier research[3]. Similar studies have been carried out for passenger airbags, using animals and three-year-old child dummies[4][5][6]. Further, ever since the introduction of airbags in mass-produced vehicles, it has become possible to investigate actual accidents in which these airbag-installed vehicles were involved[7].

With the seatbelt usage rate still dawdling at low levels, the demand for vehicles furnished with airbag systems is increasing, creating greater possibilities of out-of-position accidents. As a result, there are moves to establish out-of-position test procedures.

Under these circumstances, an SAE Information Report, entitled "Guidelines for Evaluating Out-of-Position Vehicle Occupant Interactions with Deploying Airbags,"[8] was presented to the ISO in September 1989. This report was adopted as a formal Draft Technical Report at the ISO/TC22/SC10/WG3 meeting in April 1990 (hereafter called the "ISO Technical Report")[1]. The ISO/TC22/SC10/WG3 is continuing technical discussions to formulate a standardized ISO out-of-position test procedure on the basis of the ISO Technical Report.

The ISO Technical Report covers a total of 212 test cases combining different types of dummies, static tests and dynamic tests. These test cases contain numerous items to be measured, some of which seem to overlap one another. Consequently, it is possible to develop a more effective and simpler out-of-position test procedure by selecting only those measurement items closely related to the degree of dummy setting and the injury rating indicated by dummy responses.

In the experiments, 30 out of the 212 test cases were selected, using the Hybrid III (AM50) dummy and three-year-old child dummy in combination with driver and/or passenger airbags (topdash mount and mid-mount types).

These tests were carried out for three years, from 1990 to 1992 (see Tables 1, 2, 3), and eight test cases were eventually selected by means of the following processes:

TEST METHOD

Thirty out-of-position test cases using a Hybrid III (AM50) dummy and a three-year-old child dummy were selected from the ISO Technical Report, and experiments were performed (see Table 1, Tests D1-D8, PT1-PT11, PM1-PM11). The code numbers of these test cases denote the following:

(1) Tests D1-D8: "D" signifies an airbag module for the driver.
(2) Tests PT1-PT11: "P" stands for passenger, while "T" stands for topdash mount. Thus, "PT" means an airbag module installed on the top of the dashboard, for the passenger.
(3) Tests PM1-PM11: "M" stands for mid-mount, so that "PM" means an airbag module installed in the center of the dashboard, for the passenger.

(a) Test Items

Tables 2 and 3 show dummy setting methods and notable dummy responses as the injury in the 30 test cases. The figures arranged on the left side of Tables 2 and 3 illustrate the dummy positions provided in the ISO Technical Report, while the dummy positions we adopted for our experiments, on the basis of the ISO Technical Report, are presented on the right side. The 30 test cases were experimented as follows over a three-year period (see Table 1):

① 1990: 3 cases of static single-body tests and 5 cases of dynamic system tests, using a Hybrid III (AM50) dummy in relation to the driver airbag.
② 1991: 4 cases of Hybrid III (AM50) dummy dynamic system tests and 7 cases of three-year-old child dummy dynamic system tests, all in relation to the passenger topdash mount airbag.
③ 1992: 4 cases of Hybrid III (AM50) dummy dynamic system tests and 7 cases of three-year-old child dummy dynamic system tests, all in relation to the passenger mid-mount airbag.

(b) Outline of the Tests

①Static single-body test (Table 2, Figure 1)
A Hybrid III (AM50) dummy was positioned so that part of it came into contact with the surface of an airbag module installed on the steering wheel. In this dummy position, the airbag was inflated and the dummy responses as the degree of injury were rated.
②Dynamic system test (Tables 2 and 3, Figure 2)
A white body was fixed on the sled of a HYGE testing machine, and a Hybrid III (AM50) dummy and a three-year-old child dummy were seated in the prescribed positions. Then the white body (of a mass-produced vehicle with a displacement of 3,000 to 4,000 cc) was set in motion at the acceleration (Figure 3 and 4) designated in the ISO Technical Report. The dummy responses as the degree of injury caused by the airbags were rated. (Only the vehicle manufacturer specified airbags were used in the experiments.)

(c) Measurement Items

Table 4 shows the measurement items that concern the dummies. In addition to these items, room temperature, dummy chest temperature, airbag inflation time, and sled acceleration were measured.

(d) Sled Acceleration

Figures 3 and 4 show the sled pulses obtained in our tests that conform to the ISO Technical Report. Figure 3 indicates that the maximum acceleration was 11-12G, maximum velocity 29 km/h, and duration 110 ms in the Hybrid III (AM50) dummy tests. Figure 4 indicates that the maximum acceleration was 6-7G, maximum velocity 25 km/h, and

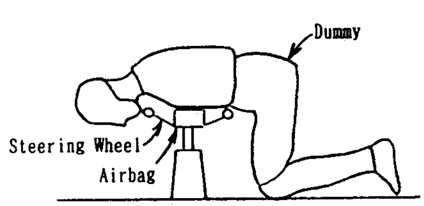


Fig. 1 Static Test (Airbag Module Evaluations)

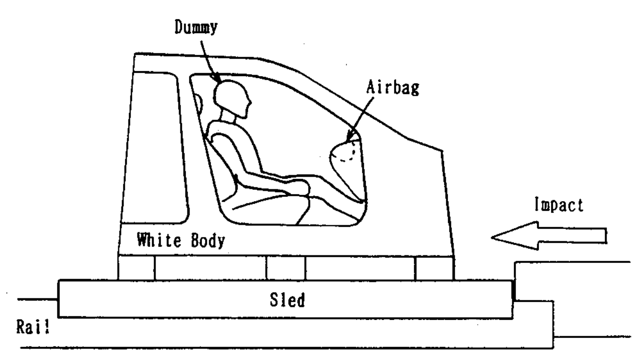


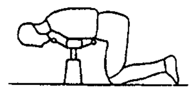
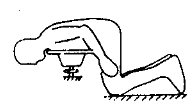
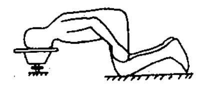
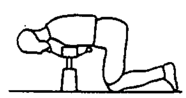
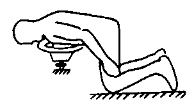
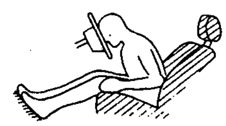
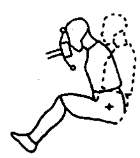
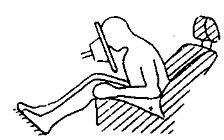
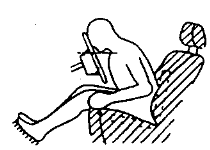
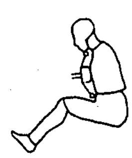
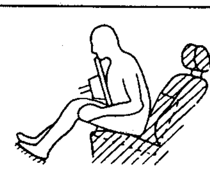
Fig. 2 Dynamic Test (Airbag module and Steering System Evaluations, and Passenger Airbag System)

Table 1 Out of Position Tests in ISO Technical Report (30 pattern)

Driver or Passenger	Airbag Position	Dummy	Tests: Static or Dynamic	Tests: Evaluations	Dummy Position (in ISO Technical Report)	Selected Mesurement Items and Test No.: 1990	1991	1992
Driver side Airbag	Steering wheel	HybridⅢ (AM50)	Static	Airbag Module Evaluations	3 patterns	D1、D2、D3 3 patterns	——	——
		HybridⅢ (AF5) HybridⅢ (AM95)	Dynamic	Airbag Module and Steering System Evaluations	6 patterns	D4、D5、D6、D7、D8 5 patterns	——	——
Passenger side Airbag	Topdash Mount Mid Mount Low Mount	HybridⅢ (AM50) HybridⅢ (AF5) HybridⅢ (AM95)	Dynamic	Passenger Airbag System	6 patterns	——	PT1 PT2 PT3 PT4 4 patterns	PM1 PM2 PM3 PM4 4 patterns
		Airbag Three-Year-Old Child	Dynamic	Passenger Airbag System	7 patterns	——	PT5 PT6 PT7 PT8 PT9 PT10 PT11 7 patterns	PM5 PM6 PM7 PM8 PM9 PM10 PM11 7 patterns
						30 patterns		

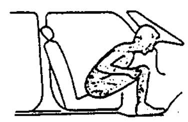
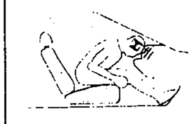
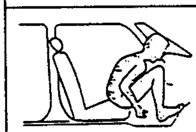
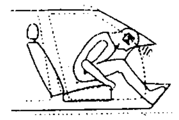
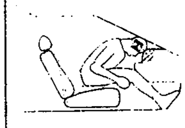
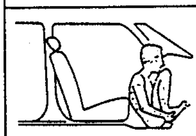
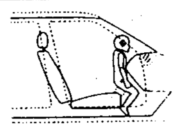
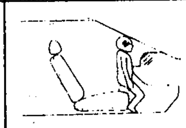
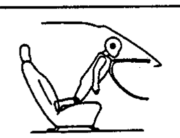
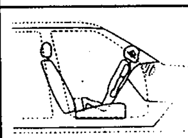
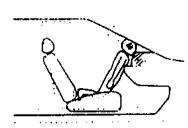
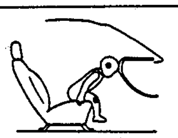
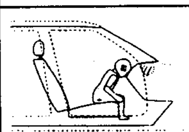
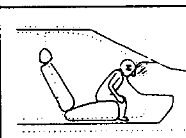
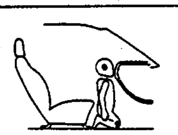
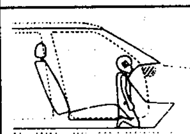
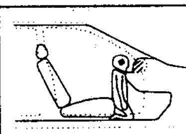
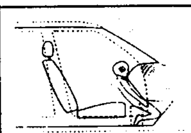
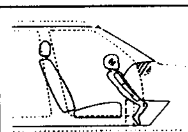
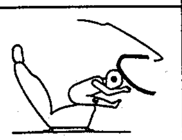
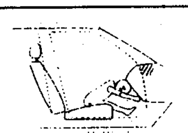
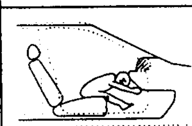
Note 1) D1～D8=Driver Side Airbag Tests.
Note 2) PT1 ～PT11=Passenger Side Topdash Mount Airbag Tests.
Note 3) PM1 ～PM11=Passenger Side Mid Mount Airbag Tests.

Table 2 Test No. and Dummy Position ('90)
Driver Side Airbag, HybridIII (AM50)

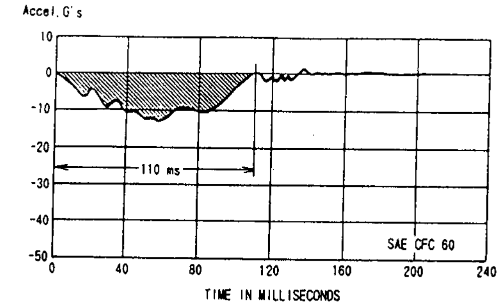
ISO Technical Report			Test		
Tests	Dummy Position	Dummy Positions and Major Injury Areas	Test No.	Dummy Position	Dummy Set-up
<Static> Airbag Module		Chest on Module (Chest)	D 1		OK
		Forehead on Module (Head, Neck)	D 2		OK
		Chin on Upper Rim (Neck, Chest)	D 3		OK
<Dynamic> Airbag Module and Steerimg System		Forehead on Module (Head, Neck)	D 4		OK
		Slumped Driver (Head, Neck)	D 5		OK
		Chin on Top of Module (Head, Neck)	D 6		OK
		Chest on Module (Neck, Chest)	D 7	———	NG Note*
		Chin on Upper Rim (Neck, Chest)	D 8		OK

Note) Head of dummy intersect the glass plane of front window.

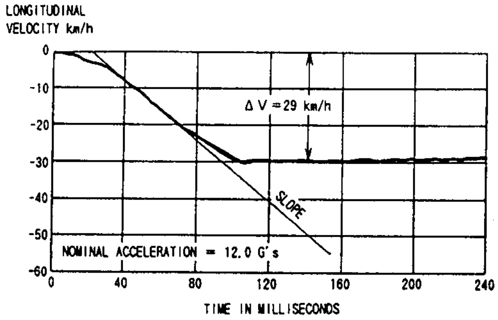
Table 3 Test No. and Dummy Position ('91, '92) Passenger Side Topdash Mount Airbag and Mid Mount Airbag

ISO Technical Report				Test				
				'91, Topdash Mount Airbag		'92, Mid Mount Airbag		
Dummy	Tests	Dummy Position	Dummy Positions and Major Injury Areas	Test No.	Dummy Position	Test No.	Dummy Position	Dummy Set-up
HybridIII (AM50)	<Dynamic> Passenger Side Airbag System		Head in contact with dashboard panel (PT1⇒Head, Neck) (PM1⇒Neck)	PT 1		PM 1		OK
			Head and knees in contact with dashboard panel (PT2⇒Head, Neck) (PM2⇒Neck)	PT 2		PM 2		OK
			Head and chest in contact with dashboard panel (PT3⇒Head, Neck) (PM3⇒Neck, Chest)	PT 3	——	PM 3	——	NG Note 1*
			Head in contact with dashboard panel at point lower than PT3 and PM3 (PT4⇒Head, Neck) (PM4⇒Neck, Chest)	PT 4	——	PM 4	——	NG Note 2*
Airbag Three-Year-Old Child	<Dynamic> Passenger Side Airbag System		Seated on front edge of seat or set standing on floor (PT5⇒Head, Neck) (PM5⇒Neck, Chest)	PT 5		PM 5		OK
			Set kneeling on seat (PT6⇒Head, Neck) (PM6⇒Neck, Chest)	PT 6		PM 6		OK
			Seated on seat with head in contact with dashboard mid-panel (PM7⇒Head, Neck)	PT 7		PM 7		OK
			Set kneeling or seated on floor (PM8⇒Head, Neck, Chest)	PT 8		PM 8		OK
			Body placed along lower dashboard panel with head located at mid-panel (PM9⇒Head, Neck)	PT 9		PM 9		OK
			Body placed along lower dashboard panel with head located at upper dashboard edge (PM10 ⇒ Head, Neck, Chest)	PT10		PM10		OK
			Upper body bent down on seat	PT11		PM11		OK

Note 1) The legs can not locate under the instrument panel as shown in the illustration.
Note 2) The dummy's knees can not be bent as shown in the illustration.
Note 3) In Tests PT7 through PT11, and PM11, the blocking of airbag by the dummy is minimized by their dummy position. Consequently, there were no injuries worthy of mentioning.

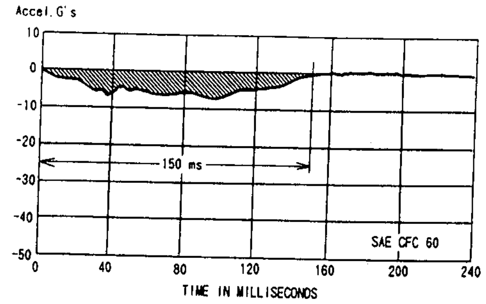


Generic Hyge Sled Pulse
for a Moderate Crash Severity

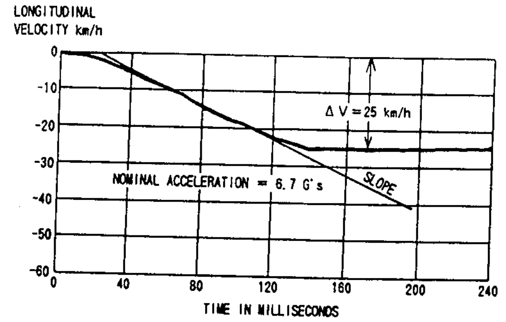


—Velocity—Time History of the Generic
Moderate Crash Severity Sled Pulse

Fig. 3 Sled Acceleration and Velocity
(Hybrid III (AM50) Dummy)



Generic Hyge Sled Pulse
for a Mild Crash Severity



—Velocity—Time History of the Generic
Mild Crash Severity Sled Pulse

Fig. 4 Sled Acceleration and Velocity
(Three-Year-Old Child Dummy)

Table 4 Measurement Points of
HybridIII (AM50) Dummy and Three-Year-Old Child Dummy

	HybridⅢ (AM50)	Airbag Three-Year-Old Child
Head	Acceleration (3 ch)	Acceleration (3 ch) Occiput (1 ch)
Neck	Force (3 ch) Moment (3 ch)	Force (3 ch) Moment (3 ch)
Chest	Acceleration (3 ch) Deformation (1 ch)	Upper Spine (3 ch) Lower Spine (3 ch) Spool (Upper-1ch, Middle-1ch, Lower-1ch)
Pelvis	Acceleration (3 ch)	——
Femur	Force (L-1ch, R-1ch)	——
Knee	Deformation (L-1ch, R-1ch)	——

duration 150 ms in the three-year-old child dummy tests.

(e) Airbag Inflation Time

Although the inflation time in the tests differed with the various airbags used, basically it was set to be the same as the timing prescribed by the vehicle manufacturer at the time the vehicle was designed, for the specific accelerations applied in the tests.

(f) Temperature Conditions

The temperature of both the Hybrid III (AM50) dummy and the three-year-old child dummy was measured by thermocouple thermometers attached to their chests, during each test. The chest temperature was adjusted so as to be maintained in not only the 19-26℃ range required by the ISO Technical Report, but also more or less in the 20.6-22.2℃ range specified by FMVSS 208 for Hybrid III (AM50) dummy tests.

RESULTS AND DISCUSSIONS

Figures 2 and 3 show the dummy positions used in the tests of the 30 selected cases. In those cases where specific dummy positions could not be realized, the reasons are explained in notes. Tables 5, 6 and 7 show dummy positions and injury rating as dummy responses (i.e., HIC36, neck moment (Y), and chest acceleration) for each mounted airbag position. Two important parameters for technical discussion and selection of dummy positions in out-of-position test procedures are the degree of dummy setting and the injury rating indicated by dummy responses. Based on these parameters, the results and discussions on the tests are presented as follows:

(a) Dummy Setting

<Hybrid III (AM50) dummy setting in relation to driver airbag>

Test code numbers and corresponding dummy positions defined in the ISO Technical Report are shown on the left side of Table 2. On the right side, actual dummy positions adopted for the experiments are shown. It was not possible to carry out Test D7, because the dummy head was blocked by the front window. In other tests, the dummy was set in positions closely matching those defined in the ISO Technical Report, although the Report fails to provide detailed definitions of dummy leg and arm positions in some test cases.

<Hybrid III (AM50) dummy and three-year-old child dummy settings in relation to passenger airbags>

Test code numbers and corresponding dummy positions defined in the ISO Technical Report are shown on the left side of Table 3. On the right side, actual dummy positions adopted for the experiments are shown. It was not possible to conduct Tests PT3 and PM3, because the dummy legs could not be placed underneath the dashboard panel as required by the ISO Technical Report (see the lefthand drawings of Figure 3), due to the presence of the lower dashboard panel. Further, it was not possible to carry out Tests PT4 and PM4 because the dummy knees could not be bent as defined by the ISO Technical Report. In other tests, dummy positions were matched closely to those prescribed in the ISO Technical Report, although the Report fails to provide detailed definitions of the distance between the knees and the like in some test cases.

(b) Injury Rating As Dummy Responses

Since out-of-position tests are aimed at reducing injuries to occupants by airbags, it is necessary to select dummy positions most likely to increase the degree of dummy responses in experiments. FMVSS 208 currently identifies the head HIC_{36} and chest acceleration as the two dummy injury parameters. Although FMVSS 208 does not provide a neck parameter, some studies have pointed out that neck moment is also an important parameter[9]. Therefore, neck moment as well as HIC_{36} and chest acceleration were measured in the experiments, and the results were as shown in Tables 5, 6 and 7. The measured values were presented in terms of percentage with the maximum value set at 100%.

All but Tests D1-D3 were dynamic tests in the experiments. However, static tests were also carried out for Tests D4-D8, PT1-PT11 and PM1-PM11, although the results of these static tests were omitted from this report. The static tests involved the same dummy positions as those shown in Tables 2 and 3, but without applying the acceleration of the dynamic tests. Figure 5 shows a comparison of dynamic and static test results, with Test D4 as an example. Neck moment (plus and minus values) is arranged along the vertical axis, while HIC_{36} and chest acceleration are set along the horizontal axis.

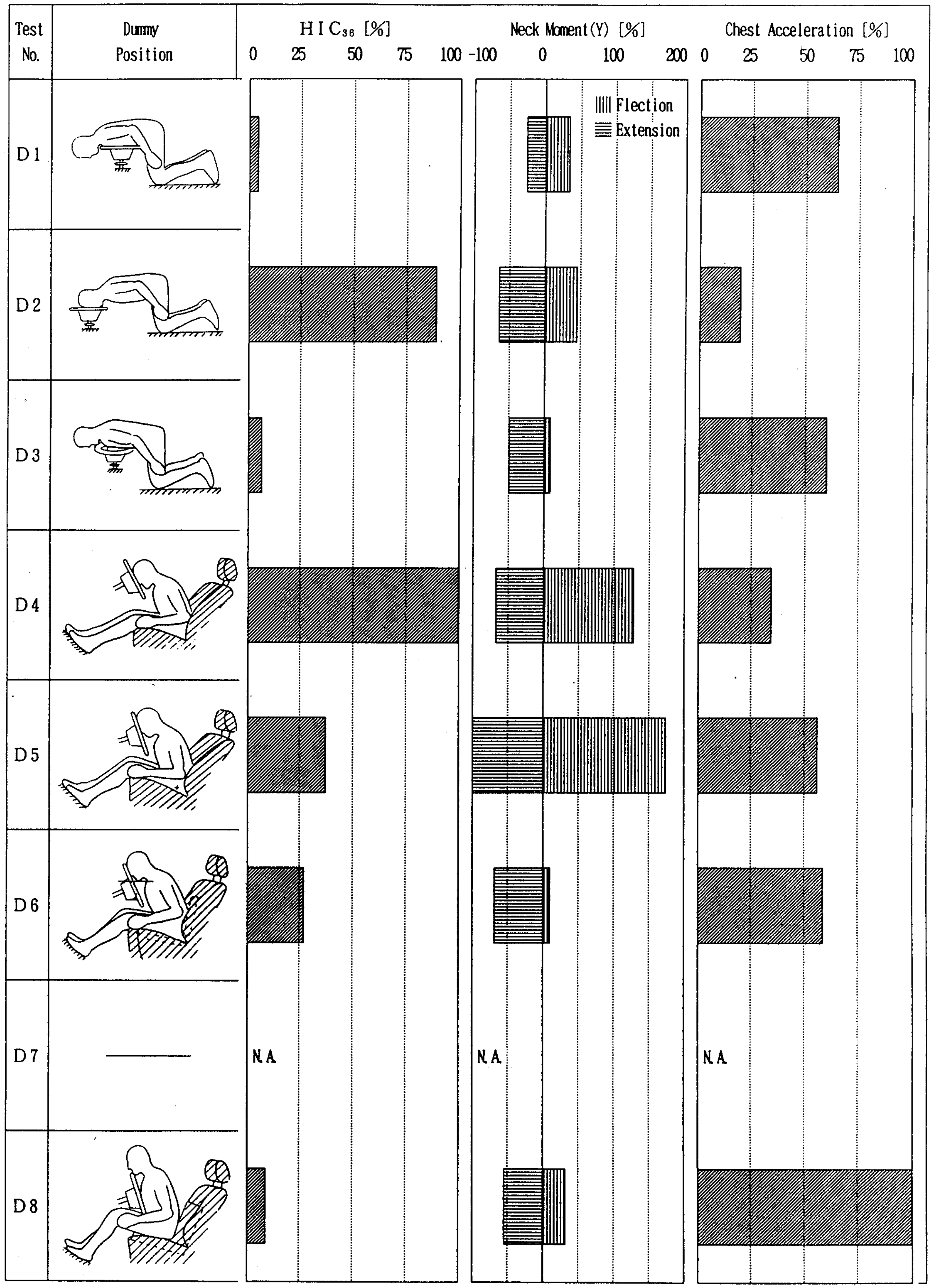
The dynamic test clearly produced larger values than the static test in all of the three parameters, and similar patterns were observed in other test cases. Since dummy positions, which are likely to increase the degree of dummy responses, must be selected, such selection was based on dynamic test results for all but Tests D1-D3. Test case and parameter features are outlined below.

<Hybrid III (AM50) dummy test in relation to driver airbag (Table 5)>

(1) High HIC values were measured in Tests D2 and D4. Because these tests required the dummy head to be positioned directly on the airbag module, it was believed that the airbag inflation force was transmitted most strongly to the head.

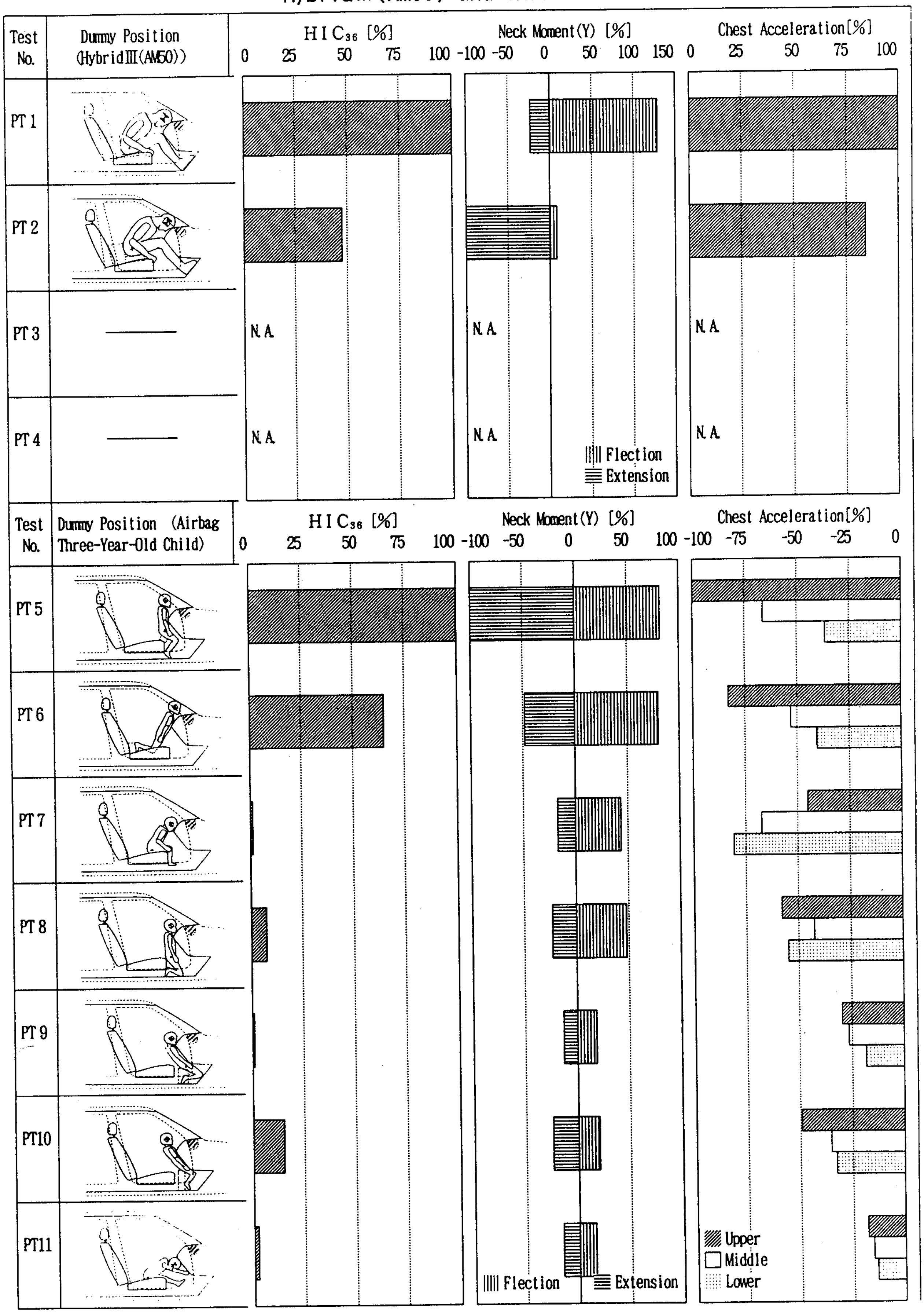
(2) High neck moment values were obtained in Tests D4 and D5. In these tests the dummy head was placed directly on the airbag module, so the airbag inflation

Table 5 Test Result (Driver Side Airbag, HybridIII (AM50))



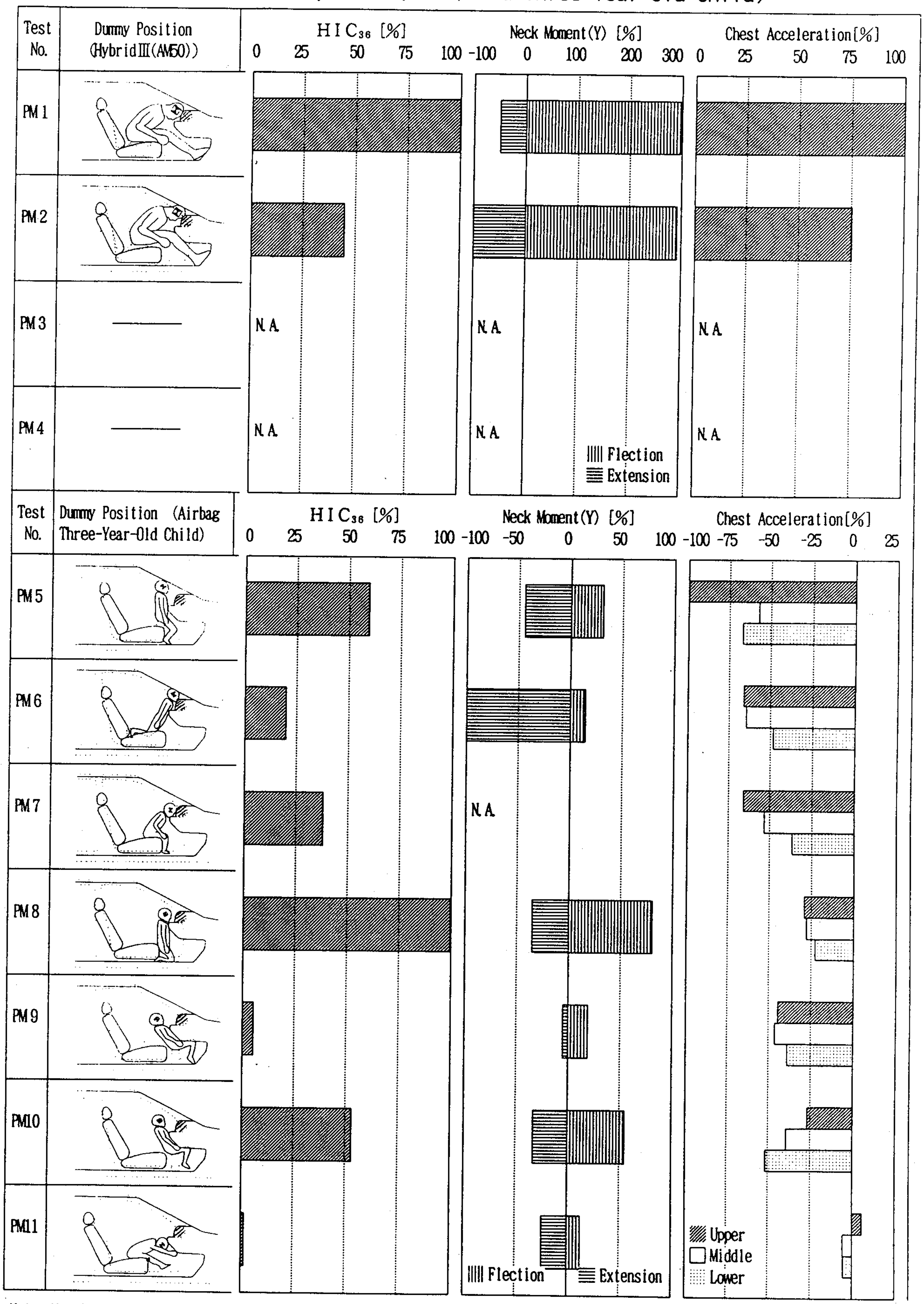
N.A = Not Available

Table 6 Test Result (Passenger Side Topdash Mount Airbag, HybridIII (AM50) and Three-Year-Old Child)



N.A = Not Available

Table 7 Test Result (Passenger Side Mid Mount Airbag, HybridIII (AM50) and Three-Year-Old Child)



N.A = Not Available

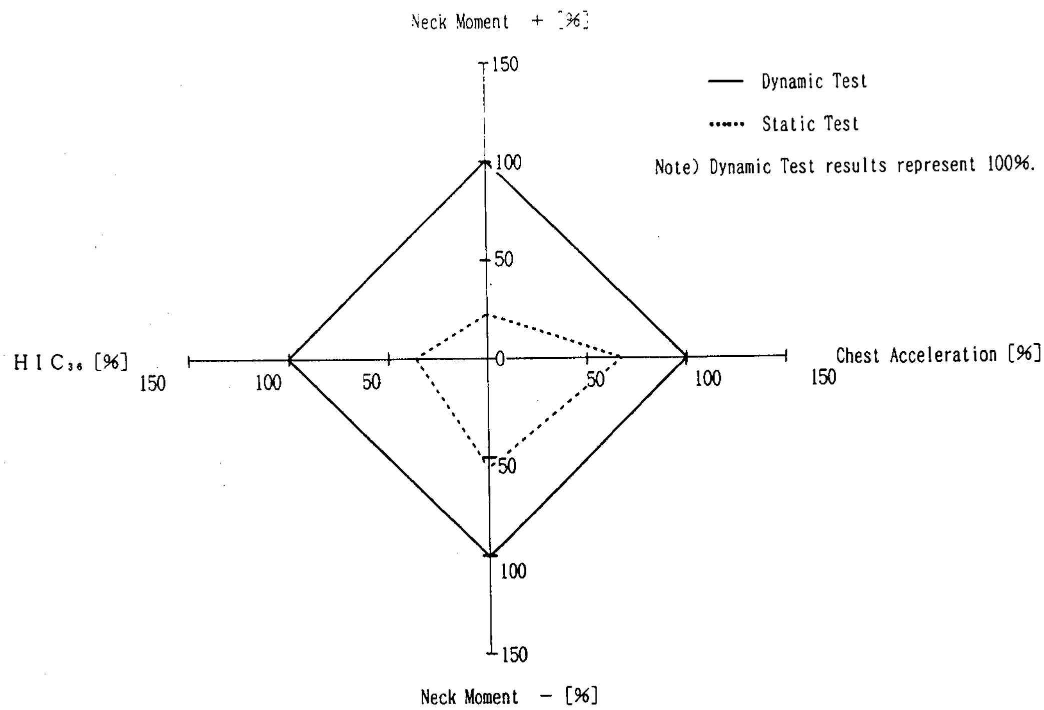


Fig. 5 Injury Patterns (Dynamic Test and Static Test)
[HybridIII(AM50), Test No.D4]

force transmitted to the head was believed to cause a great reaction force to the neck, thus generating a high neck moment.

(3) The chest acceleration was the highest in Test D8. Since the dummy chest was positioned on the airbag module in this test, airbag inflation force was assumed to have transmitted to the chest.

<Hybrid III (AM50) dummy test in relation to passenger topdash mount airbag (Table 6)>

(1) The highest HIC value was measured in Test PT1. Because this test required the dummy head to be placed near the topdash mount airbag, it was believed that the airbag inflation force was particularly directed to the head. But in view of the fact that the dummy head was placed even closer to the airbag module in Test PT2 than in Test PT1, the HIC value for Test PT2 was expected to be higher. In reality, however, the results were the opposite, presumably because in Test P2 the airbag failed to fully inflate under the weight of the dummy head.

(2) Regarding neck moment, high flection was observed in Test PT1, but high extension in Test PT2. Because in Test PT2 the dummy head was restrained by the dashboard panel and the front window, the transmission of airbag inflation force to the neck was believed to have been in reverse, when compared with Test PT1.

(3) The chest acceleration was similar between Tests PT1 and PT2. Because the dummy chest was far from the airbag module in both tests, it was explained that the airbag inflation force did not smoothly transmit to the chest in both cases.

<Three-year-old child dummy test in relation to passenger topdash mount airbag (Table 6)>

(1) High HIC values were recorded in Tests PT5 and PT6. Because these tests required that the dummy head be placed close to the airbag module, the airbag inflation force seemed to have fully transmitted to the head.

(2) Also, high neck moment values were obtained in Tests PT5 and PT6. This was presumably due to the airbag inflation force, which was transmitted to the head, generated a reaction force in the neck, which in turn generated a high neck moment.

(3) High chest acceleration values were measured in Tests PT5 and PT6. Because these tests required the dummy chest to be positioned close to the airbag module, much of the airbag inflation force was apparently transmitted to the chest area. Although Test PT7 also indicated high chest acceleration, this was because the dummy chest

crashed to the dashboard panel due to sled acceleration, not due to interference by the airbag.

<Hybrid III (AM50) dummy test in relation to passenger mid-mount airbag (Table 7)>

(1) The highest HIC value was recorded in Test PM1. Because in this test the dummy head was placed close to the airbag module, the airbag inflation force was apparently fully transmitted to the head.
(2) Regarding neck moment, flection values were similar in all tests, but the highest extension value was measured in Test PT2. Because the dummy head was restrained by the dashboard panels and front window in this test, it was believed that the pattern of transmission of airbag inflation force to the neck was different from Test PT1.
(3) Chest acceleration was practically equal in Tests PM1 and PM2. Because the dummy chest position was separate from the airbag module in both tests, it was believed that the airbag inflation force did not fully transmit to the chest.

<Three-year-old child dummy test in relation to passenger mid-mount airbag (Table 7)>

(1) The highest HIC value was measured in Test PM8. Because this test required the dummy head to be placed close to the airbag module, the airbag inflation force seemed to have fully transmitted to the head. Although Test PM7 similarly involved the placement of the dummy head close to the airbag module, its HIC value was less than that in Test PM8. Because the mid-mount airbag was installed in a dented portion on the front face of the dashboard, in Test PM7 the dummy head was in direct contact with the airbag, while in Test PM8 the head was slightly away from the airbag. In Test PM8, therefore, when sled acceleration was applied, the dummy head moved toward the airbag module, so that the velocity differential between the head and airbag became higher than that in Test PM7. Thus, it was considered that HIC was also greater in Test PM8 than Test PM7.
(2) With regard to neck moment, the highest flection value was obtained in Test PM6, while the highest extension value was measured in Test PM8. Because the dummy positions were such that the airbag inflation force transmitted most easily to the chest in Test PM6 and to the head in Test PM8, the moment acting on the neck was reversed in the two tests, with the neck serving as the pivotal point.
(3) The highest chest acceleration was recorded in Test PM5. In this test the dummy chest was placed close to the airbag module, so that the airbag inflation force was easily transmitted to the chest. Although this explanation is also applicable to Test PM6, its chest acceleration was less than that of Test PM5. This was presumably because in Test PM6 the dummy's upper body was inclined toward the vehicle front, which caused a lag between the direction of airbag inflation and the sensitivity-axis (X-axis) direction of the chest accelerometer, thus resulting in a lessened transmission of airbag inflation force in the sensitivity-axis direction.

Results shown in Tables 5, 6 and 7 generally indicated that the closer the body is to the airbag module, the higher the injury rating of this area. For example, in Figures 6 and 7, the relation between HIC (or chest acceleration) and the distance L from the airbag to the center of the head is shown (please refer to Figure 8). The smaller the value of L or the closer the airbag is to the dummy head, the higher becomes the HIC value. In contrast, the farther away the head is from the airbag, or the closer the chest is to the airbag, the higher the chest acceleration is.

Nevertheless, since neck moment is generated in reaction to the transmission of the airbag inflation force to the head and chest, the inflation of an airbag near the neck does not necessarily increase the neck moment. In the following cases, the highest injury rating as dummy responses is not always found in the body area positioned most closely to the airbag module.

(1) Where the dummy is interfering with inflation of the airbag: Test PT2 applies in this case. The dummy head was stuck between the front window and dashboard, preventing the airbag from inflating.
(2) Where the sensitivity-axis direction of the dummy sensor is lagging from the direction of airbag inflation: Test PM6 applies in this case. Because the dummy's upper body was inclined toward the vehicle front, there was a lag between the direction of airbag inflation and the sensitivity-axis (X-axis) direction of the chest accelerometer, thus resulting in a lessened transmission of airbag inflation force in the sensitivity-axis direction.

CONCLUSION

1. Selection of Dummy Positions

On the basis of test results shown in Tables 5, 6 and 7, dummy positions were selected for each airbag. From the viewpoint of injury reduction, the following parameters were used in order to select dummy positions most likely to result in serious injuries:

A: Head HIC_{36}
B: Minus (extension) neck moment
C: Chest acceleration.

In addition, the following conditions were present in selecting dummy positions:

(a) Test cases in which it was not possible to take specified dummy positions due to the construction of the vehicle and dummy were omitted.
(b) Among those test cases where the dummy position was identical, while the airbag mounted position and vehicle shape were different, only one case was selected.

Accordingly, eight test cases of dummy positions were selected from 30 prospective cases for the following reasons:

1) Hybrid III (AM50) dummy setting in relation to driver

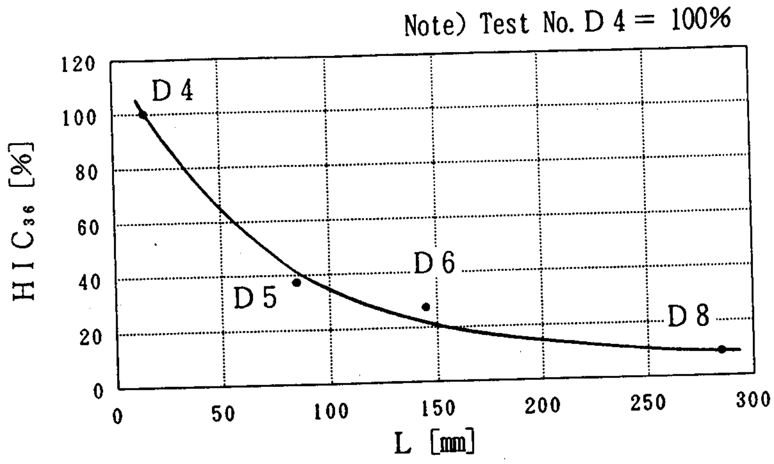


FIG. 6 HIC36 vs. L

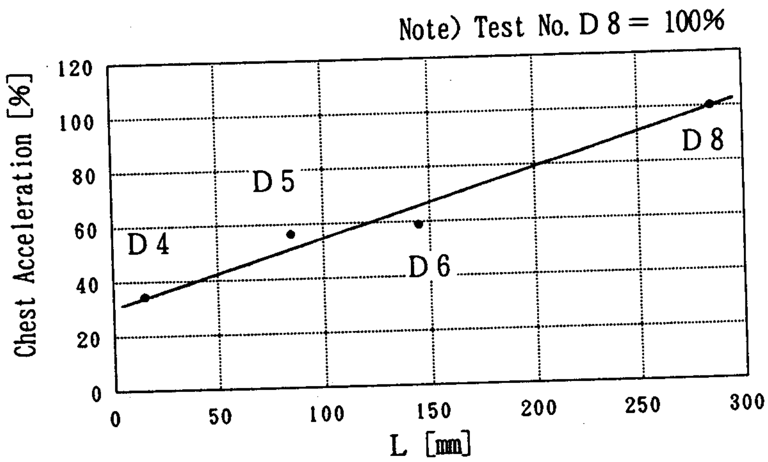
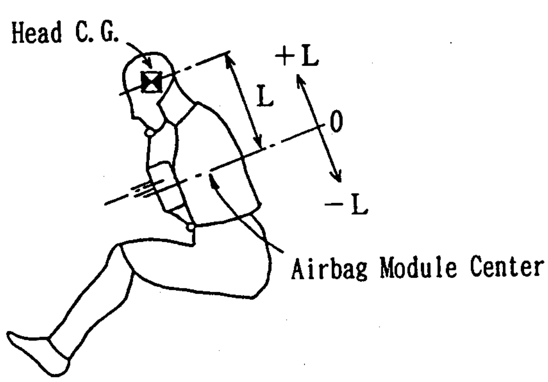


FIG. 7 Chest Acceleration vs. L



Test No.	L [mm]
D 4	15
D 5	85
D 6	145
D 8	285

FIG. 8 The Distance between Head C. G. and Airbag Module Center : L

airbag

(a) Head response: The highest value of HIC_{36} was recorded by the dummy position used in Test D4.

(b) Neck response: The highest minus moment was obtained from the dummy position used in Test D5.

But Test D5 required the dummy's upper body, with the hip point as the pivotal point, to be inclined forward until a part of its body came into contact with the steering wheel. Because the distance between the seat surface and the steering wheel varies considerably among different vehicle models, it is possible that the distance between the dummy head and the airbag vary widely at the time of dummy setting. For this reason, Test D6 was selected instead of Test D5. Test D6 recorded the second highest minus moment, and moreover involved a more uniform dummy position (chin in contact with the airbag's upper edge) so that the influence of vehicle model variation could be minimized.

(c) Chest response: The highest value of chest acceleration was measured in Test D8.

For these reasons, plus the aforementioned conditions for the selection of test cases, the dummy positions of Tests D4, D6 and D8 were selected.

2) Hybrid III (AM50) dummy setting in relation to passenger airbag

(a) Tests PT3, PT4, PM3 and PM4 were omitted due to the facts that ① the movable range of dummy hip joint was narrow and ② the required position could not be taken because the dummy knees were blocked by the lower dashboard panel.

(b) Head response: The highest HIC_{36} value was recorded in Test PT1 (also in PM1).

(c) Neck response: The highest minus moment was measured in Test PT2 (PM2).

(d) Chest response: The highest chest acceleration was obtained in Test PT1 (PM1).

For these reasons, combined with the aforementioned conditions for the selection of test cases, the dummy positions of Tests PT1 (PM1) and PT2 (PM2) were selected.

3) Three-year-old child dummy setting in relation to passenger airbag

<Topdash mount airbag>

(a) Head response: The highest value of HIC_{36} was measured in Test PT5.

(b) Neck response: The highest minus moment was recorded in Test PT5.

(c) Chest response: The highest chest acceleration was observed also in Test PT5.

<Mid-mount airbag>

(a) Head response: The highest value of HIC_{36} was measured in Test PM8.

(b) Neck response: The highest minus moment was recorded in Test PM6.

(c) Chest response: The highest chest acceleration was observed also in Test PM5.

For these reasons, plus the aforementioned conditions for the selection of test cases, the dummy position of Test PT5 was selected for the topdash mount airbag; the dummy positions of Tests PM5, PM6 and PM8 for the mid-mount airbag. Therefore, for passenger airbags, it was possible to select the dummy positions of Tests PT5 (PM5), PT6 (PM6) and PT8 (PM8), all of which provided a satisfactory dummy position for both the topdash mount and mid-mount airbags.

2. Futher items to Be Discussed on ISO Technical Report

1) FMVSS 208 designates the test temperature of Hybrid III (AM50) dummies to be within the range of 20.6 to 22.2℃. On the other hand, the ISO Technical Report proposes a corresponding range of 19 to 25 ℃, which may cause a large variation in the measurements of chest deformation in particular. It will be necessary to harmonize the test temperature range for both Hybrid III (AM50) and three-year-old child dummies.

2) In the ISO Technical Report, the description of dummy positions often requires more details so as to ensure reliable injury rating as the result of dummy responses.

3) Some of the dummy positions prescribed in the ISO Technical Report are not practical due to the interior spacing of certain vehicle models.

ACKNOWLEGEMENTS

For three years from 1990 to 1992, using a Hybrid III (AM50) dummy and a three-year-old child dummy, we were able to carry out out-of-position tests and obtain basic data on practically all airbag module installation locations, including driver airbags and passenger (topdash mount and mid-mount) airbags.

It is expected that the ISO will review the results of these and other out-of-position tests before starting the task of establishing a final test procedure. In the meantime, automobile accident cases indicate that the rate of seatbelt usage remains at low levels, while the number of vehicles furnished with airbags is steadily increasing, posing a possibility of airbag out-of-position accidents. Therefore, we wish to continue our efforts to contribute to the establishment of a harmonized out-of-position test procedure.

These experiments were carried out by the Japan Automobile Research Institute as its 1990-92 research program, "Study on Airbag Out-of-Position Test Procedures," which was undertaken at the contract of the Japan Automobile Manufacturers Association, and with the cooperation of the Japan Auto Parts Industries Association.

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Experimentally-Induced Frontal Bone/Facial Fractures in Human Cadavers with a Characterization of Impact Response

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ABSTRACT

In a frontal collision, often the kinematics are such that vehicle occupants contact interior components causing fractures of the frontal bone and the periorbital region. Few studies of impact to cadaver supraorbital rims resulting in frontal bone/facial fractures discuss tolerance levels, the relationship between force data and anatomical consequences in human tissue.

In this study, twenty frozen human cadaver heads, ages ranging from 59 to 101, were sectioned from the body at various levels between the fifth cervical vertebra and the foramen magnum. Once thawed, they were impacted in order to induce fractures that are consistent with those seen in a clinical setting. Specific impact targets were the areas of the supraorbital rims, frontal sinuses, and junctions with the nasal and ethmoid bones. An impact cart was propelled to a mean velocity of 7.16 m/s (σ = 0.55 m/s) to strike the supraorbital portion of the unrestrained head. The cart was fitted with a 4.13-cm diameter impacting pipe instrumented with a force transducer coupled with a signal analyzer in order to record force-time behavior during impact.

Testing was recorded on standard VHS video and analyses were made on data from palpation, photography, CT Scans (computed tomography), and selected anthropometric measurements. These data are discussed as they relate to the force recorded during impact. Average peak force values and calculated absorbed energies are presented and discussed as they pertain to impact response of the frontal bone/facial skeleton.

The presence of skeletal injury to the cranium and face is better indicated by the energy absorption value rather than the tolerance level. It was also noted that severe to critical injury will almost always result from the type of impact defined in this paper.

INTRODUCTION

The general mechanism of injury during a frontal motor vehicle crash is fairly well understood. In such a crash, a motor vehicle rapidly decelerates a fraction of a second before the occupant(s). This differential deceleration results in a collision (the so-called "second impact") between the occupant and the interior of the vehicle.

Tolerance data of unembalmed human heads may be valuable to engineers designing frontal crash protection or automobile interior components. Such data would also be useful for biofidelity enhancement in the development of frangible face components for dummy head forms. Melvin (1989) states that further research is needed to understand the load sharing ability of facial bones and to establish tolerable values for such loading.

This study had two major goals: 1) to produce upper facial fractures consistent with those seen in a clinical setting, and 2) to compile preliminary tolerance data with regard to the force measured during impact.

The target impact area was the upper third of the face, specifically the supraorbital rims and the naso-orbital-ethmoid complex. This particular region can be injured when occupant kinematics result in the head striking the windshield, the steering wheel, the instrument panel, a pillar support, the back of the front seat or any forward interior structure. Refer to Huelke and Compton (1983) for a more thorough discussion regarding facial injury causation.

There are relatively few reported experiments of intact unembalmed human cadaver heads in which the supraorbital rims have been the dynamic loading area. It is believed that this study is one of the largest involving this type of impact. In fact, Melvin (1989) reported that there are no response data for the supraorbital region.

MATERIALS & METHODS

Producing facial fractures consistent with those seen in a clinical setting was the primary goal of this study. The sponsor's main objective was to use the fractured specimens in a course instructing maxillofacial surgeons in the reparation of complex facial trauma. Twenty frozen, unembalmed human cadaver heads ranging in age from 59 to 101 years (8 ♂ and 12 ♀) were used for this study. All specimens had been retrieved fresh over a period of seven months. Each was frozen immediately after death and thawed prior to testing. The heads were also examined grossly and radiographically for signs of prior facial trauma. Specimen #11 may have had a previous nasal fracture. Specimen #15 showed signs of an craniotomy, and specimen #20 had an edematous right eye.

A trauma research team composed of biomedical engineers and human anatomists was enlisted by maxillofacial physicians to produce fractures consistent with those seen in actual trauma - especially those observed due to frontal motor vehicle crashes. The laboratory setting provided a safe and controlled environment for fracture generation and the collection of data. Immediately prior to impact, numerous anthropometric measurements were recorded including specimen weight, orbital indices (height/width), head circumference at the brow, and several widths between paired facial bones. This data is included in Table 1.

The testing apparatus consisted of a pneumatic-based accelerator which propelled a wheeled impact cart toward the mounted head.

Accelerator & Cart - The accelerator consisted of a piston assembly in a chamber of compressed air. The chamber was pressurized to 0.3447 MPa (50 psi) for most of the tests in order to achieve a target velocity of approximately 7.5 m/s (actual mean velocity of all tests was 7.16 m/s; σ = 0.55 m/s). A ram connected to the piston pushed the aluminum and steel impact cart (50 kgs) throughout its stroke of approximately 1.5 meters. Then the cart separated from the ram and traveled along a railway for less than a meter before striking the head. In that stretch, it was timed by a photovoltaic cell/timer apparatus allowing for calculation of the velocity. The change in velocity of the cart (Δv) from before to after impact was negligible.

Impactor & Instrumentation - Heading the cart was an instrumented 10-cm steel impactor pipe with an outside diameter of 4.13 cm. It is mounted to the front of the cart via slide pins. When contacting a specimen, the pipe was freely able to impinge on a piezoelectric quartz force transducer, model 208A03 (commercially available through PCB Piezotronics), thereby producing a measured force equal to that which is delivered to the specimen. The transducer was coupled with a Hewlett Packard 3562A signal analyzer. The analyzer recorded and stored a plot of force vs. time for each impact.

Specimen Mounting - The heads were sectioned from the cadaver at various levels of the cervical spine ranging from the C-5 intervertebral disc to the foramen magnum. In order to position them for a supraorbital strike, a bag of clay served as a cradle or a pedestal (refer to Figure 1) depending on the length of the remaining neck of each specimen. Plastic was taped to the inferior portion of the head/neck in order to control fluid loss, etc. The cart was decelerated by contacting bales of wood fiber and the head was caught in a plastic and foam nest.

Figure 1. The head was mounted on a bag of clay. Plastic and foam nest in lower left of photo will secure specimen after impact. Also notice "posterior tilt" of this specimen as mounted.

Specimen Examinations - Immediately after each impact, the heads were manually examined for laceration and fracture determination was made via palpation by maxillofacial surgeons. In tests 3a, 5a, 5b, 6a, 8a and 8b, **no** fracture was evident and the heads were remounted and impacted at progressively higher velocities until fracture was obvious. All testing and laboratory examinations were recorded on standard 30 frames/s VHS video. Additionally, 35-mm still photography was employed to document pretest and post-test conditions of the heads. Upon completion of testing, damage to all 20 heads was radiographically documented using computed tomography (CT) scans. The scans were evaluated by maxillofacial surgeons and judged to be comparable to clinical trauma. A summary of the diagnoses is given in Table 2.

RESULTS

Known cadaver data and test measurements are on the following two pages in Table 1. Table 2 contains the clinical diagnoses as determined from axial and coronal computed tomography (CT) scans. Discussion and selected computations are included in the section following the tables.

Table 1

Cadaver Data and Test Measurements

Test	1	2	3a, 3b	4	5a, 5b, 5c	6a, 6b, 6c	7	8a, 8b, 8c	9	10
History (Age, Race, Gender)	76W♀	70W♂	75W♂	87W♂	87W♂	57W♂	63W♂	86W♀	64W♀	75W♀
Cause of Death	Cerebral Edema	Prostate Cancer	Prostate Cancer	Prostate Cancer	Prostate Cancer	Respiratory Failure	Rupt. Aortic Aneurysm	Ventricular Fibrillation	Cardiac Arrythmia	Natural
Circumference @ Brow (cm)	52.5	59.5	57.5	55.0	56.0	69.0	58.0	54.5	56.0	55.5
Left Max. Orbit Height (mm)	no data	34.1	37.5	37.4	33.9	33.4	33.7	31.7	37.8	32.5
Left Max. Orbit Width (mm)	no data	41.8	38.2	37.1	38.3	35.2	37.4	35.0	38.5	37.3
Left Orbital Index (Ht/W)	no data	0.816	0.982	1.008	0.885	0.949	0.901	0.906	0.982	0.871
Right Max. Orbit Height (mm)	29.3	33.6	36.3	37.3	34.5	32.3	31.5	31.5	36.6	33.2
Right Max. Orbit Width (mm)	37.0	41.3	38.2	37.0	36.4	35.6	38.5	45.1	37.8	37.3
Right Orbital Index (Ht/W)	0.792	0.814	0.950	1.008	0.948	0.907	0.818	0.698	0.968	0.890
Avg. Orbital Index (Left+Right)/2	no data	0.815	0.966	1.008	0.916	0.928	0.860	0.802	0.975	0.881
Inter-Orbital Width (mm)	26.4	28.7	28.4	28.1	25.2	25.5	26.4	20.3	23.6	24.6
Temporal-Temporal Width (mm)	110.0	118.2	116.0	113.0	105.8	121.6	118.6	107.2	110.5	116.8
Zygomatic-Zygomatic Width (mm)	109.3	128.9	118.4	121.3	109.7	118.4	112.4	112.2	116.5	119.2
Parietal-Parietal Width (mm)	134.5	149.0	142.6	143.0	145.8	154.4	135.7	140.2	149.2	145.2
Weight as Tested (kg)	3.66	4.25	4.31	3.52	3.40	4.42	4.25	3.20	3.97	3.69
Peak Force (kN) Multiple values indicate additional tests of same specimen until fracture.	4.88	10.88	9.81 No Trigger	4.78	8.22 11.08 11.04	8.09 10.94 8.44	6.07	11.36 11.26 7.06	6.86	9.08
Velocity (m/s) Multiple values indicate additional tests of same specimen until fracture.	7.19	7.10	6.13 6.37	6.43	6.19 6.31 7.47	6.46 7.22 7.77	7.22	6.55 7.32 8.35	7.89	7.25
Specimen Cross-section Level	C-3	C-4	C-5	C-5	C-1	C-2	C-2	C-1	C-1	C-2
Head Movement R=Rotational T=Translational	T	T	R, T	T	R, R, R	R, R, R	R	R, R, T	T	T

Table is continued on the next page.

Table 2

Clinical Diagnoses from Axial and Coronal CT Scans

Specimen	NOE[1]	Sinus[2]	Le Fort[3]	AIS[4]	Additional Notes
1	✓[n]	✓	I, II, III	3	Hypoplastic frontal sinus
2	✓	✓		4	Orbital roofs fractured
3	✓	✓		4	Massively depressed frontal bone with linear fractures; Maxilla and temporal bones also fractured
4	✓	✓		4	Orbital roofs, zygoma and angular processes fractured
5	✓	✓		4	Hypoplastic frontal sinus; Orbital roofs and maxilla fractured
6	✓[n]	✓		4	Hypogenesis of the frontal sinus
7	✓	✓		4	Orbital roofs fractured
8	✓[n]	✓	III	4	Several fractures of the frontal bone
9	✓	✓		4	Orbital roofs and maxilla fractured
10	✓	✓	II	4	Hypoplastic frontal sinus; Orbital roofs fractured
11	✓	✓	I, II	4	Orbital roofs fractured and linear fractures of the frontal bone; Possible previous nasal fracture
12	✓	✓		4	Orbital roofs fractured
13	✓	✓	II	4	Orbital roofs and right orbital wall fractured
14	✓	✓	I, II	4	Segmental maxillary fracture
15	✓	✓[a]		4	Old craniotomy or previous skull fracture
16	✓	✓	I, II, III	4	Nondisplaced fractures of frontal bone
17	✓	✓		4	Several fractures to the right maxilla and angular process
18	✓	✓		4	Orbital roofs and maxillary fractures
19	✓	✓[a]	II	4	Hypoplastic frontal sinus; Right orbital roof, temporal and zygomatic bones fractured
20	✓[n]	✓[a]		3	Segmental fracture of the maxilla; Edematous right eye

[1]NOE - ✓ = Comminuted fractures of the nasal, orbital and ethmoid bones including the cribriform plate.
✓[n] = Naso-orbito-ethmoid fracture with no cribriform plate involvement noted.

[2]Sinus - ✓ = Comminuted fractures of the frontal sinuses with anterior and posterior table involvement.
✓[a] = indicates that only the anterior table was involved in the fracture.

[3]Le Fort - A grading system of facial fractures: Class I is a horizontal segmented fracture of the lower maxilla. Class II Le Fort fractures cause the complete separation of the maxilla (or maxilla and nasal bones) from the other facial bones. This results in a large pyramidal-shaped segment of bone. Le Fort III indicates the complete separation of the maxilla and other large facial bones from the base of the cranium (craniofacial disjunction).

[4]AIS - The value listed is the maximum anatomical injury rating according to 1990 Abbreviated Injury Scale published by the Association for the Advancement of Automotive Medicine (1= Minor, 2= Moderate, 3= Serious, 4= Severe, 5= Critical, and 6= Maximum).

Table 1 (continued)

Cadaver Data and Test Measurements

Test	11	12	13	14	15	16	17	18	19	20
History (Age, Race, Gender)	69B♂	86W♀	78W♀	89W♂	82W♀	75W♀	74W♀	93W♀	101W♀	73W♀
Cause of Death	Renal Failure	Brain Stem Infarction	Rupt. Aortic Aneurysm	Pulmonary Edema	Myocardial Infarction	Myocardial Infarction	Cerebrovascular Accident	Coronary Artery Disease	Pulmonary Edema	Intestinal Infarction
Circumference @ Brow (cm)	56.0	54.4	56.0	56.5	54.0	58.0	54.0	54.0	52.5	58.0
Left Max. Orbit Height (mm)	35.8	36.9	33.1	35.6	30.5	35.2	31.2	33.7	35.7	35.1
Left Max. Orbit Width (mm)	40.8	37.4	36.4	38.1	34.2	35.0	34.7	35.4	34.3	37.4
Left Orbital Index (Ht/W)	0.877	0.987	0.909	0.934	0.892	1.006	0.899	0.952	1.041	0.939
Right Max. Orbit Height (mm)	34.1	34.6	32.3	35.4	33.7	34.8	30.3	33.4	34.8	38.7
Right Max. Orbit Width (mm)	37.6	36.0	34.6	38.5	33.4	35.0	34.1	35.6	32.2	n/a
Right Orbital Index (Ht/W)	0.907	0.961	0.934	0.919	1.009	0.994	0.889	0.938	1.081	n/a
Avg. Orbital Index (Left+Right)/2	0.892	0.974	0.921	0.927	0.950	1.000	0.894	0.945	1.061	n/a
Inter-Orbital Width (mm)	30.7	21.6	28.8	22.1	26.0	24.1	25.1	27.2	26.7	24.4
Temporal-Temporal Width (mm)	118.5	114.7	126.4	111.6	111.4	112.0	111.7	107.8	110.9	120.3
Zygomatic-Zygomatic Width (mm)	117.4	112.2	121.6	118.1	112.7	116.0	108.9	109.7	113.0	124.3
Parietal-Parietal Width (mm)	140.3	130.7	137.7	137.3	128.9	140.8	137.3	144.7	136.4	137.4
Weight as Tested (kg)	4.48	3.46	3.18	3.97	3.49	4.31	3.29	3.40	3.63	3.77
Peak Force (kN)	7.88	8.06	7.07	7.45	9.33	8.46	7.73	6.61	10.39	9.89
Velocity (m/s)	7.47	7.50	7.47	7.41	7.32	7.47	7.41	7.35	7.32	7.53
Specimen Cross-section Level	C-5	C-1	Foramen Magnum	C-2	Foramen Magnum	C-2	C-2	C-2	C-2	C-2
Head Movement R=Rotational T=Translational	T	T	T	T	T	T	R	T	T	T

DATA EVALUATION AND DISCUSSION

Virtually all of the specimens exhibited a large transverse laceration to the forehead in the region of the supraorbital rims and/or bridge of the nose. This was also true on the four specimens that required additional impacts to produce a definite fracture. In most cases, fracture of the naso-orbital-ethmoid complex and the frontal sinus were obvious. Additionally, there were fractures of the base of the skull, specifically the orbital roofs and cribriform plate of the ethmoid bone. Facial impacts causing basilar skull fractures is not uncommon in motor vehicle trauma (Huelke, 1988 and Myklebust, 1988).

Refer to Table 2 for a detailed breakdown of the fracture data. It is believed that the assigned AIS values are conservative for two reasons. 1) The use of cadavers prohibits the evaluation of blood loss and physiologic parameters such as loss of consciousness, etc. 2) The grading is based solely on palpation and CT scan analyses of the skeletal tissues. A value of AIS 5 or 6 can only be assigned for injury to internal organs (brain, brain stem, or major intracranial vessels). Also, measurements of maximum skull depression and depth of penetrating injury were not recorded.

Post-test radiography indicated that the majority of the impacts resulted in severe facial trauma including comminuted fractures of several skull bones. During the experiment, on-site assessments by palpation indicated that four heads did not fracture upon first impact (tests 3a, 5a, 6a and 8a; average velocity = 6.33 m/s). Fractures were also not evident in three of these upon second impact (tests 5b, 6b and 8b; average velocity = 6.95 m/s), thus warranting a third test. Energy calculations from measured force-time data might refute the conjecture that test 6b resulted in no fracture.

The specimen mounting technique was not precisely controlled. Analyses of the videotape and force-time plots gave clues as to the reasons for non-fractures. It appears that the impacted heads that did not fracture were initially mounted with a posterior tilt. Note that the specimen in Figure 1 is angled counterclockwise from the vertical. The impact to these tilted heads was more of a glancing blow causing the head to rotate downwards (posteriorly) away from the impacting pipe as illustrated in Figure 2. Most of the heads that fractured at first impact were struck with the forehead nearly perpendicular to the plane of impact. The videotape clearly shows these heads contacted the impacting pipe for a greater period of time than the tilted heads.

In reviewing the Tabel 1 data, velocity might appear to be the only determining factor for fracture generation. The average velocity for the tests in which fractures occurred was 7.42 m/s (σ = 0.37 m/s; n=19). Test 3b resulted in fractures, but was excluded from the velocity average because force-time data was not obtained. The six non-fracture tests had an average velocity of 6.49 m/s (σ = 0.43 m/s). Test 6b was excluded from all averages and calculations due to the previously discussed conflicting results (palpation vs. energy calculation) regarding the presence of a fracture. Even though the difference between average velocities of fracture versus non-fracture impacts was approximately 1 m/s, there may be other contributing factors relating to the occurrence of fractures. Note that upon review of the videotape, rotational and translational head motions were observed (see Figures 2 and 3 above).

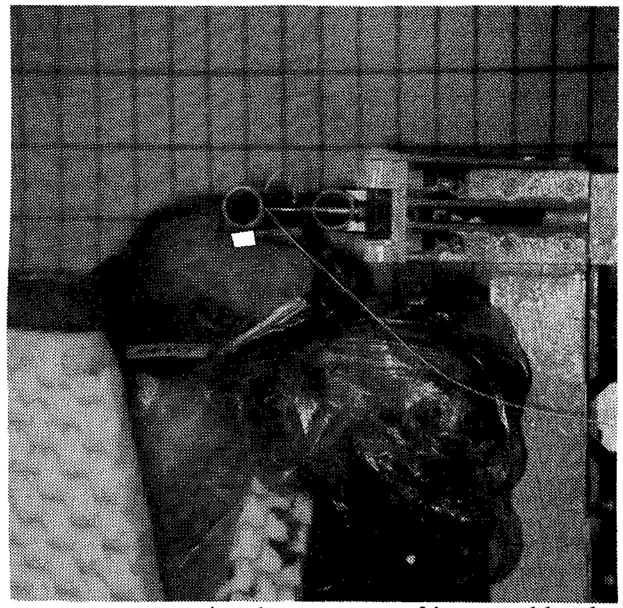

Figure 2. Rotational movement of impacted head

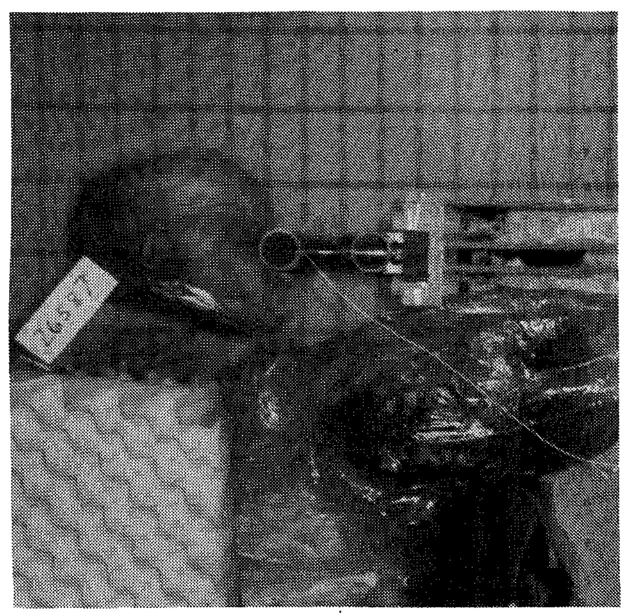

Figure 3. Translational movement of impacted head

The combined effect of lower cart velocity and head rotation was evident in the tests resulting in non-fracture. Head rotation occurred for three reasons: 1) the aforementioned "posterior tilt," 2) striking the head above its center of gravity (especially in those sectioned at more inferior cervical levels), and 3) the clay mounting structure/neck interface may have acted as a fulcrum.

The fractured heads "wrapped" around the impacting pipe causing their continued motion to be more translational (see Figure 3). In many of these cases, the pedestal of clay was analogous to a golf tee in that it allowed translation as opposed to the fulcrum effect.

In order to conclusively support this observation, the force-time curves for all 26 (no force-time data was obtained for test 3b) tests were integrated to determine the maximum head velocity. Assuming all of the force was converted to kinetic energy of the head, velocity is obtained by using the formula below:

$$v = \frac{g_c}{m} \int F\,dt \ ,$$

where
- v = velocity of the head,
- g_c = the proportionality coefficient relating force to mass & acceleration,
- m = mass of the head,
- F = measured force, and
- t = measured time.

This equation is a form of Newton's Second Law (force is proportional to the product of mass and acceleration). Figures 4 and 5 show sample curves of a non-fracture and a fracture impact, respectively. The non-fracture impacts produce smoother force-time curves as similarly reported by previous researchers (e.g. Hodgson et al, 1966-1967). For each of the non-fracture impacts, the calculated velocity fell far short of the cart velocity - indicating, conclusively, that the contact between the head and the impactor was lost early. By contrast, the same integral for those impacts that caused fracture, showed a final velocity in excess of the cart velocity - indicating continued contact throughout a more significant travel distance of the cart.

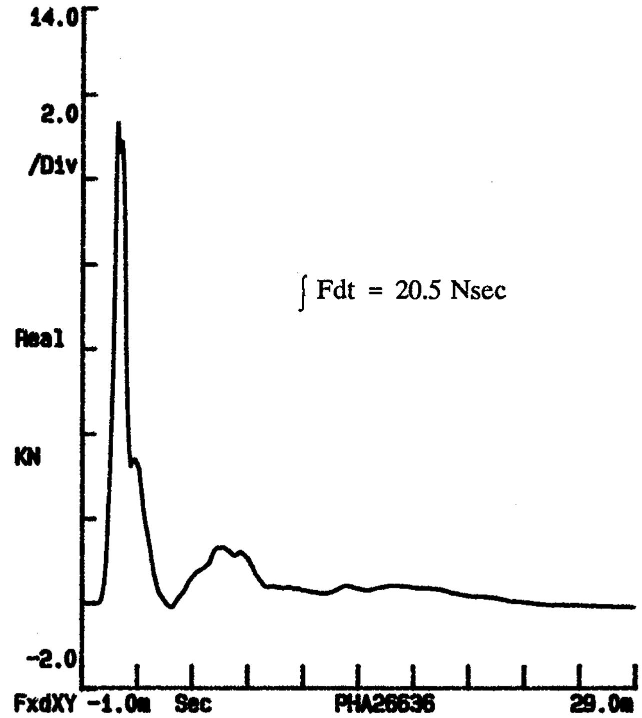

Figure 4. Force-time plot of test 8a - **non-fracture**

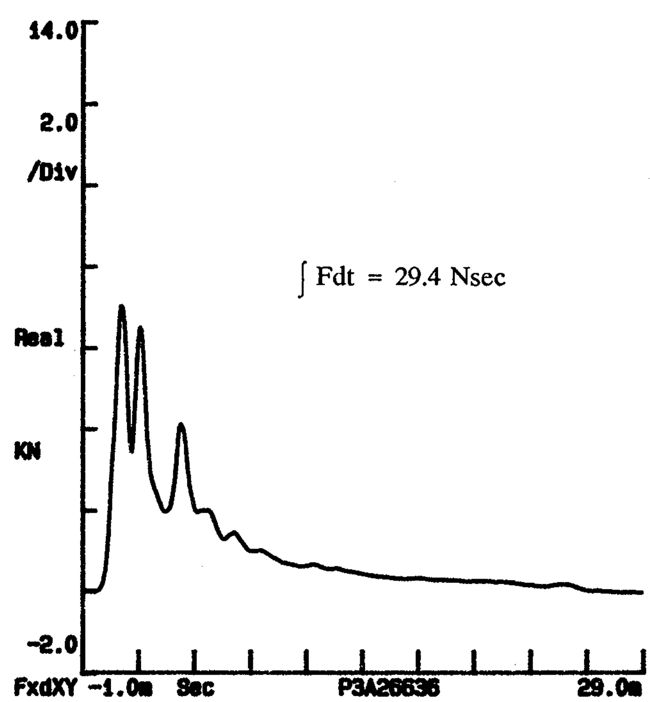

Figure 5. Force-time plot of test 8c - **fracture**

This "excess velocity" is not an actual incremental increase in the speed of the head, but is proportional to the energy absorbed by the head to cause strain and failure. Consider the following equation:

$$E = W - KE = v \int F\,dt - \frac{mv^2}{2g_c},$$

where E = energy absorbed by the head and facial bone structures in strain and failure,
W = work done on the head by the cart,
KE = maximum kinetic energy of the head,
v = velocity of the cart,
F = measured force,
t = measured time,
m = mass of the head, and
g_c = proportionality coefficient relating force to mass & acceleration.

This equation implicitly assumes negligible change in cart velocity during impact (verified by digitization) and that the final velocity of the fractured heads is, at most, the velocity of the cart.

Calculated values for E, W and KE for each test can be found in Table 3. The average energy absorbed, E, for the impacts that caused fractures is 155.1 Nm (σ = 62.5 Nm; n=19) and only 78.3 Nm (σ = 12.8 Nm; n=6). It may be of interest to note that the average E of the impacts that caused fractures involving the heads that were subjected to multiple strikes is 145.7 Nm (σ = 32.8 Nm; n=3). This value is significantly larger than the average 78.3 Nm of energy absorbed for the non-fracture impacts.

There is a stand-out energy value from an impact causing fracture. Specifically, the E value for test 19 is only 79 Nm. Perhaps degenerative changes associated with advanced age account for this lower energy to cause failure. The cadaver in this test was the oldest specimen at 101 years.

The peak force values from force-time data of the impacts causing fractures (n=19) were averaged, F_{avg} = 8.00 kN (σ = 1.82 kN), to provide a tolerance level indicating the force threshold at which fracture begins. This value is comparable to the frontal bone tolerance levels reported by Nahum (1975). It is important to note that the 8.00-kN tolerance value reported here is dependent on methodology parameters including impactor geometry, impact angle and location, and human-to-human variation. Force application time is also a critical parameter in all of the tests. This is evident in that the average tolerance value for the heads that did not fracture (n=6) was 9.97 N (σ = 1.51 N).

Nahum (1975) reported lower tolerance values for females as compared to males. However, no noticeable difference was detected in the means in this study. The average male fracture tolerance value is 8.1 kN (n=7) and the female value is 8.0 kN (n=12). Mean absorbed energy values for the fractured male and female specimens were 153.1 Nm (n=7) and 156.2 Nm (n=12) respectively.

Table 3

Calculated Energy Values

Test	Work, W (Nm)	Kinetic Energy, KE (Nm)	Energy, E (Nm)
1	221	95	126
2	202	107	95
3a[nf]	**153**	**81**	**72**
4	176	73	103
5a[nf]	**152**	**65**	**87**
5b[nf]	**151**	**68**	**83**
5c	216	95	121
6a[nf]	**189**	**92**	**97**
6c	316	133	183
7	294	110	184
8a[nf]	**134**	**69**	**65**
8b[nf]	**152**	**86**	**66**
8c	245	112	133
9	279	124	155
10	188	97	91
11	426	125	301
12	292	97	195
13	232	89	143
14	260	109	151
15	285	94	191
16	268	120	148
17	207	90	117
18	215	92	123
19	176	97	79
20	414	107	307
AVG (n=19)	-	-	155.1 (σ = 62.5)
AVG[nf] (n=6)	-	-	**78.3 (σ = 12.8)**

[nf] values in bold are data from **non-fracture** impacts

CONCLUSIONS

1) Frontal bone/facial fractures similar to those seen in motor vehicle trauma may be successfully produced in the laboratory setting.

2) Impact to the supraorbital rims, given the other methodological conditions, at speeds near 7.2 m/s will almost always cause severe to critical injury.

3) The occurrence of skeletal injury to the cranium and face is better indicated by the energy absorption value rather than the tolerance level. Energy accounts for the total time that force is applied to the head, whereas tolerance level is only a peak force value at a specified time (at which the first fracture just begins).

REMARKS

Data analyses beyond the scope of this paper may provide more useful information.

It is anticipated that tolerance levels will be specified as they pertain to certain fracture events that occur after the onset of the very first fracture. Hopefully, this can be accomplished by a more detailed comparison of the computed tomography data with the force-time curves.

Even though extensive anthropometric data has been collected and presented in this paper, most of it was not examined as it may relate to injury causation. If significant correlations or trends exist, they will be noted and investigated further.

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THE EFFECTS OF THE SKULL/DURA INTERFACE AND FORAMAN MAGNUM ON PRESURE RESPONSE DURING HEAD IMPACT

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ABSTRACT

A simple physical model was used to help evaluate the effect of the stresses generated in the brain during head impact. The biomechanical phenomena of interest were: the skull-dura-boundary, material flow through the foremen magnum, the effects of skull deformation, and the effects of free gas in the brain. The physical model was impacted by a 10 kg free-flying mass. During impact, the contact force and the acceleration as well as the fluid pressures at various points in the physical model were measured. A finite-difference simulation which can address phenomena such as cavitation as well as the fluid motion was used to evaluate the pressure response of the physical model to impact. The analysis of these data indicate that the boundary conditions at the interface of the skull-dura coupled with material flow through the foramen magnum significantly affect the stresses generated in the brain during impact to the head.

Introduction

Violent motion of the head, sufficient to cause injury, can occur as a consequence of many events, such as: falls, automobile accidents, sports activities, airplane crashes, and fights. As a result of these events, people are under peril of head injuries ending in death, short term and long-term disability. Therefore, efforts by the government and industry have been extended toward reducing head injuries resulting from direct or indirect loading.

To accomplish the ultimate goal of reducing the damaging effects of direct and indirect loading of the head, it is helpful to understand the mechanism or mechanisms of head injury; to understand the mechanisms of head injury, requires first understanding the impact response of the head. However, the head is a complex geometric structure, and the loading conditions on it during abrupt acceleration are rarely simple. Because of the potential for multiple mechanisms for many head injuries, it is worthwhile to study a limited aspect of the head injury equation, such as the skull-dura-boundary. In general, boundary conditions are considered important for the response of mechanical systems during transient events. This is also true for the skull-dura-boundary with respect to head impact response.

In terms of head injury mechanisms the skull-dura-boundary and it's response to impact is considered important (1-4). However, it is generally not addressed in head impact simulation modeling efforts. Current models assume that the brain is an isotropic homogeneous elastic material that is attached to a rigid shell See References (1-6). Such simulated attachment of the brain to the skull does not allow movement at the interface of the brain-dura-skull. The interface of the brain with the skull could confound many aspects of the response of the brain. For example, when the head receives a blow the skull deforms and accelerates. In both cases the brain is loaded through the skull-dura-brain boundary.

A simplistic physical model of the head is used to study the coupled/uncoupled effects of the skull-dura-brain, fluid flow through the foramen magnum on the pressure response of the brain to head impact. No attempt is made to model the complete response of the head to direct impact. The physical model is used to generate test data so that a finite-difference model of its response can be used to gain insight into the way the human head responds to impact.

METHODS

Physical Model

The simplified mechanical head form consisted of two parts: a polished (inside) aluminum cylinder and a rubber neck attached to the base of the cylinder (Figure 1). The cylinder was closed at each end with flat plates of 1.3 cm thick plexiglass; for most of the tests, the plexiglass was reinforced with aluminum channel. To complete the head form the cylinder was connected by a rigid joint to a flexible viscoelastic rubber neck structure; fluid flow between the cylinder and the neck was through a two-centimeter diameter hole at the head neck interface. A nine-accelerometer array, used to measure three-dimensional motion (6 degrees of freedom), was rigidly affixed to the aluminum cylinder. Pressure transducers were mounted so that pressures could be monitored at the interface of the fluid and the cylinder.

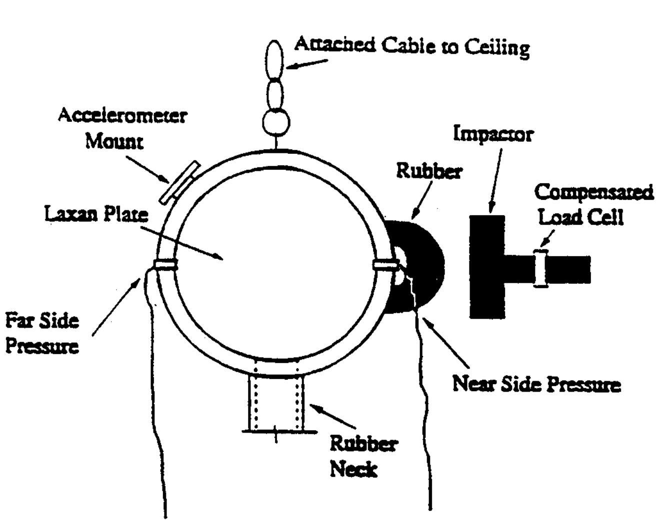

Figure 1. Test setup.

The fluid, tap water, used to fill the system was boiled for several hours and allowed to return to room temperature. Before filling the cylinder with the fluid the air in the cylinder was evacuated and a partial vacuum was actively maintained. The vacuum was used to draw the fluid through a valve into the neck, then through the hole in the base of the cylinder. During this time a vacuum was maintained until the cylinder was filled and no visible "cavities" or vacant spaces could be observed. Before each test series the mechanical head form was impacted several times and inspected to ensure that no air or cavities were visible in the cylinder.

Impactor

The impact was delivered through the center of mass of the cylinder by a 10 kg free-traveling mass fitted with a load cell assembly; the impacting surface consisted of a flat rigid 5 cm diameter disk. For more information on this impact device see (7, 8). To bring the contact force time-history closer to that of a head impact, a neoprene rubber hemisphere was fixed to the cylinder; impact to the cylinder came through the neoprene hemisphere. The force-time-history is obtained from transducer assembly consisting of a Kistler 904A piezoelectric load washer with a Kistler piezoelectric accelerometer mounted internally for inertial compensation. The piston velocity was measured by timing the pulses from a magnetic probe which sensed the motion of targets in the piston.

Acceleration Measurement -- An interrelated set of three triaxial accelerometers (a nine-accelerometer array) recorded "head" accelerations. The accelerometers were either Endevco 2264-2000 piezoresistive ones or Kistler Model 8694 piezoelectric ones. Five metal screws were attached firmly to the "aluminum cylinder" opposite to where the impact was delivered via small pilot holes drilled into the metal. Quick-setting acrylic plastic was molded around each of the screws and the nine-accelerometer plate mount, embedding the mount in the plastic. After the acrylic set, the plate was rigidly attached to the side of the cylinder. The orientation of the plate in this position is shown in Figure (1). This arrangement of nine accelerometers allows for determination of complete rigid body motion of the cylinder; for a description of its use, see Reference (7).

Pressure Measurements -- Pressures were measured with Kulite model MCP-055-5F catheter tip pressure transducers or with Endevco 8507-50 ones. The pressure transducers were screwed into tapped holes in the "skull" of the replica.

Data Handling -- All transducer time-histories, impact force, pressures, and the nine "head" accelerations were recorded unfiltered on a Honeywell 9600 FM Tape Recorder with an EMI multiplex unit or a Honeywell 7600 FM Tape Recorder. A synchronizing gate was recorded on all tapes. The analog data on the FM tapes were played back for digitizing through proper anti-aliasing analog filters. The anti-aliasing filters were four-pole Butterworth with a 3 db point at 2000 Hz. The analog-to-digital process for all data resulted in a digital signal sampled at 10,000 Hz equivalent sampling rate.

Test Matrix

Three series of tests were conducted. In the first series of tests detectable dynamic deformation with no permanent deformation was observed; by adding stiffening channel to the head form this deformation was significantly reduced for the second and third test series. The first series of tests are used to point out the difficulty of addressing pressure response on a deforming skull.

The three series of tests are:

Low severity, impact velocity 5 m/s, detectable deformation.

Low severity, impact velocity 5 m/s, no detectable deformation.

High severity, impact velocity 8 m/s, no detectable deformation.

MATH MODELS

Basic Assumption

It was assumed that boiling the tap water removed the free gas. Therefore, even though tap water has a significant number of nucleation sites to allow for fluid vaporization for the impacted cylinder and plastic neck, there was no free gas in the system.

It was also assumed that: Although there was no visible air in the physical model, it was impossible to remove all the air at the boundaries of the water and the cylinder walls. The air at these boundaries is modeled as a continuous thin layer less than 10^{-6} m thick. Finally, it is assumed that the flow velocities through the neck are proportional to the force acting on the fluid in the neck.

The model used was a finite difference model of the fluid filled head form used in the impact experiments. A computational model was developed to simulate the physical results of the cylinder impact test described above. The model is based upon linear two-dimensional equations of motion and continuity in fluid mechanics. The cylinder was modeled with a two-dimensional staggered grid that is 47 by 47 nodes, Figure 2. A quarter of the nodes are labelled even nodes, which means that they are computed every time step, while another quarter of the nodes are labelled odd nodes as they are computed every odd time step. Due to the nature of a staggered grid, half of the nodes are never computed during a run.

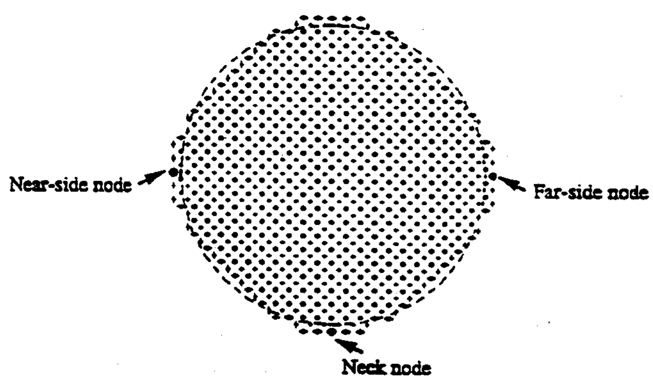

Figure 2. Finite difference model staggered grid.

The parameters used in the model were those of water under standard conditions. The density of water was 1000 kg/m^3 ; the Bulk Modulus was 2.05 GPa; the wave speed, *c*, was 1135 m/s; the step distance interval, *dx*, was 0.00318 m; and the time step, *dt*, was 2.22 (10^{-6}) sec. Vapor pressure was set at 4550 Pa. absolute. The acceleration recorded from the physical model was input to the computer model to generate pressure-time histories at various points in the cylinder. As mentioned before, determined efforts were made to remove all the air from the physical model, however, it is likely that a microscopic layer existed at the fluid/cylinder boundary. Therefore, an initial thickness of air of 10^{-6} m on the perimeter was used to model this effect. Boundary conditions around the perimeter may be set such that boundary pressures do not drop below vapor pressure in the numerical model.

Basic Equations and Theory

The equations developed here utilize Henke's method (13) that was applied to fluids by Wylie (9, 10). The linearized version of the more general compressible flow equations that describe pressure waves in a two-dimensional continuum provide the simplest case to develop the method.

$$L_o = p_t + \rho c^2 u_x + \rho c^2 v_y = 0 \quad (1)$$

$$L_1 = p_x + \rho u_t = 0 \quad (2)$$

$$L_2 = p_y + \rho v_t = 0 \quad (3)$$

$$L_3 = u_y + v_x - (u_y + v_x) = 0 \quad (4)$$

Equation (1) represents the conservation of mass condition with the isentropic relation $dp = c^2 d\rho$, in which c = sonic speed, p = pressure, u = velocity in the x -direction, v = velocity in the y-direction and ρ = mass density. Equations (2) and (3) are the momentum equations in the longitudinal and lateral directions. In the linearization of these equations it is assumed that the fluid particle velocities are much less than the sonic velocity in the fluid, and material properties are time independent. The fourth equation, which merely states an identify, completes the set of equations. For a more detailed description of this math model and the equations governing the cavitation calculation see Reference (11).

Estimation of Volume Change

To estimate the volumetric changes for the first series of tests, both a finite element model and a finite difference model are used. A finite element model of the aluminum cylinder, without water, was constructed using LS Dyna-3D. Then the finite element model was dynamically impacted in a manner similar to the test. The deformation of the model did not change the volume by more than 0.005%. The finite difference model was then used to estimate the effects of the deformation on pressure during impact by inducing volumetric changes greater than the Dyna-3D model results, up to .01%. Reduction in volume of the finite difference model was accomplished through the use of an elliptical boundary representing the cylinder. Initially, before impact, the boundary represents a cylinder; as the impact begins, the axis in the direction of impact is reduced while the axis perpendicular to the impact is increased enough to maintain a constant surface area. The amount of deformation is proportional to the acceleration and scaled such that the maximum acceleration produces a cylinder volumetric change of .01%.

RESULTS

The primary conclusions of this study are obtained by comparing the pressure response of the physical model to the pressure response of the finite difference mathematical model. In particular, the pressure response nearest to the impactor and the pressure response farthest from the impactor for the physical model are compared to the corresponding pressures for the mathematical model. The acceleration time-history from the physical model is used as the input to the mathematical model. Figure 3 has the average acceleration time history for both the 5 m/s and 8 m/s impacts.

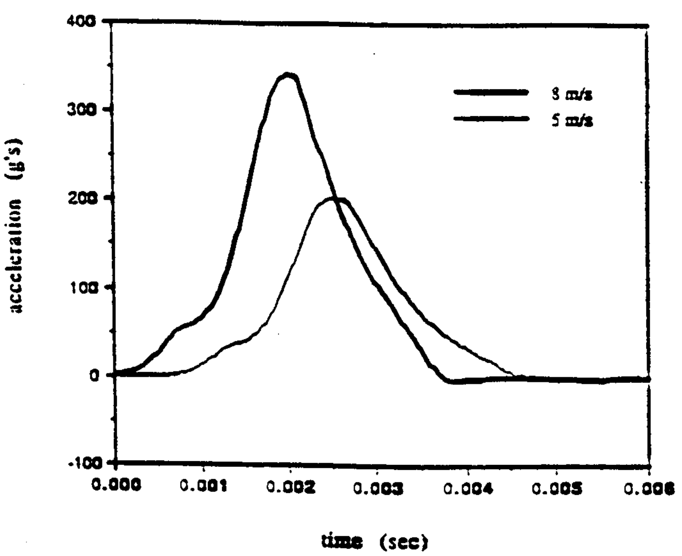

Figure 3. Acceleration time history for 5 m/s and 8 m/s impacts.

Angular Motion

Although there is a small contribution to the cylinder surface acceleration, as a result of angular acceleration, integration of the angular velocity reveals there is virtually no rotation. In addition, there was no significant acceleration outside of the tangential acceleration and the shape of the tangential time history was similar to the force-time-history; therefore, for all practical purposes, the motion during impact was one dimensional. Maximum angular acceleration, angular velocity, and angular position for all of the tests reported were below 1,000 r/s/s; 5 r/s, and 0 .05 r respectively.

Effects of Deformation Timing of Events

Two aspects of the skull cylinder and deformation were evaluated in the first test series: volumetric, and the phase relationships between the cylinder acceleration and internal pressure.

The results from the deformation of modeling exercises for the first series of tests show that: For .01% volume change the pressure relief of the neck system minimizes the effect of deformation on peak pressure. The maximum pressure predicted by the model, of an impact with deformation, was 2% greater than similar impact without deformation. However, despite the small effect of volumetric change, observation from the test data indicate that: The shape and phase relationships between the pressures and acceleration for the first series of tests are affected by the deformation. The results presented, in what follows, for the first series of tests, represents an average value for 6 tests.

During the first test series, it was discovered that the physical system deformed enough to, for some of the tests, affect the relationship between the pressure and acceleration responses during impact. This result was based upon three observations: 1) a phase lag of .4 ms ± .2 between the near-side peak pressure and the peak acceleration, 2) a phase difference of .4 ms ± .2 between the near-side peak pressure of the mathematical model and the near-side pressure time-history of the experiment without an equivalent phase difference in the far-side pressure-time history, and 3) a near side pressure initiation of .3 ± .2 ms before the acceleration and far side pressure initiation.

If the cylinder is rigid, non-deformable, then its acceleration and the near side pressure should be in phase. Indeed, for the second series of tests, both the near side pressure and the cylinder acceleration start at the same point in time. However, this was not observed in the first series of experiments. The phase difference between the initiation of near side pressure and the far side acceleration and pressure indicate that the near side of the cylinder started to move before the far side of the cylinder and that the cylinder could not be viewed as a rigid body. Since the neck acts as a pressure relief, it was possible in the first series of tests to obtain the same pressure maximum valve for both the mathematical model, without deformation, and the experimental response but it was not possible to obtain the correct phase relationship in those tests.

Therefore, there does seem to be a potential significant effect of skull deformation--even when volumetric changes are not important - on the pressures generated in the brain during direct head impact. This effect is characterized by a phase relational change between the impact force and the head acceleration, measured at a given point on the skull. This phase relationship is associated with differential motion of the skull and makes it difficult to evaluate the pressures in the brain in the first set of experiments.

5 m/s Impacts

A summary of the ranges of the six impact test data from the physical model for the 5 m/s tests without deformation is as follows: peak near side pressure 190-195 kpa, far side negative pressure -95 to -97 kpa peak, contact force of the impactor's interation with the rubber bumper 4400-4600 N, linear and angular accelerations recorded by the nine-accelerometer array on the cylinder were 2000-2100 m/s/s and 650-1000 r/s/s respectively and linear angular and velocity obtained from integration was 4.9 - 5.2 m/s and 2-3 r/s. The six tests presented here were chosen out of a test matrix of 16 tests. The requirements for the ones chosen were: 1) the impactor contact velocities were within .1 m/s of 5 m/s, 2) no visible air could be seen in the cylinder before and after impact, and 3) the peak angular accelerations during impact were less than 1000 s/s.

Although the geometry of the physical model as well as the material properties of water are well defined, two factors of potential significance are not clearly determined in this experiment, they are: 1) the exact thickness of the air between the water and the cylinder, and 2) the effective impedance of the flow of fluid through the hole in the base of the skull. In order to address the effect of these variables on the experiment's results, first the values of these variables were chosen which gave the closest fit between the data from the physical model and the simulation, Figure 4. Second, a sensitivity of both the impedance and air thickness study using the model was conducted. The results of the sensitivity study indicate that there was no significant difference in the peak pressure results, despite changes of an order of magnitude for the air thickness, from 10^{-6} to 10^{-7}, and a factor of two for the impedance of the fluid flow through the neck. The peak near side pressure changes by a maximum of 10%. It is important to note that the thickness of air in the mathematical simulation is very small (10^{-6} m). This thickness is small enough so that a uniform thickness, or even a continuous air layer in the cylinder is probably not occurring; however, the results show good agreement between the mathematical model and the testing indicating that the flow through the hole and the effect of the air as represented in this simulation are reasonable approximations to give insights into the mechanics of the impact.

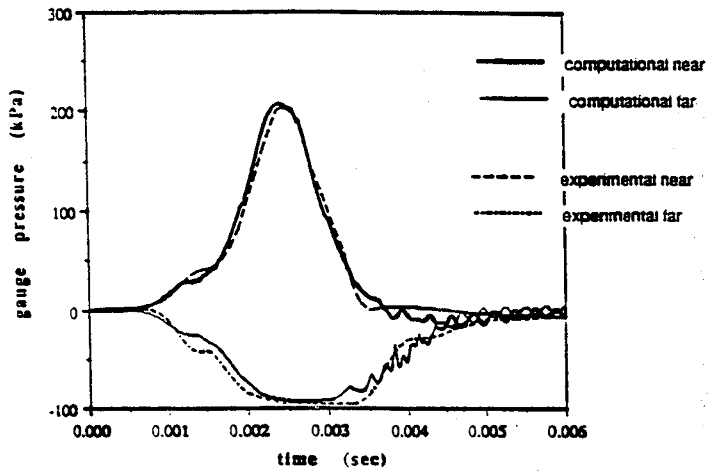

Figure 4. 5 m/s impact.

The most significant observation from these tests is that the negative pressure in the cylinder is limited to one atmosphere. There are two possible mechanisms for the limiting effect of the far side pressure. They are: 1 - fluid vaporization, and 2 - an air volume cavity forming as a result of the expansion of the air space against the cylinder wall. Inspection of the far side pressure response shows that both the physical model and the mathematical model reach a limit in terms of negative gage pressure. The mathematical model shows that this limit is adequately explained by the expansion of the air space in contact with the surface of the cylinder. A simulation of these tests without the air space, but with fluid vaporization indicates that: The correlation, between the mathematical model and the physical model, was better when the mathematical simulation included only the air space than when it included only fluid vaporization. This does not mean that some fluid vaporization is not occurring in the physical model, but rather that it is not the dominant factor limiting the negative pressure. Some evidence for fluid vaporization in these tests is that the far side pressure in the physical system rises faster than that of the model.

8 m/s Impacts

For the 8 m/s impact, the simulation was conducted using the same flow impedance through the hole in the cylinder and air layer as the 5 m/s test. Although it is not possible to determine whether fluid vaporization has occurred in the 5 m/s impacts it is reasonable to conclude that it has in the 8 m/s impacts. This is the result of the rapid rise of the far side pressure with the resultant over shoot, Figure 5.

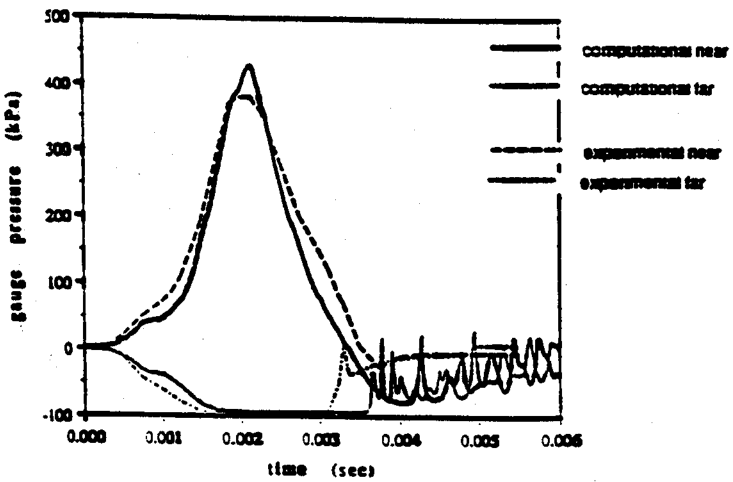

Figure 5. 8 m/s impact.

Effects of Bulk Modulus

To evaluate the effects of free gas on the effective bulk modula a series of numerical simulations were run. In these simulations the wave speed was varied from 550 m/s to 1135 m/s. The results indicate that the magnitude of the pressure and the time at which it occurs does not change significantly. However, the wave shape as well as the far side pressure does change, Figure 6.

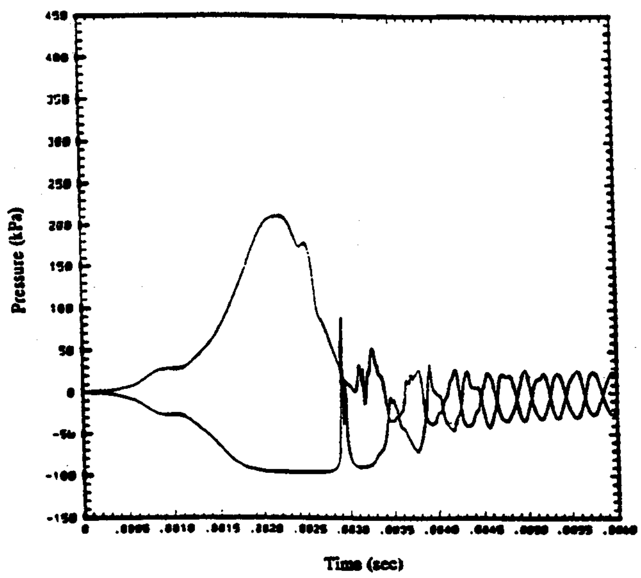

Figure 6. 5 m/s impact with a wave speed of 550 m/s.

DISCUSSION

The results presented in this paper describe the boundary pressure response to impact of a fluid-filled cylinder. The pressure response throughout the cylinder is influenced by, the air at the fluid-cylinder boundary, cavitation through fluid vaporization, and fluid flow through the hole in the base of the cylinder. The primary effect of these factors is to limit the negative pressure in the cylinder to one atmosphere.

Although the fluid-filled cylinder is different from the skull-brain system insight into the impact response of the human head can be obtained from the results. To understand the limits of this approach, as well as to characterize what can be gained from it, it is instructive to look at the complexity of the human head and some of the results from impact experiments of human surrogates.

Anatomy

The area of interest in this study is the area between the skull and the dura as well as the area below the dura. The dura-mater is a thin inelastic fibrous membrane which lines the interior of the skull. Its outer surface, adheres closely to the inner surface of the skull, forming its internal periosteum. This adhesion being most marked opposite the sutures, and at the base of the skull. Over most of the area of the skull, the dura is lightly attached, and requires very little force to move it away from the skull. This area has been called a potential void. In a limited manner the air at the cylinder fluid boundary in the physical and mathematical models in this study represents the potential void between the skull and the dura. The air layer in the mathematics model is only 10^{-6} m, which is virtually non-existent.

Below the dura is the cerebral spinal fluid; imbedded in this fluid are two spider-web-like membranes, the arachnid and pia mater. The fluid in the physical and mathematical model, immediately in contact with the air layer, is somewhat analogous to the cerebral spinal fluid.

Impact Response of the Head

Although both the physical and the mathematical model used in this study are over-simplified versions of the human head the same mechanism, a cavity forming by movement of a surface from a shell, that influences pressure in the cylinder under impact influences pressure in the human head under impact. When viewed in this manner, when the head receives a blow and a positive pressure develops under the point of impact, a very small cavity, opposite the impact, can form between the skull and the dura. This cavity formation limits the maximum negative pressure in the head to one atmosphere. Since the brain is nearly incompressible, the small amount of volume needed to create the cavity is accomplished by pushing a very small amount of material down the foramen magnum. This small volume increase is probably not enough to pull the dura permanently away from the skull, but instead the periosteum is stretched to a very small degree.

This leads to the following possibility for a negative pressure limiting impact phenomena that could occur at the skull dura interface: During severe impact to a human head, a greater amount of tension would develop between the cerebral spinal fluid and the dura, then the dura and the skull. The dura would then move with the brain cerebral spinal fluid. As the dura moves away from the skull, a small cavity (a thickness less than 10^{-5} m) could form representing a slight stretching between the skull and the dura of the periosteum. Although it may be possible that enough surface tension will develop between the skull and dura for a cavity to form on either side of the dura, this does not seem as likely as the above suggested mechanism. Therefore, it is this motion of the dura as coupled with the small fluid flow through the foramen magnum that can have a significant effect on the pressure response of the brain during impact. If the impact is severe enough, it may be possible to produce fluid vaporization and associated violent cavity collapses. This violent cavity collapse, which could be a mechanism of injury, is strongly modified by the dura motion.

Head Impact Experiments

Pressure limiting effects have been observed in impact tests using repressurized human cadavers and live anesthetized primates. In these tests negative pressures less than 1 atmosphere have not been observed in non-fracture experiments (4, 7, 8). This was believed to be a result of fluid vaporization. It was hypothesized that fluid vaporization prevented the negative one atmosphere. It was observed that despite the possible fluid vaporization causing the limitation on the pressure, no injury was observed in cases in which fluid vaporization was believed to occur. The theory was that the fluid vaporization was occurring in the cerebral spinal fluid and was not significant enough to cause injury. In addition to this proposed mechanism it is possible that the negative pressure limitation was also controlled by the motion of a thin air membrane on the pressure transducers which could not be eliminated.

Modeling Head Impact

For modeling the brain-dura-skull-interface, several assumptions have been made (1, 5, 6, 12). One assumption is that no fluid vaporization occurs. A second assumption is that there is solid contact between the brain and the skull. These assumptions allow the elimination in the mathematical model of a difficult non-linearity. Most modelers have chosen to ignore the skull-dura interface and assume that the brain contacts the skull with a no slip condition. A better approach is to assume that the cerebral spinal fluid and possibility the brain is in contact with the dura and that the dura lies loosely up against the skull. This configuration, along with the flow through the foramen magnum, can have profound effects on the impact response of the head in terms of negative pressure as discussed in this paper.

Because of differential motion of the skull, there can be significant differences in the phase relationships between the acceleration of different parts of the skull and the pressures as discussed here. This has significant implication for modeling efforts. That is because the acceleration obtained from the skull of a human surrogate is used to drive the model of that human surrogate. Therefore, the magnitude of the pressure response may not be affected by skull deformation. However, the phase relationship between a measured pressure and measured acceleration most likely will.

Although it is possible to eliminate the free gas in the experiments with the cylinder, it is not possible to eliminate the free gas in the re-pressurized human cadaver. Experiments run to date do not boil the fluids used to re-pressurize; no attempt has been made to eliminate the free gas. Even if that was done, the postmortem process that occurs shortly after death and the inability to insure complete pressurization would preclude elimination of free gas in the test subject. The addition of free-gas can manifest itself in two ways: one is increased nucleation sites for cavity formation and two as a reduction in bulk-modulus or wave-speed.

In this study the reduction in wave-speed was addressed. It appears that reduction in wave speed does not significantly (less than 5%) reduce the maximum pressure near the impact site. However, as the wave-speed is reduced the shape and phasing of the near-pressure time history changes. In addition the shape of the pressure response distal to the impact changes as a result of wave propagation, both increased magnitude and reduced velocity. Although these changes are detectable in the model results they indicate that free-gas in the repressurized cadaver will not greatly change the gross impact pressurize response from that of a live human. However, the introduction of free-gas increases the number of nucleation sites and the magnitude of the cavity collapse - the cavitation effect increases. This implies that the re-pressurized cadaver may be useful for developing math models of the impact response of the head if care is taken to understand the limitations that free-gas might impose.

CONCLUSION

The skull-dura interface is a critical aspect of head impact response. The cavity forming near the skull-boundary dura limits the maximum negative pressure that can occur in this area of the brain. In addition, this area of the head needs to be considered for 1) modeling head impact response, and 2) evaluation of injury mechanisms which involve pressures in the brain.

1. In a head impact skull deformation has an effect on the pressure magnitude and phase. However, the pressure magnitude is strongly modified by the foramen magnum.
2. In a typical impact in which the head acceleration is over 190 g and the head deformation causes a slight increase in volume, it is likely that some form of cavity, either by fluid vaporization or expansion of the potential void between the skull and dura, will form. As a result of this cavity, a small amount of brain cerebral spinal material may flow down theforamen magnum.

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Finite Element Dummies for Frontal Impact

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ABSTRACT

In occupant safety assessment, numerical simulation of crash events provides a valuable tool for the automotive engineer. In this field, realistic models of the occupant or its surrogate in the development process - the Dummy - are of particular interest.

While Dummy models based on Rigid Body Dynamics yield satisfactory results in most loading situations during a Frontal Impact, Dummy models partly or completely realized with fully deformable Finite Elements can potentially cover a wider range of problems and can be adapted to a specific degree of result depth, due to the higher level of modelling.

In this paper the different levels of modelling of the Hybrid III Dummy Family are considered; starting with relatively simple Rigid Body Dummies to fully deformable Finite Elements Modules. First tendencies in the development process can be achieved with Rigid Body Dummies. Rigid Dummy Models with moving spring-connected parts, e.g. for Thorax deformation, give more detailed results about the injuries of the occupant when parts of the car interior penetrate the chest. The best and most detailed results can be achieved with fully deformable Finite Element Modules, e.g. a Thorax model with ribs.

For an efficient usage of the Finite Element Method in this field it is necessary to have all Dummies available, with all segments from rigid through fully deformable. For this reason, the Hybrid III Dummy Family for Frontal Impact is under development. Based on the modelling and validation of the individual components of the Dummies, full models are assembled. The modelling and validation process is presented for some examples, together with comparisons of experimental and numerical results. Standard certification procedures, like drop-, impactor- and sled tests serve as a tool for the evaluation of the FE- models. Here, the close collaboration between those carrying out the experiments and those setting up the models, is essential in steadily improving the models.

INTRODUCTION

The numerical simulation with Finite Element Method (FEM) is nowadays used in all fields of industry to support the construction process. With the efficient use of simualtion it is possible to consider the behaviour of new constructions under operation conditions in an early state of the development process. This reduces the duration and costs of new developments and increases the design quality due to investigation of a higher number of variants.

In occupant safety assessment in particular, numerical simulations of crash events provide a valuable tool for the automotive engineer. It is possible to investigate the vehicles under all impact conditions such as Frontal , Side , Rear Impact and also Roll-over. In this field, realistic models of the occupant or its surrogate in the development process - the dummy - are of particular interest.

Commonly, dummy models based on the dynamics of linkages of rigid bodies are used to predict the behaviour of the crash victim. These models are based on data of the victim, its environment and the crash conditions. Validated data sets for the different dummy types make the modelling of a crash event very efficient. A significant shortcoming of such an approach, however, is the need to provide experimental force/deflection data as input for the contact modelling. In addition the geometry of the real dummy is satisfied only poorly, e.g. by ellipsoids. Therefore, the validity of such simulations is limited to those conditions that are used in the experimental evaluation of , for example the force/deflection characteristics.

Finite Element dummy models, on the other hand, can potentially cover a much wider range of loading situations. Even when they are a linkage of rigid bodies, the higher quality of modelling and discretization allows the simulation of more details of the crash events. The engineer has the freedom to use the FE-dummy as rigid, quasi-rigid, partly deformable and completly deformable. As the level of modelling is fundamentally different, such models are based essentially on material properties and the geometry of the surrogate to be discretized.

Experimentally derived characteristics of a dummy are not required as input, but serve as a source of validation for the model. Once a model is set up and validated against tests, it should not only yield good results in a specific loading case, but in any crash situation. Moreover, such Finite Element dummy models can also be used for dummy development purposes. In this paper, the modelling and validation of the HYBRID III - Dummy Family is presented. The code used for the simulations is the nonlinear explicit Finite Element code PAM-CRASH.

THE FINITE ELEMENT PROGRAM PAM-CRASH

PAM-CRASH is a three-dimensional Finite Element program for the nonlinear dynamic analysis of structures with large deformations. Therefore, it is particularly suited for crashworthiness simulations in the transportation industry. PAM-CRASH has been used since 1985 for crash analyses / 1 /. It is vectorized for Supercomputers and optimized for UNIX-Workstations, which now provide the necessary calculation speed and disk capacity.

PAM-CRASH is a Lagrangean program, the FE-Mesh is fixed to the material and moves with the material. The program allows the modelling of 3D structures of arbitrary geometry using Finite Elements such as shell, beam, bar and brick elements.

For analysis of the structure of car bodies and components of the car interior, mainly shell elements are used. To simulate the unfolding and deployment process of an airbag an elastic multi-layer membrane elment has been developed, to model the orthotropic material behaviour of airbag gores. For the simulation of knee bolsters and other paddings, there are material models available, which represent the behaviour of foam and honeycombs.

One of the most important qualities of PAM-CRASH is the algorithm to find and to consider the contact between different parts of a structure or between two impacting structures.(/ 2 /).

A penalty function is used to avoid the penetration of two surfaces. This function penalizes a node which has penetrated an element. A force is applied to the penetrating node and the nodes of the penetrated element. The force depends on the penetration depth and the stiffness of the surface. Friction will be calculated from the normal force and acts in the opposite direction to the relative movement of the nodes.

In recent years a large variety of new options, element and material models has been implemented in PAM-CRASH. Elaborate seat belt models with nonlinear materials, sliprings, retractors/pretensioners and belt-to-dummy contact, as well as sensor options and simple and elaborate airbag models, including aspiration, jet momentum deposition and multi-chamber options are some of the options needed to perform industrial simulations of occupant safety with PAM-CRASH.

Not only advanced techniques were requested by the automotive industry but also the possibility to simulate dummies as articulated rigid body models. This was provided by introducing the appropriate joint and hinge mechanisms and a rigid-body-to-plane soft contact with finite penetration and user-defined nonlinear reaction.

Intense efforts of material and model calibration are needed in order to establish reliable and economic finite element models of mechanical occupant surrogates.

NUMERICAL MODELS FOR THE HYBRID III DUMMY FAMILY

For the simulation of restraint systems during impact situations it is essential to have suitable dummy models available corresponding to the requested result depth.

First Generation : Articulated Rigid Body Dummy Models

The earlier occupant simulation codes were based on articulated rigid body assembly techniques. The occupant is represented by a number of connected rigid ellipsoids. The segments symbolize the different body parts and therefore they are combined with joints. The joints are assigned to the appropriate characteristics.

Since 1989 the interaction of occupant and car structure could be simulated with the dynamic coupling of PAM-CRASH to industrialized occupant simulation programs, e.g. MADYMO. MADYMO provided the rigid ellipsoid dummy and PAM-CRASH the Finite Element car structure, restraint systems and other parts of the car interior.

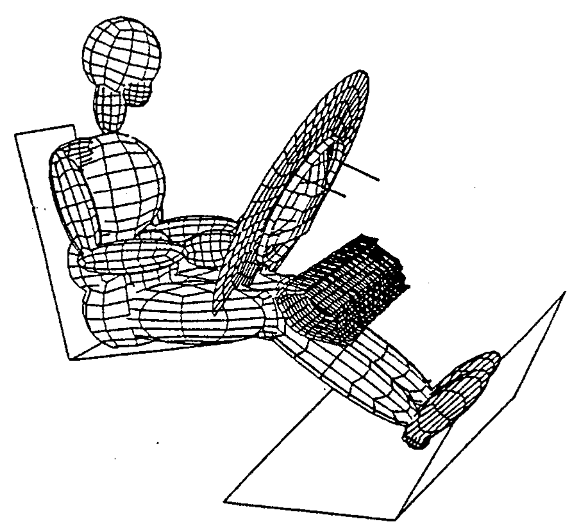

Fig. 1 Occupant Interaction with airbag, steering wheel and kneebolster (Initial position) / 3 /

The nonlinear coupled equations of motion of the dummy model in MADYMO are Runge-Kutta integrated with the contact forces of the parts that interact with the Finite Element car structure applied as external loads. The resulting dummy displacements are then introduced as moving boundaries into PAM-CRASH, that will use explicit time integration to move the car structure in the ensuing time increment. Figure 1 shows a typical application of the coupling approach.

For the simulation of seatbelts, for example, the contact between dummy and belt can be realized in different ways.

The belt elements are fixed to the dummy upper torso and the characteristic correlates to a given force/displacement function.

A more precise possibility would be to model the seat belt partly with membrane elements and to use the friction together with the contact algorithm in PAM-CRASH to apply the restraint force to the dummy.

The first possibility is especially suited for ellipsoid dummies. The surface of these dummies has no realistic shape, so a friction dependent contact for the seat belt would end with an early sliding off the spherical surface of the ellipsoids by the belts. Therefore, it is necessary to adapt the surface shape of the dummy model more to reality.

Second Generation :
Finite Element Rigid Body Dummy Models

For this purpose Hybrid III dummy datasets have been developed and validated in PAM-CRASH by ESI which take into consideration the CAD-geometry of the dummy surface. (Fig. 2)

The first development phase has been to model the dummy as rigid. There are corresponding joint models available, such as Spherical/Cardan Joint and Flexion-Torsion-Joint. Additionaly, a universal spring/damper-element, which transfers user-defined nonlinear force/moment characteristics into translational and rotational movements, can be used. The simple modelling of chest deformation in rigid body dummies can be realized by this element.

With all these options and elements it is possible to model every dummy in PAM-CRASH.

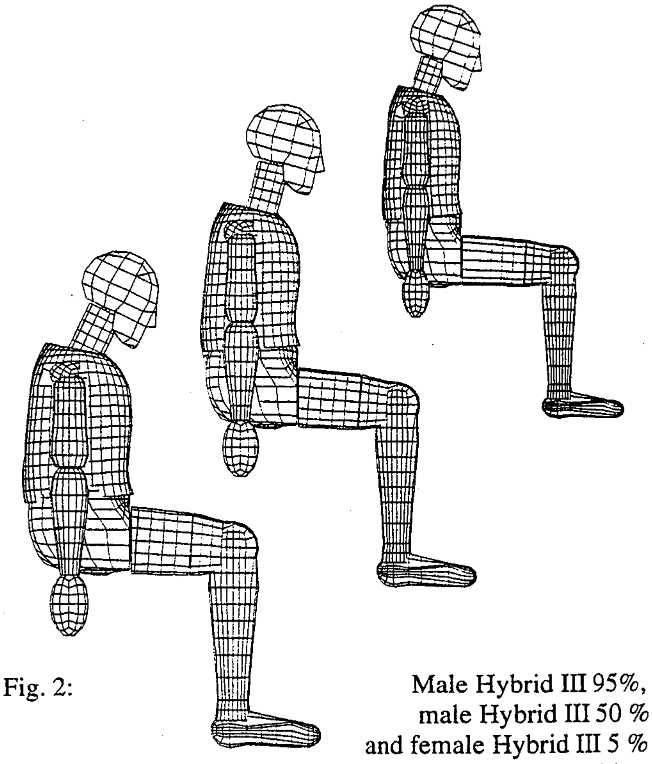

Fig. 2: Male Hybrid III 95%, male Hybrid III 50 % and female Hybrid III 5 % in reference position

After the validation, the joint and spring/damper characteristics were tested with a simulation of dummy-restraint system interaction during a sled test. This has been already done for the Hybrid III dummy family. In Figure 3 the Hybrid III 50% can be seen during a numerical simulation of a sled test.

Figure 4 shows the chest deformation / 5 /, where the chest plate is supported by the calibrated system of four springs and dashpots, permitting a first order analysis of chest deformation due to the action of the shoulder belt. The same modelling technique can be used for contact with airbags and steering wheels.

Extensive modelling capacities were implemented into PAM-CRASH that comprise nonlinear belt materials, belt sliprings, retractors, pretensioners and belt-to-dummy contact, as well as sensor models, needed to trigger various actions. The sliprings permit friction sliding of the belt material from one side of the slipring to the other, and retractors/pretensioners permit to define belt material to be fed in and out.

A special body-to-plane contact algorithm permits, e.g., to simulate the actions between rigid or deformable dummy segments (pelvis, back) and seat cushions. A plane of finite or infinite extension, represented by Finite Elements, may be penetrated to finite distances by the dummy segments and the contact forces are calculated according to the largest normal penetration and the penetrated volume. A user-defined nonlinear reaction force is applied to each penetrated node of the part, in proportion to its penetrated depth and its tributary area.

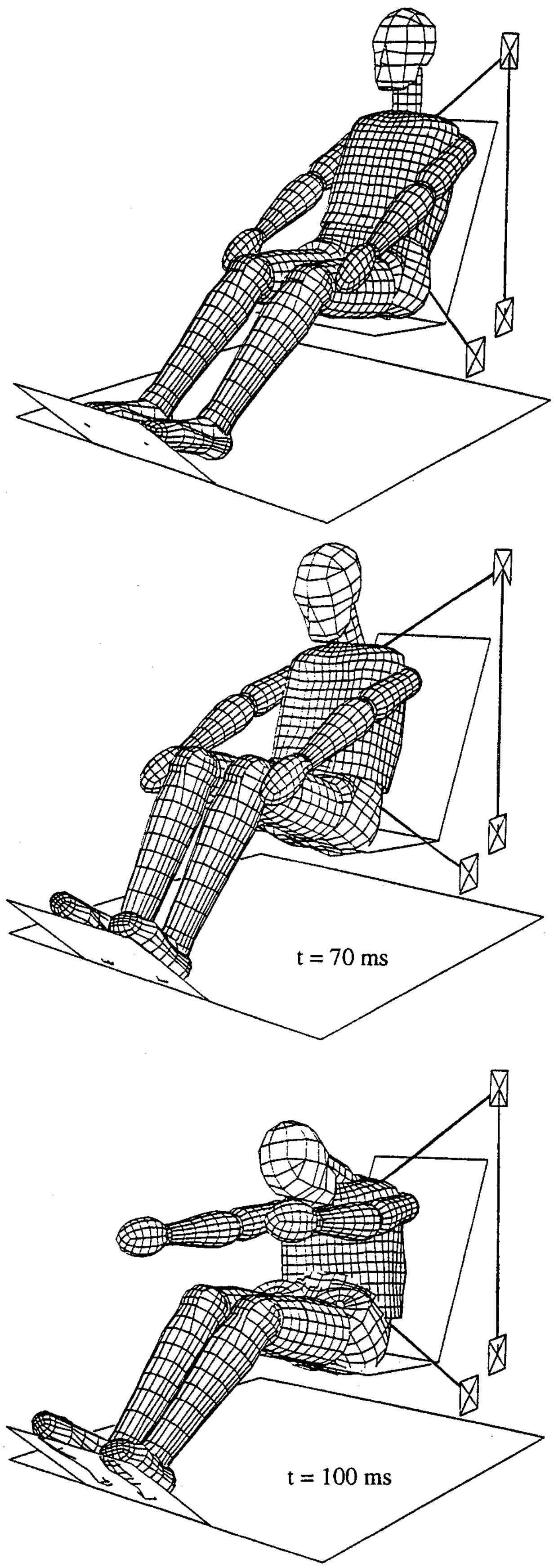

Fig. 3: PAM-CRASH Hybria III 50% with Seat belts

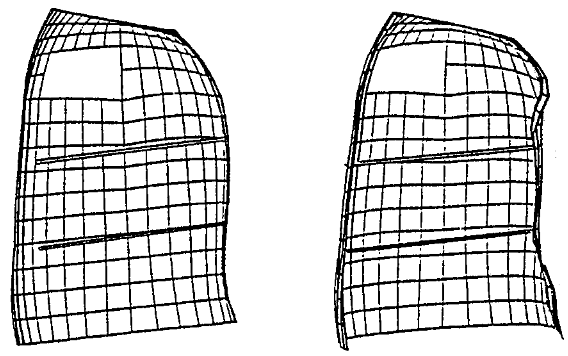

Fig. 4. Deformed and undeformed dummy chest (cut view).

Figure 5 shows a comparison between simulation results and experimental data, e.g. acceleration magnitude of the dummy head.

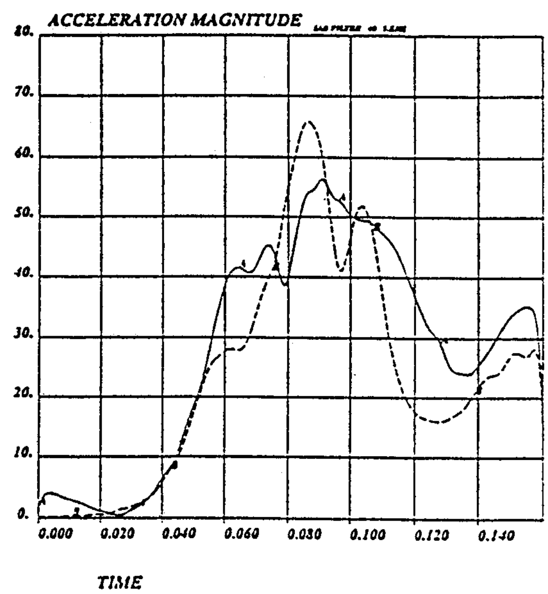

Fig. 5. Time history of the acceleration magnitude of the head (----: Experiment; —— : Simulation)

Third Generation :
Finite Element Dummy Models

For detailed investigations, the rigid body models are often not sufficient. In a Frontal Impact the accurate chest deformation is of special interest.

The occupant model for a specific simulation problem can be assembled by a graphical interactive preprocessor. For a Frontal Impact the Hybrid III dummy could be defined with a fully deformable chest, to get more accurate answers about the injury risk in a special impact situation.

Figure 6 shows an assembled Hybrid III 50 % dummy model with deformable FE-chest and rigid body head and extremities.

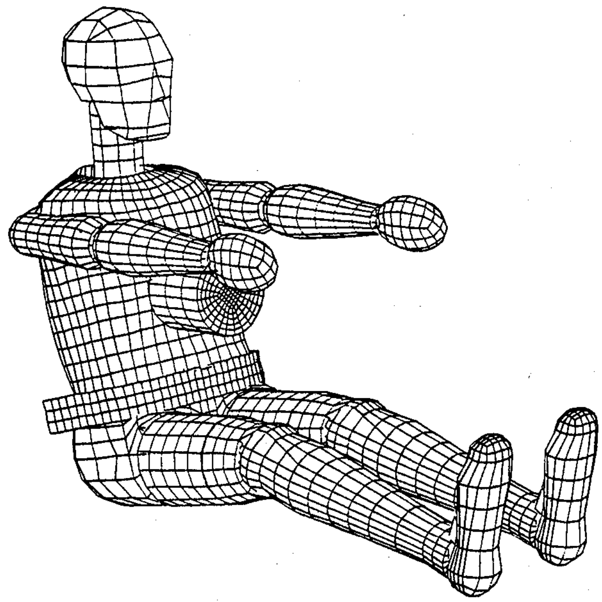

Fig 6: Validation Impact test for the deformable chest of the Hybrid III 50 %, initial position.

Essential ingredients for successful modelling of mechanical dummies and their environment, are adequate nonlinear viscous and/or crushable foam models. Several models have been added to PAM-CRASH. A nonlinear crushable foam material model with permanent deformations can serve to simulate the action of paddings of the car interior, with which the dummy models might interact. A nonlinear elastic foam material model with hysteresis has been calibrated to represent foams of mechanical dummies with reversible deformation. A rubber-like material model (Blatz Ko) can serve to represent rubbery solid parts of the dummies. These material models will be enhanced in the next future.

Figure 7 shows the deformable thorax and the sternum foam in details. The model of the thorax was done in a joint project between ESI and the Wayne State University. (/ 6 /)

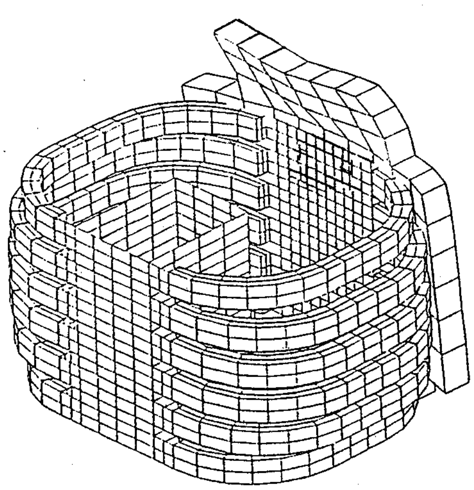

Fig. 7. Fully deformable FE-Thorax of a Hybrid III 50 % dummy

In Figure 8 the impact during the simulation can be seen in a cut view. The comparison to the corresponding test results shows good agreement. In Figure 9 the impact force versus the displacements is compared to the test result for an impact velocity of 6.7 m/s. (/ 7 /)

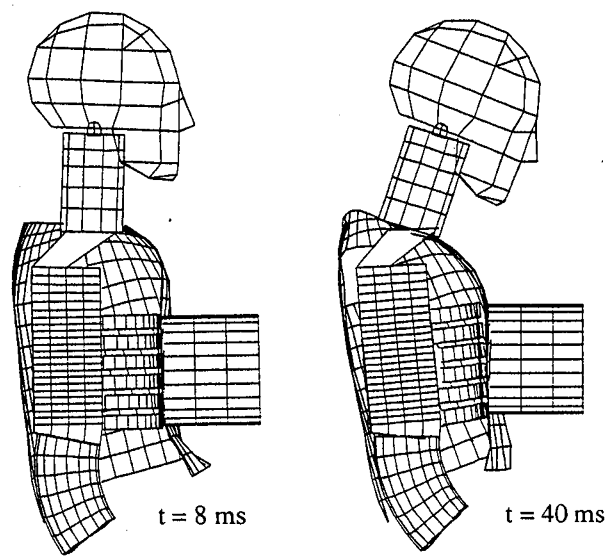

Fig. 8. Validation test for FE-thorax (cut view)

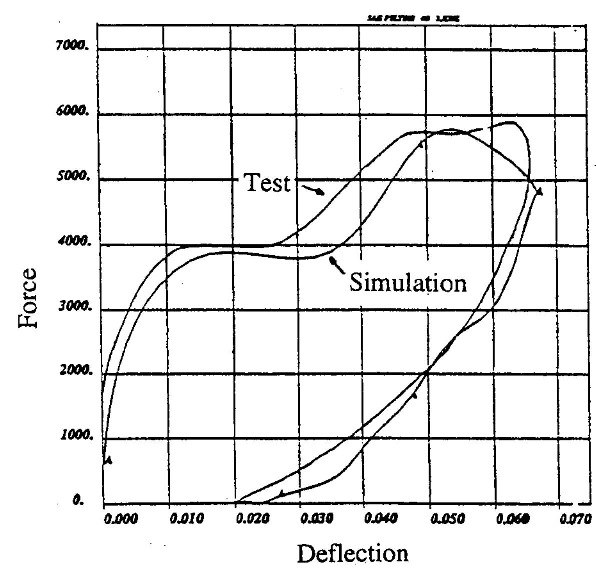

Fig 9. Time history of impact force versus sternum deflection.

SUMMARY

With the flexibility of FEM, the detail of the car interior through the complete car structure can be simulated and investigated. The same flexibility is obvious in the modelling of dummies.

For such requirements a problem adaptive degree of modelling is the solution. In PAM-CRASH the user has the possibility for each degree of accuracy to adapt the dummy model with different modules. The user has the choice between the following degrees of modelling :

– Articulated Rigid Body Segments which can be used in the coupling with e.g. MADYMO or without coupling.

– Finite Element Rigid Segments which consider the CAD-geometry and where the deformation is represented by spring/damper-systems (Lobdell, / 8 /). These segments are only available in PAM-CRASH.

– Full deformable Finite Element Segments with the CAD-surface (only in PAM-CRASH)

The modelling and the validation of the Hybrid III family is under continuous progress. The second generation dummy family is available. The deformable parts such as thorax, neck and head are under development. The validation is realized in a joint project with the car industry and independent institutes.

The numerical simulation is highly developed, to fullfil all demand in industry. It should support, in an early stage of the development process of a new vehicle the experimental departments. Simulation results show first tendencies of a prototype behaviour and they help to avoid the first principal mistakes. The experimental efforts can be reduced to specific investigations and concentrate on optimization work. The cooperation between simulation and experiment leads to an efficient development process.

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Feasibility Study of Optical Deflection Sensing System in the AATD Thorax

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ABSTRACT

The optical thorax deflection sensing system (for the Hybrid III dummy), introduced at the 13th ESV Conference, was studied for the feasibility in Advanced Anthropomorphic Test Device (AATD) dummy which the SAE Task group on Frontal Impact Dummy Enhancement has been developing as a next-generation dummy. The optical thorax deflection sensing system measures the displacement of target points based on trigonometry by sensing the light of LEDs attached to the target points within a thorax with cameras fixed to the spine. The camera layout used before could not be employed because the lateral distance between the target points in the AATD dummy is greater. It was found that the system can be made feasible in the AATD dummy by rearranging the combination of the target points and cameras and optimizing the relative position between cameras and mirrors.

OPTICAL THORAX DEFLECTION SENSING SYSTEM FOR HYBRID III DUMMY

In estimating the thorax injury of the driver and passengers involved in a crash, the degree of thorax deflection as well as the deceleration applied to the thorax is essential.[Ref. 1] The Hybrid III dummy has a thorax deflection sensing system, but the system measures only the fore-and-aft displacement at a single point on the center of the sternum and does not give the general deflection of the whole thorax.[Ref. 2]

The authors had developed a three-dimensional thorax deflection sensing system for Hybrid III dummy and introduced it to 13th ESV Conference.[Ref. 3] The following describes the three-dimensional thorax deflection sensing system for the Hybrid III dummy.

[1] Configuration (See fig. 1)
  *Deflection is measured at four points inside the sternum. LEDs are positioned at each of these points.
  *Each pair of position-sensing detector [PSD] cameras is attached to the upper and lower portions of the thoracic spine by brackets.
  *Mirrors are arranged on the brackets to create the required distance between LEDs and the cameras.

[2] Principle of Measurement
  The light from each LED is picked up by a pair of cameras fixed to the thoracic spine. The three-dimensional displacement of each LED is determined through trigonometric calculation.

[3] Performance
  See Table 1.

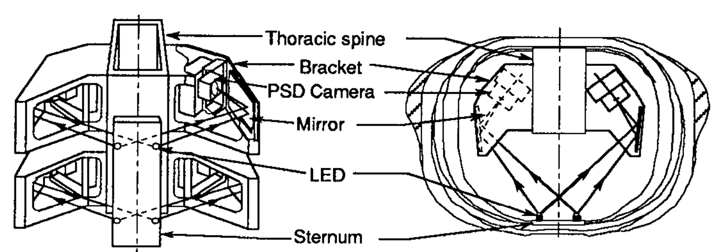
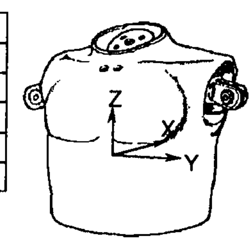


Figure 1. Configuration of three-Dimensional Optical Thorax Deflection Sensing System for Hybrid III

Table 1. Ranges and Accuracies of Measuremen

Deflection Measuring Range	X	~76mm
	Y	−50~50mm
	Z	−20~20mm
Deflection Measuring Accuracy	X	less than ±2.5% of F.S.
	Y	less than ±5.0% of F.S.
	Z	less than ±5.0% of F.S.

*Above performance could not be accomplished at some portion in measuring range.



AATD THORAX

The AATD dummy under development by the SAE Task Group on Frontal Impact Dummy Enhancement has a thorax with the following properties. [Ref. 4]

*The thoracic spine is divided into the upper and lower portions.

*It has seven pairs of ribs inclining forward about 20 degrees.

*The sternum connects the upper four pairs of ribs, below which no portion of the sternum extends.

*The three-dimensional deflection sensing system for the four target points on the ribs is a new addition.

The four target points of which deflection is measured are located at the ends of the No.3 ribs and No.6 ribs. A double-gimbaled string potentiometer with a telescopic joy stick is under consideration as the means of measurement.

The authors investigated the feasibility of the optical deflection sensing system in the AATD dummy thorax.

FEASIBILITY STUDY

Preliminary Investigations

The target points where the deflection is measured are the same as those on the current AATD dummy, i.e., the ends of the No.3 ribs and No.6 ribs [A, B, C, and D in Photo. 1].

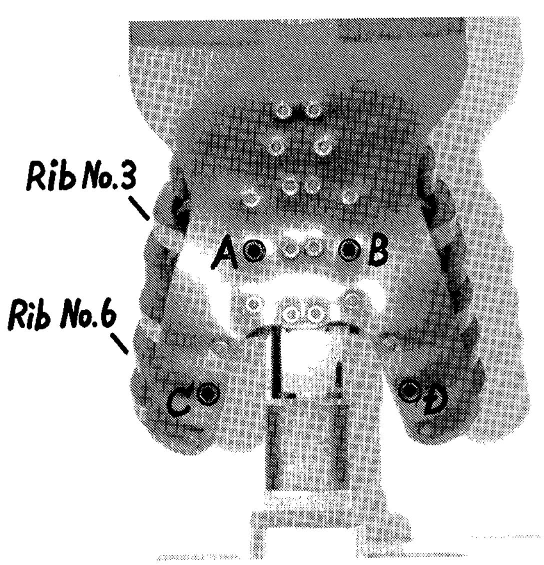


Photo 1. Front View of AATD Dummy Thorax

The range of deflection of these points were set to be the same as the target values for the previous deflection sensing system for the Hybrid III dummy .

X: 0 to 76 mm.
Y: -50 to 50 mm.
Z: -20 to 20 mm.

The authors first used the same method in the previous deflection sensing system for the Hybrid III dummy to check whether the range of deflection of the target points can be covered by the vision of the cameras. In the previous system, the upper pair of cameras cover the upper pair of target points and the lower pair of cameras cover the lower pair.

The results are shown in Fig. 2. Figure 2 is the horizontal sectional view of the No. 6 ribs. The hatched areas show the range of deflection of the target points and the darkened area is the range visible from the cameras. In other words, less than half of the deflection areas is covered by the cameras.

The AATD dummy thorax has a greater lateral distance between the target points at the ends of the No. 6 ribs. Because of this, the arrangement used in the previous system was found to be incapable of covering the deflection range of the target points.

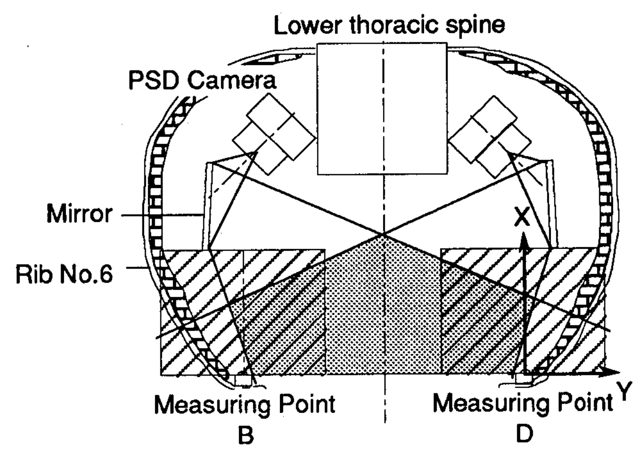


Figure 2. Sectional View at No. 6 Ribs Using the Arrangement of the Deflection Sensing System for the Hybrid III Dummy

Review of Target Points and Cameras Combination

The angle of vision of the cameras is fixed. Therefore, to cover a larger portion deflection range of the target points, the following two measures are possible.

[1] Reducing the distance between the two target points covered by one pair of cameras.

[2] Increasing the distance from the cameras to their target points.

There are three combinations of the two target points from the total of four points. Each distance between each pair of target points of the three combinations is shown in Table 2. The pair with the smallest distances is A - B. However, the pair C - D has a distance of 164 mm, which is larger than the 142mm distance between A - C and between B - D.

Therefore, the combination where the distances between the target points is the smallest is combination II [A - C and B - D].

Table 2. Combinations of Target Points and Distances between Target Points

Combination	Pair	Distance	Optimum
I	A-B C-D	80mm 164mm	
II	A-C B-D	142mm 142mm	○
III	A-D B-C	182mm 182mm	

To increase the distance between a target point and a camera, the following can be used.

[1] Making the combination of each target point and each camera not on one side of the thorax as in (a) in Fig. 3 but along the diagonal line as in (b) in Fig. 3.

[2] Making the light path longer by reflecting the light from the LED on a mirror, as in (c) in Fig. 3.

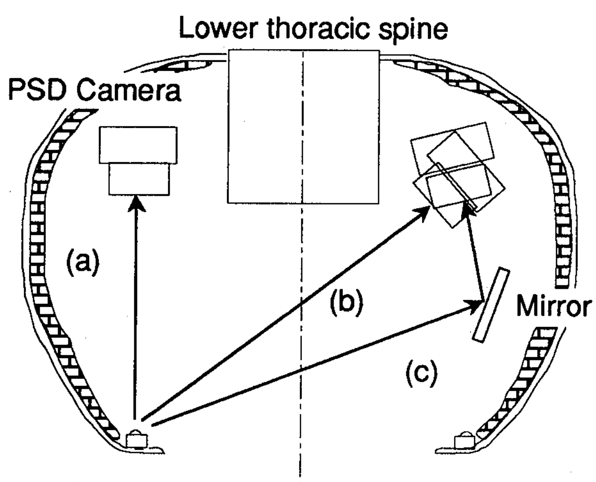


Figure 3. Combination of Target Point and Camera [Sectional View of a Thorax]

OPTIMUM SYSTEM

Based on the study above, the authors reviewed the combinations of the target points and cameras to set the locations of the cameras and mirrors and optimize angle of attachment.

Optimum Configuration

Figure 4 is a frontal view of the AATD dummy thorax seen from above. The relationship of the cameras and target points is such that the pair of cameras on the left (1 and 3) observe the pair of target points on the right (B and D), and the pair of cameras on the right (2 and 4) observe the pair of side target points on the left (A and C). The upper two cameras (1 and 2) receive the light from LEDs directly. The lower two cameras receive light after being reflected once by the mirrors. The upper and lower cameras are fixed by one bracket on each side. The brackets are fixed to the lower thoracic spine.

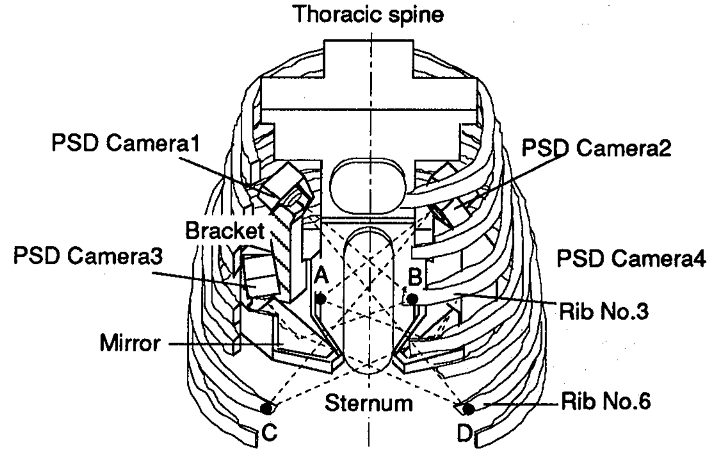


Figure 4. Frontal View of AATD Thorax from Above

Measuring Range

The coordinate system for the deflection sensing consists of the Z - axis, which is the axis of the lower thoracic spine, the X - axis, which is perpendicular to the Z - axis and in the vertical plane, and the Y - axis, which is perpendicular to both the Z and X axes [See Figs. 5 and 6].

Figures 5 and 6 are the sectional view and side view of the AATD dummy thorax. Figure 5 is symmetrical and the following description limited to the measuring ranges of target points B and D on the right side. The deflection range of target point B is the descending line hatching and that of C is the ascending line hatching. The camera's field of visions is the darkened area which covers most of the deflection ranges.

The cameras and brackets are arranged to that even when the ribs deflect under impact loads, they avoid any interference with other ribs by keeping proper clearances . [the clearances are shown by the arrows in circles in Fig. 5.]

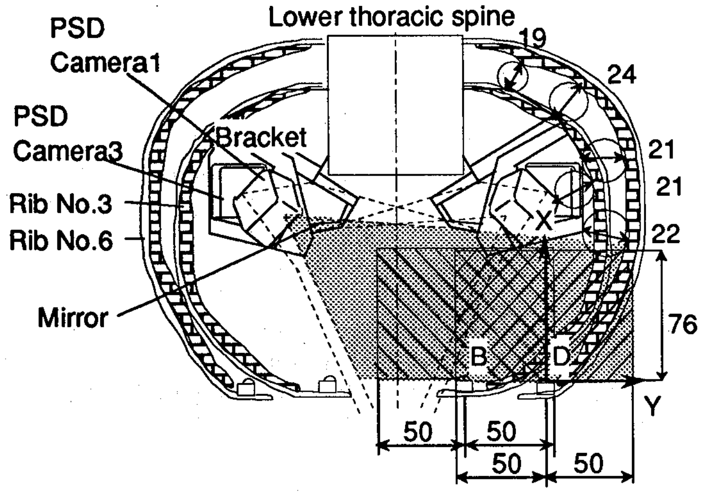


Figure 5. Plan View

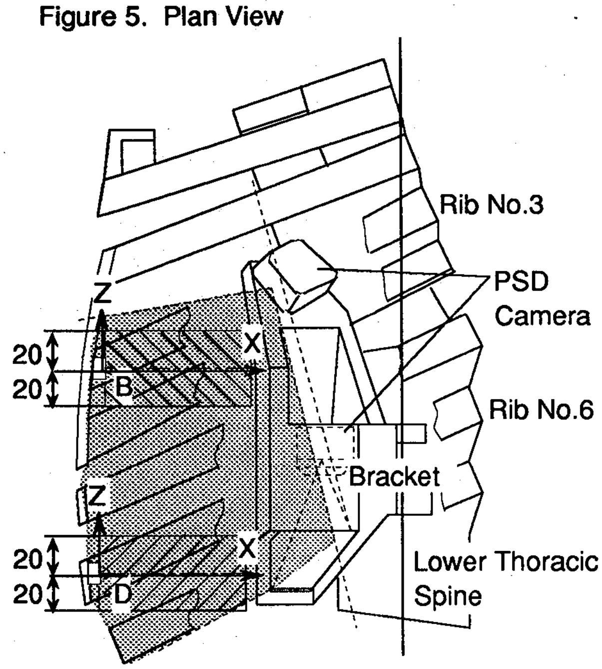


Figure 6. Side View

Figures 7 and 8 show the fields of vision of the upper and lower cameras. The inside of each circle is the range visible from each camera. The ribs No.3 to No.7 are in the vision of the camera. The blackened points at the ends of the ribs No.3 and No.6 are the target points B and D, respectively. The cubic body with descending hatched lines is the deflection range of target point B and that with ascending hatched lines is that of point D.

When the mirror interferes with the deflection range of target point D, the camera can not pick up the light from the LED. In that area, measurement is not possible. To prevent interference with the deflection range of D, it was necessary to reduce the mirror size. However, cutting the size of mirror reduces the reflecting surface of the mirror and reduces the vision of the camera as shown by area α in Fig. 8.

In comparing and evaluating the three conditions, the first in which no part of the mirror interferes with the deflection range of D [Cut 1], the second one in which all of the deflection range of D next to α enters the vision field of the camera [Cut 3], and the third which is between Cuts 1 and 3 [Cut 2], the authors consider Cut 2 to be the optimum.

In area β, very small portions of the deflection range are out of the camera's field of vision. It was difficult to enlarge the field of vision of the cameras. The areas where the measurement is impossible were thus limited to the outer edge of the deflection range so that they would cause no problem in practical use. Based on these considerations, this system should be optimum.

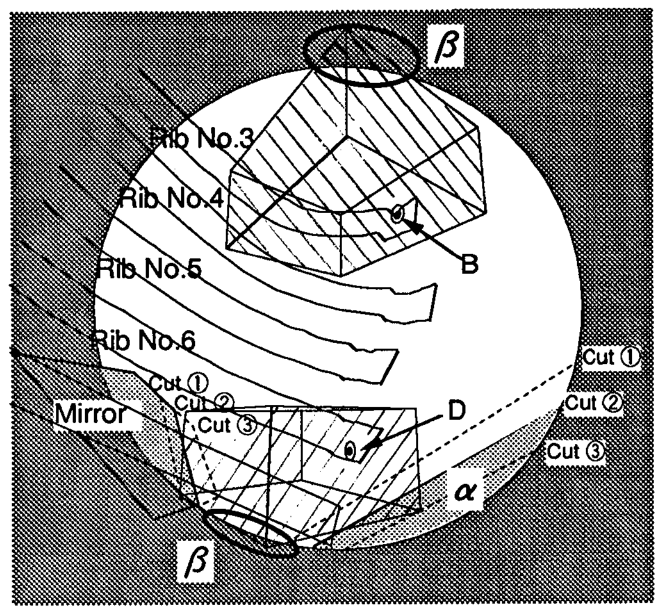


Figure 7. Field of Vision of Camera 1

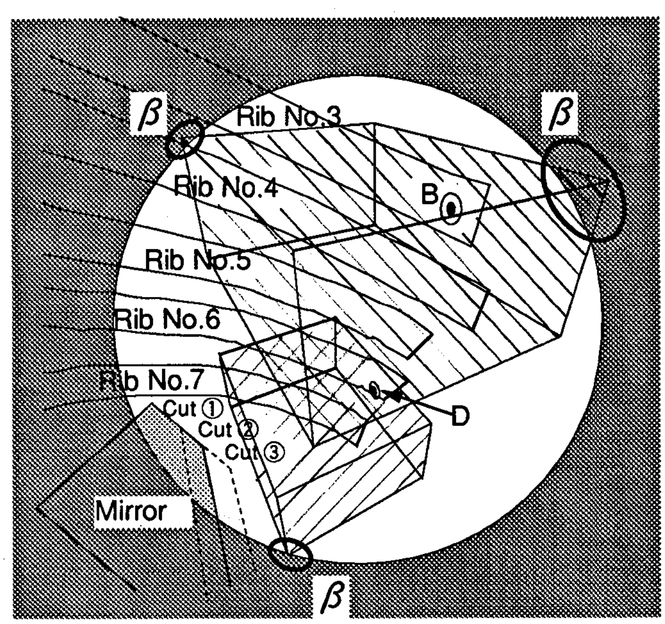


Figure 8. Field of Vision of Camera 3

Figure 9 shows the possibility of measurement with in the deflection range of the target points. The white circles indicate the locations where measurement is possible and the black circles indicate the locations where measurement is impossible. Except for some edge areas around X = 0 mm and 76 mm, measurement is possible in almost all areas. This indicates that the system is suitable for practical application.

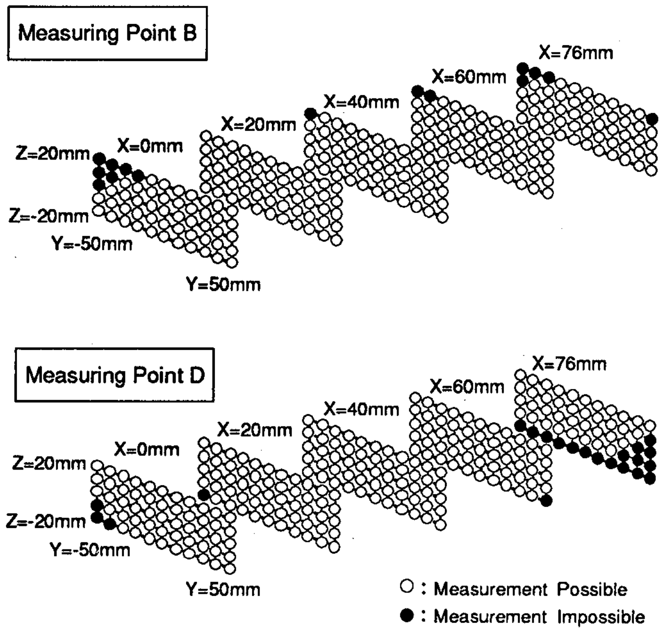


Figure 9. Areas where Measurement is Possible

CONCLUSION

The AATD dummy has a larger lateral distance between the target points, which made the same camera layout as used for the Hybrid III dummy useless. However through rearrangement of the combination of the cameras and target points and optimization of the mirror locations relative to the cameras, the optimum configuration of the optical deflection sensing system covering almost all of the target point deflection ranges was determined.

The measuring accuracy cannot be estimates before confirmation by actually building the system, but it is estimated that accuracy similar to that the previous system may be achieved.

As for impact resistance, temperature characteristics, and frequency response, they already verified on the previous system, and the fundamental configuration was not changed from the previous system. There should be no problem in practical application.

From the above, it is considered that the optical thorax deflection sensing system is feasible in the AATD dummy thorax.

Acknowledgments

The feasibility study requires the detail dimensional data inside the AATD dummy. The University of Michigan Transportation Research Institute (UMTRI) was kind enough to arrange for the authors to get a set of AATD dummy thorax. Using it, the relative locations of the thoracic spine and ribs and the clearances could be precisely checked.

The authors would like to thank the members of the SAE Task Group on Frontal Impact Dummy Enhancement who gave special attention and useful advice to the study, especially Dr. Schneider of UMTRI and Mr. Haffner of NHTSA.

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Measurement of submarining on Hybrid III 50° & 5° Percentile Dummies

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Paper N° 94 S1 W 23

ABSTRACT

Instrumentation for the study of submarining on the Hybrid II test dummy has already been described in a previous paper. The instrumentation consisted basically of two 2D force transducers installed in the dummy's pelvis. This system has been evaluated, improved and installed on the 50th percentile Hybrid III dummy. The aim of this paper is to describe the general concept arrived at through this study, namely:

- Detection of movement of the lap-belt via a simple system installed in the iliac wing of the pelvis.
- Measurement of the amplitude of submarining via a 2D force transducer installed back from the iliac crests.

This work, carried out in conjunction with FTSS, required changes on the levels of the spinal/lumbar column connection and measurement of thoracic deflection. The assembly was tested in various impact configurations (subsystem and sled configuration tests). The corresponding results show that the system detects submarining well and does not affect the overall response of the instrumented dummy by comparison with a standard dummy.

The new system detecting seat-belt slippage was also installed on the 5th percentile Hybrid III dummy. Sled tests gave reliable recordings of the detection of submarining.

From the results available, it seems that the two versions presented (50th and 5th percentile) enable improved study of submarining and accordingly the optimization of occupant restraining systems.

INTRODUCTION

Instrumentation for the study of submarining has been developed at the Laboratory of Accidentology and Biomechanics P.S.A. Peugeot Citroën/RENAULT in conjunction with First Technology Safety Systems for the 50°P Hybrid II dummy. This instrumentation consists of two sensors measuring seat belt forces on the abdomen during submarining along two axes (anatomical X and Z). It is supplemented by gauges bonded onto the aluminium structure of the pelvis at the level of the iliac wings. These gauges detect the moment at which the seat belt passes from the iliac wings onto the abdomen. The benefit of equipping dummies with instrumentation of this type is to be able to study submarining precisely, in terms of duration extent and time of occurence, which is practically impossible with standard measurements or a film analysis.

The following study describes the adaptation and improvement of this instrumentation on the 50°P and 5°P Hybrid III dummies.

TECHNICAL DESCRIPTION OF THE SYSTEM

Sensor to detect seat belt sliding (SWING)

This sensor detects seat belt presence or not on the iliac wings. Installed in the left and right iliac wings, its role is to warn of any submarining and of when it occurs. This sensor is an improvement on the sensor developed for the 50°P Hybrid II by Bendjellal in 1989 (2).

<u>**Description**</u> - The SWING (Sensor Iliac Wing) can be likened to a flexible pin equipped with strain gauges (Figure 1).

<u>**Location**</u> - This sensor is mounted forcibly in a housing created in the iliac wing. This housing is extended by a groove to enable it to be deformed by seat belt forces, and this deformation has repercussions on the sensor (Figure 2). Two types of pelvis are equipped with this housing, the pelvis of the 50°P Hybrid III, and the new 5°P SAE version (Figure 3). The advantage of this type of location is that it does not alter the geometry of the iliac wing.

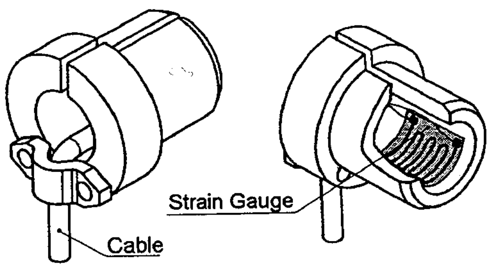

Figure 1 SWING sensor for detection of submarining

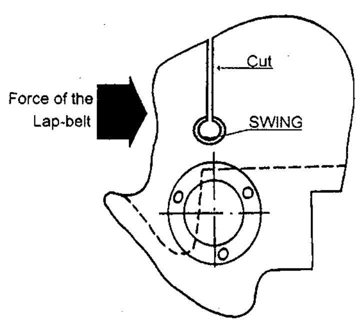

Figure 2 Operating principle of SWING sensor (Adaptation to the Hybrid III 50°P Pelvis)

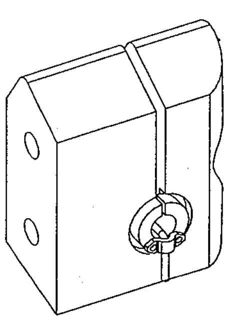

Figure 3 Location of SWING in the Hybrid IIII 5°P pelvis

CAP-SM2D, two-dimensional submarining sensor

This sensor was originally developed for 50°P H II, based on a sensor designed by Leung (1) in 1979 and improved by Bendjellal in 1989 (2), which measures the force exerted by the seat belt during the submarining phase. These sensors are used in pairs, and hence indicate the left and right submarining forces along anatomical X and Z.

<u>**Description**</u> - The submarining sensor consists of two elements:

- A sensor part formed of 2 beams equipped with strain gauges measuring the forces applied by the seat belt along the anatomical X and Z axes, and a protective aluminium casing (Figure 4).
- A support for sensor fastening in the dummy.

There are two types of support, one for the H II dummy and one for the 50° P H III dummy. The sensor part is identical in both dummies (Figure 5). The support/sensor assembly makes up the CAP-SM2D (Figure 6).

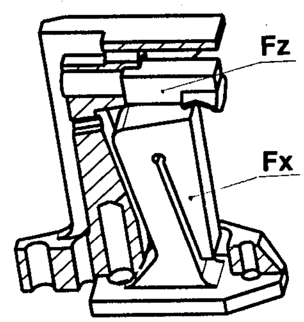

Figure 4 Submarining sensor

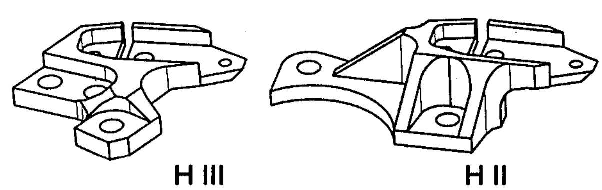

Figure 5 Support for the Hybrid III and 50°P Hybrid II

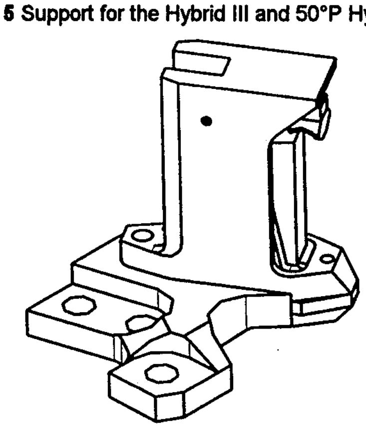

Figure 6 CAP-SM2D assembly

Location (Figure 7) - The CAP-SM2D can be installed at present on the H II and 50°P H III dummies, but not on the 5°P H III for reasons of size. It is installed on the lumbar column support, to which a slight modification is required. Moreover, the installation of the CAP-SM2D in the 50° P Hybrid III poses a problem of interaction between the protective casing of the standard deflection sensor and the casing of the CAP-SM2D, as shown in Figure 8. To solve this problem of size we have replaced the standard rotary deflection sensor (rod potentiometer) with a string potentiometer, which has enabled us to reduce the width of the spinal column/thoracic column interface.

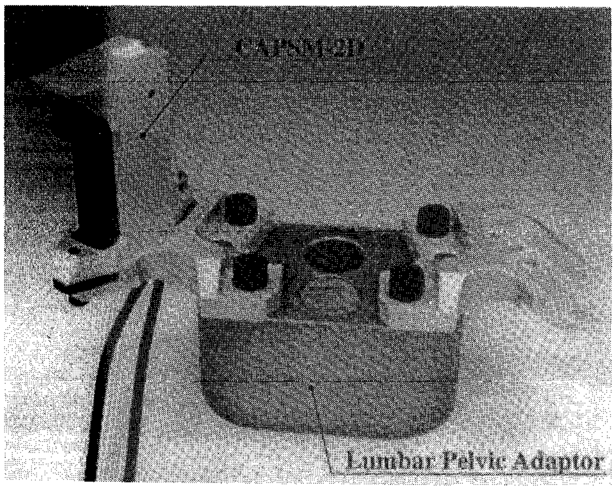

Figure 7 CAP-SM2D on the lumbar column support

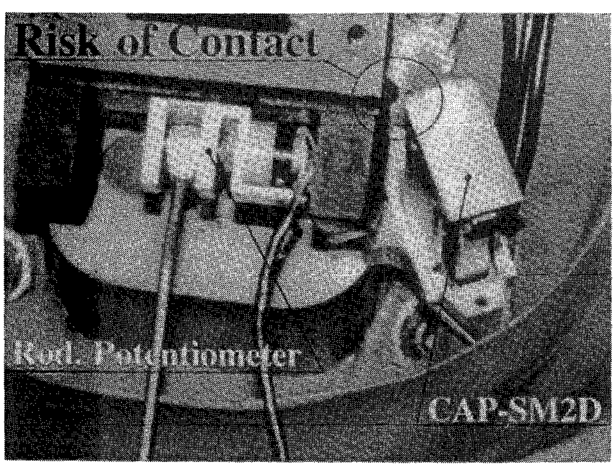

Figure 8 Contact between CAP-SM2D and rod potentiometer

Change made in the standard thoracic deflection measurement

Description - We have therefore taken the opportunity to try to improve the standard deflection measurement, especially since it poses certain problems of reliability. F. Bendjellal shows this in the comparative study performed for ACEA (3) in which it is apparent that in certain impact conditions the standard potentiometer does not always deliver a measurement, which is not the case for the string potentiometer.
A mounting bracket has therefore been developed to place this string measuring system inside the dummy, allowing the installation of 5 sensors (Figures 9 and 10):

- One string potentiometer (BIOSID type)
- Three single-axis acceleration sensors (ENDEVCO 7264 or ENTRAN)
- One angular velocity transducer MHD (ATA)

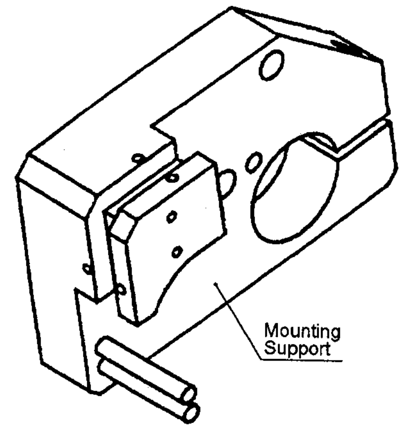

Figure 9 Bracket for the 50°P Hybrid III column

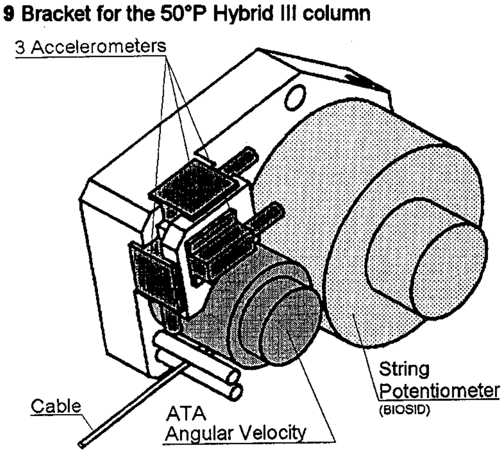

Figure 10 Thoracic instrumentation assembly

The string potentiometer replaces the standard rod potentiometer. The three acceleration sensors correspond to the measurements of thorax accelerations, and the angular speed transducer has been added to make it possible to measure directly the thorax kinematics during the impact.

Location (Figure 10) - The assembly is installed in a spinal column of a 50°P Hybrid III. By eliminating the standard rotary measurement of deflection, it has been possible to reduce greatly the risks of contact with the CAP-SM2D. It should be noted that this assembly can also be used in a conventional column.

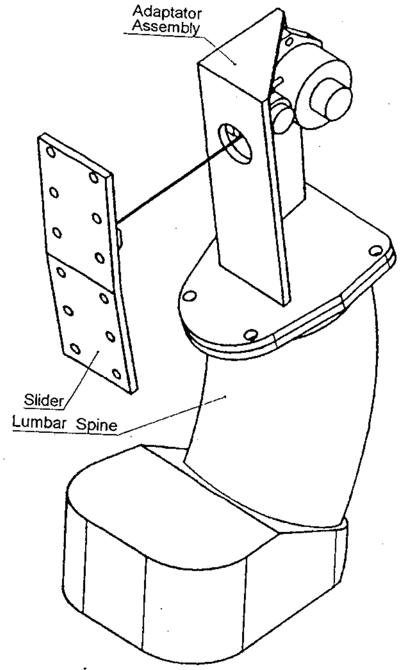

Figure 10 Modified assembly for the chest string potentiometer

Description of the overall chest-pelvis system

The overall system for the 50°P Hybrid III, shown in Figure 11, contains 7 extra measurement channels by comparison with conventional instrumentation.
Three instrumentation combinations are possible. These are:

- Prototype 50°P Hybrid III assembly equipped with two SWINGs, two CAP-SM2Ds and the string potentiometer.
- Prototype 50°P Hybrid III assembly equipped with two SWINGs
- Prototype 5°P Hybrid III assembly, new SAE version equipped with two SWINGs.

VALIDATION OF STRING POTENTIOMETER

These tests were performed at FTSS.

Description of tests (Figure 12)

A guided 5 kg mass of diameter 150 mm was dropped onto the thorax alone. Deflection was measured at the centre of impact. One thoraxe was used in these tests, equipped with the string potentiometer or a standard rod potentiometer. The measurements performed in these tests were:

- Impactor acceleration
- Thoracic deflection (string potentiometer or rod potentiometer)
- Two sternum accelerations
- Two sternum displacements (2 linear potentiometers)

8 tests were performed, at 2, 4, 6 and 7 m/s

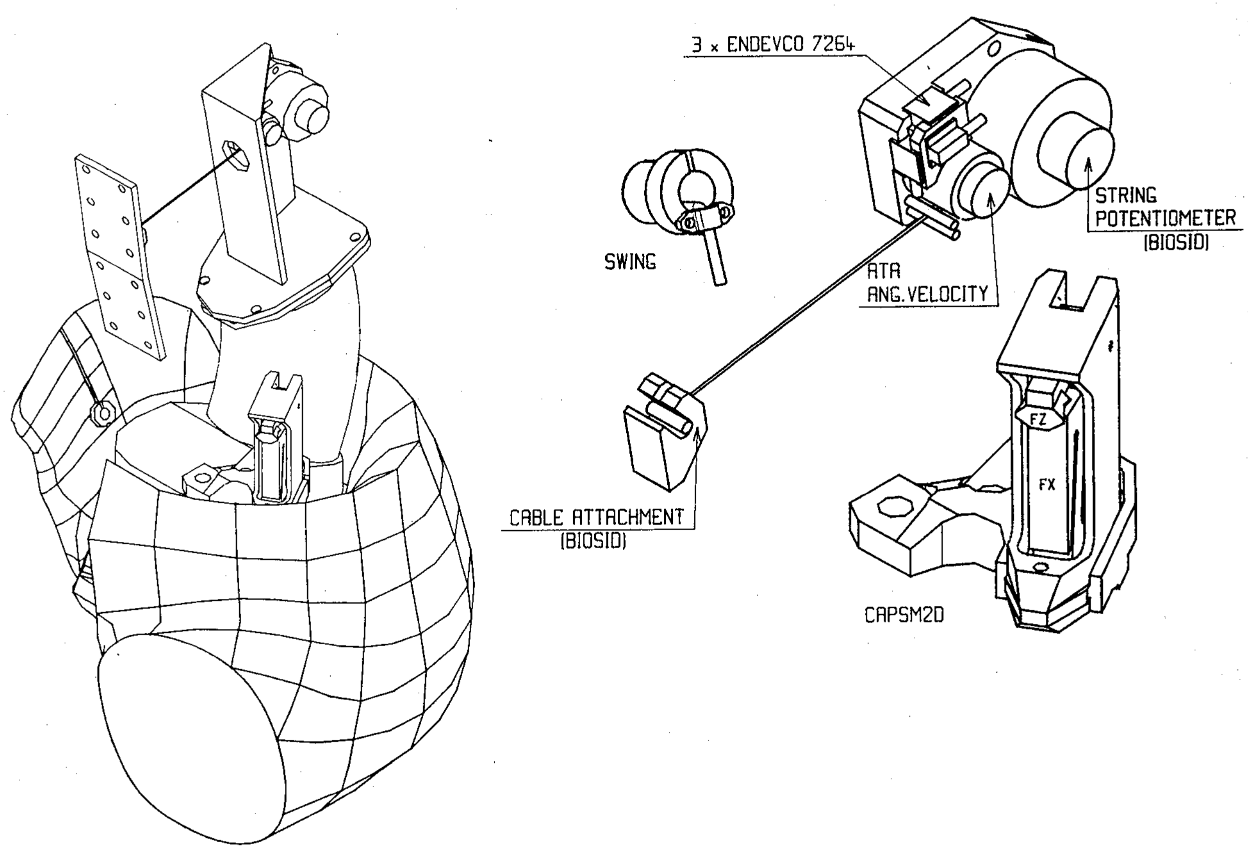

Figure 11 Overall chest-pelvis assembly for the 50°P Hybrid III dummy

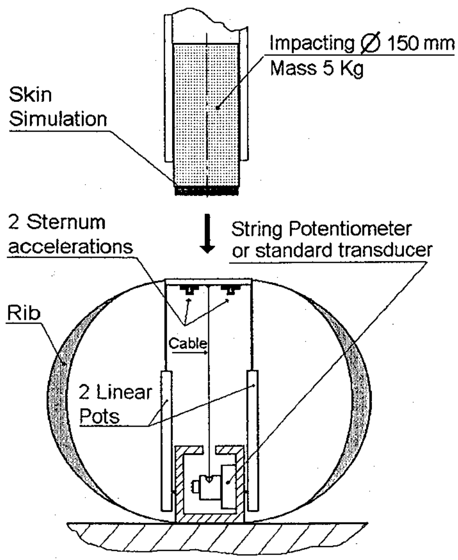

Figure 12 Drop test configuration

Analysis and discussion

8 tests were performed at 4 different speeds - 2, 4, 6 and 7 m/s - with the string potentiometer and the standard rod potentiometer. Tables 1 and 2 summarize the results obtained in these tests.

Test results for the string potentiometer (Table 1)

Test N°		S1	S2	S3	S4
Velocity	(m/s)	2	4	6	7
Acc Right	(G)	54	96	72	86
Acc Left	(G)	50	90	78	95
String Pot.	(mm)	10	20	31	42
Linear pot. Right	(mm)	13	21	31	49
Linear pot. Left	(mm)	11	18	32	51

Test results for the rod potentiometer (Table 2)

Test N°		R1	R2	R3	R4
Velocity	(m/s)	2	4	6	7
Acc Right	(G)	53	65	92	157
Acc Left	(G)	50	56	103	153
Rod Pot.	(mm)	10	20	32	37
Linear pot. Right	(mm)	14	20	33	40
Linear pot. Left	(mm)	13	20	43	35

Figures 13, 14, 15 and 16 show the responses of the two types of potentiometer (string and rod) as a fonction of time. It can be seen that these responses are relatively identical in shape and amplitude up to 6 m/s.
Comparaison betwen linear potentiometer and string/rod pot. readings will not be discussed here. Corresponding data are provided only for information purpose.
These results show that the string potentiometer is suitable for measuring the thoracic deflection. It behaves well relative to the rod systems up to an impact velocity of 6 m/s.

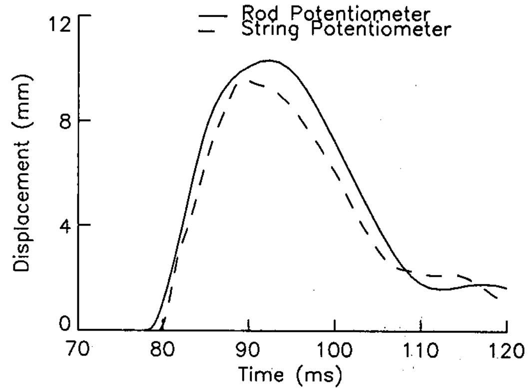

Figure 13 Responses of string and rod potentiometers at 2 m/s.

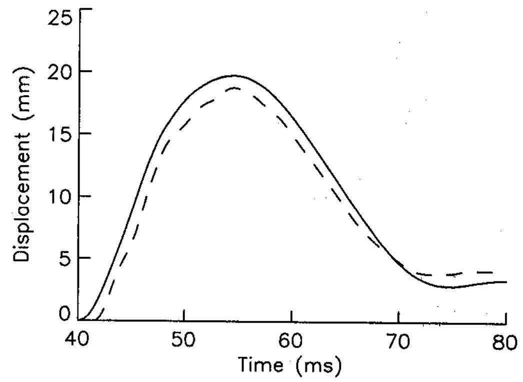

Figure 14 Responses of string and rod potentiometers at 4 m/s.

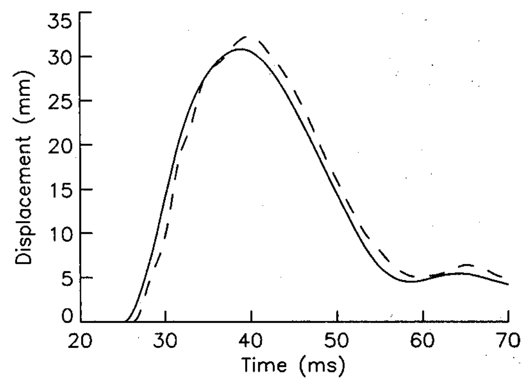

Figure 15 Responses of string and rod potentiometers at 6 m/s.

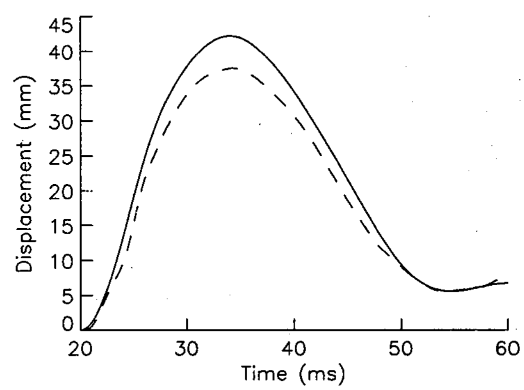

Figure 16 Responses of string and rod potentiometers at 7 m/s.

VALIDATION OF THE PROTOTYPE 50°P HYBRID III IN HYGE SLED TESTS.

To validate the prototype, we compared it with a standard dummy. To do this, tests were performed at P.S.A on an inverted catapult.

Description of the tests

The tests were performed on the seat cushion of a car body. The two dummies were positioned simultaneously as left and right back-seat passengers (Figures 17 and 18). For the tests with submarining, the restraint conditions were degraded by increasing the length of the belt buckle and placing it more horizontally (the same as for the lap belt) and by eliminating the anti-submarining boss. Two tests are described here, and the test conditions and the results obtained are summarized in Table 3.

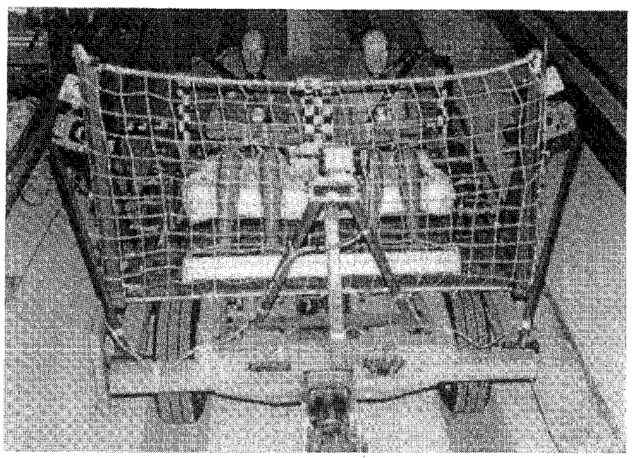

Figure 17 Configuration of Hyge sled test, prior to impact

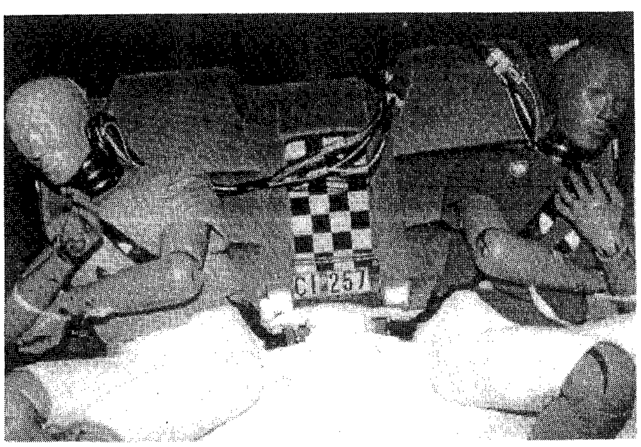

Figure 18 CI 257 configuration post impact

Analysis of prototype measurements

Summary table (Table 3)

Test No.		CI 257		CI 235	
Seat position		Left	Right	Left	Right
Dummy type		Stand.	Proto.	Stand.	Proto.
Thorax Acceleration	X (G)	62	52	55.6	48.7
	Z (G)	-20;18	-25;25	-27;22	-11;15
Pelvis Acceleration	X (G)	35	28	41	/
	Z (G)	30	27	23.7	26.1
Lumbar column force	Fx (daN)	170 -265	400 -310	246 -287	223 -211
	Fz (daN)	50 -240	168 -170	-119 77.	-123 173
	My (N.m)	57	66	38.2	24.6
Belt Force	Lap (daN)	900	850	766.3	720.1
	Shoulder (daN)	900	970	663.5	696.4
Submarining		Yes	Yes	No	No
Fx Right	(daN)	/	2	/	0
Fz Right	(daN)		1	/	0
Fx Left	(daN)	/	160	/	0
Fz Left	(daN)	/	160	/	0
Belt Buckle Angle	(Deg)	54	55	52	52
Belt Buckle length	(mm)	280	280	335	335
Lap belt Angle	(Deg)	60	57	70	70

Response of the CAP-SM2D and SWING with submarining - Using these sensors, submarining can be broken down into three phases in the CI 257 test (Figure 19).

- **Phase 1**: Pelvis movement forward over the seat belt, and loading of the iliac wings. A correlation is observed between the rise of the signals coming from the right and left SWING channels and the lap belt force.

- **Phase 2**: Slippage of the seat belt from the iliac wings onto the abdomen. This can be observed on the SWING channels by a drop in the signal, which takes place rapidly on the left side, and in two plateaux on the right side, before the drop in the seat belt force signal. In this specific case, the drop in the SWING signal was not very sudden, which indicates submarining of relatively low violence.

- **Phase 3**: Presence of the seat belt on the abdomen. The amplitude of this phenomenon is measured by the CAP-SM2D. Relatively slight submarining is measured on the left along anatomical X and Z, of approximately 160 daN. On the right side there is practically no submarining, which is consistent with the measurement on the right SWING channel.

These six measurement channels enabled us to describe accurately and in detail the submarining sustained by the dummy in test CI257. By cross-checking, which can be performed with the SWING channels, the CAP-SM2D and the lap belt force, it can be known with certainty whether submarining occurs and what is its amplitude.

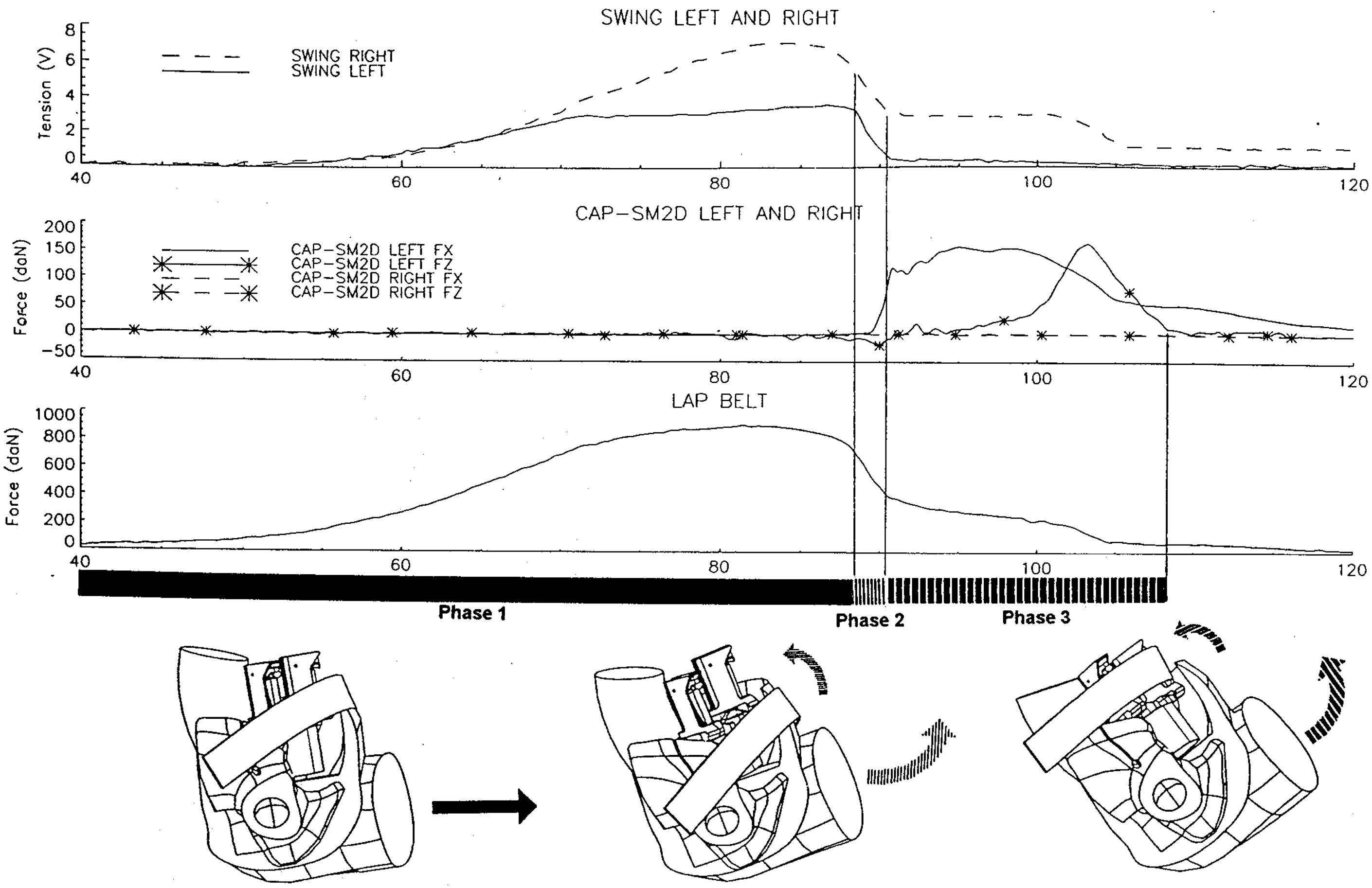

Figure 19 Submarining analysis based on the prototype channels in test CI257

Response of the CAP-SM2D and SWING without submarining - When no submarining occurs, as in test CI 235, the CAP-SM2D sensors detect nothing. The responses of the SWING sensors are correlated throughout the impact with the measurement of the lap belt force (Figure 20).

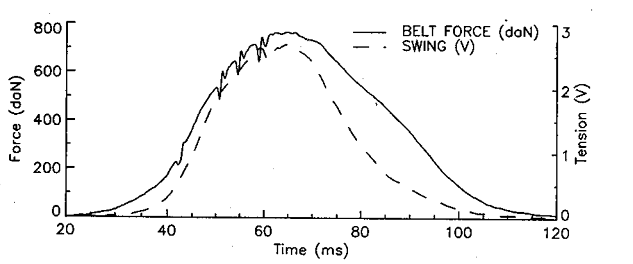

Figure 20 Comparison of the responses of the SWING sensors with the lap belt force.

Comparison of standard measurements

In these tests, we have compared the acceleration and kinematics of the thorax and pelvis, and lumbar forces, to evaluate the influence of the prototype instrumentation on the dummy responses.

Test CI 257 - At the level of pelvis and thorax accelerations (Figure 21) a slight difference is observed, which is accentuated around 60 ms, which corresponds to the start of submarining.

At the kinematic level (Figure 21), the comparison is good, even after 60 ms.
On the other hand, the lumbar measurements (Figure 21) diverge sharply above 70 ms. This is due to the design of the CAP-SM2D which prevents the seat belt from being supported by the ribs and lumbar column during submarining; the forces generated by the seat belt are therefore transmitted directly to the pelvis.
It may be pointed out that the movement of the seat belt onto the ribs and the column in a standard dummy interferes with the thoracic deflection measurement. The standard potentiometer, located at the base of the spinal column, sustains the seat belt force directly during submarining, and this can even damage the sensor, which gave unusual high deflections measured on the standard dummy. This phenomenon cannot occur with the string potentiometer, which is located higher in the thorax.

Test CI 235 - At the level of pelvis and thorax accelerations (Figure 22), a good similarity is observed, except for thoracic acceleration along Z. This difference is again found at the level of force Fz and lumbar moment My (Figure 22). These responses, which are hard to explain, do not seem to be due to the prototype instrumentation, because no physical contact was observed on the CAP-SM2D.
Moreover, no major differences are observed at the kinematic level (Figure 22).

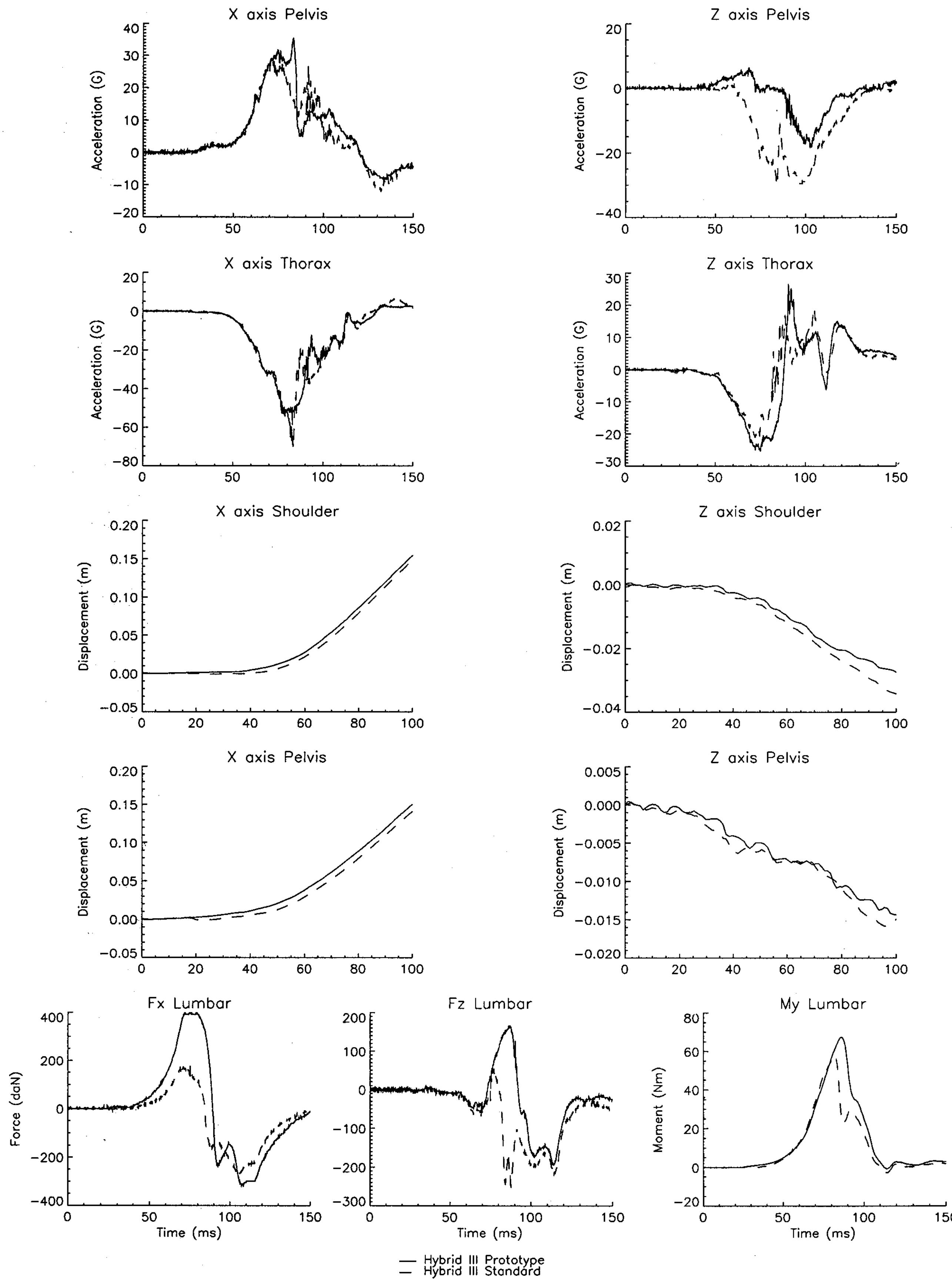

Figure 21 Comparison of thorax, pelvis and lumbar column responses for test CI 257 with submarining.

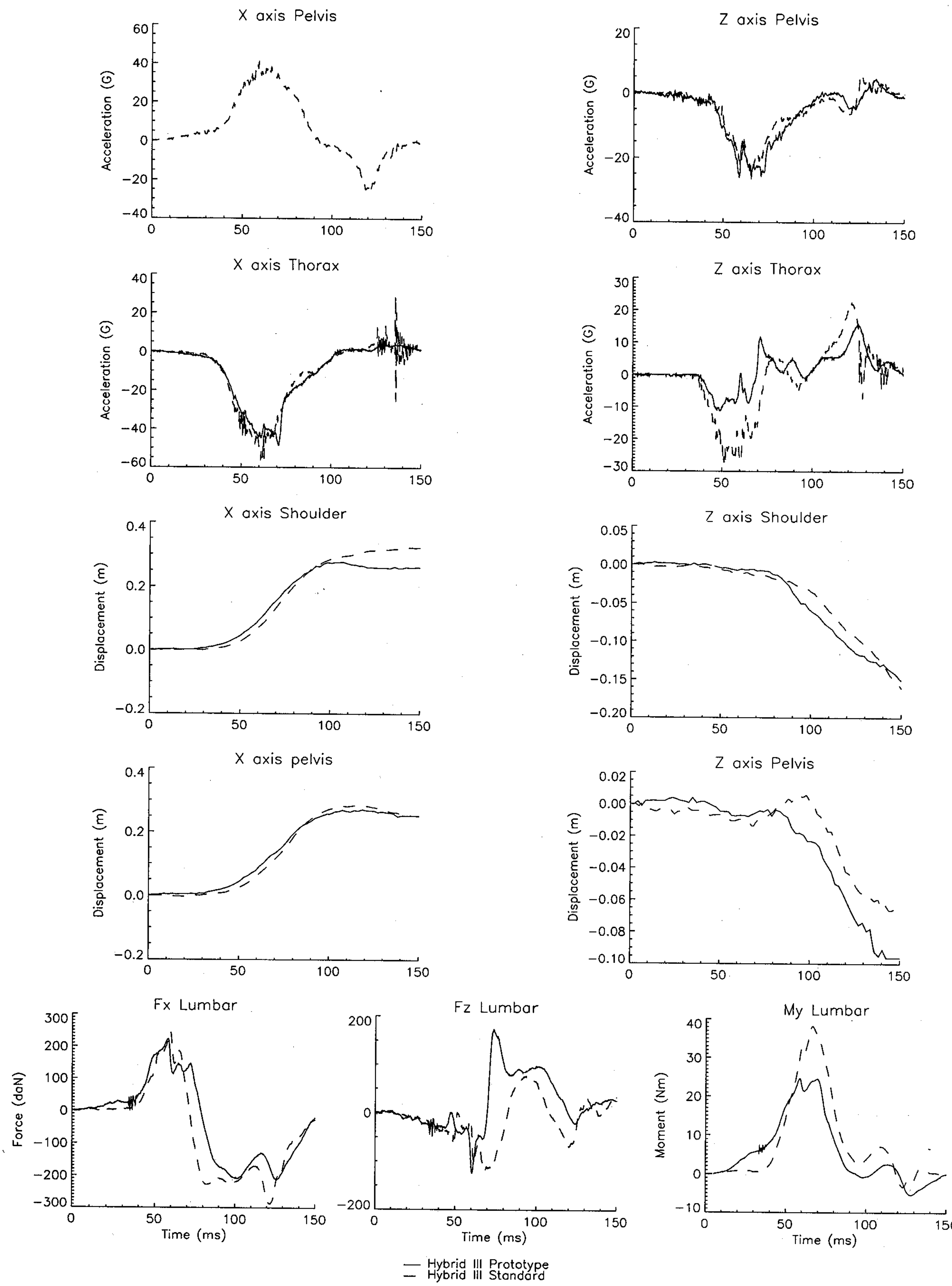

Figure 22 Comparison of thorax, pelvis and lumbar column responses for test CI 235 without submarining.

It can be said that the prototype instrumentation interferes little with the dummy responses, whether at the level of kinematics or accelerations. However for the lumbar channels, major differences are found, which can be explained in the case with submarining. In the absence of submarining, further tests must be carried out to answer the questions raised by this study.

CONCLUSION

The system for the study of submarining operates satisfactorily. The CAP-SM2D and SWING detection systems offer wider scope for investigation of submarining by providing additional information concerning duration, amplitude and time of occurrence. These detection systems will also make it possible to correlate with the dummy responses the injuries observed on PMHS during submarining. This information will be precious to determine, from the family of available dummies, that which is most suitable, especially in terms of biofidelity, for the study of submarining. The aim being to improve occupantprotection against this phenomenon.

Acknowledgements

This prototype is the result of collaboration between the Accident Research and Biomechanics Laboratory associated with Peugeot and Renault and First Technology Safety Systems. The authors would like to thank Sophie Mairesse, Maxime Moutreuil and Gilles Corbin of the L.A.B for their measurement services, Jean-François Huere and François Laurent of P.S.A for carrying out the catapult tests, Muir Parker, Gerald S. Lock and Joshua Y. Zhu of F.T.S.S. for carrying out the deflection tests and providing prototype parts, Craig Morgan of Denton Corp. for his technical assistance and collaboration in manufacturing of the SWING sensor, and all those who contributed to the completion of this project.

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Impact Studies of Embalmed Human Cadaver Thighs and Femurs

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ABSTRACT

Research was performed in an attempt to better define tolerance levels (magnitude of loading that yields a specific degree of injury) of the human thigh. The objectives of this study are to ultimately provide data to be used in the enhancement of crash dummy biofidelity and the development of artificial bone for a frangible experimental dummy (FrED©).

For this study, seventy femurs and twenty-five intact lower limbs from embalmed human cadavers have been subjected to dynamic impact loading. The bones and limbs were mounted in one of two different configurations that simulate: 1. Standing- Specimens were simply-supported with the long axis placed perpendicular to the plane of impact and the direction of impact was either anterior-posterior or lateral-medial. 2. Sitting- Specimens were suspended by cord with the long axis parallel to the plane of impact. Mass was placed at the proximal end of these bones or limbs to emulate constraints imparted by the pelvis and other upper-body components. The impact points in this configuration were the condyles of the femurs or the flexed knee of the intact legs.

The impact apparatus consists of an accelerator that propels a cart headed by a pipe/or plate instrumented with a force transducer. This provided a data record of the transient (ms) relationship of the force (kN) applied to the specimen during impact. The gross response of the thigh to dynamic impact was recorded by standard 30 frames/s VHS video. Several impacts were also captured on a Kodak Ektapro high-speed video system at 1,000 frames/s. Additional data were collected from radiographs and photographs.

The femur appears stronger when impacted in the anterior-to-posterior (a-p) direction than the lateral-to-medial (l-m) direction. Also, soft tissue damage was masked due to the fixation process, and it was concluded that the soft tissue did not play a role in affecting fracture outcome.

INTRODUCTION

This research project is the result of a collaborative effort between anatomists at the University of Louisville School of Medicine and Biomedical Engineers from the University of Tennessee Engineering Institute for Trauma and Injury Prevention.

Progress made since the introduction of the research in 1986 has been significant and includes the design and installation of a state-of-the-art impact testing laboratory; the completion of impact tests using human legs, animal legs, and simulated leg structures; and development of a basic understanding of the response of the human leg to impact loading. Other contributions include appropriate biological and structural material testing, development efforts for a computer-based simulation of lower leg response to impact loading, clinical studies of accidents involving traumatic leg injury, statistical studies of traumatic injuries, whole body vibration research, underwater impact injury studies, head impact tolerance and experimental injury research, various accident reconstruction projects, causal mechanism analyses of human injury, and other biomechanical laboratory experimentation.

This paper presents some results for the purposes of understanding fracture behavior of the human femur and thigh during impact loading.

MATERIALS & METHODS

Human cadavers were bequeathed to the University of Louisville School of Medicine for the purposes of research and education. Use of cadaver specimens for this research project was authorized by the Human Tissue Use Committee in the Department of Anatomical Sciences and Neurobiology at the University of Louisville Health Sciences Center in Louisville, Kentucky, U.S.A.

Lower limbs and femurs were collected from dissection laboratories after completion of medical and dental gross anatomy courses. At least six months prior to this study, the cadavers were embalmed via femoral artery injection of a fixative composed of 20% Isopropyl Alcohol, 20% Propylene Glycol USP, 4% Formaldehyde (Formalin), 4% Phenol and 52% warm water.

Radiographs were made of the intact lower limb specimens, then the limbs and femurs were transported to the test facility.

All specimens were tested at the Impact Biomechanics Laboratory, a special facility in the Department of Industrial Engineering at the University of Tennessee, Knoxville, Tennessee, U.S.A. The testing apparatus consisted of a pneumatic-powered accelerator which propelled an impact cart. The impact cart was headed by an instrumented pipe or plate. Specimens were mounted in a variety of configurations in an impact zone.

Accelerator & Cart - The accelerator consisted of a piston that was powered by compressed air. A ram on the end of the piston contacted the cart throughout its stroke of approximately 1.5 m. The impact cart is constructed of aluminum and steel and weighs approximately 50 kgs. It was guided into the specimen impact zone by a rail system. The cart travels free of the ram for less than a meter and trips a photovoltaic cell/timer apparatus which measures time to travel a given distance. This allows for the calculation of cart velocity just prior to impact. The change in velocity (Δv) of the cart between the end of the ram stroke and the end of the impact has been measured at less than 4% during most impacts.

Impactor & Instrumentation - Heading the cart was one of two different instrumented impactors. Used most often was the laboratory standard 10 cm section of steel pipe with a 4.13 cm outside diameter. The other impactor was a steel plate measuring 2.5 cm by 10 cm. Both were mounted in the same fashion - by slide pins on the front of the cart. When contacting a specimen, the pipe or plate was freely able to impinge on a quartz force transducer, model 208A03 (commercially available through PCB Piezotronics). The transducer was coupled with a Hewlett Packard 3562A signal analyzer. The analyzer recorded and stored a plot of force versus time for each impact.

Specimen Mounting - The thighs and femurs were mounted in one of two test configurations that simulated a standing or seated individual. To simulate standing, the specimen was simply supported with the long axis placed perpendicular to the plane of impact. The specimens were mounted such that either the lateral or anterior surface of the midshaft was impacted. Thus, the direction of impacts were anterior-posterior or lateral-medial.

In the tests simulating a seated person, the lower limb or femur was suspended by cord with the long axis placed parallel to the impact plane. The impact occurred at the knee of the intact lower limbs and at the condyles of the femur. A mass was placed at the proximal end of the specimen in order to simulate the inertial constraints imparted by the pelvis and other upper body components (see Figure 1).

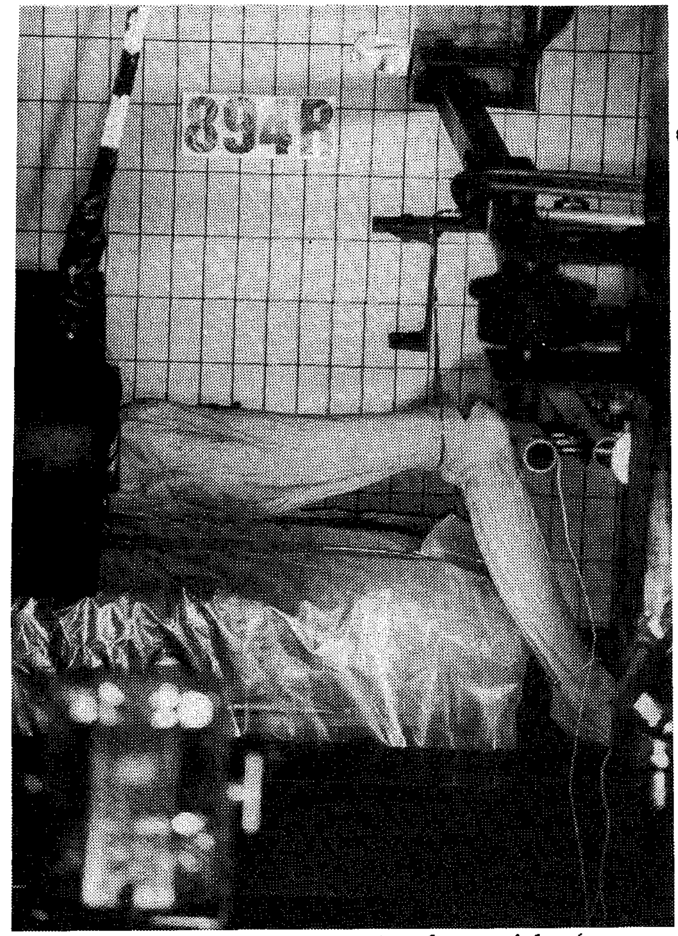

Figure 1. Test set-up for axial (or longitudinal) impact of intact human cadaver thighs. Note instrumented impact pipe lined up to strike the knee. Cylinder holding clay is situated at the hip.

For the bone impacts, the mass placed at the head of the femur was modified to include a simulated acetabular cup. Additionally, a Hybrid III crash dummy foot was suspended from the distal femur in an effort to address the constraints due to the leg.

RESULTS

Tables 1 and 2 summarize the impact response characteristics of the embalmed human femur and thigh respectively. The test conditions and results for these studies are presented. Additionally, fracture patterns are tabulated for each test condition. The tables are followed by a brief discussion of selected data.

Table 1
Dynamic Response Characteristics of
The Human Femur to Impact Loading

All bones specimens were embalmed and impacted midshaft while simply-supported, unless noted otherwise.

n	Impact Direction	Impactor	Average Force (kN)	Standard Deviation (kN)	Average Velocity (m/s)	Fracture Classifications	Remarks (Raw data notes for researchers)
2	A-P D⅓ Femur	Pipe	4.22	0.49	7.5	(n=2) 50% Tension Wedge; 50% Comminuted	
2	A-P Femur	Pipe	1.00	0.64	Static	(n=2) 50% Tension Wedge; 50% Transverse	TAK Machine
4	A-P Femur	Pipe	8.2	1.86	6.6	(n=4) 50.0% Oblique; 50.0% Transverse	From UT Fresh Tissue Bank
30 26*	A-P Femur "	Pipe "	5.76 5.78	1.93 1.41	7.5 7.5	(n=32) 40.6% Comminuted; 12.5% Segmental; 6.3% Compression Wedge; 15.6% Oblique; 21.9% Side Wedge; 3.1% Tension Wedge	* Specious values for #798L/R, 720L and 551L excluded in 2nd "n." (776L & 779L did not trigger)
2	L-M P⅓ Femur	Pipe	5.60	1.63	7.5	(n=3) 33.3% Tension Wedge; 33.4% Comminuted; 33.3% Oblique	(997L did not trigger)
17	L-M Femur	Pipe	3.16	1.89	7.1	(n=18) 27.8% Oblique; 16.7% Tension Wedges; 11.1% Compression Wedges; 27.8% Segmental; 11.1% Other Wedges; 5.6% Comminuted	(698L did not trigger)
1	L-M Femur	10 cm Plate	4.57	na	7.5	(n=1) Compression Wedge	
10 8*	AX Femur "	10 cm Plate "	7.11 7.08	2.32 1.73	6.8 6.6	(n=10) 80% Involved Hip; 40% Involved Shaft; 20% Involved Knee	* Specious values for 557L and 4L were excluded in 2nd "n." Percentages > 100 due to multiple fractures per specimen.

Table 2
Dynamic Response Characteristics of
The Human Thigh to Impact Loading

All intact specimens were embalmed and impacted midshaft while simply-supported, unless noted otherwise.

n	Impact Direction	Impactor	Avg. Force μ (kN)	Std. Dev. σ (kN)	Avg. Vel. (m/s)	Fracture Classifications	Remarks (Raw data notes for researchers)
4	AX Knee	Plate	8.82	1.45	7.5	(n=4) 50.0% Comminuted Patella only. 50.0% Comminuted fractures of Femur, Tibia and Patella.	No additional mass behind hip.
1	AX Knee	Pipe	4.50	na	7.5	(n=1) Fractures of the neck and condyles.	38 kg mass behind hip.
1	AX Knee	Plate	11.07	na	7.5	(n=1) Comminuted patella. Femur not fractured.	11 kg mass behind hip.
4	AX Knee	Pipe	10.24	1.47	7.5	(n=4) 75.0% Comminuted Patella and distal Femur. 25.0% Comminuted Patella only.	11 kg mass behind hip.
2	AX Knee	Pipe	8.07	4.06	7.5	(n=2) Both had comminuted Femur, Tibial Condyles & Patella.	18 kg mass behind hip.
4	A-P Thigh	Pipe	5.81	1.78	7.5	(n=6) 16.7% Neck fractured. 50.0% Oblique 50.0% Wedge formation. 16.7% Transverse.	919L & 879L had false force triggers. Percentages > 100 due to multiple fractures per specimen.
6	L-M Thigh	Pipe	6.17	1.81	7.5	(n=6) All comminuted. 1 fracture of Femoral Neck.	

DISCUSSION

Area under the force-time curve for each a-p impacted femur was determined. The average value is 2658 N-ms. The value for the l-m loaded femurs was 2254 N-ms. The a-p loaded bone, therefore, does not absorb much more energy than the 1-m loaded bone, although the strength is much greater in the a-p direction. Note that the average breaking force in the a-p direction is 5,697 N as compared to 3,053 N for impacts in the l-m direction.

Most of the fractures in the a-p tests were comminuted. Interestingly, however, few produced tension or compression wedges. The vast majority of the comminuted fractures were side wedges. The side wedges were equally dispersed as lateral and medial wedges. Approximately one fourth of the fractures were oblique, and one was a shatter.

The axial impacts of intact thighs produced severely comminuted fractures - although the neck (or hip) was rarely involved. Two-thirds of the comminuted fractures involved the patella with shaft of the femur, whereas the remaining impacts resulted in fractured patellas alone. The radiograph depicted in Figure 2 shows a relatively common fracture pattern seen in this study. There are comminuted fractures of the patella, femoral condyles and distal femoral shaft. Extensive dissection was performed on the intact thighs and it was clear that fixation drastically stiffened the soft tissues making them highly resistent to strain and failure.

Almost all perpendicular impacts to the intact thigh (a-p and l-m) resulted in comminution of the femur and wedge formation was prevalent.

CONCLUSIONS

In consideration of the data, it is apparent that the femur is stronger and stiffer when impacted in the anterior-posterior direction than when impacted in the lateral-medial direction. Bone is non-homogeneous, anisotropic and has properties that vary according to location on the bone. This directional change in properties, therefore, should be expected.

Bone develops in such a way that it is stronger in areas encountering greater stress. Since normal body activities (running, jumping, etc.) apply a moment to the femur similar to three-point loading in the a-p direction, this strength increase in the a-p direction is understandable.

No notable effects of age vs. strength or of age vs. stiffness were evident. While it is acknowledged that the bones of a 20-year-old would, on average, be stronger than 80-year-old bones, no data from this study supports that assumption as the specimens ranged in age from 53 to 89 years old.

Comparison of the fracture data of the bare femur versus the femur with all its associated soft tissue yielded no noticeable differences. In other words, the contributory role of embalmed soft tissues in affecting fracture outcome is minimal.

ACKNOWLEDGEMENTS

This research reported on in this paper was supported by a grant from the Japan Automobile Manufacturers Association.

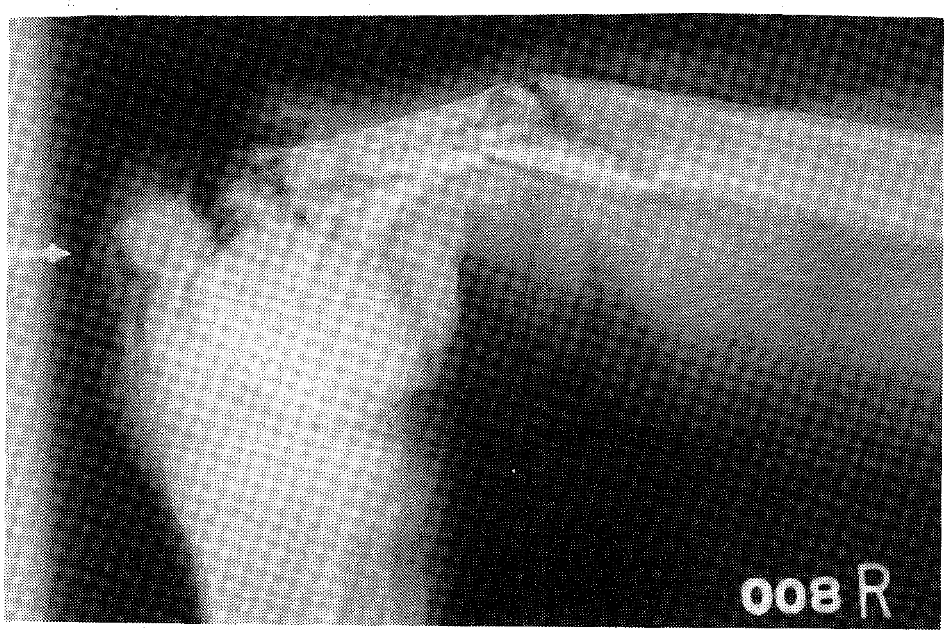

Figure 2. Lateral X-ray view of the comminuted knee. Arrow indicates point of impact.

Technical Session 2

Intelligent Vehicle/Highway Systems: Human Factors

Chairperson: André Chapon, France

Automotive Head-Up Displays for Navigation Use

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94-S2-O-02

ABSTRACT

Although originally developed for aircraft use, head-up displays (HUDs) have recently found application in automobiles. It is projected that there will be two major categories of HUD applications in the 21st century, based on a consideration of technological progress in associated hardware and the implementation of road-vehicle communications infrastructure. The first will be as an interactive display system that improves both operating ease and display legibility. The second will be as a navigation system capable of giving drivers a large quantity of complex information efficiently and safely.

This paper discusses the effectiveness of HUDs in these two major applications based on the results of preliminary visual-optical experiments. It is shown that drivers can receive some critical or emergency information from their effective forward field of view while looking at a HUD, when the angle of depression of the display is small. The use of HUDs as interactive display systems can capitalize on the small angle of depression that is one of the advantages of the HUD design. A new HUD system for navigation use is also proposed. Other advantages of HUDs include the long distance to the displayed image and the ability to superimpose the displayed information on the foward view in a compatible manner. The use of HUDs in navigation systems can effectively exploit these advantages. It is thought that a navigation system built around a HUD could contribute to enhanced driving safety, because drivers need not divert their attention from the road in order to see the displayed information.

INTRODUCTION

The head-up display is a device which presents information to the viewer without requiring the person to divert his or her attention from the primary field of view. The HUD is focused at a significant distance and has an element which combines displayed information with the outside world. Head-up-displays were first installed in military aircraft during World War II, and a HUD was implemented in an automobile for the first time in 1988. That application displayed a digital speed reading in the lower right part of the windshield.[1] A projection of future progress in hardware technologies and the implementation of road-vehicle communications infrastructure suggests that there will be two broad categories of automotive HUD applications in the 21st century. One will be as an interactive display system that provides improved ease of operation and display legibility. The other will be in navigation systems that provide drivers with a large volume of complex information quickly and safely. This paper discusses the effectiveness of HUDs in these two categories based on the results of preliminary experiments concerning human vision characteristics and optics. The application of HUDs to navigation systems is proposed as a means of improving driving safety in the coming years.

CURRENT HUD SYSTEMS

Aviation HUDs are widely used in commercial aircraft today. These HUD systems typically consist of an ultrahigh-brightness cathode ray tube (CRT) as the display source, lenses for forming the image at optical infinity and a combiner, which is a semi-transparent sheet. Pilots see the displayed information through the combiner. The items displayed by aviation and automotive HUDs are compared in Table 1.

Table 1 Information displayed by aviation and automotive HUDs

A) Aviation HUD
(1) weapon-aiming symbols
(2) image by forward-looking IR camera
(3) aircraft data (fuel, altitude, speed, engine data)
B) Automotive HUD
(1) navigation symbols, image by forward-looking IR camera
(2) automobile data (speed, warnings)

The first commercial automotive HUD was installed in the Nissan Silvia in 1988 and consisted of an ultrahigh-brightness vacuum fluorescent display (VFD), aluminum-coated mirror and combiner that was coated on the windshield. The information displayed was a digital speed reading. The distance from the driver's eyes to the image was 1.1 meters. General Motors implemented a commercial HUD in production vehicles in the U.S. market in the fall of 1988. That system also used a VFD and incorporated an aspherical mirror in the projector. The projector was larger than that used in Nissan's system, but more information was displayed and the distance to the image was increased to about two meters.(2) In 1991, Toyota introduced a HUD in its Crown model. The information displayed was similar to that of GM's system and the distance to the image was also around two meters.(3)

The authors conducted a survey among owners of Nissan and GM vehicles equipped with a HUD. Among the 400 owners polled, 80% of them said that they were satisfied with the current system and use it most of the time. The reasons they gave for being satisfied with the HUD included easy recognition of displayed information during high-speed driving and the minimal change in line of vision required.

ADVANTAGES OF AUTOMOTIVE HUDS

According to research on human factors in aircraft operation, aviation HUDs have two major advantages. These are minimal eye accommodation and the small amount of movement in the pilot's line of vision needed to recognize the displayed information and foreground objects such as clouds, the sky and other flying objects.(4)

Automotive HUDs also have two similar advantages. First, drivers can recognize the displayed information quickly because the image is projected on the windshield and its angle of depression is small. Second, only a small amount of eye accommodation is required because the distance between the displayed information and the driver is much longer than with a conventional display. This advantage is especially significant to drivers with presbyopia.(5) Still another advantage of automotive HUDs is that drivers can obtain selected information from the displayed image or from the forward view by means of peripheral vision.(6)

REQUIREMENTS OF HUDS

Operation and recognition time during driving

Some examples of operation and recognition times for conventional instrument tasks and navigation tasks during driving are shown in Table 2.(7) A task involving some kind of operation requires much more time than simply reading a speed indication. Display systems that include operational tasks represent the category of interactive system applications for which new display technology is required to assure safe operation during driving.

Table 2 Operation and recognition time during driving

Task	Mean Display Dwell Time (Td)
Speed	Td< 1.0 (s)
Fan, Vent	1.0 <Td< 2.5 (s),
Temperature, Zoom Level	2.5 <Td< 4 (s),
Tune Radio, Cruise Control	4.0 <Td< 8.0 (s),
Roadway Name with Zoom	8.0 (s)<Td

Information Demands for Future Automobiles

Vigorous research and development work has been proceeding in recent years on Intelligent Vehicle-Highway Systems (IVHS) that aim to overcome safety, traffic and environmental problems by linking the road and vehicles into an integrated system. In the U.S., IVHS America has been organized to promote related R&D activities. One of the most promising areas of research involves active navigation and route guidance systems, which also provide drivers with information on traffic congestion. Once such road-vehicle systems are in place, drivers will be able to obtain information not only from sources around the vehicle, such as from road signs, but also from remote sources concerning traffic congestion, direction to turn at intersections, recommended route to follow and correct lane position for subsequent maneuvers. It will be necessary for in-vehicle display systems to present more complicated information or warnings than navigation systems in use at present. Thus, the category of navigation system applications requires display technology that can present information to drivers efficiently and safely.

Needs Analysis and HUD Advantages

Head-up-displays offer the best solution for the construction of systems that can improve both operating ease and display legibility, as well as for configuring systems that can present complicated information to drivers in a safe, nondistracting manner. The small angle of depression of HUDs can be used advantageously to create interactive display systems for improved operating ease and better legibility. Meanwhile, the long distance to the HUD image and the compatibility between the superimposed information and the forward view can be utilized effectively to create navigation systems capable of presenting complicated route guidance information to drivers for improved transportation efficiency.

APPLICATION OF HUDS TO INTERACTIVE DISPLAY SYSTEMS

An interactive display system includes control switches, such as those for the car audio system or air conditioner, and switch inputs affect the displayed information and vise versa. These systems are generally installed in the center console of automobiles. Some systems have the display screen and switches integrated into one unit, and others have them located separately, with the control switches positioned on the center pad of the steering wheel. Current navigation systems that display maps are also one type of interactive system, inasmuch as drivers must operate switches to change the degree of map enlargement or input the intended destination.

Future interactive display systems will include not only the above-mentioned control switches and navigation map operations, but also route guidance displays and selective acquisition and display of information from sources outside the vehicle. It is envisioned that future systems may be located in the center console, main meter area of the instrument panel or in the windshield area in the form of a HUD.

Problems with Interactive Display Systems

Current interactive display systems present no problem if drivers use them while the vehicle is stopped, but two problems can arise when drivers use them while driving. The first is that drivers must take their eyes off the road to check control switch positions before operating them. The second problem is that drivers must also divert their attention from the forward view to confirm the results of switch operations. The switch position problem can be resolved by locating switches within easy reach and by using well designed switch shapes that allow the driver to tell the switch setting by simply feeling the switch involved. The following discussion will deal with the second problem that drivers must take their eyes off the road. It will present the results of experiments that examined the correlation between the location of the display and the driver's performance.

Experimental Conditions

The experiments were conducted after analyzing the actual operation of interactive display systems under real-world driving conditions from a visual-optical perspective. It was assumed that watching the forward view is usually the driver's main task during driving and that operating an interactive display system is a secondary task. Table 3 compares the driver's task of recognizing the forward view and the main task designed for the experiment. Table 4 compares a driver's operational task and the secondary task designed for the experiment.

Table 3 Comparison between actual driving and experimental conditions

Driver's recognition of forward view and main task of experiments

Driver's recognition of forward view	
1. Searching:	watching the forward view (paying attention to anything unusual)
2. Sensing:	becoming aware of something unusual
3. Recognition:	identifying something unusual
4. Judgment:	deciding the need for action
5. Operation:	for example, braking
6. Confirmation:	confirming safe status
7. Return to 1	
Experiments	
1. Watching the screen: searching for the forward view target	
2. Finding the target	
3. Recognizing the target	
4. Deciding the need for action	
5. Pushing the switch	
6. Confirming target's disappearance	
7. Return to 1	

Table 4 Comparison between actual driving and experimental conditions

Driver's operational task and secondary task of experiments

In-vehicle display/operation of controls
1. Recognition: confirming A/C temperature setting
2. Decision: deciding the need for action
3. Operation: for example, pushing a switch
4. Judgment: comparing result with target value
5. Confirmation: confirming result and target value
6. Return to No. 2
Experiment
1. Watching CRT screen
2. Deciding the need for action
3. Pushing keyboard switches
4. Comparing result with target
5. Comparing result with target
6. Return to No. 2

<u>Evaluation System</u> - The evaluation system consisted of seven elements as shown in Fig. 1-(a). These included a white screen containing nine color CRTs, which represented the forward view, a color CRT for displaying the secondary task, two personal computers (PC-1 and PC-2) for controlling the displays, a light for the screen, an infrared camera for monitoring the subject's eyes and a monitor. The luminance of the screen (forward view) was kept to 2 cd/m^2 by the light. The nine CRTs were set five meters in front of the subject and the color CRT for displaying the secondary task was set at a distance of 0.8 meters as shown in Fig. 1-(b). The latter CRT, corresponding to the HUD, was rotated in each experiment among positions a, b, c, d and e, representing different angles of depression, as shown in Fig. 1-(c).

<u>Forward View Targets</u> - Traffic regulations in Japan pertaining to head lamps mandate sufficient brightness so that drivers can see a child at a distance of 50 meters during nighttime driving. In this experiment, a 20 milliradian black circle and black square were used as the forward view targets to represent a one-meter-tall child standing at a forward distance of 50 meters, as shown in Fig. 2-(a). (One milliradian is the angle subtended by an

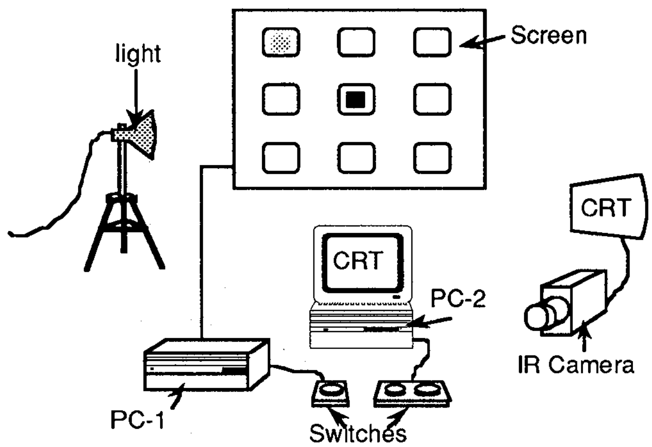

Fig. 1-(a) Evaluation system

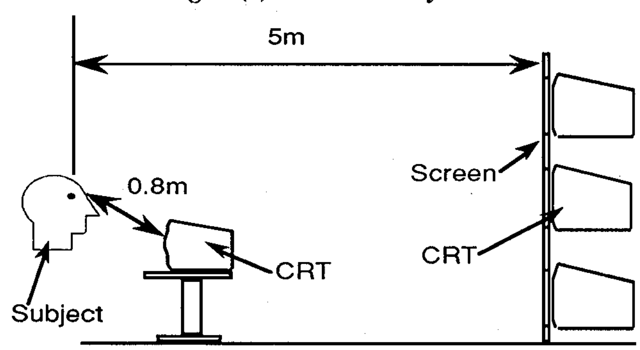

Fig. 1-(b) Evaluation system -side view-

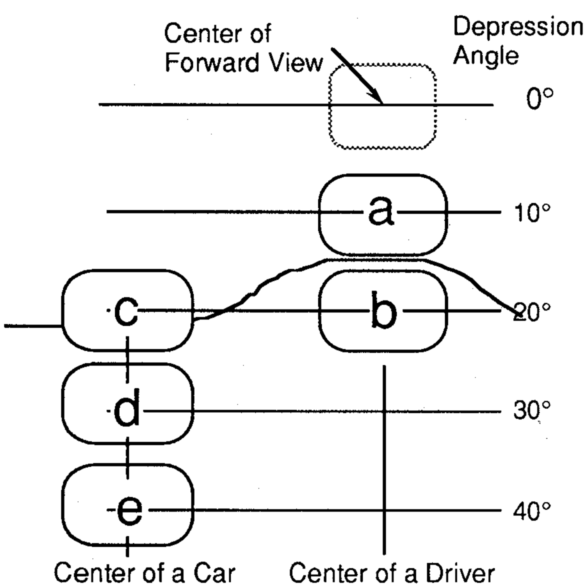

Fig. 1-(c) Positions of CRT

object one meter high when viewed from a distance of one kilometer; 1 mrad = 0.0573°). The subjects were instructed to push a switch only when the black circle was presented. Recognition time was defined as the time between the presentation of the target and the subject's pushing the switch, which caused the target to disappear. Since the targets were displayed at random on the nine CRTs, the subjects had to first search for the target and then recognize it.

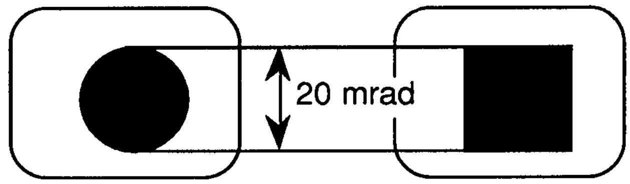

Fig. 2-(a) Forward view targets

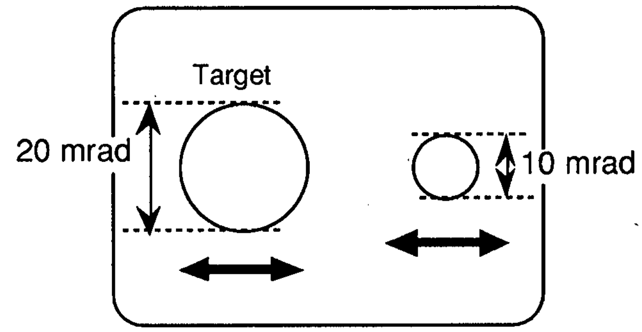

Fig. 2-(b) Secondary task

__Task__ - Figure 2-(b) shows the secondary task of the interactive display system. This chasing-type task simulated the operation of tuning a radio. Using keyboard switches, the subjects moved the small circle to chase the large circle which moved horizontally in an irregular manner. The score for accomplishment of the task, denoted as D, can be expressed as

$$D = \Sigma d^2$$

where d is the distance between the centers of the two circles. A lower score indicates a higher level of task accomplishment.

__Time Chart__ - A time chart showing the timing for displaying the forward view target and for evaluating secondary task accomplishment is given in Fig. 3. The recognition time is the interval between the presentation of the black circle and the pushing of the switch. The black square was shown for only two seconds and then it automatically disappeared. Evaluations were made on the basis of 30 exposures of the black circle.

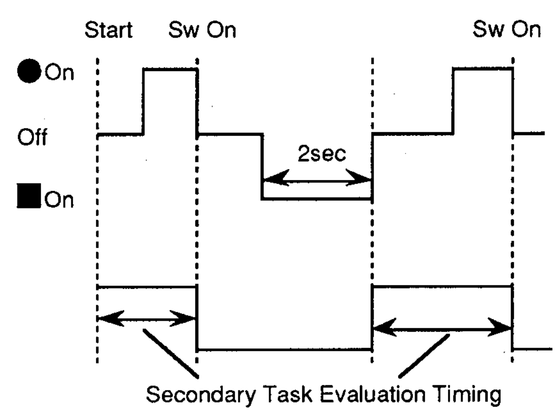

Fig. 3 Time chart

Subjects - The subjects were two males, one each in his twenties and thirties. Both possessed a driver's license. The ages and visual acuity of the subjects are shown in Table 5.

Table 5 Subjects

Name	Age	Visual acuity
E. I.	22	0.6/1.0
J. F.	34	1.0/1.0

Experimental Procedure - Experiments were conducted according to the following procedure.

(1) Ten-minute adaptation time was allowed for the subject's eyes to become accustomed to the darkness of the laboratory.

(2) The subject performed 30 trials as practice.

(3) As the main task, the subject was instructed to push the switch immediately if the black circle appeared and to ignore the black square if it appeared.

(4) As the secondary task, the subject was instructed to move the small circle so as to chase the large circle, using the right and left switches on the keyboard.

(5) Experiments were conducted at each display position in the order of c, d, e, b and a.

(6) The time of the control task, which was either the main or the secondary task, was measured.

Results

The results for the number of eye movements per minute are shown in Fig. 4. For display positions (d) and (e), the numbers were extremely high.

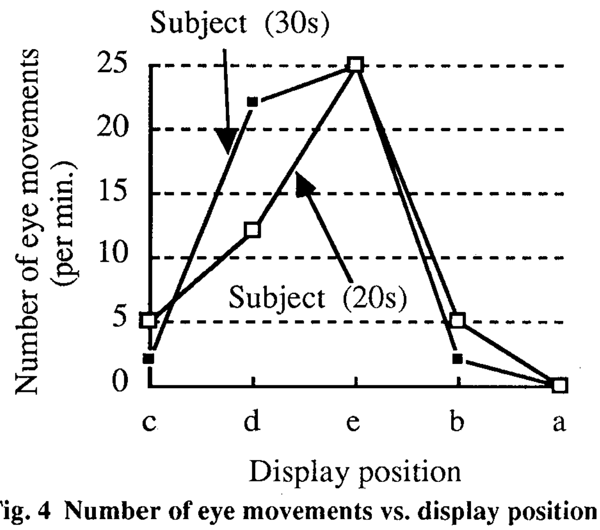

Fig. 4 Number of eye movements vs. display position

The correlation between the results for the main task and the secondary task in position (a) for the subject in his thirties is shown in Fig. 5. Figure 6 shows the results for position (e). The correlation between the results of the main task and the secondary task for the subject in his twenties is shown in Fig. 7. Figure 8 shows the results for position (e). In these figures, the horizontal axis indicates the subject's performance of the main task and the vertical axis indicates that for the secondary task.

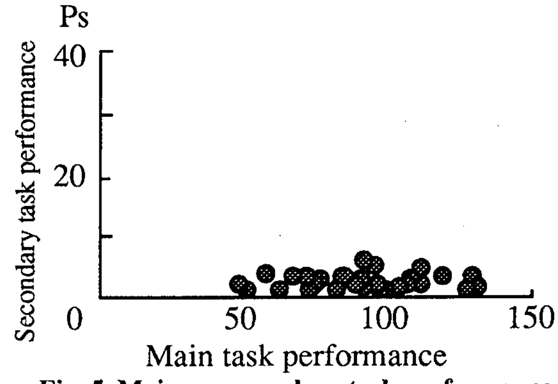

Fig. 5 Main vs. secondary task performance in position (a) -Subject(30s)-

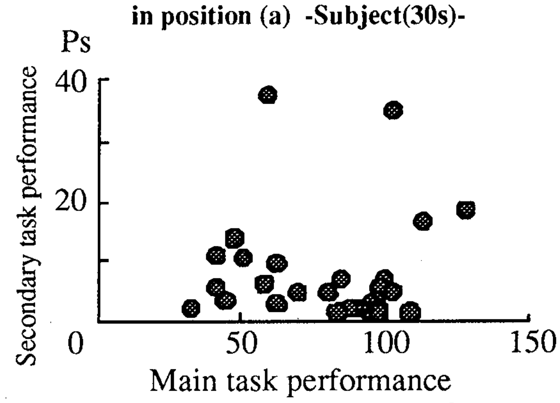

Fig. 6 Main vs. secondary task performance in position (e) -Subject(30s)-

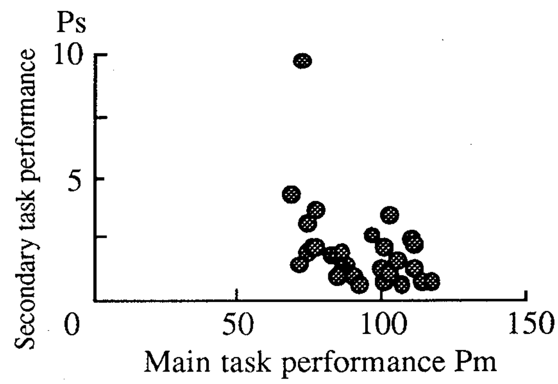

Fig. 7 Main vs. secondary task performance in position (a) -Subject(20s)-

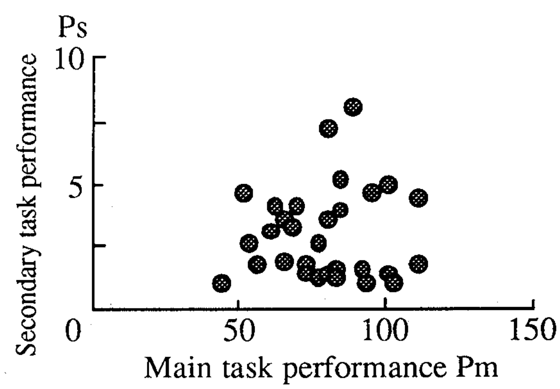

Fig. 8 Main vs. secondary task performance in position (e) -Subject(20s)-

The performance score for the main task, Pm, can be expressed as follows using the reciprocal of the reaction time:

$$P_m = (1/t_n)/(1/t_0) \times 100\%$$

where t_n is the reaction time in seconds for the main task in the n-th trial and t_0 is the control reaction time in seconds when the subject performs only the main task. The performance score for the secondary task was normalized using the control reaction time. The performance score for the secondary task, Ps, can be expressed as

$$Ps = Dn/Do$$

where Dn is the performance score in the n-th trial and Do is the control performance score when the subject performs only the secondary task.

The data in Figs. 5-8 indicate that the performance scores for the main task were higher than 50% when the CRT (HUD) was at position (a). As the position changed from (a) to (e), the performance scores for both the main and secondary tasks decreased. The performance scores for the main task were lower than 50% at position (e), and the performance scores for the secondary task also declined. The following observations can be made from these results:

(1) When the HUD has an angle of depression smaller than 30 degrees, the number of eye movements per minute tends to be large.

(2) The HUD provides improved performance with respect to both ease of operation and display legibility.

(3) In the case of a head-down display (HDD), the reaction time for the forward view target is much longer when the subject is watching the display at the time the target is presented. The score for accomplishment of the secondary task decreases when the subject is watching the forward view carefully.

Discussion

Under actual driving conditions, the driver's entire field of vision extends over a range of about 210 degrees, while the sensitive area of the retina is only about two-degrees wide. Therefore, drivers have to move their eyes to bring objects into the sensitive area in order to obtain information. Drivers obtain information not only by foveal vision but also by peripheral vision.

There are two indexes of peripheral vision. One is reaction time, which indicates the effective field of peripheral vision as a result of eye movement and it can be called the dynamic effective field of view. The other index is response eccentricity, which is the distance between the target and the subject's fixation point at the moment of response. This index represents the so-called "functional" field of view.

Peripheral vision decreases with an increase in situational demands. In more demanding situations, the functional field of view at each fixation point narrows, and a delay occurs before the subject becomes aware of an object presented peripherally. This suggests that delays may occur before drivers become cognizant of relevant objects in their peripheral field of view under demanding driving conditions. For example, when driving in heavy traffic, the functional field of view at each fixation point becomes narrower.[8]

In this experiment, the functional field of view of the subjects was narrower than under a static condition because the assigned secondary task on the interactive display system was a more demanding requirement than simply reading a displayed speed indication. When the CRT representing the HUD was in position (a), the subjects recognized the forward view target within their functional field of view, because of the short distance between the target and the display. In the case of position (e), the distance between the target and the display was greater, making it difficult to recognize the target within the functional field of view. This suggests that there is an ideal position for a HUD where it will improve both ease of operation and recognition of the forward view.

As mentioned earlier, the secondary task simulated the operation of tuning a radio. Under more demanding conditions, such as reading more complicated displayed information, the performance differences seen for the different display positions might increase further on account of the narrowing of the functional field of view at each fixation point. Therefore, the following recommendations are made for the design of interactive display systems.

1. The display should be installed with an angle of depression of less than 20 degrees, thereby enabling drivers to recognize anything unusual in the forward view while operating the interactive display system.

2. A HUD should be used, with the angle of depression set at less than 10 degrees, in order to obtain both excellent ease of operation and a short reaction time.

APPLICATION OF HUDS TO NAVIGATION SYSTEMS

Current navigation systems can be broadly divided into two categories on the basis of the position of the display. One category is the head-down display (HDD) and the other is the head-level display (HLD). The HDD is typically a 4- to 6-inch-diagonal CRT or active matrix liquid crystal display (LCD) installed at an angle of depression of 20-40 degrees. The HLD is typically a 4- to 6-inch-diagonal active matrix LCD installed at an angle of depression of 15-20 degrees. The HLD requires less eye movement than the HDD during driving.

A navigation system with voice route guidance has also been developed in Japan. The system informs the driver, for example, to "turn right about 700 meters ahead" or "turn right at XXXX town about 300 meters ahead." An HDD navigation system with voice route guidance offers the advantage of less frequent glancing at the display and shorter dwell time than conventional HDD navigation systems.[9] However, voice route guidance systems could encounter difficulties in explaining complex intersections.

As the proverb says, " a picture is worth a thousand words." Using suitable display graphics may provide easier-to-understand route guidance.

Future navigation or route guidance systems may incorporate a HUD. It is envisioned that the display area will be larger and the displayed information much more complex than in the case of current HUDs, which usually display a digital speed reading. A HUD route guidance system has been developed as part of the Road and Automobile Communication System (RACS) project. This system uses a HUD and a 6-inch-diagonal CRT for map displays. The HUD shows intersection maps giving the name of the intersection and an arrow that indicates the route to follow.[10]

Problems with HUD Navigation Systems

The results of an experiment that examined how displayed patterns affected the driver's ability to recognize objects in the forward view indicate that a display with a fill factor (F factor) of 50-60% results in poorer recognition. In this experiment, the complexity of the displayed pattern was expressed as the F factor, i.e., the ratio of the area of on-segments to the entire display area. The F factor was varied from 0%, equal to a condition without any displayed information, to 100%, equal to a bright rectangle presented by a HUD.[11]

The experimental results suggest that HUDs with a large display area need to use simple patterns, which means either the smallest or largest F factor possible. Using negative display patterns results in a smaller F factor, but the large display area might be annoying to drivers.

New HUD System Proposed for Navigation Use

A new HUD system for navigation use is proposed, which is called "On-the-Scene HUD" and is capable of displaying complex information but has a small F factor. An example is given here of an application of this system for route guidance.

In general, a HUD system shows a plan view of the configuration of an intersection and an arrow to guide the driver, as illustrated in Fig. 9. In contrast, the On-the-Scene HUD treats the forward view seen through the windshield as one part of the display and superimposes only the guiding arrow and a place name, as shown in Fig. 10. Since the configuration of the intersection and other landmarks are not displayed, the F factor is extremely small.

Experimental Conditions

Table 6 shows the timing for displaying route guidance information and examples of the types of information displayed. Experiments were conducted using a situation where a road sign was displayed within the range of the driver's vision (item (d) in Table 6). A comparison was made between a conventional HUD and the On-the-Scene HUD in terms of recognition performance, based on a visual-optical perspective.

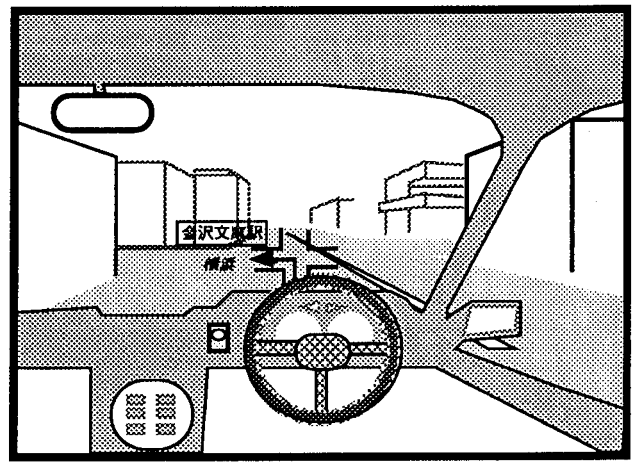

Fig. 9 Conventional HUD

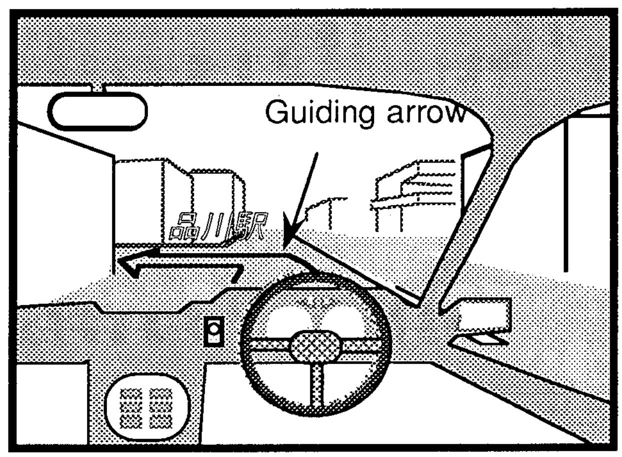

Fig. 10 On-the Scene HUD

Table 6 Guidance timing and display information

Timing	Examples of displayed information
(a) Before starting out	Destination input
(b) During driving	Remaining distance to next action point
(c) Preparing for next action	Direction to turn, intersection map
(d) Road sign within driver's range of vision	Direction to turn, landmark, intersection map, road sign
(e) Beginning of turning action	Direction to turn, next action
(f) After turning action	(b) or (c)

Evaluation System - The evaluation system consisted of seven elements as shown in Fig. 11. These included a white screen with a color LCD projector (representing the forward view), a color CRT as the HUD information source, a combiner, a personal computer for controlling the displays, switches, a camera for monitoring the subject's eyes and a video cassette recorder. The white screen was positioned two meters from the subject and the distance to the HUD image was also set at two meters. The size of the

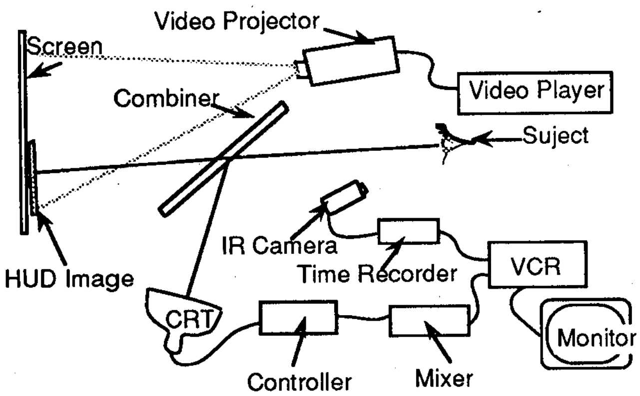

Fig. 11 Evaluation system

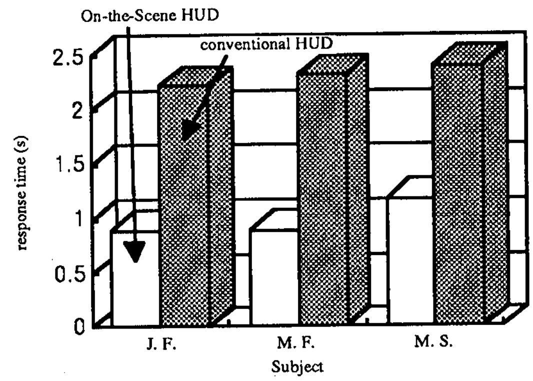

Fig. 12 Measured response times

conventional HUD image and that of the On-the-Scene HUD were set at 35 milliradians x 50 milliradians (V x H). The luminance contrast, C, of the conventional HUD and the On-the-Scene HUD was set at around 1.75 and was defined as

$$C= (Bo + Bb)/Bb$$

where Bb is the luminance of the screen and Bo is the luminance of the displayed images. The following were the display position parameters:

Position of conventional HUD: in front of the subject and with an angle of depression of seven degrees

Position of the On-the-Scene HUD: in front of the subject and with an angle of depression of 0-7 degrees

Forward view: still images of actual road scenes were presented by the LCD projector

Subjects - The subjects were three males in their twenties or thirties and all of them possessed a driver's license (Table 7).

Table 7 Subjects

Name	Age	Visual acuity
J. F.	34	1.0/1.0
M. F.	38	1.2/1.2
M. S.	38	1.2/1.2

Experimental Procedure - The experiments were conducted according to the following procedure.

(1) Ten-minute adaptation time was allowed for the subject's eyes to become accustomed to the darkness of the laboratory.

(2) The subject was instructed to push the switch immediately if the conventional HUD or the On-the-Scene HUD presented an image of the intersection at which he was supposed to turn.

(3) The subject's response time, frequency of glancing at the display on the displayed information were measured.

(4) Two types of intersections were used in the experiments.

Results

The measured response times are shown in Fig. 13. The average response time for the On-the-Scene HUD was about 60% shorter than that for the conventional HUD. The average frequency of glancing at the display was 40% lower for the On-the-Scene HUD than that for the conventional HUD. The results of these preliminary experiments suggest that the On-the-Scene HUD is better suited for route guidance applications than the conventional HUD because it shortens the recognition time for the displayed information without interfering with the forward view or annoying the driver.

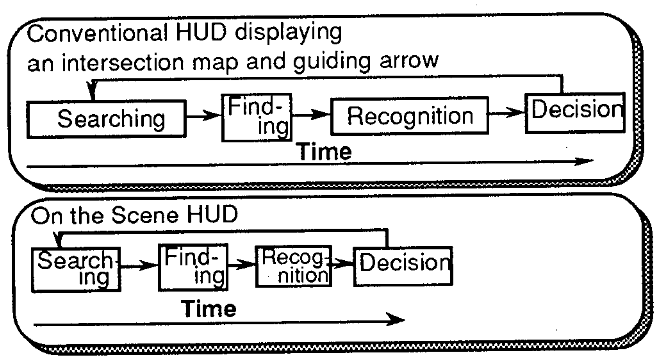

Fig. 13 Comparison of procedures

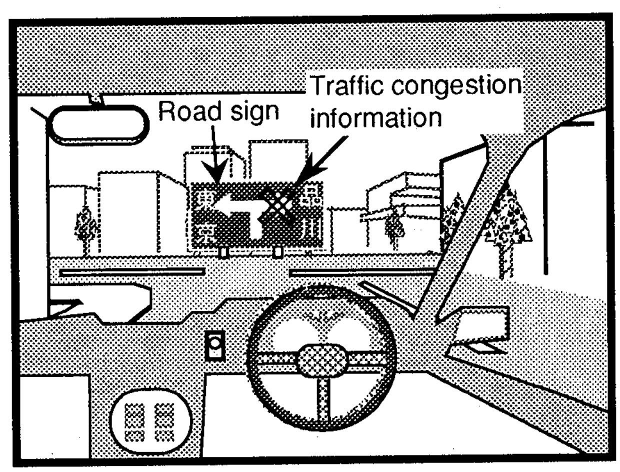

Fig. 14 Traffic congestion information by On-the Scene HUD

Discussion

One reason why the On-the-Scene HUD allows a shorter recognition time for route guidance information than a conventional HUD is that drivers can find the action point on the road more easily. The On-the-Scene HUD superimposes the displayed information on the real road itself in a compatible manner. Drivers can recognize the intersection at which they are supposed to turn and promptly make a decision to act. In the case of a conventional HUD, which displays an intersection map and a guiding arrow, drivers need time to search for the real-world intersection that is the same as the one indicated on the two-dimensional map and also recognition time for comparing the intersection name or real-world landmark with those indicated on the map. Figure 14 compares the procedure involved with each type of display. The On-the-Scene HUD has the particular advantage that it is easier for drivers to recognize the displayed route at a complex intersection. The On-the-Scene HUD also offers the same advantage over a voice route guidance system.

Another example of the use of the On-the-Scene HUD is illustrated in Fig. 15, which shows traffic congestion information superimposed on a real road sign.

CONCLUSION

The results of preliminary visual-optical experiments suggest that interactive display systems and navigation systems are two major categories for future HUD applications.

The information needed by drivers can be broadly divided into two categories. The first category concerns information from the vehicle itself (housekeeping information) such as the engine speed or amount of fuel remaining. The second category concerns information from the outside world. Housekeeping information is displayed on the instrument panel, making it necessary for drivers to shift their line of vision from the road to the instrumentation. The action of watching the instrument panel, even for an extremely short period of time, is comparable to entering a different world. Designing a display system with a small angle of depression is one way of making it possible for drivers to obtain some critical or emergency information from their effective forward field of view even while they are looking at the instrument panel. Under a more demanding condition than simply reading displayed information, such as in the case of an interactive display system or when reading complex information, the driver's effective forward field of view becomes smaller than usual. Since a HUD offers the advantage of a small angle of depression, it provides an excellent solution in this regard. Current HUDs that display a speed reading or warnings make use of this advantage. The application of HUDs to interactive display systems can exploit this advantage to its maximum extent.

The other category of information pertaining to the outside world is currently obtained through the windshield from the actual forward view. Navigation systems show outside information calculated from a map database, and thus navigation information can be placed in the second category concerning the outside world. Using a HUD for navigation purposes is suitable from this way of thinking.

Furthermore, two other advantages of HUDs can be utilized effectively to present information to drivers without requiring them to take their eyes off the road. These are the greater distance to the displayed information and capability of superimposing it in a manner that is compatible with the forward view. With a HUD system, drivers can obtain displayed information from "the same world" as that constituting the forward view. The newly proposed On-the-Scene HUD does not display an intersection map or other landmarks but superimposes the minimum amount of information on the forward view in a compatible manner. It is expected that this system will be useful in building high-performance navigation tools and that it could also contribute to enhanced driving safety.

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EURO-SCOUT - safe driving with real time traffic information

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ABSTRACT

Due to an increasing mobility rate we are experiencing several problems resulting from the insufficient traffic infrastructure. Driving in this enviroment without stress, without loosing time, and safely guided by all relevant information - this is the paradise vehicle drivers are dreaming of. One step to a solution, which may be applied in short term, is the use of information and communication systems, e.g. telematics, between driver and infrastructure.

These systems enable prognostics of traffic patterns and communicate the information without delay tailored to each individual driver needs. Combined with an ergonomic means of information dissemination in the vehicle, the driver will be able to drive to his destination in a guided mode with real-time information, reflecting all current traffic problems. As a consequence, stress reduction, shorter drives, reduction of obsolete traffic (search, congestion, etc) and an increased level of safety have been experienced.

This paper describes the system EURO-SCOUT, an interactive route guidance and information system which fulfills the above requirements.

OVERVIEW

EURO-SCOUT is a dynamic and interactive system, which makes use of three basic system components:

(1) a central computer system for each geographic region, capable of storing all relevant information of the street network together with all attributes including a database, which reflects the travel times for all links in this network, classified according to day and short time intervals,

(2) in-vehicle-units which show the driver information and recommendations from the central computer system and which collect travel times for the central computer, when the vehicle is moving inside the network, and

(3) a communication system between the central computer system and the in-vehicle-units, which is based on the infra-red communication technology the in-vehicle-units and the beacons, located at the street side (usually in connection with standard traffic lights).

The Central Computer System

The central computer system utilises real-time traffic data, which consists of journey and congestion times for each link of the street network, transmitted from the vehicles via the beacons. This transmission is absolutely anonymous. The information is used twofold:

Database-update - real-time information will be used to build up a historic database, where all traffic information for each link will be stored as a statistic value. In order to be able to differentiate this information according to traffic needs, classification will be done in fixed time intervals for different type of days. This will enable the distinction of working day, weekends, etc.

Detection of anomalies - The second purpose is to detect traffic anomalies. Whenever the real-time value (of course, only if a relevant number of vehicles have issued this value) is different from the current data base entry, a nontypical situation is detected and will be handeld accordingly.

Data usage - The database contains all relevant information to have prognostics of the typical traffic pattern or to use adapted values in case of anomalies. The routing algorithm is calculating the fastest or other type of routes, based on those traffic prognostic values.

In addition, facilities are available to gradually adapt the routing algorithms to enable a manual interface for the handling of special traffic situations or to implement certain traffic guidance strategies.

The central computer system offers highly interactive services to allow an operator to view the current traffic state, adapt the database and the algorithms and to individually enter new information.

In order to support other services, such as information about public transport, guidance to available parking facilities and hazard warnings, the computer system may be linked to other traffic computers.

Beacons

The beacons represent the direct link between the central computer and the in-vehicle-units. They contain all information, which are relevant to the local environment of the beacon. This is mainly the description of all links from the beacon to at least the neighbouring beacons or to destinations within the beacon area. Each link will be completely attributed to support the other services and to anable the vehicle to perform position tracking with map-matching methods.

Since the beacons use infra-red transmission technology, vehicles can detect the point of exit from the lightbeam very accurately. This allows for an easy update procedure of the vehicles' position, avoiding extensive positioning hardware and software in the vehicle. The system does therefore not require the use of GPS-services.

In-vehicle-units

Hardware - The in-vehicle-units consists of four main components:

- The main computer (about one third the size of a simple car-radio),
- The display and command unit, which is removable and may be operated outside the vehicle,
- The magnetic field sensor, to enable the position tracking together with the wheel signal and
- the infra-red transceiver for the communication with the beacons.

This, of course, is only one example of an in-vehicle-unit. There is no reason to have a different design or different integration with other systems or the car instrumentation. The only important factor is the conformity to the infra-red data transmission protocol.

Data collection - Since vehicles are an active element in the traffic flow, the easiest way to detect traffic is to use the vehicles themselves as traffic probes. The in-vehicle-unit is able to determine the travel times between fixed points as they are provided by the street network. The quick transmission of these travel times to the central computer guarantess an effective way of measuring traffic. The in-vehicle-unit is designed that in addition to travel times also congestion speeds, congestion time (time that the vehicle is below a certain speed) etc will be collected and transmitted.

It is important to note, that the measuring points are not only beacon positions. The in-vehicle-units is able to store a number of traffic values for specified links, which will be transmitted to the central computer in one transmission when passing a beacon. Also, as soon as link information from the beacon is received, traffic data collection through the in-vehicle-unit begins. The vehicle driver is neither required to switch the display of the in-vehicle-unit on nor to enter a destination.

Driver information - To start a guided journey, all the driver has to do is to enter a destination and to press the start button. He then receives visual and audible guidance information. These are clear and unequivocal and do not distract him from the task of driving. In fact, they even help him to concentrate better on the traffic because it is left to the system to select the road and provide detailed road environment information.

The vehicle receives the guidance recommendations in the form of a data package every time it passes a beacon. The vehicle is "forwarded" from beacon to beacon until the last one before its destination is reached. From here it receives information up to a "departure point" - the end of the guided mode. The vehicle now operates in the autonomous mode, where an arrow on the display indicates the direction of the destination. This autonomous mode is also used when starting a journey or, in other words, before the first beacon contact has taken place.

When several vehicles with different destinations pass a beacon, all of them receive the same data package. Each vehicle then filters out the data relevant ot its programmed destination. The remaining data will not be used. Thus, it is ensured that the destination entered at the start of the journey does not leave the vehicle and that the guidance procedure will take place completely anonymously.

The basic recommended route is always the fastest. Variations can be "the correct one" (e.g. for heavy trucks), "the cheapest one" (e.g. not using toll roads) etc. The central computer will provide different recommendations according to each specified class of vehicles.

Other variations are possible, through the use of a "Dual-Mode-Route-Guidance" in-vehicle-unit (DMRG) with different levels of support for the driver. The most noteworthy supplement is the ability to use the local database of an autonomous system on board, whenever the driver the is outside the beacon area, either because he leaves the support beacon area, or he is driving on lower class streets (e.g. in residential zones), which are on purpose not supported by the central computer network.

TRAFFIC REQUIREMENTS

As all partners in the controverse discussion on traffic agree, the goal of any future achievement cannot be to fill the street with vehicles until the full capacity is reached. Without discussing the political environment here, it is obvious that a technical system should <u>not</u> fix a traffic strategy on its own. Therefore, some key ideas have influenced the design of the EURO-SCOUT system:

1. There must not be the need to support point-to-point navigation for each indiviual user. The system should concentrate on guiding on the main roads, leaving additional functions to the in-vehicle-unit.

Consequence: The central computer uses the primay street network for calculation of routes. The definition of the primary network will be based together local authorities on the existing physical street network and with appropriate traffic requirements. It is possible to modify the primary street network during system operation.

2. The in-vehicle equipment should be as simple as possible, whithout prohibiting more complex and comfortable units if wanted. For the basic function, the in-vehicle should not be required to have a database on board.

Consequence: The central computer will pass via the beacons all relevant information, that allows the vehicle to follow routes within guided mode.

3. Real-time traffic management according to the specified traffic strategies is more important than individual guidance. Changes to the physical layout and to the dynamic attributtes of the network must be employed rapidly.

Consequence: The central computer is the only place, where data is handled and changed. Any influence, be it either automatic through real-time traffic flow measurement of be it manually through the operator will be transmitted without delay to all beacons and hence to all vehicles. Direct interventions in traffic occurrences are now possible. By guiding equipped vehicles appropriately, parts of traffic flows, can be distributed, shifted and for instance diverted around residential zones, schools, hospitals etc. Thus, public authorities responsible for traffic management are provided with an outstanding intrument for asserting their traffic policies without the absolute need for prohibitions and unpopular restricitions.

4. The communication infrastructure should not be costly

Consequence: Beacons are designed for easy installation and use widely an existing infrastructure to connect to the central computer. Information is clustered in such a way that, the communication between central computer and beacons is limited to update information only, whereas the vehicle passing by the beacon always receives the full data set.

5. The gathering of traffic information should be done implicitly be the system itself.

Consequence: The in-vehicle-unit is designed such that the information gathering and the transport to the central computer does not require any additional hardware.

SAFETY REQUIREMENTS

The use of EURO-SCOUT should neither endanger the traffic situation as a whole nor the individual driver. It is therefore mandatory that any information dissemination must follow restrictive guidelines. The goal is that the driver should not be overloaded with information. On the other side, he needs to get the relevant information for his task.

Information to the driver

Interestingly enough, it is noted that for any type of service very few information items need to be given to the driver while driving. They can be classified as follows:

Guidance information - this information will be given verbally and displayed on a simple screen. The information will consist of simple instructions: "perpare for a turn", "please turn ..." etc. Any new information will be initiated by an audible signal, so that the driver does not need to watch the screen to view the next action.

The audible instructions shall be clear and concise. The visual instructions shall be easy to recognise, hence only simple pictograms will be displayed giving the following information:

- distinction between crossing and round-about locations, or the normal "follow main road" symbol,
- simple overview of the structure at the next action location (e.g. connecting streets)
- display of the lane recommendation to be used to follow the recommended route
- display of the distance to the next action with a bargraph, which diminishes while approaching that point
- indication of the distance to the final destination

Other information - Other information to be displayed are the name of the destination and specific indications as they will be necessary during the journey. They will always be concise and easy to understand. The only interaction that may be required from the driver under any circumstances is the positive answer to a question. For example: "no parking within city - use public transport ?" If the driver does not answer within a specified time frame, the question is automatically answered with a "no". Also, any such information will be accompanied by an audible signal, however, to avoid a lot of different speech output, the in-vehicle-unit will usually request the driver to look at the display for further display.

This method allows for complete information dissemination to the driver with the lowest possible distraction from the traffic.

SUMMARY

EURO-SCOUT is a step to help todays and future traffic problems. The approach has been demonstrated in a number of world wide field tests. The main consideration has been the development of a communication means, that allows the traffic authorities to plan for smoother and safe traffic, have interactive capabilities to support the traffic flow in case of traffic anomalies and to provide best information to the individual driver without overloading him.

In Germany, a private operating company will install in the first step the infrastructure in two cities and operate the system in a commercial manner.

Behavioural and Cognitive Impact of Night-Time Driving with HUD Contact Analogue Infra-Red Imaging

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ABSTRACT

This paper outlines the preliminary results of a field evaluation of a prototype near infra-red Vision Enhancement System (VES) using a contact analogue Head-up Display (HUD) presentation. The evaluation compared speed, cognitive workload and reaction times for the detection of simulated pedestrians while driving a route with the operational VES *and* without the VES at night. Results indicated that VES operation necessitated greater mental demand and effort, and resulted in slower speeds (at least initially) as well as a generalised trend to greater speed variation over time. The results are discussed in terms of the functional qualities of the demonstrated VES prototype.

INTRODUCTION

Driving is a complex psychomotor task largely dependent on vision as the predominant channel by which the motorist interfaces with information in the driving environment (Byrnes, 1962 cited by Davison, 1978). Thus, the functioning of the visual system contributes significantly to the safe operation of a vehicle. The functional capacity of the visual system, however, can be exceeded by the conditions imposed by the driving environment. For example, it has been demonstrated that visual acuity, stimulus identification and distance estimation, area (locus) of eye scanning and viewing distance, as well as colour and contrast sensitivity are degraded in darkness (Andreassend, 1976; Dewar, 1973; Morris, Mounce, Button, & Walton, 1977; Staplin, 1985; Sturr & Taub, 1990; Rumar, 1964; Vaswani, 1977). These decrements are compounded by glare from oncoming vehicle headlights and other light sources (particularly in conjunction with precipitation or high relative humidity) which disrupt the adaptive capacity of the visual system (Dewar, 1973; Jung, 1977; Morris, et al., 1977; Rumar, 1964; Schoppert & Hoyt, 1968).

Many motorists fail to appreciate the limitations of their visual functioning at night (Leibowitz & Owens, 1986). Accordingly, motorists may routinely behave in a manner that is not supported by their visual ability. Consequently, accident rates at night are commonly much higher than during the day (controlling for difference in traffic volume) for a variety of accident types (e.g., Darzentas & McDowell, 1981; Leibowitz, 1985; Owens & Sivak, 1992 cited by Owens, Helmers, & Sivak, 1993; Russell, 1974; Schoppert & Hoyt, 1968).

A number of proposals have been made for the development of an in-vehicle VISION ENHANCEMENT SYSTEM (VES) to supplement (or supplant) the availability of visual information which would otherwise be inaccessible to the human operator under environmental condition of restricted visibility. It is supposed that "this technology offers an unprecedented possibility to enhance visual access to the traffic environment at night" (Owens et al., 1992, p. 366).

Generically, these systems employ an optical device (e.g., infra-red camera) to receive "visual" information on an alternative wavelength for which the informational content of the scene remains largely intact (e.g., 8 - 13μ), though not within the visible spectrum to which the human visual system is most sensitive. This alternative wavelength image may subsequently be processed in real-time to a format perceivable by the motorist and may be projected through a Head-Up-Display (HUD) within the forward field of view. The processed virtual image is presented as an enhanced representation of the forward scene superimposed in a fixed focal plane over the actual scene (i.e., contact analogue format).

The intent of any VES is to improve motorist safety by enhancing the availability of visual information which the motorist *could not* otherwise acquire under conditions of restricted visibility. And yet, a VES should not incur contaminant effects such as imposing an excessive cognitive workload or evoking performance compensation (e.g., higher speeds) from the consumption of any realised safety benefit.

This paper outlines the preliminary results of a field evaluation of a prototype of a near infra-red VES using a contact analogue HUD presentation. The evaluation focused on the behavioural and cognitive effects of the VES on motorist performance over successive trials along a standard driving route which incorporated a pedestrian detection task. Specifically, the evaluation compared speed, cognitive workload and reaction times for the detection of simulated pedestrians while driving a route with the operational VES *and* without the VES. By recording performance over successive trials, the profile of developing familiarity with the VES could be examined. In addition, the potential for development of a behavioural set indicative of system dependency was investigated by examining performance subsequent to a simulated system failure.

METHOD

Vision Enhancement System

For the purposes of this trial a Near Infra-red camera and infra-red illuminators were mounted in a Jaguar saloon vehicle. The images produced were processed and presented to the driver via a head up display as a monchromatic contact analogue green image focussed at approximately 5 meters in front of the driver. The HUD used produced an instantaneous field of view of around 13 degrees.

Standard Driving Route

The standard driving route comprised approximately 1 km of rural roadway which included a bend midway. Both ends of the route had a layby so that the test-vehicle could turn around and travel the route in both directions. As shown in Figure 1, the route was demarcated into 3 zones by roadside markers. This demarcation scheme defined a straight portion (A) and the entrance and exit to the bend section within the route (B & C).

Three pedestrian silhouettes were laid aside the roadside markers at boundaries of the 3 zones. These silhouettes served as targets for the pedestrian detection task. Each pedestrian silhouette was comprised of a plywood cutout of a head and torso (≈ 1 m x 0.60 m) which stood approximatley 1.7 m high on a pole. Each target wore a large coat selected on the basis of visibility in darkness under normal and infra-red viewing to be moderately conspicuous.

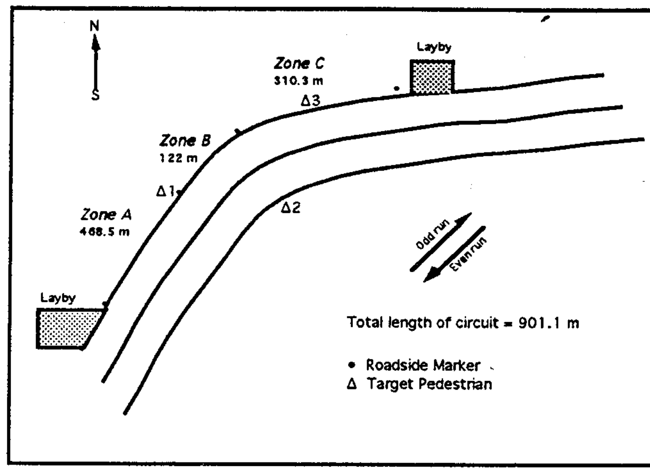

Figure 1. Schematic of standard driving route and zone sections (including target pedestrian locations).

Procedure

Five subjects (3 male, 2 female) participated in the field trail (median age = 26). Each subject was given a 1 hour familiarisation session with the VES within a 2 week period preceding the field trial. Subjects were introduced to the functioning of the VES unit (including on-off and image brightness controls) and drove the operational VES vehicle at night over a selected route comprised of a range of driving environments and road types.

The field trial was comprised of 2 experimental sessions: with the VES operational (VES) and without the VES operational (NON-VES). Each session was conducted at night in good to fair weather and lasted approximately 1 hour. The presentation order of experimental session was balanced across the subjects. Subjects completed 4 practice trials on the route immediately preceding each experimental session with VES or NON-VES. During these practise trials, subjects set their preferred level of image brightness.

Each experimental session involved driving with dipped beams along the standard route 20 times in succession (10 runs in each direction). Prior to 4 of the runs in each session, a pedestrian silhouette was stood up along the roadside. Pedestrian target position relative to the approach of the subject was chosen to achieve certain approach characteristics in terms of the field of view of the subject. Two different pseudo-random orderings for target placement were devised for each session to deter expectancy effects. Table 1 lists the random orders for pedestrian target positioning in each session (see Figure 1) and the ensuing approach characteristics. Early during run 17 of the VES session, the system was shut down in the guise of a spontaneous system failure.

Table 1
Target Pedestrian Position, Approach Characteristics and Presentation Schedules.

Target Position	Direction of Travel	Approach Characteristic	Schedule 1 Run #	Schedule 1 Run #
1	N	- long distance	11	3
1	S	- centre of FoV	4	16
1	N	- darker clothing	19	19
2	N	- periphery of FoV	15	13
3 + 1	S	- double target	8	8

Subjects were instructed to continuously travel the route sequence in their usual driving manner and indicate the detection of any pedestrian target by activating a sensor linked to the washer/wiper switch.

An experimenter operated a time logging event recorded from the back seat. At the start of the run, the experimenter recorded an event at the start roadside marker. At each successive marker demarcating a zone boundary, pedestrian silhouette, and end point of a run, an additional event was recorded. In this manner a time-line was recorded for each run which located the temporal location of each event. Subjects response to the detection of a pedestrian silhouette was linked to the event recorder through the washer/wiper switch.

From the resultant partitioning of the recorded event time-line representing the temporal sequence of events in each run, it was possible to derive travel time through each demarcated section of the route and reaction times to the pedestrian targets (in terms of time preceding arrival at target location). For presentation purposes, travel time was converted to speed based on the time travelled over each zone of a specified distance (zone distance ∏ zone travel).

The NASA TLX-R was administered as a measure of mental workload in the end layby before the first run and after runs 5, 10, 15, and 20 (also after run 17 during VES operation in which the system failure was simulated).

RESULTS

Because of the small number of subjects, to minimise subsequent loss of subjects in this repeated measure design due to missing data, the number of levels in the repeated measure factors considered in the analyses was minimised (e.g., collapsing across levels of least critical factors) with the sympathetic use of paired t-tests and one-way ANOVAs to explicate simple effects.

Speed

To compare the profile of speed between VES and NON-VES operation across the series of runs, speed *over the entire route* (calculated from total travel time) was plotted for run 1, 10 and 20 (ANOVA). As shown in Figure 2, VES operation yielded significantly slower speeds for the first run [$t(4) = 4.21$, $p < .01$] as well as (marginally) for the last run [$t(4) = 2.59$, $p = .06$]. The main effect for ordinal run was significant [$F(2,8) = 6.99$, $p = .01$], although the general trend toward faster speeds in latter runs was statistically significant only for the NON-VES session [$F(2,8) = =4.09$, $p < .06$]. The main effect of experimental session approached significance [$F(1,4) = 4.62$, $p < .10$] with a slower overall speed in the VES session ($M = 55.55$ kph) than in the NON-VES session ($M = 61.36$ kph).

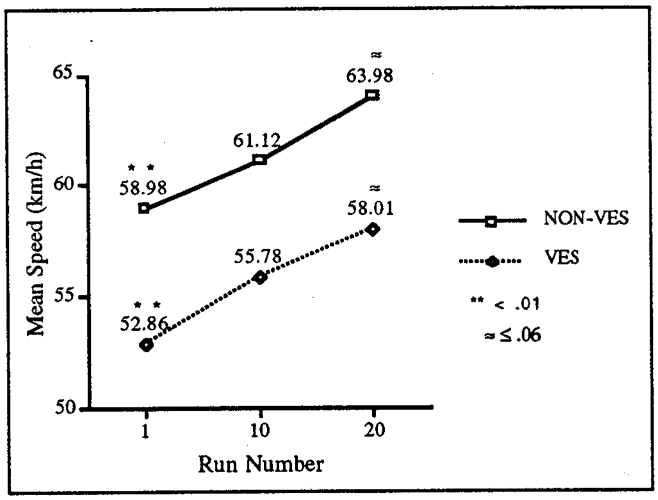

Figure 2. Average speed over entire route (calculated from total travel time) for runs 1, 10 and 20.

As shown in Figure 3, the *variability* in the speed (across runs) within the curved section of the route was significantly greater during VES operation [B: $t(4) = 2.75$, $p < .05$; C: $t(4) = 5.17$ $p < .01$].

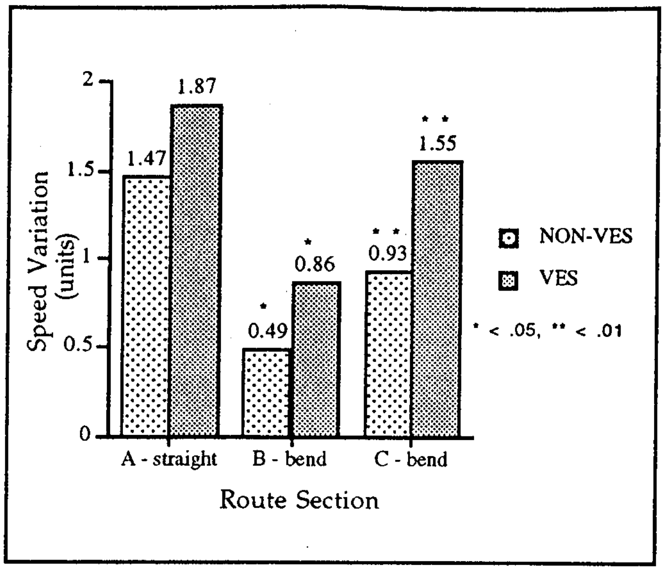

Figure 3. Mean variation in speed (units are standard deviations expressed as seconds in travel time) across all runs (excluding run 17) within zones A, B, and C (refer to Figure 1).

Mental Workload

For each administration of the TLX-R, the six constituent scales (Mental Demand, Mental Effort, Physical Demands, Time Pressure, Distraction, Stress Level) were averaged to yield a composite score. To compare the profile of indexed mental workload between VES and NON-VES operation, composite TLX-R scores were plotted for the initial administration period at the outset of each session and subsequent administrations after runs 10 and 20 (ANOVA). As shown in Figure 4, VES operation incurred a significantly higher mental workload across the run series [initial: $t(3) = 2.99$ $p < .05$; after 10: $t(4) = 2.98$, $p < .05$; after 20: $t(4) = 3.56$, $p < .05$]. The main effect of experimental session was also significant [$F(1,3) = 9.05$, $p < .05$] with a higher overall rating of mental workload expressed for the VES session ($M = 35.2$) than for the NON-VES session ($M = 23.8$). The apparent increase in TLX-R composite scores with latter trials was not significant within either session [$F(2,6) = 0.37$, ns.].

A post-hoc inspection of which individual constituent scales from the TLX-R distinguished between VES and NON-VES operation revealed that "Mental Effort" (described to subjects as "the mental effort required by you to maintain a safe level of driving - Was little concentration required, or did you have to concentrate a lot during the course of the trial?") and "Mental Demand" (described to subjects as "any mental demands placed on you by the driving task (e.g. in planning, thinking, deciding, remembering, looking, searching) - Was the driving task mentally easy or demanding?") were the predominate sources of significantly ($\alpha = .01$) greater mental workload during VES operation.

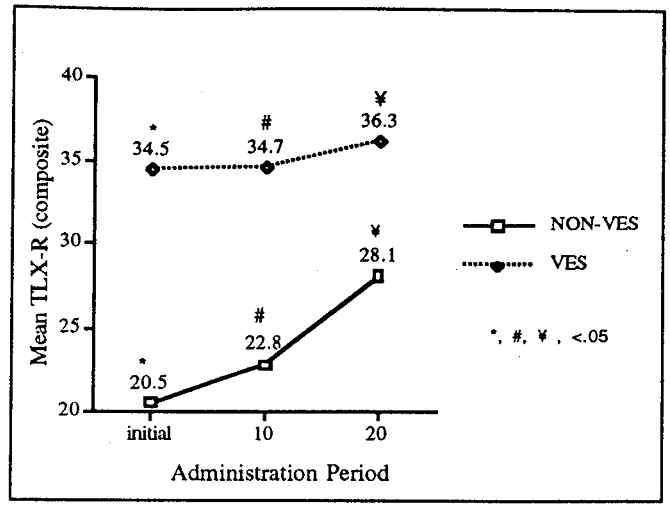

Figure 4. Mean composite TLX-R ratings of mental workload prior to initial run and after runs 10 and 20.

Pedestrian Detection

There was no significant difference in reaction times (nor the number of targets detected) for any of the pedestrian target placements or approach characteristics between VES and NON-VES operation.

System Failure

Speed was compared across runs 16, 17 and 18 (ANOVA) in the VES session to investigate the effect of the simulated system failure conspired in run 17. Similarly, mental workload composite scores were compared across the 4th (after run 10), 5th (immediately after run 17) and 6th administration (after run 20) of the TLX-R. It was apparent that average speed over the entire route (calculated from total travel time) was not significantly affected by the manipulated VES failure [$F(2,8) = 0.49$, ns.], nor was the composite TLX-R rating of mental workload [$F(2,8) = 0.34$, ns.].

DISCUSSION

The apparent behavioural and cognitive performance of subjects suggests that driving at night with the prototype VES operational necessitated greater mental demand and effort than without the VES operational. VES operation resulted in slower speeds (at least initially) and a generalised trend to greater speed variation. The VES did not lead to quicker reaction times to targets, or to an increased number of targets being recognised.

This series of results are somewhat counterintuitive. It might be expected that the increase in visual information available within the HUD would lead to decreased mental workload, and to improved performance in target recognition. Indeed concerns have been expressed (e.g. Rumar 1993) that the provision of additional information may manifest itself in increased and inappropriate speed.

These are preliminary results, and by the nature of the data, are not diagnostic. They do however show that some of the initial concerns that even protoype VES may lead to behavioural adaptation in the form of increased speed (with the concommitant safetey decrement) to be unfounded. Indeed, even after the one hour training period with the VES it seems that subjects excercised extra caution when completing the course. Further studies will be required to determine whether this behaviour changes with exteded exposure to the system or whether there are particular performance characteristics of the visual display that change the nature of the task fundamentally leading to increased workload.

Increased workload may be acceptable if there is a demonstrable net increase in utility to the user of the VES i.e. the driver feels that performance on the driving task is helped by the presence of the system. In this experiment, the simple criteria of reaction time to roadside dummies did not reveal a sigificant advantage. Further research should investigate target aquisition in more detail and should also address other criteria such as the lane maintenance, speed and distance judgement.

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The Field of Vision of Drivers During Nighttime

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Abstract

In normal situation the field of vision of drivers is defined for the situation "straight road". By means of video recording of street situations and computer generated street geometries the frequency distribution of location of traffic signs, pavement markings, objects, lighting equipments etc. in the field of observation of a driver is derived.

These recordings were made for a typical range of streets in Germany at a overall length of 5500 km. The data have been determined based on a computer evaluation system.
From these results new requirements can be derived for example on behalf of:

- light distribution of car headlights
- retroreflection of traffic signs, pavement markings
- glare values for headlamps
- light distribution for rearward lighting
- optical guidance of drivers.

Introduction

In the last years new technologies increased the luminous flux and the luminous efficiency of car headlamps. Also new reflective materials for traffic signs and optical guidance are avialable. Most of the requirements for materials and headlamps are based on the situation "straight road". But for the description of the real situation an evaluation of street geometry is necessary. Caused by crests, sags and curved road the position of the objects is very different to the strait, leveled road.

For that reason more than 5500 km of german streets have been recorded on video tape during daytime. These tapes have been evaluated on a special computer video geometry evaluation system.

Street Geometry Recording

For the recording of the streets on video tapes first a statistical evaluation of street types, traffic densities typical topographic data for german streets was necessary. Based on these data a road course was chosen that gives a representative cut for all street situations.
For the video tape recording a video camera was mounted in the test car behind the windscreen. The video pictures were recorded on a professional video tape recorder. Data from a distance measurement system and a character generator first have been faded into the picture. This allows an exact determination of the position of every single object along the course. Before the start of the recording an exact geometrical measurement of the total system was made. This was necessary for the geometrical calculation of the position of the objects. Figure 1 shows the scheme of the test car evaluation system:

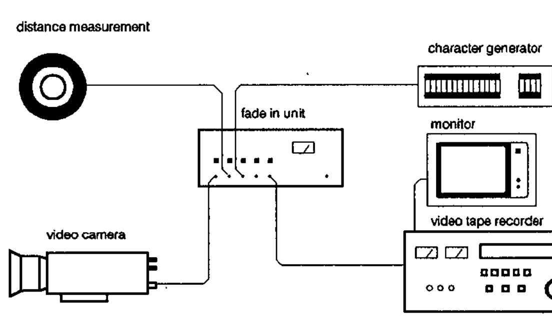

figure 1: scheme of the recording system in the test car

The videocamera was special adapted and had an observation field of 32° horizontal and 20° vertical. It was fixed mounted behind the windscreen, no rotation was possible along the course.

Street geometry evaluation

For the evaluation of the geometry data a special test set up has been contstructed. The video picture of the recorded video tape was given to a frame grabber, that allows still video pictures. This picture is given to the computer and a special overlay technique allows to fade in a calculated street geometry into the picture. The evaluation person can now adapt the generated geometry to the real street course in the certain picture.

Figure 2 shows the scheme of the evaluation system.

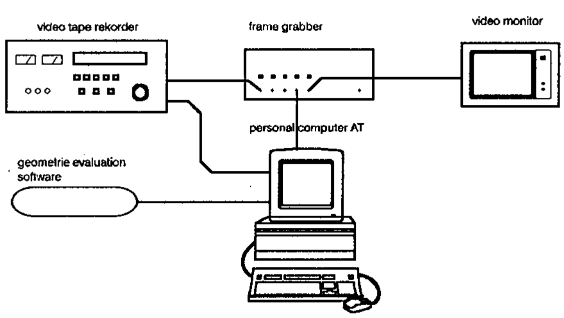

figure 2: scheme of the geometry evaluation system

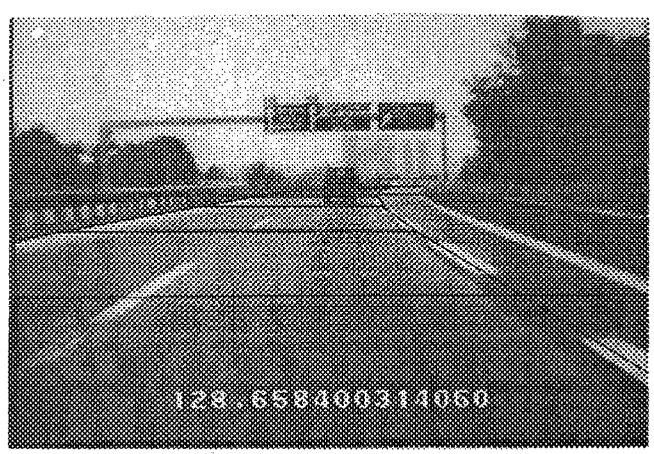

figure 3: video picture of an evaluation

Figure 3 shows the video picture of the geometry evaluation. The black lines are the adapted road course lines.

From these lines the road course in case of curves, crests or sags is known for every evaluated picture. The numbers in the lower part of the picture are the total distance, the tape number and the recording date.

The next step of the evaluation was the determination and classification of objects in the street surrounding.

The object classes are:

- signpost
- traffic sign
- overhead traffic sign
- delineator
- delineation line
- guidance beacon
- other car
  - headlamp
  - drivers eye
  - rearward lights
  - mirrors
- motor bike
- bicycle
- pedestrians
- other objects

The objects in the video picture have been marked by a cursor, the distance is determined too. The evaluation person classifies the object to the computer. From these data the computer calculates the positions and the angles to the observer. For every object the position, the evaluation distance, the road geometry, the street number/type and the object classification is stored. The computer consideres also parameters like position of the evaluation car on the street, inclination angles of the car caused by braking or acceleration, actual number of driving lane e.g..
Based on these data a lateron calculation of the object position for certain distances is possible. Figure 4 shows the evaluation of the objects for the car in front of the test car and the over-head

signs. The white lines are the distance lines, adjustet by the evaluation person.

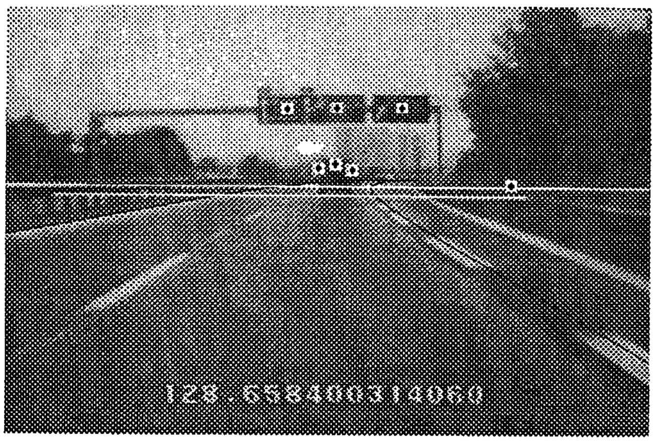

figure 4: evaluation of the car in front and the overhead traffic signs

A data bank system for all german streets has been realized.

Results of the evaluation

The final data of this investigation show the distribution of all objects in night time street situations, necessary to be seen by the driver of a car. The results are so complex, only a short introduction on examples could be given here.

Rural Street

The first part of data deals with the position of objects on rural street.

Traffic signs

The figure 5 shows the position of overhead traffic signs on the german " Autobahn ".
Every point gives the position of the middle of one traffic sign in a distance of 100 m in front of the car. The distribution is the result of both the mounting point and the curvature of the street. It shows that the horizontal distribution is much wider than the vertical, resulting from the smaller curve radiuses compared to crests and sags.

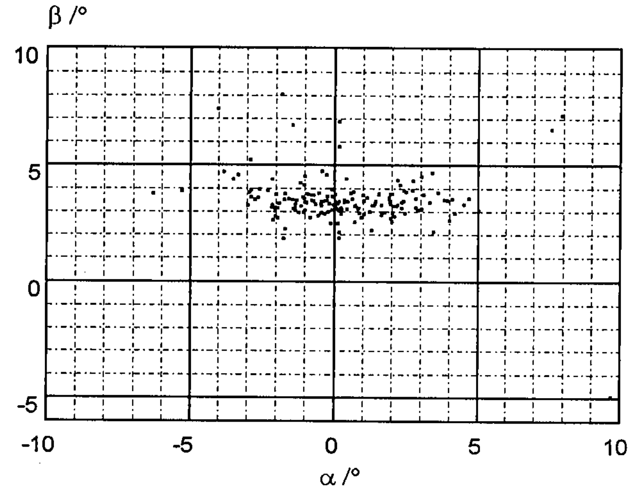

figure 5: distribution of overhead traffic signs on Autobahn, distance 100m related to drivers eye

All the angles shown in the pictures are related to the eye position of a driver in the height of 1,20m and the middle of the current lane.
Figure 6 shows the position of shoulder mounted traffic signs on larger rural streets called " Bundesstraße " . These are mostly streets with a width of more than 6m and a high traffic density. The distance to the traffic signs in the following figure is 50m.

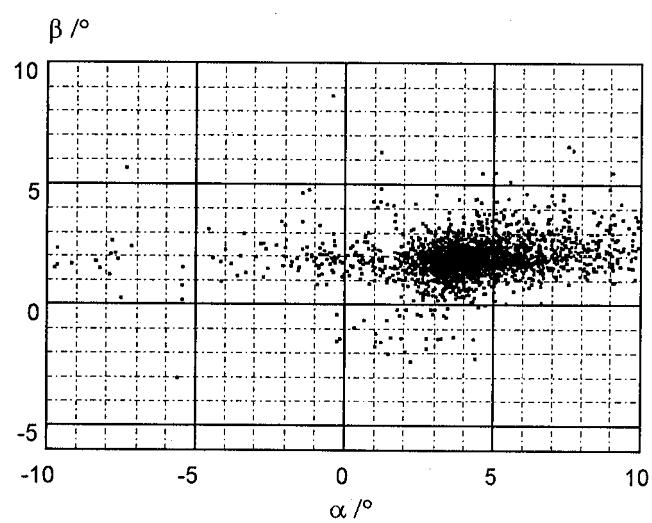

figure 6: Distribution of right shoulder mounted traffic signs on larger rural streets, distance 50m related to drivers eye

The figure shows that the horizontal angles, in which the traffic signs are located in a distance of 50m are between more than 10° on the right side and up to 5°on the left. The vertical angles for this distance are mainly from 0° up to 4° up.

Influence of the distance

The following figure 7 shows the same distribution for a distance of 75m. Therefore all positions are calculated to this distance seperately for every single traffic sign. This calculation is depending on the curves and crests/sags of the street geometry in which each sign was evaluated.

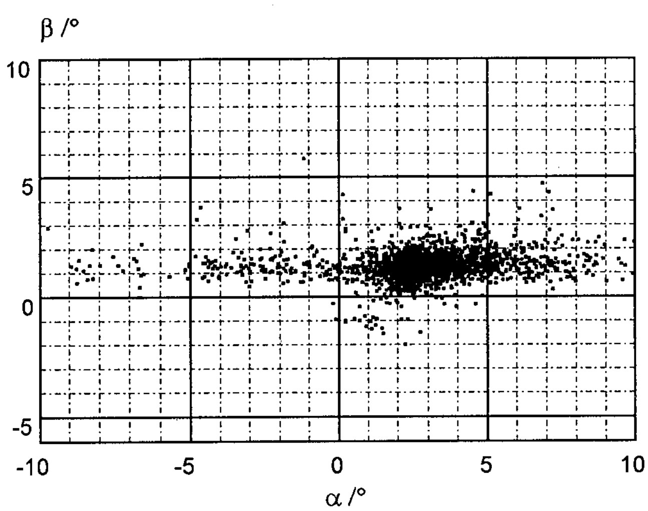

figure 7: Distribution of right shoulder mounted traffic signs on larger rural street, distance 75m related to drivers eye

In the distance of 75m the distribution shows another shape. Traffic signs determined in curves with smaller radiuses move along this course. These are the points with horizontal angles of more than 0° on the left and 6° on the right. All other traffic signs move closer to the 0° point.
This behaviour is confirmed when the same calculation is done for a distance of 100m in front of the car. Figure 8 shows the results.

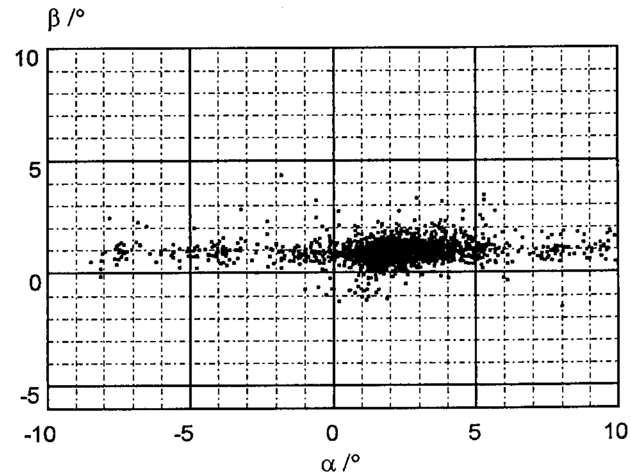

figure 8: Distribution of right shoulder mounted traffic signs on larger rural street, distance 100m related to drivers eye

Optical guidance

The collected data on street geometry considering the curves and the crests /sags allow also the calculation of the position of road markings. In figure 9 this has been done for the larger rural street, " Bundesstraße ". The main distribution was found in the horizontal angles from 7° on the right to 7° on the left. The larger amount of points above 7° on the left come from the roads with more than two lanes.

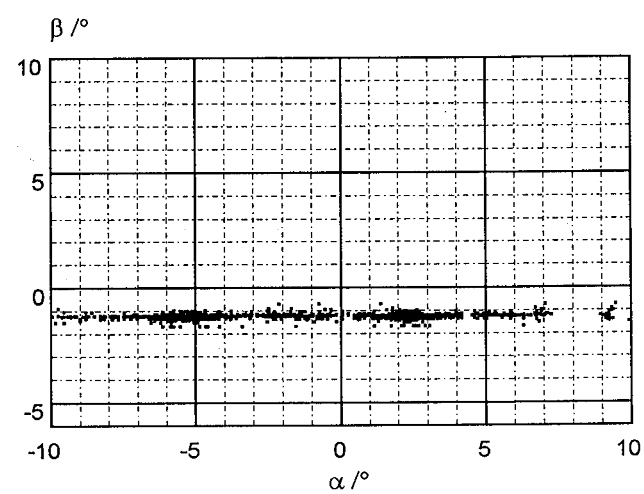

figure 9: Distribution of road markings on larger rural street, distance 50m related to drivers eye

Urban street

In urban street situations the distribution of the location of objects is not as concentrated as in rural streets. The fixation points of traffic signs are not always single poles but also walls and light signal poles e.g.. The road curvature has much smaller radiuses, and also smaller crests and sags could be found here.

The following figure 10 shows the distribution of right "shoulder" mounted traffic signs under urban conditions. The positions are measured in a distance of 50m. It shows horizontal angles of the main distribution from 2° on the left to more than 10 ° on the right. The large angles on the right side come from driving on the second or sometimes on the third lane of the road. But also the vertical angles are much wider with values from 0° up to more than 4°. These are the signs with a higher mounting height but not the overhead mounted signs, they have been evaluated seperately.

For the calculation of the absolute height the road course is one factor but also the drivers eye height of 1.2m has to be considered.

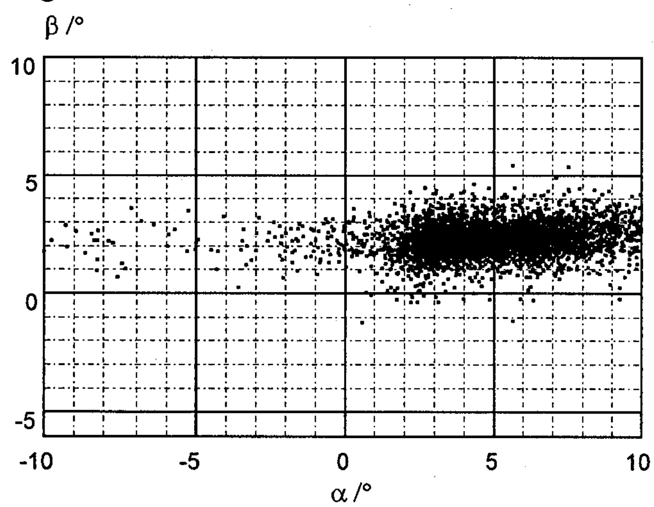

figure 10: Distribution of right "shoulder" mounted traffic signs on urban street, distance 50m related to drivers eye

Based on these results exact entrance and observation angles of retroreflective traffic signs and road markings can be calculated. The requirements on the materials but also on the illumination can be improved.

Driver Workload Assessment of In-cab High Technology Devices

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Paper No. 94-S2-O-06

ABSTRACT

In the advent of the Intelligent Vehicle Highway System (IVHS) program, a variety of high technology in-cab devices have been proposed for use in heavy trucks and cars. These include land navigation and route guidance systems, text messaging systems, cellular phones and other communications systems, vehicle subsystem status and monitoring systems, Advanced Traveler's Information Systems (ATIS), and collision avoidance systems (CAS). Among other issues, concern has been expressed that many of these devices introduce subsidiary tasks and make information available which may compete with the driver's primary task of safely controlling the vehicle at all times. The challenge of design, evaluation, and implementation of high technology from a driver-centered perspective is to determine the efficiency, effectiveness, and safety of such devices.

Battelle, with its subcontractor R&R Research, Inc. and a team of consultants, is under contract to the National Highway Traffic Safety Administration (NHTSA) to develop a workload assessment protocol suitable to assess the safety implications of high technology systems that might be introduced into heavy trucks. There is every expectation that the workload assessment protocol will also be applicable to cars. This effort includes task analysis, literature review, definition of a baseline heavy vehicle configuration, workload assessment protocol development, data collection, and evaluation of two devices with the developed workload assessment methodology. This work will contribute to identification of biomechanical, perceptual, cognitive, and response demands imposed by high technology devices.

As part of this effort, Battelle has considered the problem of workload assessment methods and measures. A variety of measures and methods have previously been developed to evaluate in-cab devices in terms of driver workload. These range from analytical tools to on-the-road testing with an instrumented vehicle. Device attributes, subjective assessments from drivers, driver behaviors, and driver-vehicle performance all provide useful information on the potential of a device to compete with the driving task for the driver's attention and resources. This paper will present an overview of those measures and methods which have proven useful in assessment of selected in-cab devices. The implications of these techniques and protocols for safety evaluation of IVHS in-cab driver interfaces will be addressed.

INTRODUCTION

The Intelligent Vehicle Highway System (IVHS) program attempts to enhance surface transportation safety, efficiency, and comfort by applying advanced technologies, including information processing, communications, control and electronics. A variety of high technology in-cab devices have been proposed for use in heavy trucks and cars. These include land navigation and route guidance systems, text messaging systems, cellular phones and radio systems, vehicle subsystem status and monitoring systems, Advanced Traveler's Information Systems (ATIS), and Collision Avoidance Systems. A primary goal of IVHS is to reduce the number and severity of crashes. Thus, concern has been expressed that many of these devices may introduce subsidiary tasks and make information available that may compete with the driver's primary task of safely controlling the vehicle at all times (Dewar, 1988; IVHS America, 1992). The challenge of design, evaluation, and implementation of high technology from a driver-centered perspective is to determine the efficiency, effectiveness, and safety of such devices.

Battelle, with its subcontractor R&R Research, Inc. and a team of consultants, is under contract to the National Highway Traffic Safety Administration (NHTSA) to develop a workload assessment protocol suitable to assess the safety implications of high technology systems that might be introduced into heavy trucks; this protocol will eventually be applicable to cars as well. This effort includes task analysis, literature review, definition of a baseline heavy vehicle configuration, workload assessment protocol development, data collection, and evaluation of two devices with the developed workload assessment methodology. This work will contribute a means to identify and measure biomechanical, perceptual, cognitive, and response demands imposed by high technology devices.

As part of this effort, Battelle has considered the problem of workload assessment methods and measures. A variety of measures and methods have previously been developed to evaluate in-cab devices in terms of driver workload. These range from analytical tools to on-the-road testing with an instrumented vehicle. Device attributes, subjective assessments from drivers, driver behaviors, and driver-vehicle performance all provide useful information on the potential of a device to compete with the driving task for the driver's attention and resources. This paper will present an overview of those measures and methods which have proven useful in assessment of selected in-cab devices. The implications of these techniques and protocols for safety evaluation of IVHS in-cab driver interfaces will be addressed.

BACKGROUND

On the definitions of Driver Workload and High-Technology In-cab Devices

Nagel (1961) wrote that it would be "... an ungrateful and pointless task to canvass even partially the variety of senses that have been attached to the word 'cause'" (p. 73). The same can be said of the word 'workload'. The emphasis of the NHTSA project is device-induced interference with the driving (vehicle control) task. Beyond this, the term 'workload' might best be treated as a primitive and left undefined.

The term "device" is intentionally broad and is primarily intended to encompass driver information systems. Thus, route guidance systems, trip recorders, text message displays, cellular phones, CB radios, vehicle subsystem status displays, and Advanced Traveler's Information Systems (ATIS) are all included. Note that there are also IVHS crash avoidance system (CAS) concepts (e.g., sensors, processors, and display systems) whose primary intent is to promote safety by means of hazard detection and warning (and possibly control intervention). While some of the workload assessment procedures may apply to CAS evaluations also, these devices have a somewhat different range of design issues and driver effects that are not the focus of a driver workload assessment program (cf. Ervin, 1994).

Assumptions about Drivers, Driving, and Safety

Vehicle control can be considered an intermittent closed-loop control task in which some degree of error in lateral or longitudinal control is permissible. This allows the driver to break away from the road scene to attend to other tasks (such as in-cab device interactions). Driving places heavy demands on visual attention. During in-cab interactions (among other visual diversions), the driver takes eyes off the road to look at the in-cab control and display. The driver samples the road scene when confidence in situational awareness fades due to memory effects (forgetting) or to anticipated changes in driving conditions. Thus, visual allocation measures are a potentially rich source of workload information. Driver inputs to control the vehicle are made through vehicle interfaces (steering wheel, pedals), so measurement of these driver behaviors are considered important. Many in-cab devices demand manual actuation that can interfere with manual control, so manual activity is also considered an important driver behavior. Regardless of whether or not an in-cab device demands visual resources, the extent to which it takes the driver's mind off the driving situation is of concern.

The normal driver is assumed to be rational within the constraints of that driver's motivations and situational understanding. This situational understanding rests upon a schema of the driving conditions (traffic, roadway, vehicle, environment) that generates expectancies the driver uses for situation assessment and prediction of future states (Wierwille, Tijerina, Kiger, Rockwell, Lauber, & Bittner, 1992). Based on the driver's situational understanding and motivations, the driver has a variety of workload management strategies that generally work quite well (see **Table 1**). Thus, drivers will tend to use in-cab devices safely or not at all (Rockwell, 1988). Safety is compromised when the driver believes it is appropriate to

Table 1.
Driver Strategies for Coping with High Workload and the Use of In-cab Devices.

When confronted with high workload, drivers are likely to do one or more of the following: · delay the start of an in-cab interaction · finish an in-cab interaction before entering a "high" workload driving condition · stop an in-cab interaction · increase attention to one of the concurrent tasks · increase the headway to the vehicle ahead · slow down the vehicle to decrease driving demand · turn off onto a side road, access road, or other less congested roadway · pull off the road to avoid driving workload altogether · delegate some tasks, perhaps to a team driver or automation (e.g., cruise control) · accept poorer performance on one or perhaps both tasks (e.g., miss some information coming in on voice communications, increase lane deviation if considered safe to do so) · narrow the field of attention (e.g., ignore driving condition factors in the periphery) · rely more on expectations and assumptions than feedback processing · monitor the road scene less often because of attention to the in-cab device (or vice versa) · pursue possible explanations (e.g., while making decisions about unexpected events) less thoroughly

work with in-cab devices when, in fact, safety hazards exist on the roadway or suddenly develop. This might be considered a failure to correct the schema with new information because of in-cab device distraction, among other reasons.

Based on a review of the driver performance and workload literature (Wierwille, et al, 1992), the following additional assumptions are made:

· Drivers may be able to do several things at once but they can focus consciously on only one task at a time. Generally this focus is visual in driving. Thus, visual allocation is a primary safety-relevant driver behavior.

· Device design or operating practices that constrain the driver's freedom to decide when and if to use that device are troublesome (particularly relevant for Commercial Vehicle Operations).

· Once a driver begins a task, there is a tendency to want to go back and finish it (Zeigarnik, 1965). This impulse to complete interrupted tasks grows with the relevance of the task to current goals of the driver. Furthermore, unfinished tasks take up space in the driver's working memory, memory that must be shared with the last recollection of the driving situation. Thus, in-cab devices that are complex and that motivate the driver to persevere may be especially problematic.

· If device interaction is perceived as a risk with loss consequences (e.g., the driver will lose data or effort expended) in the face of certain loss (e.g., pull off the road and stop to complete the in-cab task safely), the driver may tend toward a riskier option which keeps the vehicle on the road and moving to the next destination.

· Switching one's attentional focus from task to task can take time and effort. In particular, what a person is thinking about determines the contents of working memory and the contents of working memory determine what the person is prepared to think about and react to.

· Delays in meeting a schedule represent a pervasive stressor that can increase driving and in-cab device demand, especially for commercial drivers.

Figure 1 presents a causal chain that guides the choice of driver workload measures. Driver attitudes, motivations, and acceptance of the technology affect driver behaviors. Driver behavior patterns affect driver-vehicle performance, along with other forcing functions caused by the roadway, pedestrians, environment, and other vehicles. Unintentional changes in driver-vehicle performance, in turn, are assumed to lead to increased exposure to a crash hazard. Given that the roadway is a somewhat forgiving environment, increased exposure to hazards only sometimes leads to increased crash involvement. Note that this causal chain is subject to variation due to driver individual differences, different driving conditions, and in-cab device differences. A major IVHS safety evaluation challenge is to ascertain the extent to which driver workload changes with a given IVHS device against the background variation caused by these other factors.

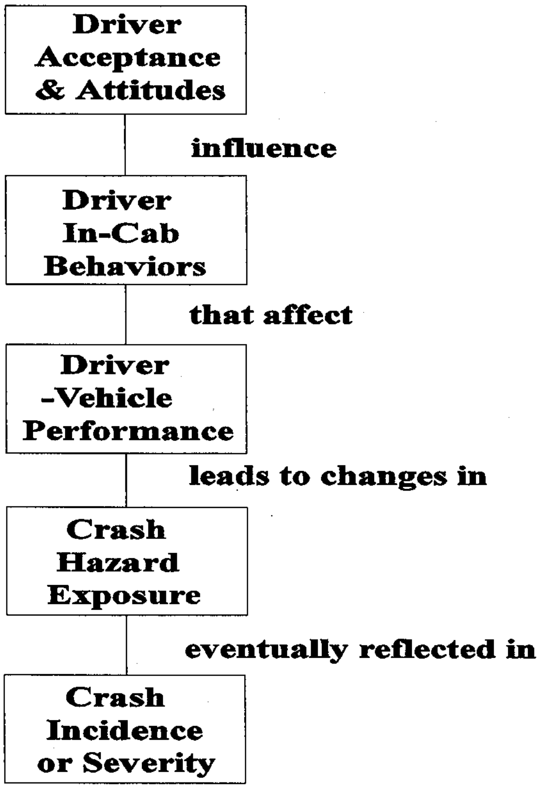

Figure 1. Causal Chain Assumed for Driver Workload Assessment

MEASURES IN WORKLOAD ASSESSMENT

Driver Behavior Measures

Driver behavior is a focus of workload assessment. Because of the primacy of vision in driving, the project is making use of visual allocation measures (glance location, duration, and frequency) to assess where the driver is gazing at any given time. **Table 2** presents visual glance duration and frequency data from our pilot study using 7 subjects. The data indicate that the measures do vary with device type, an important property of a workload measure. However, a safety-relevant assessment requires more than simply that a measure be sensitive; there must be a connection to highway safety. As part of this project, Wierwille and Tijerina (in press) reported on an attempt to relate in-car visual demands to crash occurrence. **Figure 2** presents the number of crash occurrences from the North Carolina accident data base. These data indicate that visual allocation within the vehicle is associated with numerous crashes. Furthermore, these crashes are associated with a wide variety of interior sources of distraction. The introduction of any new item into the cab of a car or truck that requires vision while the vehicle is in motion can be expected to cause some increase in crash incidence. Current project work is oriented toward development of a prediction model that relates visual allocation estimates associated with various interior sources to crash incidence.

Other driver behavioral measures include measures of control manipulation such as steering wheel movements, pedal activations, and manual activity measures (e.g., hand-off-wheel time, hand-on-device time). Wierwille et al (1992) review a number of studies that indicate the sensitivity of steering wheel measures to workload variations. Kurokawa and Wierwille (1991) also found that total hand-off-wheel time was lengthened when a simulated instrument panel configuration contained microclutter (i.e., more buttons in the same amount of space). Most recently, Knipling and Wierwille (1994) have reported steering wheel measures are useful for detecting drowsy drivers. If drowsiness represents a high degree of inattention to the driving situation, the same steering wheel measures may be useful as workload measures. Finally, brake pedal activation is a traditional safety-relevant measure used for measuring object and event detection latency; a driving simulator may be especially appropriate for this type of assessment and is incorporated as part of Battelle's approach.

Secondary measures have been favored in traditional workload research. In the present case, IVHS device use is, itself, a secondary task to driving. Unlike classical workload research, the goal is not to assess primary task (driving) workload by means of secondary task (device use) performance, but rather assess the interference caused by the secondary task. Furthermore, introducing a workload protocol secondary task to assess device demand reflects a third level of concurrent tasking on the driver. The interpretive difficulties are easy to imagine and difficult to resolve. Thus, the emphasis of the driver workload assessment should be to measure the extent to which in-cab device use adversely affects driver behaviors or driver-vehicle performance under realistic driving conditions and driving tasks.

Driver-Vehicle Performance Measures

The safety-relevant emphasis demands, concurrent with in-cab device use, measures of driver-vehicle performance in terms of lateral control, longitudinal control and object and event detection. This provides measures of the extent to which an IVHS device intrudes on the driving task. An unintentional disruption of vehicle control while interacting with an in-cab device is taken as prima facie safety-relevant. Such measures include lane excursions, changes in travel

Table 2.
TRUCK DRIVER WORKLOAD TASK 5 PILOT STUDY
SUMMARY OF COMMANDED TASKS-ALL SUBJECTS (P1-P6,P9)

Command	No. of Trials	Total No. of Glances	Average Glance Duration (Secs.)	Variance of Glance Duration (Secs. Sq.)	10th %tile Glance Duration (Secs.)	90th %tile Glance Duration (Secs.)	Mean No. of Glances	Min. No. of Glances	Max. No. of Glances	Average Time Off Road* (Secs)
Left Mirror-Detect (3)	17	24	1.38	0.39	0.67	2.23	1.41	1	3	1.95
Right Mirror-Detect (8)	17	26	1.22	0.27	0.57	1.73	1.59	1	4	1.94
Left Mirror-Discrimination (15)	12	16	1.52	0.41	0.70	2.17	1.50	1	3	2.28
Right Mirror-Discrimination (19)	14	26	1.45	0.38	0.73	2.43	1.86	1	3	2.69
Read Exact Speed (1)	21	27	1.60	0.28	1.00	2.40	1.29	1	2	2.06
Read Speed & Compare to Posted Limit (11)	16	20	1.42	0.26	0.77	2.08	1.25	1	2	1.77
Read Air Pressure (2)	19	38	2.11	1.32	0.67	3.85	2.00	1	9	4.21
Read Engine RPM (5)	18	28	1.66	0.50	0.73	2.55	1.61	1	3	2.67
Read Fuel Gage (16)	18	32	1.88	0.50	0.75	2.77	1.78	1	4	3.34
Read Clock (9)	17	32	1.20	0.28	0.48	1.77	1.88	1	7	2.25
Read Elapsed Time (20)	12	32	1.65	0.27	0.98	2.33	2.67	1	6	4.40
Radio Volume Up/Down (4)	34	55	1.10	0.18	0.40	1.47	1.62	1	3	1.78
Select Preset Station (17)	16	51	1.46	0.50	0.63	2.50	3.19	1	7	4.65
Tune Radio to 90.5 (18)	16	125	1.77	0.41	0.97	2.67	7.81	3	18	13.81
Change CB Frequency (6)	33	122	1.34	0.22	0.73	2.00	3.76	2	7	5.04
Turn CB Volume Up/Down (7)	24	31	1.06	0.14	0.50	1.53	1.29	1	3	1.37
AC Temp Up/Down (21)	5	12	1.65	0.51	0.80	2.57	2.40	1	4	3.97
Fan Speed Higher/Lower (22)	7	12	1.35	0.23	0.62	1.90	1.71	1	3	2.31

*Product of Average Glance Duration and Mean Number of Glances

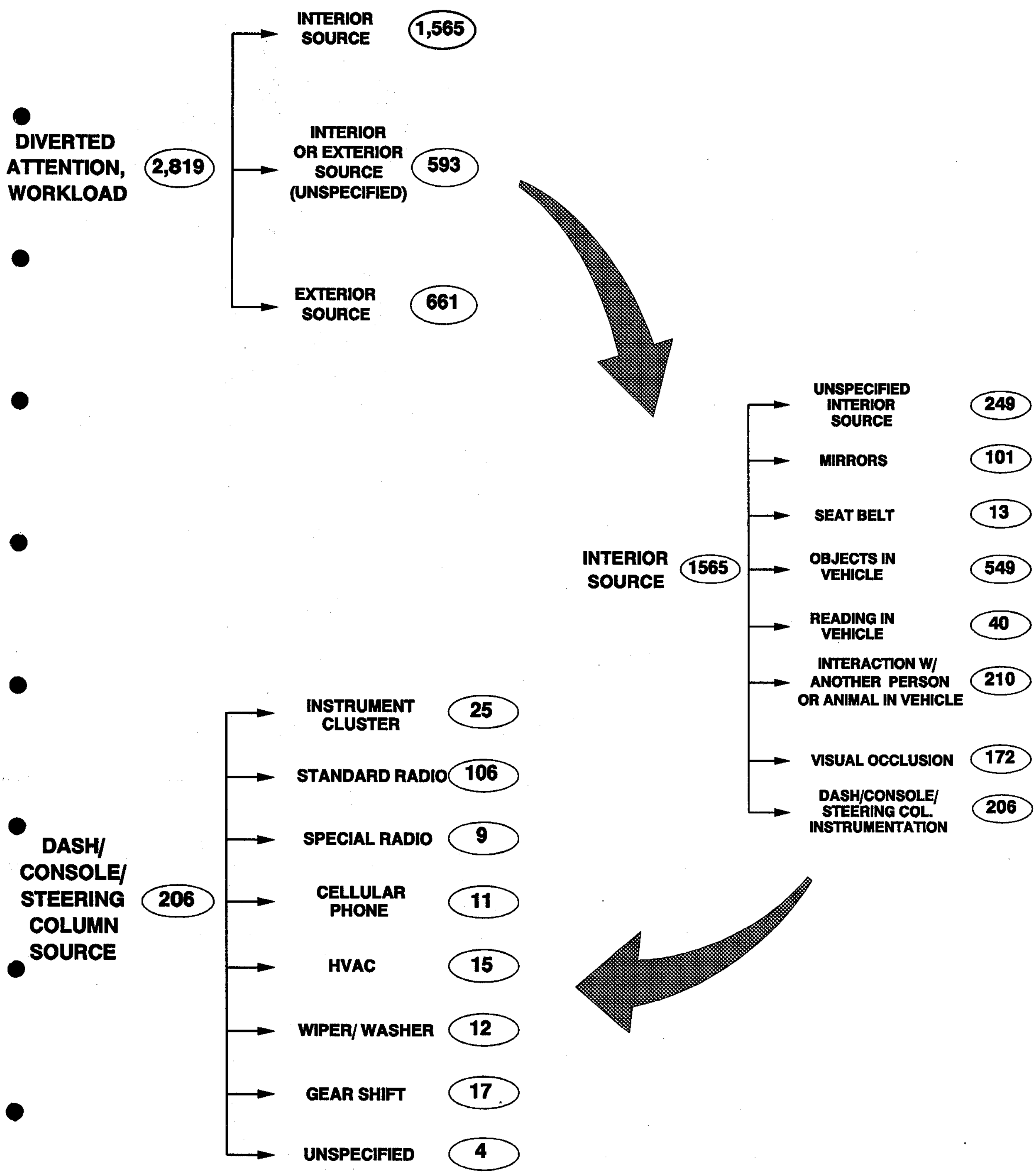

Figure 2. Number of crashes distributed by sources of attentional distraction, broken down into interior source and dash/console/steering column instrumentation group (Source: Wierwille and Tijerina, in press)

velocity (mean and variance), abrupt lateral maneuvers or high longitudinal decelerations indicative of surprise braking or evasive steering, shortened following distances or time headway while using the in-cab device, and so forth. Depending on the device, way finding performance might also be included in driver-vehicle performance. For assessment of a route navigation system, for instance, measures of time-to-arrival, number of wrong turns, missed exits, and so forth could provide quality of driving measures that reflect upon safety.

Subjective Assessment and Driver Acceptance Measures

Subjective assessments are planned for the workload assessment program because such techniques (e.g, TLX, SWAT, Modified Cooper-Harper Rating Scale) may provide useful information. How useful these measures will be is unknown since, among other problems, it is unclear what is more important with an in-cab device, average subjective workload or peak subjective workload (Green, 1993b). It is expected that driver comments solicited through subject debriefings are expected to be a valuable source of information on driver acceptance, preferences, and impressions of device functionality (Underwood and Gehring, 1994).

Table 3 summarizes the range of workload measures being investigated for the driver workload assessment project. The emphasis of this workload assessment project is on driver-vehicle performance measures (primary task performance measures), safety-critical driver behaviors (visual allocation. manual activity, pedal activation), and driver acceptance (subjective workload ratings and driver comments, after device use, of device features and functionality). This approach is consistent with that proposed by other researchers in the field (Noy and Zaidel, 1990; Green, 1993a).

METHODS IN WORKLOAD ASSESSMENT

Study Design

Assessing the workload demands of a device is complicated by the fact that workload may vary as a function of the driver, the driving maneuver and the driving conditions at play during the test, in addition to the device. Age and sex are typically considered important driver factors. In terms of driving conditions, a conjoint analysis of paired comparisons for various driving conditions on the associated workload judged by professional truck drivers indicated the following in terms of rank-order of importance: Traction > Visibility > Traffic Density > Highway Type > Lighting (Kiger, Rockwell, Niswonger, Tijerina, Myers, and Nygren, 1992). Other factors that can affect the workload measurements are driving maneuvers and, presumably, driver aids (e.g., route guidance system, paper map). Some of these factors can be manipulated by subject selection and assignment, by scheduling the data collection run, and by route selection. Other factors cannot be controlled, such as weather and moment-to-moment driving maneuvers.

Williges, Williges, and Han (1992) have discussed a number of efficient experimental designs that allow for evaluation of a large number of factors with a relatively small number of data runs or subjects. These designs are known as 2^{k-p} fractional factorial designs or central composite designs. As implied by the name, a fractional factorial design consists of a fraction of the complete factorial experiment. Depending on the details of the design, it is sometimes possible to accurately assess individual factors and two-factor interactions under the assumption that higher-order interactions among factors will be nonexistent or negligible. Box, Hunter, and Hunter (1978) discuss this point at length and argue that it is plausible in a wide variety of situations. A central composite design provides an experimental plan that allows for efficient estimation of a second-order polynomial model including main effects, pure quadratics, and two-way interactions. These designs have a place in driver workload assessment and may, indeed, be essential to a thorough assessment.

Regardless of the study design, there is a basic process that is advocated for the driver workload assessment. **Figure 3** indicates the process in a flow diagram. Any device assessment should begin with a task analysis and human factors evaluation of the device. This will provide a wealth of information about device function and form, intended uses, failure modes and effects, and other idiosyncracies that might be exercised during the workload assessment. Armed with this knowledge, measures, appropriate driving conditions, and relevant driving tasks (maneuvers) are determined for preparing the detailed study design. The collection process can then be conducted using an efficient study design as discussed by Williges, Williges, and Han (1992). By appropriate collection of baseline data, it is possible, at least in principle, to assess the device effects distinct from the nature of that activity (e.g., navigation), relative to normal driving without in-cab task interference. Additional points regarding data analysis and interpretation are provided below.

Data Analysis

The key data analysis goal is to determine if in-cab device use degrades safety in statistically reliable ways. Analysis of Variance and Regression (univariate and multivariate) techniques, along with Chi-square and t-tests, provide a standard means of statistical analysis. Given that workload is a function of the driver, device, and driving conditions, other techniques may be appropriate as well. For example, discriminant analysis will be investigated to ascertain if a model can be built that will detect when the

Table 3.
Driver-Vehicle Performance Variables and Potential Measurement Methods

Parameter	Variable	Example Measures	Potential Instrumentation and Measurement Methods
Longitudinal Control	Vehicle following	Time headway, following distance mean and standard deviation, closing velocity mean and standard deviation	Range and range rate detector, video cameras & videotape, observations
	Longitudinal velocity and acceleration	Mean and standard deviation of speed, brake applications, peak longitudinal deceleration	Speedometer readings, longitudinal accelerometers, brake pedal sensors, video cameras & videotape, observations
	Heading	Yaw standard deviation, yaw rate standard deviation	Yaw/yaw rate accelerometers, accelerator and brake pedal sensors, video cameras & videotape, observations
Lateral Control	Lane keeping	Mean and standard deviation of lane position, lane exceedence frequency, durations	Lane tracker hardware and software for data reduction
	Lateral acceleration &. deceleration pattern	Peak lateral acceleration, lateral acceleration standard deviation	Lateral accelerometers, Steering wheel sensors, video cameras & videotape, observation
Driver Resources	Visual allocation	Glance duration, Glance frequency, Glance distribution	Video cameras & videotape, oculometer
	Driver inputs to vehicle controls	Steering Wheel position and rate, Brake pedal application and pressure, accelerator pedal reversals	Steering wheel potentiometer and rate sensor, brake pedal switch, pedal pressure transducer, accelerator pedal switch, angle sensor
	Manual allocation	Hand-off-wheel time, hand-on-device time	Video cameras & videotape, observations.
External Conditions	Road scene	Traffic and Road Conditions: Roadway type, traffic density, events	Video camera & videotape, observations, traffic information center data
		Road conditions: day vs. night, weather conditions	Video camera & videotape, observations, traffic information center data

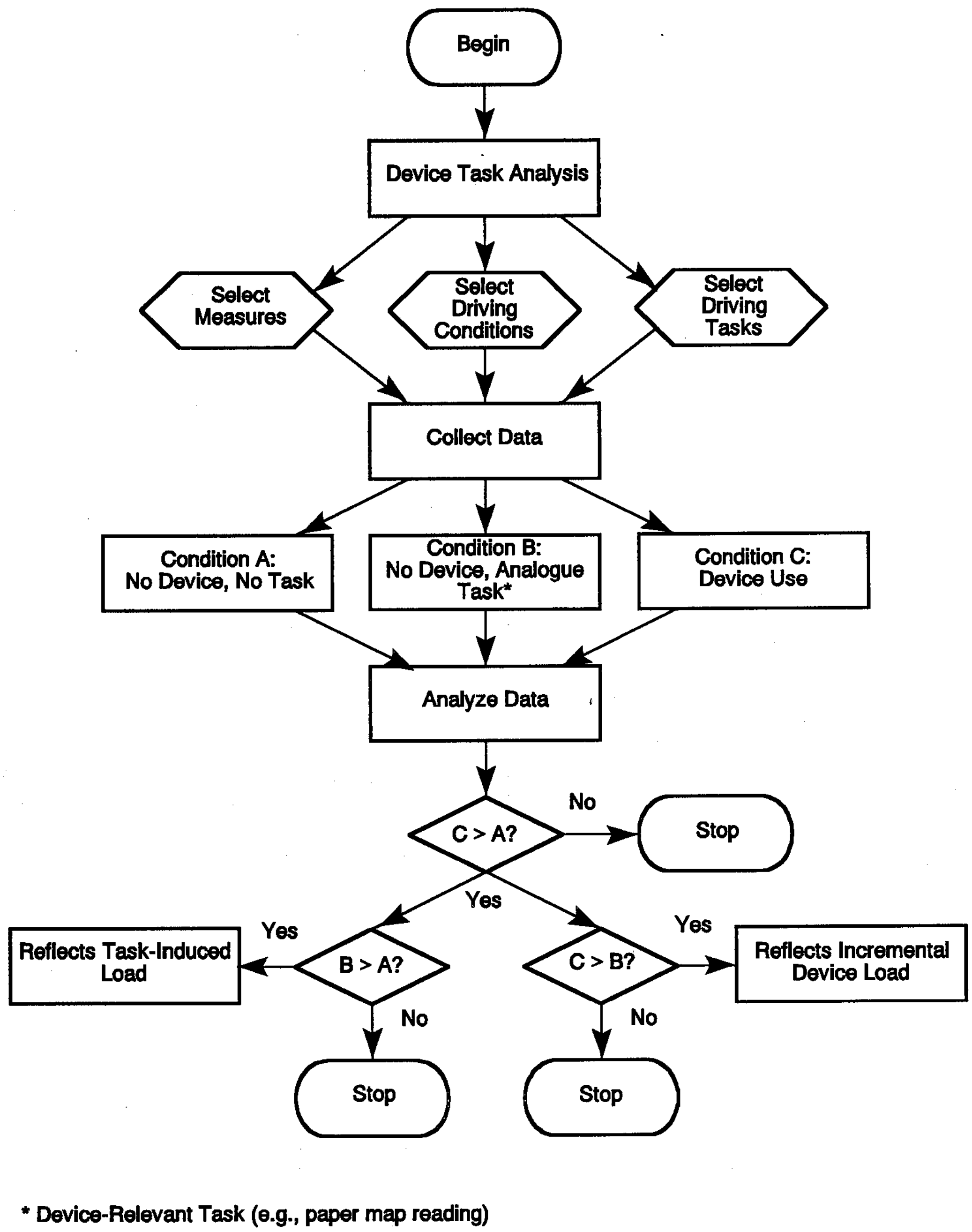

Figure 3. Candidate device assessment process

driver was and was not working with the device. Neural networks also provide a potentially valuable means to attempt to discern if there is driver interference caused by device use. A learning set (data sets obtained with and without conditions of device use) can be used to train the neural network, after which the neural network can be applied to recognize any behavioral or performance "syndrome" that might be indicative of device interference. A third method may make use of principal components analysis to derive component scores that might support composite measures of driving quality or driver effort. These data analysis alternatives will be investigated as data from the instrumented vehicle becomes available. Finally, multivariate data plots will be used to assess the data using exploratory data analysis software (e.g., the S language).

Data Interpretation

The philosophy of safety-relevant device assessment adopted in this project is comparative in nature. If the concern is that an IVHS device may distract the driver, it must be admitted that there are already many distractions both in and out of the cab of a car or a heavy truck. Therefore, it is important to consider a baseline. For comparative purposes, IVHS device use can be compared to normal driving without the device in the cab. It is possible that a new device is no more demanding than some common in-cab activity conventionally found in trucks and cars to today. Examples include tuning the radio, adjusting the CB channel, checking the gauges, and so on. Thus, common in-cab tasks may be used as anchors for IVHS device-induced workload scales (see **Figure 4**). It is also reasonable to compare IVHS device workload with a non-IVHS analogue. Dingus and Hulse (1993), for example, note that it is certain that any navigation technique will involve greater attention demand than circumstances of non-navigation driving, all else being equal. Therefore, it is appropriate to include a paper map or a paper text direction list as baselines to provide an accurate comparison for IVHS evaluation. Note that this comparative method does not imply that commonly accepted in-cab transactions are necessarily safe. For example, cellular phone use may be an example of unsafe-but-common device use (McKnight and McKnight, 1991). In principle, it should be possible to compare the IVHS device to commonly used technology and determine if it equals or exceeds the workload imposed by common devices suspected of being unsafe. At present, there does not appear to be a clear safety threshold that can be applied to any given measure because any given measure, even if it can be related to crash incidence through actuarial studies of crash databases, will almost certainly be smooth, without sharp discontinuities that indicate safe/not safe conditions (Green, 1993b).

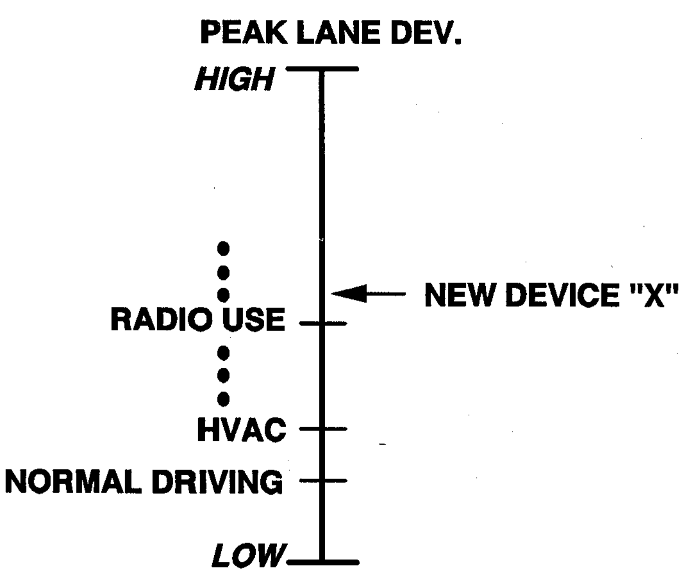

Figure 4. Example safety-Relevant Workload Scale

THE ROLE OF WORKLOAD ASSESSMENT IN IVHS SAFETY EVALUATIONS

The elements of a comprehensive IVHS safety evaluation is currently a subject of discussion and debate. Based on Franzen (1994), safety evaluation of IVHS technologies includes the following areas:

- direct effects of the Man-Machine Interface (MMI) on the user
- direct effects of roadside systems on the user
- indirect behavior-modifying effects on the user
- indirect behavior-modifying effects on the non-user
- modification of interaction between the user and the non-user
- modification of accident consequences
- modification of exposure
- modification of modal choice
- modification of route choice
- modification of speed choice.

The assessment of direct effects of the MMI on the driver is the most immediate safety consequence and the focus of workload assessment. This includes assessment of device use on lateral control, longitudinal control, and object and event detection while interacting with the device. Indirect behavior-modifying effects on the driver can also be addressed by a workload assessment protocol. The primary examples of such behavioral effects include changes in driver visual allocation (glance duration, frequency, and distribution), as well as manual activity (steering motions, hand-off-wheel time and frequency) in the presence of IVHS technology. These effects can be assessed by a workload assessment protocol.

Examples of safety assessments that are not directly workload-related are provided in other sections of the above listing. Indirectly behavior-modifying effects on the non-user might, for example, include a non-IVHS user imitating the travel speed by another driver who does have IVHS technology. This could lead, for example, to the non-user driving at excessive speed relative to the information available to that driver or the performance capabilities of the non-equipped vehicle. Modified interaction between user and non-user might include the following scenario. A non-user stopped on a side road intersecting a main thoroughfare on a foggy night perceives the headlights from an oncoming car. The non-user thinking that no sane person would be driving through the thick fog at high speed proceeds across the intersection. Too late, the driver realizes that the oncoming car was indeed traveling at high speed; that vehicle was equipped with all weather/night vision enhancement. This is an example of IVHS-related modification of the interaction between a user and non-user. This is not within the scope of a device-based workload assessment.

Perhaps the most basic safety measures are crash incidence and severity statistics. However, crashes are infrequent events (Farber, 1991) and it is possible that such indicators will not show problems during the course of any but a large scale demonstration that runs for several years. The philosophy of device assessment proposed here is that crashes are an eventual consequence of workload but that a) the roadway system is, in large measure, forgiving of driver variability in control and attention, and b) crash occurrence depends on stochastic variations that juxtapose the subject vehicle and other vehicles, pedestrians, and roadside appurtenances at inopportune times, and c) therefore, crashes are avoided largely by the grace of these stochastic variations occurring in a forgiving environment. An actuarial analysis should reveal the consequences of MMI impacts on driver performance and behaviors.

The last four categories of safety concerns are strategic in nature. Exposure implies that more drivers are on the roadway because the enhanced transportation efficiency of IVHS permits it. This effect will depend, in part, on the level of IVHS technology infusion in the fleet, and in part on the specific nature of a given system. A workload assessment protocol will not likely be relevant here directly, though indirectly exposure effects may influence the driving conditions under which the technology is used. Selection of mode of transportation, route taken, and speed are all considered outside the realm of a device-induced workload assessment but do, of course, have safety consequences.

To the above safety areas, two additional considerations must be added: learning the IVHS and driver acceptance. Burgett (1992) has pointed out that learning to effectively use IVHS technology is important from the standpoint of safety. That learning impacts safety is inferred from data like that of Perel (1983), who indicated that about 34 percent of passenger car drivers (in accidents) had less than 6 months familiarity with the accident vehicle. The initial period of learning to use the in-cab device may be the time period in which the driver is at greatest risk. Given that drivers may or may not receive proper training and orientation to the IVHS technology, this could pose a serious threat to highway safety. A workload assessment might demonstrate this effect objectively. Thus, repeated application of the workload assessment measures could allow for a structured assessment of the time course of learning.

Driver acceptance has recently been added to the list of safety evaluation areas (Bolczak, Wagner, and Koziol, 1994). Acceptance determines the frequency with which system functions will be used and hence the familiarity the driver develops with that function. As such, acceptance determines if a function will be used and, if used, how the driver interacts with the device. This may range from slow and attention consuming (for seldom-used or complicated functions) to well learned, almost automatic routines. The subjective assessment portion of device evaluation may shed some light on this important aspect of driver-IVHS interaction.

CONCLUSIONS

Safety evaluation is largely inferential in nature. Clearly, one cannot take a crash which occurs during a test as the only means for assessing that a device may be unsafe. Apart from the ethical and liability considerations, such a criterion would be too strict given that crashes are rare events. Instead, what are needed are assessment data from which one may infer safety implications. Driver workload assessment will fill this need with safety-relevant measures of driver in-cab behavior, driver-vehicle performance, and driver attitudes.

To make the notion of inference and safety-relevant measures clearer, consider the following example. The driver's visual resources are critical to driving safely. The driver cannot take eyes off the road for more than an instant without increasing the risk of some mishap, be it a rear-end collision, a roadway departure, or whatever. This suggests that the duration and frequency of glances required of an in-cab device might be good, safety-relevant measures with which to infer the (visual) workload imposed. Similarly, if the driver, while reading the device display, shows poorer lane keeping performance, that also has safety relevance. It suggests that the vehicle is more likely to cross the lane boundaries or is closer to those boundaries than normal. In either case, there is, in the evaluation, no crash. Instead, the inference to be drawn is that a device that prompts longer or more frequent glances and/or poorer lane keeping, indicates a decreased capacity on the driver's part to control the vehicle and maintain the same margin for error and recovery.

There are many things both in and out of the vehicle that can be distracting. It is also true that a driver can be temporarily distracted while on the road without a crash. The driver often takes eyes off the road, hand off the wheel, and mind off the road scene...for a moment...with no resulting crash. The point is, however, for technology not to encourage such diversions from the driving task by introducing new and more compelling distractions into the driver's world. While the driver may indeed take eyes off the road and be less precise at lane keeping, this reduces the driver's margin of error and recovery, and such variations are indeed what causes crashes when conditions are just so.

ACKNOWLEDGEMENTS

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Study on Active Safety Using Driving Simulator: "Driver's Steering Quality in a Monotonous Driving"

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Paper No. 94-S2-O-07

ABSTRACT

This paper concerns driver's steering quality, which could be one of the highest potentials to detect driver's performance deterioration. In an attempt to reduce the number of traffic accidents, several types of intelligent vehicles are under research, such as DRIVE, IVHS and ASV. One of the applications could be a supporting system for a driver, which should function through detecting driver's status such as psychophysiological status.

Using a chassis-dynamometer-type of driving simulator, driver's steering quality was investigated in a monotonous driving condition. A monotonous driving could induce drowsiness, hypoalertness and sleep at the wheel, which might deeply affect the characteristics of steering wheel operation. Additionally, a drunken driving was also investigated as one of the hypoalertness conditions.

The results indicate that a comparatively high correlation was shown among the frequency characteristics of steering wheel angle operated, physiological status and vehicle's lateral fluctuation, which implies the possibility that the characteristics could be one of the measures to represent driver's steering quality.

INTRODUCTION

According to NHTSA statistics* for 1990, 57,000 crashes, about one percent of the crashes occurring in the U.S. that year, resulted from driver drowsiness. This estimate is said to be probably conservative, because drivers themselves may have often been unaware of the role that drowsiness had played in their crashes. Our study on the experience of danger in a drowsy driving, where about 2,000 daily drivers answered to the questionnaire in May, 1993, indicates that about 60% of them experienced the danger in a drowsy driving as shown in Figure 1. Though the results would be also conservative for the same reason, it, at least, indicates that some countermeasures against a drowsy driving must be available for safer driving.

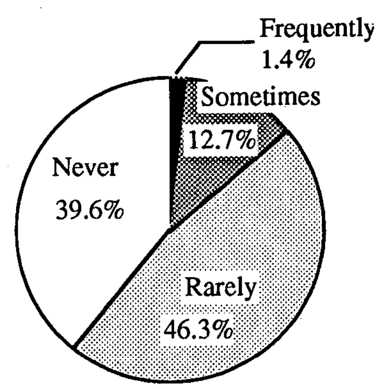

Figure.1 Experience of danger in a drowsy driving

A drowsy driving could be detected by two types of measures; one for the driver's operation and the other for driver's physiological status. Our previous research* implied that "asleep at the wheel" would be detected by the combination of both measurements. On the other hand, Figure 1 tells us that people drive once in a while with the impaired performance, mostly without any serious accidents by "asleep at the wheel".

One possible hypothesis is that if driver's steering operation would be modelled with some quantitative

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* See reference (1)

* See reference (2)

measures, it could tell the quality impairment of the driver related to drowsy driving and the like, appearing on the steering wheel operation.

The purpose of this paper is to model or quantify driver's steering quality on steering wheel operation, comparing a drowsy and a drunken driving with a normal one. A chassis-dynamometer-type of a driving simulator was developed and applied to this tests for the purpose of safety and data repeatability.

DRIVING SIMULATOR APPLIED

Figure 2 shows the appearance of the driving simulator applied to this research. It consists of a four-wheel flat belt chassis dynamometer and a computer-generated scene of road environment for a driver's view as shown in Figure 3.

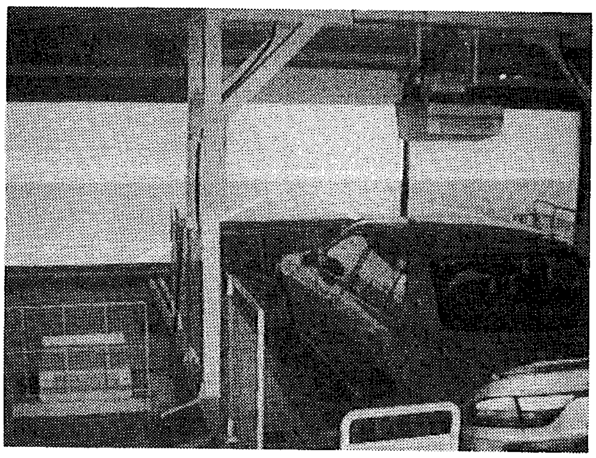

Figure 2. Appearance of Driving Simulator

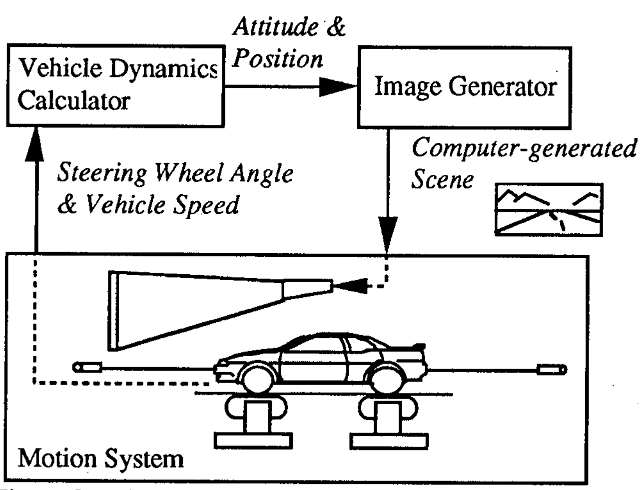

Figure 3. Diagram of Driving Simulator

PRELIMINARY TEST

In general, human behaviors should be explained by the prediction, the effort and the circumspection. On the other hand, human operation characteristics should physiologically consist of the kinesthetic recognition and the visual one.* In addition, the operation by the kinesthetic recognition would mainly relate to the prediction, because it should have a feedforward process. The operation by the visual recognition could relate to the effort and the circumspection, because it has an instantaneously feedback loop, for example, to improve a lanekeeping performance.

Preliminary tests were, therefore, conducted to identify the components mentioned above on steering wheel angle operated, which might model or quantify driver's steering quality.

Frequency Characteristics of Steering Wheel Angle Operated

To identify the components by the kinesthetic and visual recognitions, the tests, where drivers were restricted in their field of view, were conducted on the driving simulator. Figure 4 shows the restriction conditions of the vehicle field of view. The case A, in which the lower view is restricted, is for identifying the kinesthetic component and the case B, in which the upper view is restricted, is for the visual one. In each cases, the sight distance was set at 5 - 20 m. The drivers drove on a simulated winding road shown in Figure 5 under various conditions in the case A and B.

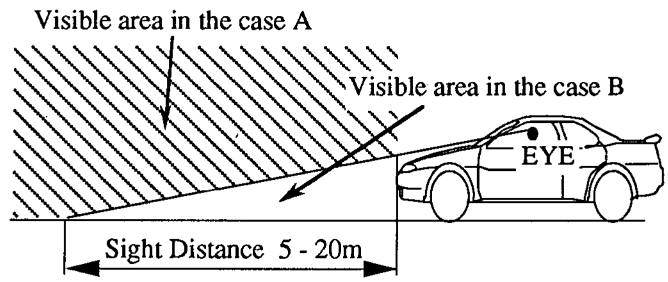

Figure 4. Restricted Vehicle Field of View

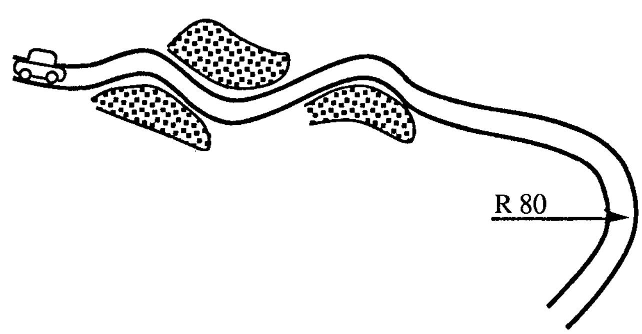

Figure 5. Simulated Winding Road Configuration

* Many studies related to driving strategy have been conducted, e.g. reference (3) - (5).

The Test Results

Figures 6 through 9 show the influence of the field-of-view restriction on the steering wheel operation in case of the vehicle speed of 30 km/h. Figure 6 indicates the influence of the case A, where the peaks of steering wheel angle in the frequency range 0.1 to 0.2 Hz were distinctly influenced. Figure 7 shows the lanekeeping performance influenced by the case A, which implies that drivers took an inefficient route of the winding road because of lack of the road shape information to be predicted.

On the other hand, the case B indicates the distinct influence in the range of 0.3-1.0 Hz as shown in Figure 8. In the lanekeeping performances in Figure 9, the upper view restriction produced the better performance, which implies that the lack of the upper view forced the driver to make more efforts to lanekeeping. This could explain the increase in the level of steering wheel angle in the range of 0.3-1.0Hz.

Furthermore, both Figures 6 and 8 show the peak at about 0.05Hz, which is the same frequency as calculated from the road shape and the driving speed.

All the above could identify the three components on steering wheel angle operated, that is, a road shape component, a kinesthetic(predictive) one and a visually feedback(corrective) one as shown in Figure 10.

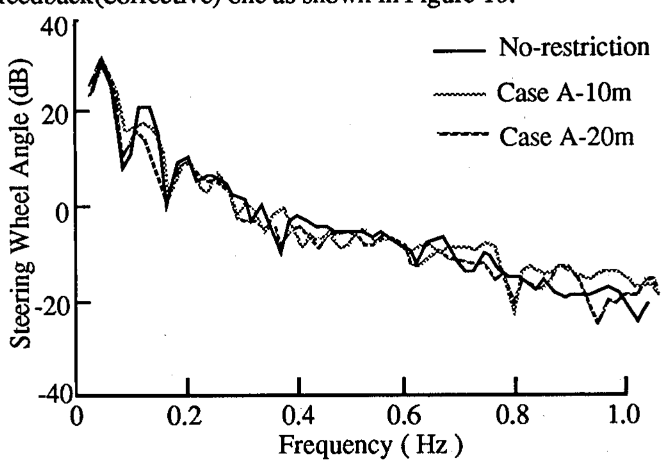

Figure 6. Frequency Characteristics of Steering Wheel Angle

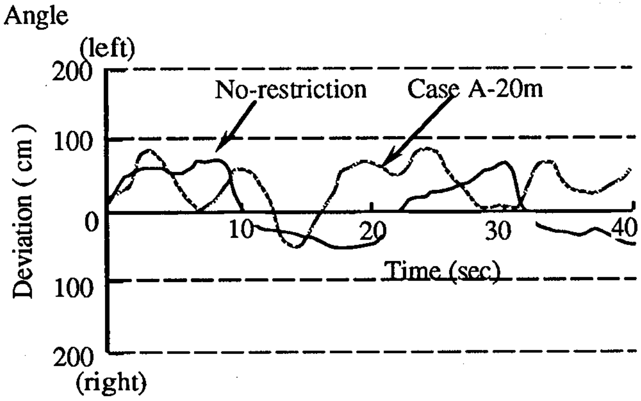

Figure 7. Lanekeeping Performance

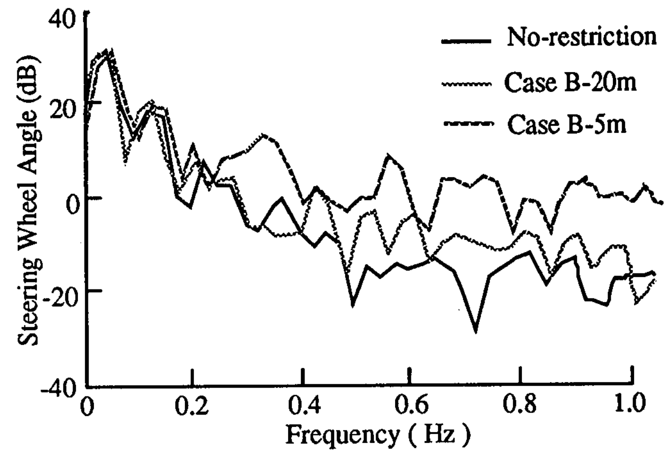

Figure 8. Frequency Characteristics of Steering Wheel Angle

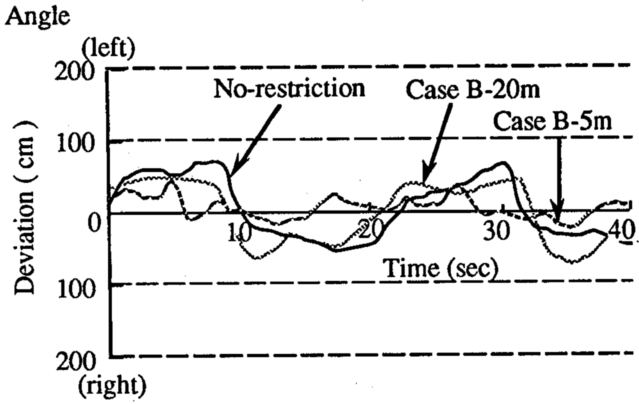

Figure 9. Lanekeeping Performance

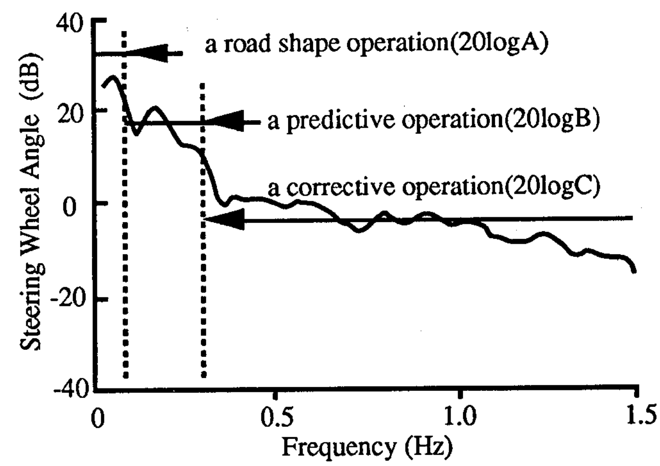

Figure 10. Concept of The Handling Performance

The Observations on Deterioration of Steering Wheel Operation

The preliminary tests assume that three human factors, which are related to driver's prediction, effort and circumspection on steering operation, could be obtained from the three components on steering wheel angle operated as shown in Figure 10. Since the component of a road shape is considered the driving target, the proportion of the kinesthetic (predictive) component to the road shape one, 20logA/20logB, would be the level of driver's prediction. And the proportion of the visually feedback component to the kinesthetic one, 20logC/20logB, would be deeply related to the level of driver's corrective effort. Then the visually feedback one, 1/20logC, itself could be explain as the level of driver's circumspection, that is, the less the visually feedback one, the more the circumspection.

Those human factors, that is, the prediction, the effort and the circumspection were applied to the following main tests to identify driver's steering quality impairment.

MAIN TESTS

A monotonous road was simulated as shown in Figure 11. The tests were conducted in the three conditions, that is, a normal condition, a drunken one and a drowsy one. The reason why a drunken driving condition was applied is that "drinking" could affect surely and continuously driver's performance, which means that the data are easy to obtain.

In the drunken driving tests, four average-skilled drivers participated. At first, they drove a car on the simulator in a normal condition, and then started drinking alcoholic liquors at their paces. At every thirty minutes, the subjects drove the simulator for fifteen minutes while their breathing alcohol levels and equilibrium characteristics were measured.

In the drowsy driving tests, six average-skilled drivers participated, who were instructed to continue driving until falling asleep, judged with their facial expression by the experimenter.

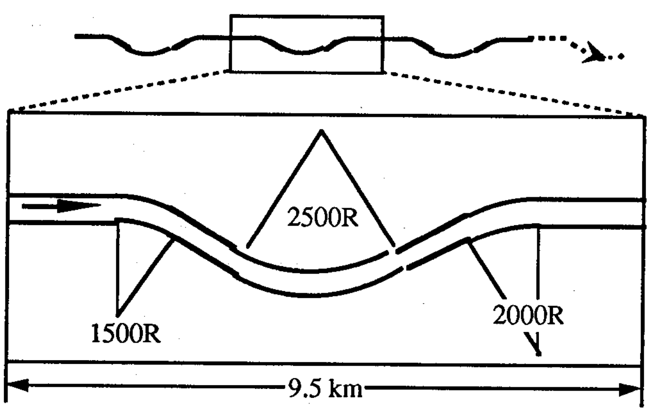

Figure 11. Simulated Monotonous Road

The Test Results in a Drunken Driving and Observations

Figure 12 shows the blood alcohol levels estimated from subjects' breathing alcohol level. In the figure, the data at 0 min shows a normal condition where they start drinking and the others show drunken conditions.

Figure 13 indicates that fluctuation of standing C.G.(center of gravity) of each subjects tends to increase related to increase of blood alcohol level, which implies that subjects' equilibrium control becomes worse.

Figure 14 shows lateral fluctuation. Lateral fluctuation was defined as follows:

$$LF = |dLP/dt| \quad (1)$$

where, LF : Lateral fluctuation (m/s)

LP : Lane position (m)

Lateral fluctuation would be an index of lanekeeping performance. It also tends to increase related to increase of blood alcohol level with similarity to fluctuation of C.G. In other words, it would be said that "drinking" produced the deterioration of driver's performance.

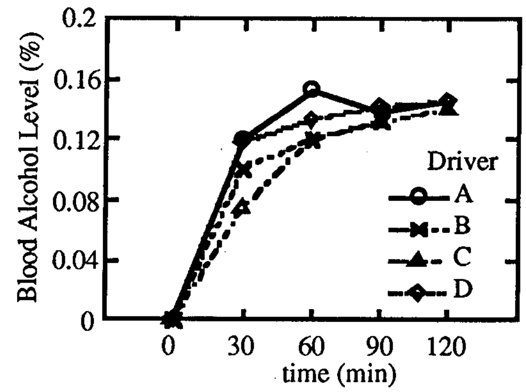

Figure 12. Blood Alcohol Level estimated from the breathing alcohol level

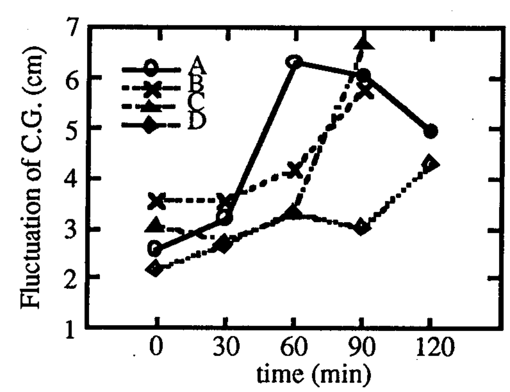

Figure 13. Fluctuation of driver's C.G.

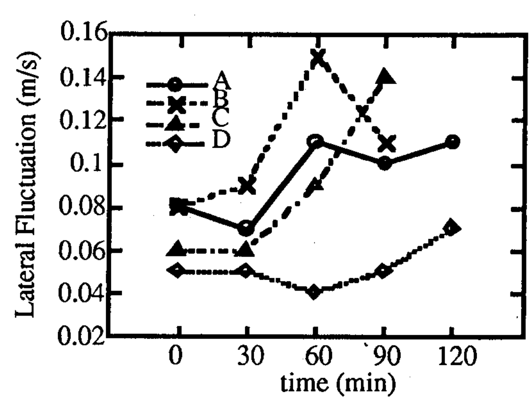

Figure 14. Lanekeeping Performance

Figures 15 through 17 show driver's prediction, effort and circumspection in a drunken driving. The values of 20logA/20logB, 20logC/20logB and 1/20logC were recalculated with human factors of P, Q and R respectively. These factors were defined as follows:

$$P = \log(200A)/\log(200B) \quad (2)$$
$$Q = \log(200C)/\log(200B) \quad (3)$$
$$R = 1 / \log(200C) \quad (4)$$

where, A : a road shape component (deg)
B : a predictive operation component (deg)
C : a corrective operation component (deg)
P : driver's prediction (no dimension)
Q : driver's effort (no dimension)
R : driver's circumspection (1/dB)

In the equations (2) through (4), to prevent zero-devide, each value of A, B and C was multiplied by two hundred. The reason was that each of the minimum values of A, B and C was 0.05 deg in accordance with the steering angle sensor resolution.

The values in Figures 15 through 17 are averaged ones for eight minutes.

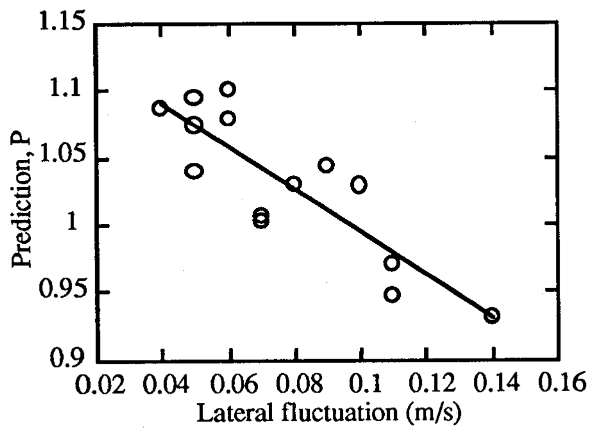

Figure 15. Prediction vs Lanekeeping Performance

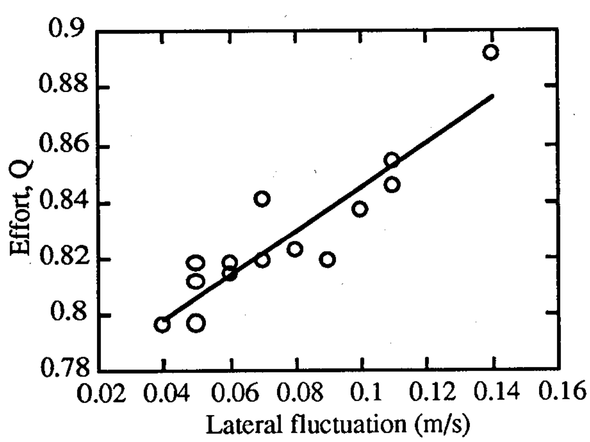

Figure 16. Effort vs. Lanekeeping Performance

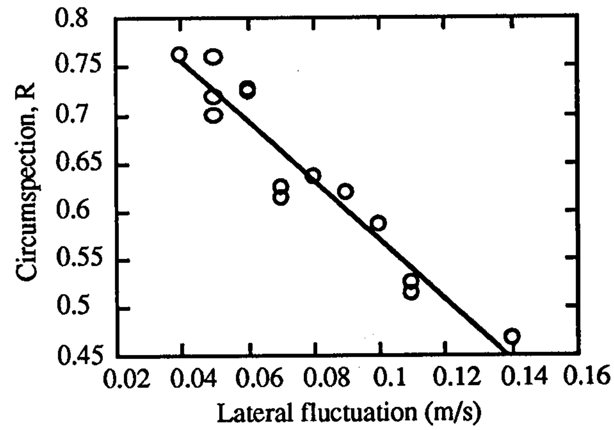

Figure 17. Politeness vs.Lanekeeping Performance

These figures show that each of prediction P, effort Q and circumspection R apparently correlates with lateral fluctuation (correlation coefficients > 0.85).

The results above could imply the possibility of explanation of driver's steering quality impairment by the human factors thus introduced. In Figure 15, the less the prediction, the more the lateral fluctuation. In Figure 16, the more the effort, the more the fluctuation, which could mean that the conflict between lanekeeping will and "drunken" produces more corrective operation. In Figure 17, the more the circumspection, the less the fluctuation.

Additionally, the more rational frequency ranges for P, Q and R were sought so that the correlation coefficient between each of the human factors and the lateral fluctuation could be the highest. Table 1 shows the frequency ranges for A, B and C studied.

Figure 18 shows correlation coefficient between each of P, Q and R and lateral fluctuation. Case 0 shows the highest correlation coefficient.

Table 1
Studied Frequency Ranges for A, B and C

Case	Frequency Range		
	A	B	C
0	0.04 - 0.11	0.11 - 0.30	0.30 - 0.63
1	0.04 - 0.11	0.11 - 0.23	0.23 - 0.63
2	0.04 - 0.11	0.11 - 0.40	0.40 - 0.63
3	0.04 - 0.09	0.09 - 0.30	0.30 - 0.63
4	0.04 - 0.07	0.07 - 0.30	0.30 - 0.63
5	0.04 - 0.14	0.14 - 0.30	0.30 - 0.63

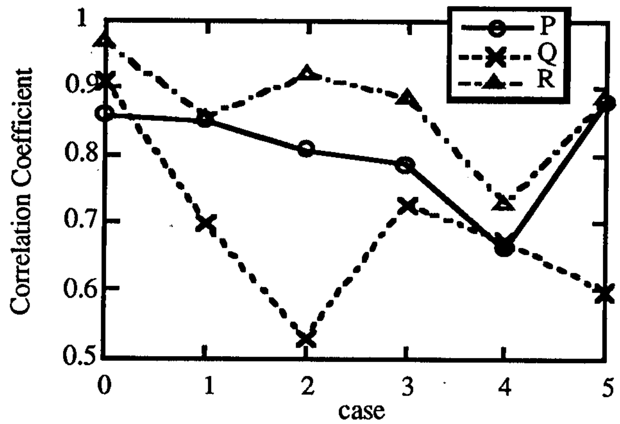

Figure 18. Influence of Frequency Range for P, Q and R

The Tests Results in a Drowsy Driving and Observation

The results are shown in Figures 19 through 21. The values in these Figures are averaged ones for eight minutes. Although these indicate less correlation than those in the drunken driving, the tendencies are similar to those in the drunken driving. The less correlation could result from the momentary attack of drowsiness in contract with rather steady state of the drunken condition.

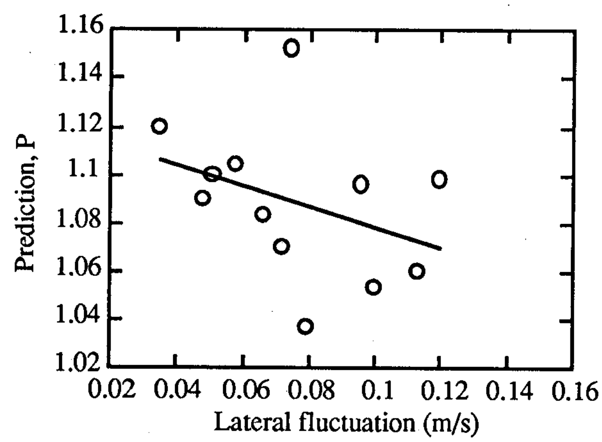

Figure 19. Prediction vs Lanekeeping Performance.

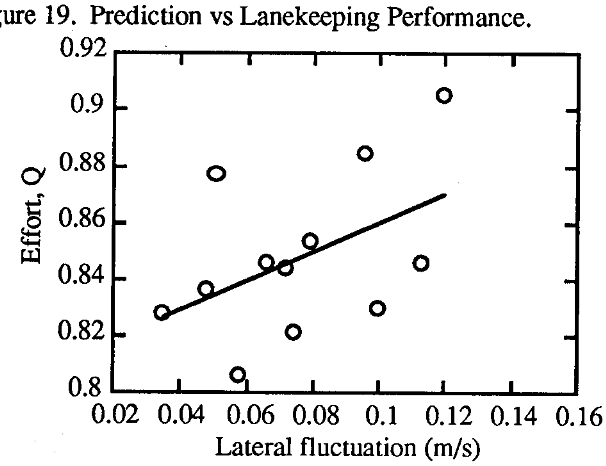

Figure 20. Effort vs. Lanekeeping Performance.

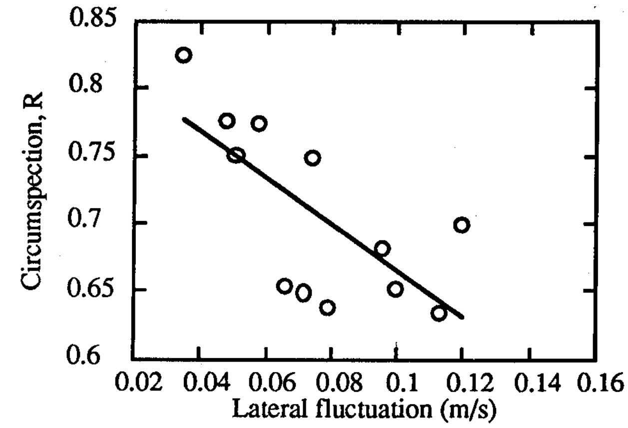

Figure 21. Politeness vs. Lanekeeping Performance.

REVIEW

The human factors introduced by the frequency characteristics of steering wheel angle seem to explain driver's steering quality. Figure 22 shows the time history of P, Q, R and lateral fluctuation in a drunken driving.

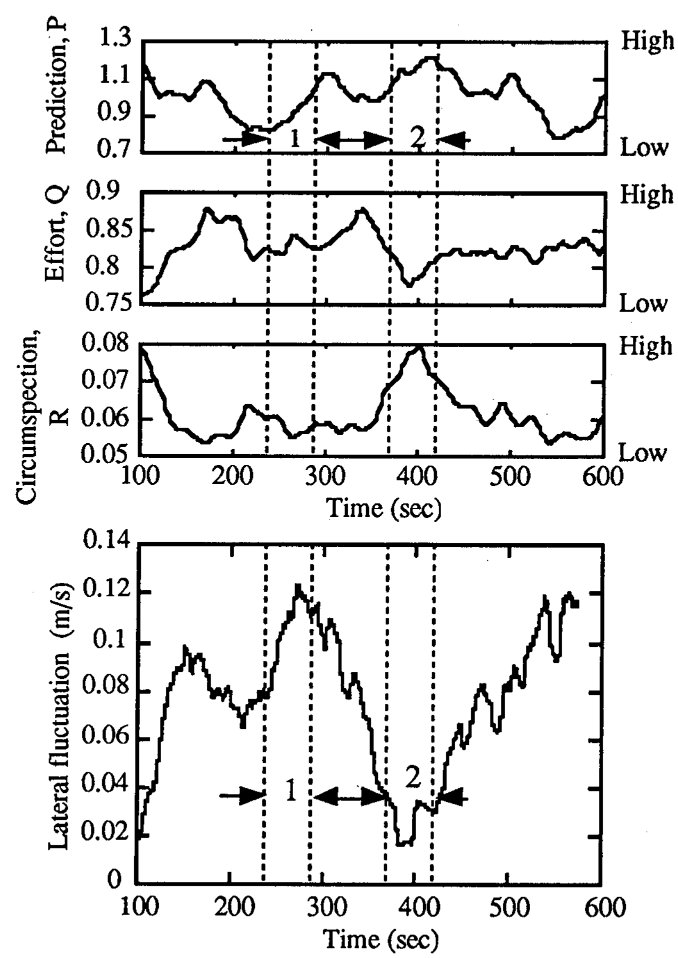

Fig.22 Time History of P, Q, R and Lateral fluctuation.

In the time region of "1", the value of lateral fluctuation is considerably high, which means driver's steering quality impairment, where P is medium or low, Q is medium and R is considerably low. On the other hand, in the time region of "2", the fluctuation is considerably low, which means a high quality of driver's steering, where P is considerably high, Q is low and R is considerably high as shown in Table 2. These results imply that the combination of the levels of the prediction, the effort and the circumspection would explain the driver's steering quality.

On the other hand, the less correlation coefficients between the lateral fluctuation and the human factors in a drowsy driving in Figures 19 through 21 would seem to result from the long averaging duration. Since the drowsiness attacks the drivers momentarily, the long duration could bring the less correlation. An appropriate duration might be applied to a drowsy driving.

Table 2
The Condition of Lateral Fluctuation, P,Q and R

Region	Lateral Fluctuation	P	Q	R
1	High	Mid/ Low	Mid	Low
2	Low	High	Low	High

SUMMARY

Driver's steering quality was analyzed, comparing a drunken and a drowsy driving with a normal driving using the driving simulator. The three human factors on steering wheel operation, that is, the prediction, the effort and the circumspection were introduced with the frequency characteristics of steering wheel angle operated. The factors could well explain driver's steering quality impairment, which implies the possibility of modelling driver's steering quality or steering wheel operation.

The results of this research have encouraged us to proceed the further research to confirm the assumption in detail, which could provide the driver model referring to a driver's skill and like that. Furthermore, our final target would be to adapt a vehicle to a driver's status including the skill, which could produce the most efficient relationship among a driver, a vehicle and a road environment.

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AN ON-BOARD SYSTEM FOR DETECTING LAPSES OF ALERTNESS IN CAR DRIVING

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ABSTRACT

Analysis of the circumstances surrounding motorway accidents clearly points to drowsiness at the steering wheel as one of the main causes. It is therefore not hard to understand the growing interest shown by the car makers in rapidly developing a system for detecting lapses of alertness. Renault's *Département Biomédical de l'Automobile* recently organized a series of tests to validate such a system. 21 tests were performed on a driving track at night. Numerous lapses of alertness were obtained, leading to drivers often dozing off and leaving the road. This paper presents the results of the physiological recordings (electroencephalogram, electro-oculogram) and the behavioural recordings (analysis of the video film of the driver's face). It is shown how we establish a physiological reference of the driver's level of alertness from this data. The correlation between the results provided by the EEG and those obtained by behavioural analysis is discussed. We look at our multi-sensor approach, based on the analysis of driving behaviour, and the respiratory signal as well as the automatic processing of the film of the driver's face. The study of the driver's reactions based on mechanical signals collected on the vehicle is also briefly described.

INTRODUCTION

Every year the association of French motorway companies publishes an analysis of fatal crashes occurring on motorways as a function of the accidents' causes. Out of 1,508 accident reports over the five-year period from 1988 to 1992, it appears that the chief causes remain fatigue, inattention and drowsiness in 29% of cases [1], with the percentage varying little from one year to the next. If alcohol is added to these three causes, the percentage rises to 31% for the year 1992.

This same association emphasizes the need for the driver himself to recognize the "warning signs" of fatigue and to adopt a method to enable him to "reactivate" his alertness. A survey of 323 drivers made it possible to establish the list of symptoms most often cited. These symptoms are, in decreasing order, blinking of the eyes, yawning, drowsiness, sore eyes and the need to move about. 95% of the people questioned "diagnose" the lapse of alertness themselves [2].

Similar surveys are carried out in the USA. Out of 50,000 fatal crash cases, 13% were attributed to the dozing off of the driver [3]. In many studies, one notes that most of these accidents occur between 1 a.m. and 6 a.m. and between 1 p.m. and 4 p.m., with the period between 4 a.m. and 6 a.m. being the most dangerous. One also observes that a large number of these accidents involve truck drivers and that people experiencing problems sleeping are more exposed to this risk [4].
It appears clearly from these surveys that the study of lapses of alertness at the steering wheel is an important activity of which the population is increasingly aware. While the motorway companies endeavour to inform drivers of the warning signs of hypoalertness and to advise them to have a good driving attitute (a stop every 2 hours etc ...), the car makers are more concerned with early detection of hypoalertness, in order to inform the driver and to offer him to stop while it is not too late, or in order to reduce the accident risk by mean of an action on the vehicle it self (for example decreasing speed and a compulsory stop). This latest use of detection of hypo-alertness would be all the more justified as the vehicle is heavier (truck and motor-coach) and so, more dangerous for other drivers.

THE PRINCIPLE BEHIND A SYSTEM FOR THE DETECTION OF HYPOALERTNESS

Originally focusing on the analysis of steering wheel angle, Renault's studies are nowdirected to integrate the following complementary factors in order to improve the reliability and robustness of its system :
a more thorough analysis of driving strategy, an analysis of the driver's breathing and lastly an automatic analysis of the video of the driver's face.

Analysis of driving behaviour

Renault's *Département Biomédical de l'Automobile* has been studying such a system for a number of years. It is based on the hypothesis that a driver's driving behaviour is altered during periods of decreased alertness. The principle behind the system is therefore to analyze driving behaviour in order to estimate the level of alertness and warn drivers of any lapse. The system must meet the following specifications :

* It must measure a sign inherent in the driving task without interfering with it.
* The sign chosen must be indicative of the driver's alertness.
* The system must take into account differences from one individual to another in the driver population.
* The system must be capable of detecting driver's slight hypo-alertness very early before any accident, before the hypo-alertness been obvious.
* The system must carry out real-time analyses and inform the driver of a deterioration in his alertness.

The study phase for such a system involves a large number of tests performed on different drivers, on different itineraries and possibly different vehicles. These tests must include physiological recordings on the driver to determine a reference for his alertness level as well as mechanical recordings such as the steering wheel angle signal. This phase of the study aims at extracting from the steering-wheel angle signal those parameters which will give the best correlation to the level of alertness as determined by physiological analysis.
In the beginning, Renault focused on the steering wheel angle signal because it made the development of a simple system possible. For this purpose, Renault carried out tests on a driving simulator to investigate how the transitions between waking, hypoalertness and sleep influence steering wheel movements. The protocol applied during these 27 tests and the results obtained are described in our previous publications [5], [6], [7], and [8]. Three parameters derived from the Steering Wheel Angle were adopted to provide a satisfactory representation of the driver's alertness level [8].

Analysis of the respiratory signal

Above we have described the importance of analyzing the driving task to determine the alertness level. Parallel to this approach, Renault has been studying, in collaboration with the *Centre de Recherches en Automatique de Nancy*, how the analysis of a driver's breathing regularity can contribute to the prediction of a deterioration in alertness. As the measurement of breathing can be carried out without inconveniencing the driver, unlike with other classic physiological signals discussed later in this paper, this signal could be integrated into the final device in order to aid in the diagnosis of alertness in the same way as analyzing driving behaviour can. However this approach still needs to be confirmed in a real-life driving situation

The automatic analysis of a video film of the driver's face

With the aim of increasing the strength of the alertness deterioriation detection system, Renault is also pursuing research into the automatic processing of the video film of the driver's face. The advantage of such an approach is that it doesn't depend on the type of vehicle or on conditions outside the vehicle. It is necessary to carry out image processing followed by measurements of relevant parameters based on eye and eyelid movement. There remain a number of technical hurdles to be overcome before this approach will be operational.
While experiments on simulators enabled to carry out in complete safety the study of the influence of lapses of alertness on driving, the results obtained needed to be confirmed in a real-life driving situation. These new tests on private track also allowed us to take into account a wider range of mechanical signals thereby allowing a more thorough analysis of driving behaviour. These tests should be regarded as an intermediate stage in the validation of our system, between the simulator and driving on the open road whitch involves a large number of intervening factors such as traffic density, overtaking, road layout, etc. These affect one's driving and interfere with changes in behaviour which are solely due to a deterioration in alertness. We will now look at tests carried out on the test track.

PRESENTATION - TEST TRACK EXPERIMENTS

We performed 21 experiments, at night, on volunteer subjects. The vehicle used was a Renault 25 with power steering, fully equiped for the test requirements. This experimental projet was submitted to an ethics committee for approval.

Test subjects selection

The subjects were recruited on the basis of four criteria:

-a preliminary EEG recording performed in the laboratory. This examination enabled us to select only those people showing a strong tendency to emit alpha waves. The conventional test involves using electrodes in position O1-O2 in accordance with Jasper's International System, to observe any appearance of such waves when the eyes close and to check their attenuation during specific mental activity (e.g. mental calculation) [9].

-a conventional medical examination to eliminate those individuals subject to loss of consciousness or, for instance, suffering from sleep disorders.

-a series of psychotechnical tests, conventionally used for the recruitment of heavy machinery drivers. For us, the aim was merely to eliminate those subjects having real problems of motor coordination or emotional control and to check that no major anomaly could become a source of accident. Four tests were performed. The Ricossay test is a psychomotor evaluation which identifies the value of motor coordination and the existence of tremors. The measurement of the auditive response time makes it possible to study psychomotor reflexes. Bonardel's complex response test requires rapid organization of motor coordination. Bonardel's concrete intelligence test (B101) identifies the ability to adapt, to learn and to take decisions when faced with a new situation (e.g. a situation of danger).

-a questionnaire concerning sleeping and driving habits, supplemented by the Horne and Ostberg questionnaire by which individuals can be classified into three groups: morning subjects / intermediate subjects / evening subjects, according to their optimum conditions of physical and intellectual fitness. Accordingly, out of 21 people, we selected seven "morning" subjects, six "intermediate" subjects and eight "evening" subjects. **Figure 1** shows the age breakdown according to the gender of the subjects selected. Most of the subjects are in the 25-40 age bracket. Five people out of 21 have five years or less of driving experience.

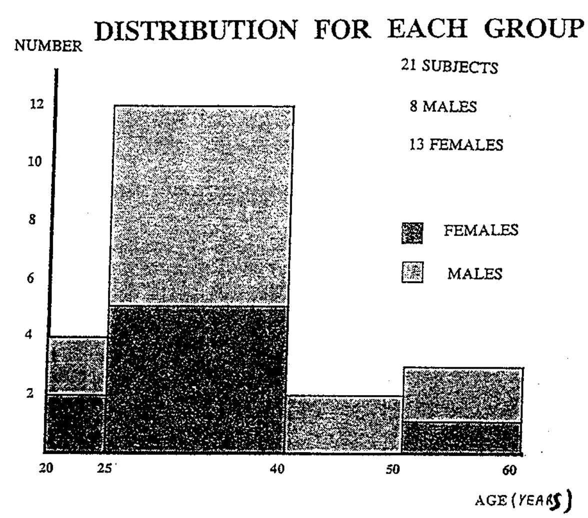

Figure n° 1 Distribution of age for each group

The driving test track :

The test track used is the speed ring whitch Renault make use of in his center at Aubevoye, devoted to driving security. The track is over a distance of 4432 meters, with two straight stretches of 800 meters each, two constant-profile corners (radius of curvature 300 m) of 750 meters each and four transition clothoïds of 310 meters each. Only the flat part of the track was used to avoid the passive driving of the vehicule in corners.

Instructions :

The subjects were asked to drive at 120 km/h on the horizontal plane of the inside edge of the track. A lane approximately 3 to 4 meters wide was materially represented by reflective cones placed all around the track. Since the track was not lit and communication with the other occupants of the vehicle was limited to the strict minimum, everything was organized to rapidly obtain lapses of alertness. A co-driver was in the front passenger seat to ensure safety by means of dual foot controls and through the possibility of "grabbing the steering wheel" whenever the subject dozed off and was leaving the road. To ensure that this co-driver would stay alert, he was replaced every hour by someone who was rested. In the back seat, a researcher had the task of monitoring the operation of all systems and checking the quality of the signals recorded. Test length varied depending on the alertness of the subjects and their ability to continue to drive safely. Generally, the test started around midnight and could last until 6 o'clock in the morning. The subject was asked to fill out an initial questionnaire immediately before testing. The questions concerned his job, the quality of his sleep and whether he had taken any sleeping pills or stimulants during the preceding two weeks. The subject was also asked at what time he had gotten up and gone to bed the previous night. A second questionnaire, at the end of the test, was designed to obtain the subject's subjective evaluation of his alertness during testing.

Signals recorded :

-Electroencephalogram (EEG): Two 2-pole derivations (O1-O2 and F3-F4, System 10/20)
-Electro-oculogram (EOG): Two 2-pole derivations (vertical and horizontal).
These four signals were referenced relative to an ear electrode. The pre-amplifiers were positioned directly on the subject's head to minimize wire length and induced noise. The signals were then amplified and filtered in the [1.6 - 30] Hz band.
- Variability of driver's breathing
-Steering wheel angle - Potentiometric sensor accurate on the order of degree
-Vehicle speed
-Vehicle accelerations (longitudinal, transverse, vertical)
-Force applied to the accelerator pedal
-Use of the brake
-Use of turn signals
-Vehicle rate of yaw.
All these signals were recorded analogically on magnetic tape.
-Video recordings by cameras sensitive to visible and near infrared ranges
- film of the driver's face
- film of the road ahead of the vehicle (for the purpose of image processing to obtain the vehicle's position in relation to the left-hand white line).
For safety reasons, each of the researcher in rear seat position and the co-driver had a video monitor allowing them to view the subject's face continuously. The researcher could also monitor the EEG signals to detect lapses of alertness as quickly as possible. Comments on the state of the subject, the test procedure or the signals were recorded by the researcher. It was possible to synchronize the video recordings with the signals by means of two clocks. We will now present some of our overall results from these tests before giving a more detailed description of the methodology used to establish the physiological references; a necessary step in validating the different approaches previously mentioned.

General results: - On average, the tests lasted 4 hours 6'. **Figure 2** give the driving time for each subject and **Figure 3** gives the results obtained in terms of lapses of alertness.

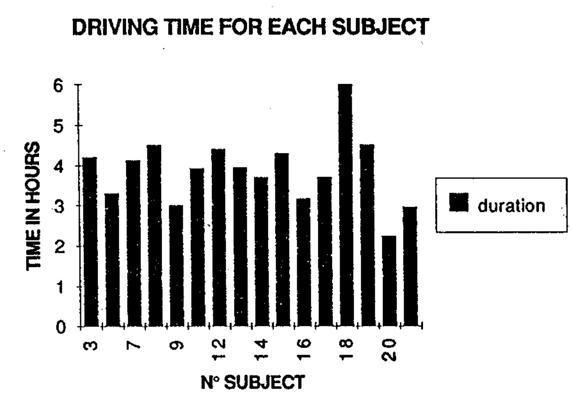

Figure n° 2 Driving time for each subject

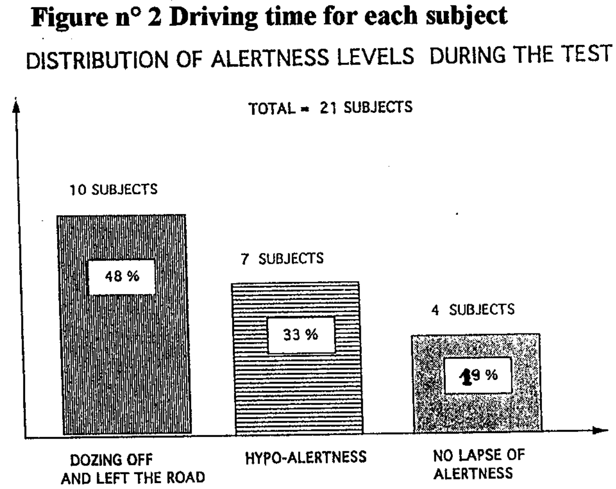

Figure n° 3 Distribution in term of alertness Level

Almost 50% of the subjects had very severe lapses of alertness (interventions by the co-driver due to dozing off). 33 % of the subjects had slight lapses of alertness, not associated with dangerous driving. Only 19% of them showed no lapse in alertness. It is hard to establish a relationship between the overall level of the subject's alertness during the test and how long he had slept the previous night. On the other hand, the post-test questionnaires revealed that the subjects had generally well-evaluated their own level of alertness.

ESTABLISHING THE PHYSIOLOGICAL REFERENCE:

The aim is to continuously produce, throughout the entire test, a physiological reference for the driver's level of alertness, based on physiological data (EEG, EOG) and behavioural data (video film of the face). Several stages are needed to obtain a final classification according to different levels of alertness :

EEG Signal :

Although numerous physiological indicators are available to describe an individual's level of alertness, the EEG signal remains the most predictive and the most reliable [10], [11], [12]. Many authors have demonstrated the importance of the alpha rhythm in the EEG signal to describe the appearance of initial lapses in alertness [13], [14]. A recent study [15] suggests an individualized evaluation of the alpha wave rate (in relation to the eyes closed reference obtained at the beginning of subject testing) and emphasizes the importance of measuring this rate over a short time period in order to avoid averages which could mask the phenomenon being studied. The visual interpretation of our signals in terms of lapses of alertness was performed by a specialist in neurophysiology. A classification according to three levels of alertness was thus carried out for all the tests (1 : high alertness, 2 : incipient hypoalertness, 3 : pronounced hypo-alertness). This is based chiefly on the quantity of alpha bursts present in the plotted graph, but also on the appearance of theta waves, characteristic of more severe hypoalertness [16]. The change in these three levels of alertness over time is plotted.

Analysis of the film of the face:

A good deal of work has been carried out on behaviour, especially to study questions of alertness at work. An individual, assigned a given task, carries out a group of activities whose goals appear to be different [17]. We are concerned here more especially with activities having no purpose i.e. not essential to perform the task. These activities include so-called comfort movements, self-centered gestures and ludic activities [18]. They are sometimes referred to as "collateral activities" [19]. It is demonstrated that the more monotonous a situation is, the more frequent such activities are [20]. They can be interpreted as the expression of a conflict between the task to be performed and the capabilities of the subject at a given time [21]. Numerous authors have endeavoured to establish a relationship between collateral activities and the central activation system, and particularly the concept of alertness. One of the hypotheses, confirmed by numerous studies, links the appearance of such activities to a general activation level so weak that there is no longer any consistency between what the individual has to do and what he can do [22]. The characteristics of eye movements (identifiable either on the EOG signal or on the film of the face) are also an important factor for the study of changes in the alertness level. The length of time the eyes are closed seems to be a fundamental parameter, as are slow eye movements (SEM) [16], [23]. The latter are defined as unintentional pendular and convergent movements of the eyes. They accompany a drop in cerebral activation [24].

Physiological reference :

All this data is used to perform behavioural analyses based on the film of the driver's face. A behavioural repertory is first established for each subject Then, in parallel with the diagnosis resulting from the EEG, the change in behaviour is interpreted to obtain a final classification according to three levels of alertness. Level 1 corresponds to high alertness, level 2 represents slight hypoalertness which is not yet associated with dangerous driving but of which the driver must be informed by the on-board system, while level 3 corresponds to pronounced hypo-alertness (the driver should have been warned before this level is reached). **Figure 4** gives an example of a classification obtained for a subject who has dozed off.

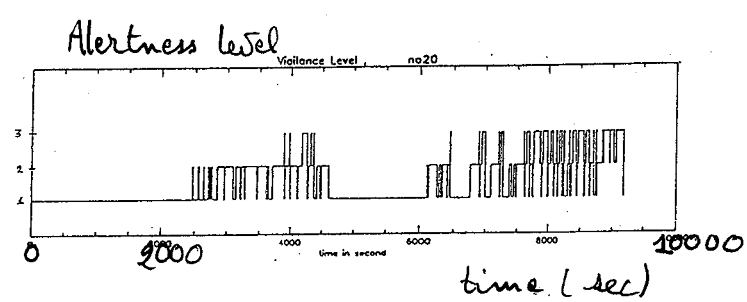

Figure 4 Example of an alertness classification

One observes that the level of alertness deteriorates gradually and includes a phase of recuperation in the middle of the test, following a break. At the end of the test, the subject is mainly in level 3. **Figure n° 5** give the percentage of time the driver spent in each of the three levels

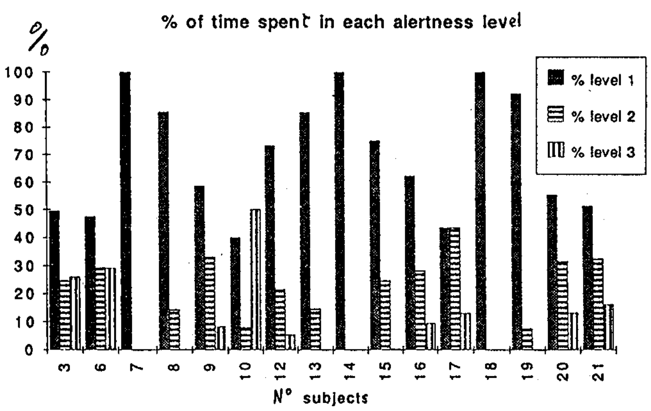

Figure 5 % of time spent in each level

Figure 6, in the form of a summary table, gives the results obtained from 16 tests analyzed.

Subject n°	Duration of the trial	% time spent in level 1	% time spent in level 2	% time spent in level 3	Number of time driver leave the road	occurence of slow eyes movements	Quality of the information given by EEG
3	4 h 12	49	25	26	10	OUI	AVERAGE
6	3 h 18	42	29	29	2	OUI	BAD
7	4 h 08	100	0	0	0	NON	GOOD
8	4 h 03	85	14	1	4	NON	BAD
9	3 h 00	59	33	8	12	OUI	GOOD
10	3 h 55	42	8	50	4	OUI	GOOD
12	4 h 24	74	21	5	13	OUI	AVERAGE
13	3 h 57	85	15	0	0	OUI	AVERAGE
14	3 h 42	100	0	0	0	NON	GOOD
15	4 h 18	75	24	1	0	NON	GOOD
16	3 h 10	62	28	10	7	OUI	GOOD
17	3 h 05	43	44	13	3	OUI	AVERAGE
18	6 h 00	100	0	0	0	NON	GOOD
19	4 h 30	92	8	0	0	OUI	GOOD
20	2 h 14	55	32	13	9	OUI	GOOD
21	3 h 00	51	33	16	6	OUI	AVERAGE

Figure 6 summary table of the 16 tests results

We can note that slow eye movements are frequently observed. Except for 3 subjects who suffered no lapse of alertness, very long periods are spent in level 2 or even 3. The correlation existing between the results obtained from the EEG and those obtained through the behavioural analysis is good in most cases. However, some subjects pose a problem, in the sense that the EEG analysis did not prove sufficiently reliable. In most of these cases, the problem is due to non-detection of the periods of low alertness which appear obvious on the film of the driver's face. These results clearly show the need for behavioural analysis to establish a physiological reference.

In this phase of the study, the analysis of the video film of the face was done manually and was used to establish the physiological reference which would validate the system during the study phase. Given the relevance of the information to be found in the image of the driver's face, we are studying the technical feasability of carrying out automatic processing of this data. This processing system would then be integrated into the final alertness detection device.

ANALYSIS OF MECHANICAL SIGNALS :

After the physiological reference has been established, the mechanical signals must then be analyzed to determine whether they also contain information relating to the driver's alertness, and if this information can be sufficient in itself. Should the latter not be the case, we must then determine what its contribution to the final device can be. This work is already in progress and here we present a brief synthesis of past published work in this field and describe the general characteristics of the mechanical signals recorded during our tests.

In published work on this subject we can find a number of studies analyzing driving in order to establish an objective measure which characterizes either driving performance or the difficulty of driving under specific conditions. This research is chiefly being carried out through the analysis of steering wheel movements. Tracking the vehicle's lateral position in the lane is also often used. Vehicle acceleration as well as the displacement of the brake pedal and accelerator are sometimes considered [29]. Frequency or dispersion parameters, computed on the steering wheel angle, are suggested as a means of differentiating between high risk drivers from "good" drivers in order to recognize inexperienced drivers from those with experience, and to evaluate the effect of fog, alcohol and certain medications on driving.

In the tests we realised, subject had driving impairment, leading them to driving errors and even leave the road. Those events occured most of the time in alertness the level 3. **Figure n° 7** give the distribution of such events in relation to alertness levels

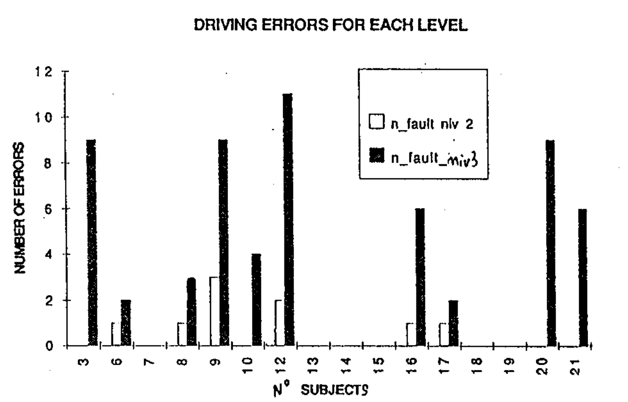

Figure7 Driving errors in relation to alertness level

Steering wheel angle:

In this section we will discuss certain elements from publications related to the analysis of driving performance through the use of driving wheel angle. Many authors have studied the mathematical properties of the steering wheel angle signal [25], [26], and have established a relationship between these properties and the concepts of performance or alertness [27], [28]. With regard to having a better understanding of the driver-vehicle pair, a model has been put forward [25]. According to this model, the driving strategy at the steering wheel level can be broken down into two tasks - the general directional steering task and the correction task. The former involves the anticipation of a turning on the part of the driver by giving his steering wheel the "deduced" angle while in the latter he corrects the difference between the actual position and the desired position. Each of these phases corresponds to a different frequency band; low in the first case and higher in the second. The aim of many articles is to put drivers into different categories using steering wheel angle, for example, differentiating between experienced and inexperienced drivers, or between high risk drivers and those which are "safer" [35]. Some studies examine steering wheel angle as a function of outside conditions such as in the case of reduced visibility [33] and [34]. And lastly, a number of studies look at steering wheel angle as a revelant signal in the evaluation of the effect of driving while under the influence of alcohol [30], medication [31], or in the case of fatigue [36] and [37]. These studies often resort to frequential computations on the steering wheel angle signal or to dispersion parameters on this signal. Many of these studies have been carried out on a driving simulator, but few in a real-life situation. As for our experiments on a test track, the steering wheel angle signal is a non-stationary signal or zero mean in the straight sections and whose continuous component is approximately 25 degrees at the turns. Since the track is looped, this pattern is repeated throughout the test. Whether in the straight sections or on cornering, one observes around the mean of this signal "micro-corrections" corresponding to directional corrections performed by the driver to stay on course.

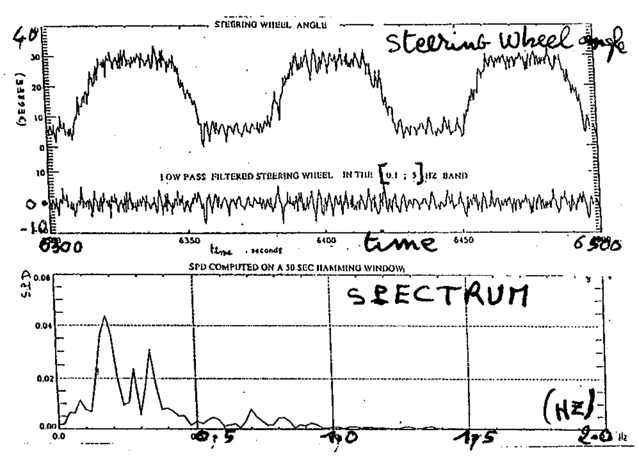

Figure 8 Steering wheel angle -and its spectrum

The main frequencies contained in these micro-corrections are below 1 Hz. It is these corrections that must be analyzed in terms of lapse of alertness. One observes that the characteristics of these micro-corrections change with the driver's level of alertness. The very low level frequency components due to turning can be eliminated by using high-pass filtering at 0.1 Hz to retain only the useful components of the signal (**Figure 8**). It is important to note that differences between the micro-corrections of individuals in the driver population are relatively large.

Vehicle speed :

When the driver's task is to comply with a set speed (which was the case in our tests), this signal is not easily used on its own. It can be used as a complementary element to explain variations in steering wheel angle or position. It can also give supplementary information as to the level of alertness. In fact, as alertness decreases, the subject finds it increasingly difficult to perform his tasks, whether it be maintaining the trajectory or holding the speed at 120 km/h. However, the results obtained on this signal are fairly variable from one subject to the next.

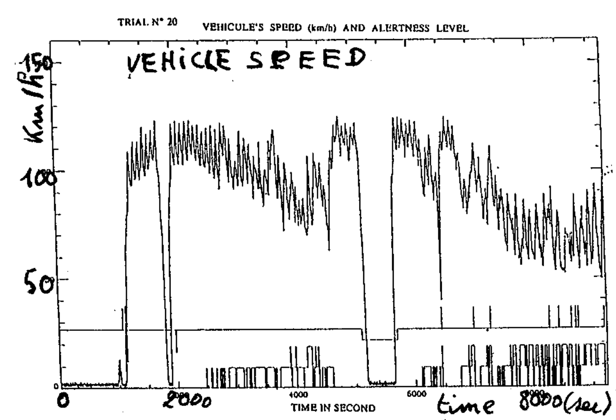

Figure 9 Example of vehicle speed during a test and associated alertness level

Many tend to slow down as their alertness decreases. Others, on the contrary, speed up. Yet, the increase in variability of the signal around the set value seems to be a feature common to all the subjects. **Figure 9** gives an example of changes in this signal, and the corresponding levels of alertness, for a subject who had dozed off several times.

Vehicle trajectory :

Data concerning vehicle trajectory is given in various articles in order to quantify the driving performance of the driver. It has been used in particular to compare driving behaviour on two and four lane motorways [32], and to study the effect of alcohol on driving [30], as well as that of various medications [31].

This trajectory is calculated by processing images obtained from the film of the road. We thereby obtain the vehicle's position relative to the left-hand white line **(Figure 10).** This signal is also related to the steering-wheel angle signal but they each provide complementary information.

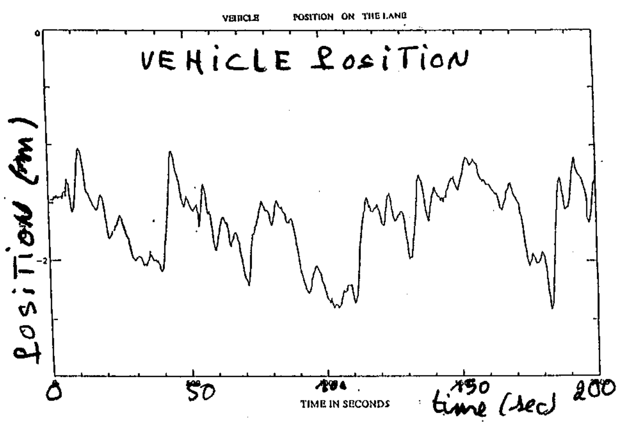

Figure 10 Evolution of the car position

Accelerations, Rate of Yaw and Pressure on the accelerator :

The relevance of acceleration data in analyzing driving behaviour and the demands made on the vehicle by the driver has recently been mentionned [29]. This data especially makes it possible to notice differences between different categories of drivers such as men-women, or beginners-professional drivers. Transverse accelerations are mentioned as resulting in better distinctions between drivers than longitudinal accelerations, although a combination of the two gives the best results in analyzing differences.

Longitudinal acceleration and pressure on the accelerator pedal are related to the vehicle's speed and its variations and can characterize a subject's driving style. In our case, vertical acceleration provides information concerning the state of the road surface and can be useful in explaining certain disruptions in the steering wheel angle or the lateral position. The rate of yaw and transverse acceleration are related to the steering wheel angle signal.

CONCLUSIONS AND PROSPECTS :

We have chosen to approach the problem of detecting hypoalertness at the wheel using three complementary means; the analysis of driving behaviour, and of driver breathing regularity as well as the automatic processing of the driver's face video. The development of an on-board system for detecting lapses of alertness when driving inevitably requires a stage of validation in real-life driving conditions. In the analysis of driving behaviour, latest tests carried out on a driving simulator made it possible to select relevant parameters concerning mainly the steering wheel angle signal. We have now supplemented this data with driving test track data which will make it possible to define these parameters more precisely, taking into account new factors inherent in real-life driving. More in-depth analysis, bringing into play all of the mechanical signals, is being done. Parallel to the analysis of driving, validation of the detection of hypoalertness through the analysis of the respiratory signal in real-life driving conditions is being carried out. Lastly, we plan to develop a system for the automatic processing of the image of the driver's face to diagnose deterioration in his alertness. Developing and validating these approaches require that we have access to an alertness level reference that was obtained in as reliable a manner as possible. Simultaneous analysis of physiological signals and behavioural data provides good results for establishing a physiological reference of the alertness level in a real-life driving situation.

Other tests are currently carried out on the open road, with the results being validated using trucks. A Safrane is also being equiped with the complete system to offer volunteer drivers the opportunity to give their subjective evaluation of the system.

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Car Phone and Road Safety

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94-S2-O-09

ABSTRACT

The car phone equipment rate is increasing. However, one may ask if using a phone, even if it is handsfree, while driving does not not induce any additional risks for the driver. The aim of the present study is to experimentally assess the potential risk on road safety when using a handsfree phone while driving in situation of interactive conversation.

This exploratory research was carried out on an interactive driving simulator and was based on about 40 routes performed by 17 subjects.

In a first step, the observation of speed variations induced by the use of a phone brings two types of reaction into prominence : 1) no effect, and 2) a more rigid driving behaviour. This latter is shown by a speed increase or decrease, or by a longer period of oscillations around the required speed, or even by a total loss of speed control. These reactions were compared to answers to a questionnaire asking for the causes of difficulties encountered and how the driving task was disturbed by phoning while driving, and vice versa. This comparison has allowed us to see how the subjects have managed the dual task; in most cases, they have used a time sharing strategy during which the main task, i.e. driving, is often perturbed by the second one, i.e. phoning.

Although modest, the car phone equipment rate is steadily increasing in France. The demand for this product is raising due to new technological features, to the adoption of GSM Pan European System and to the possibility of using the telephone as a transmission carrier of traffic and guidance information. However, one can wonder if the use of a telephone in a car - even a handsfree system - does not lead to additional risks for the driver.

PROBLEMATICS - AIMS

Telephoning while driving represents additional information for the driver to process. Some studies *(1,2,3,4,5,6)*, carried out in real driving situations or on a driving simulator, have shown that the use of a car phone increases the drivers' mental load, and leads to damage their driving performance. Is there no risk that the resulting mental load modifies the driver's behaviour up to leading to risky situations ? The aim of the present study is to experimentally assess the potential risk on road safety connected with the use of a handsfree car phone while driving *(7)*.

METHODOLOGY

The research was done on an interactive driving simulator in order to place all the drivers in the same driving conditions. Seventeen subjects were recruited according to two age groups - nine were 18-35 years old and eight over 45 - in order to carry out the following experimentation : to hold a phone conversation in response to the call of a subscriber being in the network, while driving on a simple route (the same for all subjects) and trying to respect speed instructions (90 or 130 kph).
In this experimentation, only the speed of the vehicle has been considered as an objective parameter. Morover, subjective aspects have been collected with the aid of a questionnaire concerning 1) the possible causes of difficulties encountered during the conversation (noise, understanding, dual task, simulator use), 2) the tendency to change one's driving while telephoning, and 3) the difficulty in telephoning while driving.

About forty routes have been performed.

RESULTS

The analysis of results deals with speed variations during the routes on the one hand, including the comparison with and without telephone call, and responses to the questionnaire on the other hand.

Speed variations

The analysis consists in observing speed signatures i.e. the variation of speed as a function of time. Figure 1 gives an example of signature.

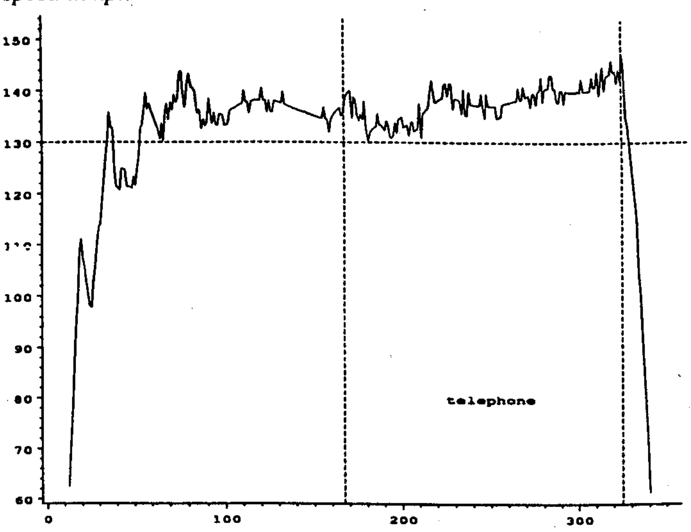

Figure 1 : Example of signature of speed

It is thus possible to discriminate two types of behaviour as regards speed :

1) the "**without effect**" cases (18 cases out of 39), for which no driving modification has been detected in the comparison *before call / during conversation* :

- some, after stabilization, are keeping a constant speed,
- others have some difficulty to stabilizate the speed (symetric and steady oscillations of about 15 to 20kph),
- a few others, at last, have significant difficulty to stabilizate the speed (oscillations of more than 50 kph).

2) those for which the fact of phoning has resulted in a sort of "**behaviour stiffening**" as if, being unable of doing two tasks simultaneously, they postponed one task or the other alternately, sometimes giving a greater importance to driving or to phoning at other time. This principle is illustrated by the Figure 2.

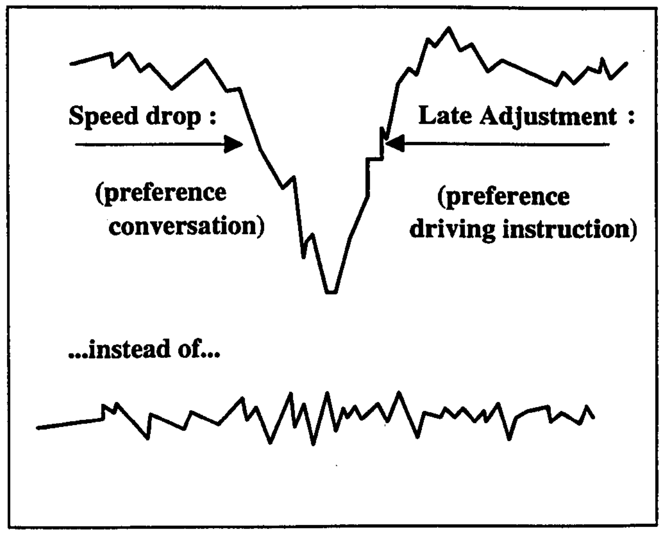

Figure 2 : Principle of "behaviour stiffening" in relation to speed

This behaviour was translated into different ways :

- by a steady increase of speed (about 30 kph) without any attempts to correct it,
- by a constant speed
- by an increase of the period of speed oscillation (e.g. from 60 sec to 100 sec, or from 90 sec to 160 sec),
- by a loss of speed control, leading to oscillations whose amplitude can be over 80 kph.

For all the cases observed in this category (21 out of 39), it seems that there was a conflict between the two tasks, driving and telephoning, and driving has often lost his status of prime task.

Note : the statistical analysis does not show any significant differences between situations with and without telephone, whatever the age group, at the most only a tendency to increase the speed when the restriction was fixed at 130 kph.

Responses to questionnaire

After each test, three questions were asked to the drivers :

- the possible causes of difficulty,

- the tendency to change one's driving while telephoning,
- the discomfort experienced by the fact of telephoning while driving.

Causes of difficulty - Figure 3 displays how causes are distributed according to age category and speed.

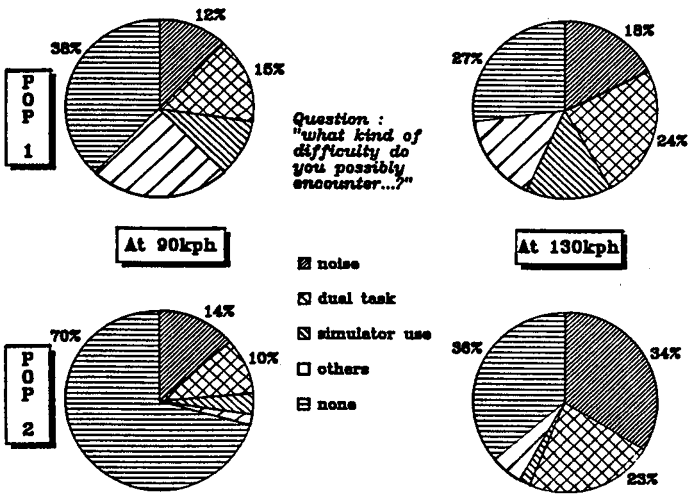

Figure 3 : Causes of difficulty

It appears, globally, that young subjects (POP1) have felt more difficulties than the older (POP2) ; the main causes are noise and dual task *(8)*.

Driving while telephoning - The graphs of Figure 4 show that the fact of telephoning would rather encourage drivers to slow down whatever their age, particularly at 130 kph : 1 out of 2 (1 out of 3 at 90 kph) *(8)*.

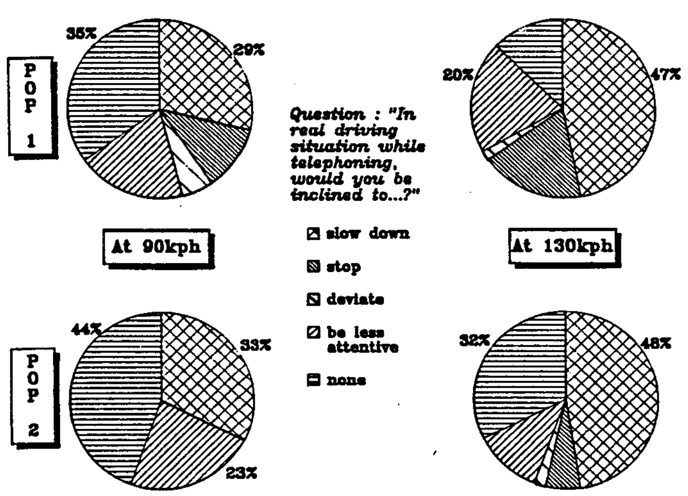

Figure 4 : Tendency to change one's driving while telephoning

Telephoning while driving - As it can be noticed from Figure 5, it does not seem that drivers over 45 are faced with many difficulties. On the other hand, at 130 kph, more than half younger drivers have been hindered up to being unable to pursue conversation or to asking the caller to repeat, or to feeling like hanging up *(8)*.

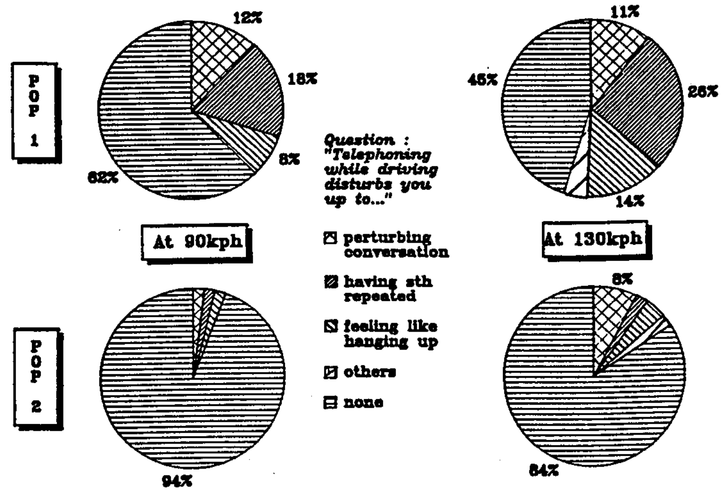

Figure 5 : Difficulty to telephone while driving

DISCUSSION - SYNTHESIS

At the end of this exploratory study, it seems that, in the majority of cases, a phone call constitutes a source of conflict for the driver, which he can more or less easily manage.

- Out of the seventeen subjects of the sample, only two of them did not modify their speed and did not feel any trouble while telephoning.
- For nine subjects, there was a conflict provoked by the increase of the mental load but driving kept its status of prime task. In this case, the drivers felt some trouble which led them whether to modify their speed or to declare they would have slowed down in real driving conditions, or to less keep up with the conversation or to have something repeated.
- For the other subjects, there was a mental overload : the dual task constitutes a well known source of difficulty which, in real driving conditions, would lead to whether paying less attention to the road, or to slow down or even to stop. This overload forces the driver to have something repeated and would even prompt him to hang up. And so, the conflict will become a hard situation to manage; the secondary task will often override the prime task.

The Presentation of Headway Information to Drivers

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Paper No. 94-S2-O-10

ABSTRACT

A large projection screen was used in conjunction with a stationary vehicle to investigate the most appropriate way of presenting headway information to drivers. Videos of moving approaches to a parked vehicle were shown on the screen, and overlaid by various auditory and visual displays to simulate head-up presentation of headway information. Subjects seated in the stationary vehicle were required to operate the brake pedal to indicate the last moment at which braking must commence in order to avoid collision with the vehicle shown on video. Objective measures of subjects' braking responses were captured via activation of the brake pedal, and subjective preferences concerning the various interface options were recorded by questionnaire. Analysis of the objective data showed a significant difference between 'abstract' and 'pictorial' display conditions, with the 'abstract' condition producing earlier braking. The subjective data revealed that subjects preferred the 'abstract' visual display and a non-speech auditory display. The findings are discussed with respect to the design of collision avoidance headway displays. The work reported here was conducted under the BRIMMI project: part of the EUREKA PROMETHEUS Programme.

INTRODUCTION

Recently the development of in-vehicle collision avoidance systems (CAS) has become possible due to advances in sensor technology. The purpose of these systems is to alert the driver to potentially hazardous situations, and thereby reduce the risk of accidents caused by detection failures. However, there are significant human factors problems to be overcome before the potential of anti-collision technology can be realised. Assuming that the initial uptake of CAS will be for systems exerting a minimum level of intervention, the immediate problem concerns the assignment of an appropriate sensory modality for warning presentation. The focus of the current discussion concerns the warning presentation mode and display format of collision information to the driver.

As driving is predominantly a visuo-spatial task, which places its greatest load on the visual attention system, warnings presented via a visual display may themselves go undetected. In contrast, the auditory mode of information presentation appears to offer a natural choice for designers of in-vehicle systems in that the output of both speech and non-speech displays is eyes-free: that is, the user can attend to an auditory display whilst engaged in a simultaneous task requiring both visual and physical performance, irrespective of where they are looking. However, despite the potential flexibility of both speech and non-speech auditory displays for in-vehicle use, the range of individual differences in hearing acuity and the variability of noise levels in the vehicle environment preclude absolute reliability in the detection of auditory warnings. Therefore, In view of these first results, it is advisable to carry on a more systematic investigation of the various elements found in the driving situation such as lane keeping, speed, reaction time, eye direction. Age and practical experience of car phone will be taken into account in this further stage.

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Tome 1: Rapport technique - Rapport n° 9207 - Mars 1993

*Tome 2: **Résultats** - Rapport n° 9208 - Mars 1993.*

given that visual and auditory warnings can pass undetected, it is likely that a successful CAS design will feature the provision of redundant information via the available sensory modalities, ie visual, auditory and tactile. Haptic information can be used as a supplementary display channel when the primary visual or auditory channel is degraded or overburdened, or as a substitute display channel if the primary channel is closed (Sorkin, 1987). For a more detailed discussion of the general suitability of visual, auditory and haptic feedback for in-vehicle display applications, see Stokes, Wickens and Kite (1990).

The aim of the present study is to examine interface issues relating to the presentation of headway information to drivers. Given the assumption that a successful CAS design will feature redundant information presented via the available sensory modalities, and that the existing research has compared the efficacy and acceptability of warnings presented in different modalities in isolation, eg Panik (1984), Janssen and Nilsson (1991), the current study will investigate combined modality warning presentations, ie integrated visual and auditory warnings. Haptic displays are not considered because the available experimental facilities are unable to support this mode of information delivery.

EXPERIMENTAL DESIGN

In all, six conditions were tested: 'abstract' and 'pictorial' visual displays combined with speech and non-speech auditory displays yielded four 'warning' display conditions; an 'informative' display condition, ie a 'fill bar' type visual display; and a non display mediated 'control' condition where subjects made 'free' braking decisions.

The abstract, pictorial and informative visual displays employed in above conditions are shown in Figures 6 to 8 (Appendix 1). The 'abstract' display is continuous rather than discrete and based on the familiar 'traffic light' sequence, such that green represents a safe headway clearance. The 'pictorial' display comprises an iconic vehicle representation whose appearance coincides with warning activation, and is replaced within 0.2 seconds by a similar but larger icon. In the case of the 'fill bar' the size of the display corresponded to the inter-vehicle headway. This display was accompanied by a series of auditory tones whose temporal separation was reduced as headway decreased.

The experiment employed a within-subjects design, where all subjects participated in each of the six conditions described above, with the presentation order balanced across subjects. Each condition comprised a block of 16 short video sequences showing approaches to a parked vehicle at various approach speeds and distances. Approach speeds of 30mph and 40mph, and distances corresponding to initial TTC values of 8 and 12 seconds were used within each block, with 4 repetitions of each speed-distance combination. The presentation order of the video sequences was randomised across the blocks, but given the inflexibility of the videotape medium, the order remained constant within each block.

All visual displays were presented in the upper right hand side of the video sequence. The abstract and informative displays measured approximately 24 by 4 inches, and the larger pictorial display approximately 12 by 12 inches. The auditory displays consisted of a single warning tone (500 Hz) in the non-speech conditions and the phrase "Danger Ahead" in the speech condition. Both displays were of 0.86 seconds duration, and presented via a pair of miniature speakers (Sony SRS-37), mounted on the rear parcel shelf of the experimental vehicle. A TTC warning activation criterion of 4 seconds was employed in the experiment, based on the recommendations of Horst (1984).

Subjects

12 male and 12 female subjects with ages ranging between 23 and 57 were recruited from the general public. Subjects were required for approximately 90 minutes and paid £15.00 for their participation. 2 male subjects were used in pilot trials.

Materials

An off-road test facility was used for production of the required video footage. A vehicle equipped with video recording facilities and a Leica ODIN distance measuring system was used to approach a stationary vehicle from a sufficient distance to allow constant approach speeds of 30 and 40 mph over 300m. The approach was made on a collision course and so the approach vehicle was required to veer off course to avoid collision.

Procedure

A large screen projection facility comprising an overhead multiscan projector (Sony VPH - 1271QM), a Super VHS video player (Panasonic AG 7350), and large projection screen, was used for the study in conjunction with a stationary experimental vehicle. Videos of moving approaches to a parked vehicle were shown on the screen, and overlaid by visual and auditory displays to simulate the head-up presentation of headway information.

Subjects seated in the experimental vehicle were required to operate the brake pedal to indicate the last moment at which they considered braking must commence in order to avoid collision with the vehicle shown on video. The positioning of the vehicle in front of the screen facilitated a 25° vertical by 40° horizontal viewing angle consistent with the field of view of the lens used to record the video image. The video footage continued until shortly before a collision would have taken place (ie a final TTC value of 2 seconds). The video remained blank in between video sequences.

Objective measures of subjects braking responses were captured via activation of the brake pedal. On completion of all six blocks, a final questionnaire was presented to subjects concerning the various displays.

RESULTS

Objective Data

Paired t-tests were employed to examine the differences between the 'informative' and 'warning' displays; 'abstract' and 'pictorial' visual displays; and 'speech' and 'non-speech' auditory displays. There was no significant difference between the scores in the informative display condition and the combined scores of the warning display conditions, or between the speech and non-speech conditions. There was however a significant difference between the abstract and pictorial display conditions ($t=3.55$, $p<.005$) with the abstract condition producing generally higher braking scores, ie corresponding to earlier braking.

An Analysis of Variance (ANOVA) was carried out on the subjects braking data. The ANOVA contained three within factors: Display, Approach Speed and Duration. The significant results are presented in Table 1.

Table 1
Significant Results from ANOVA on Braking Data

Factor	df	Sum of Squares	Mean Square	F-value	P-Value
Display Condition	5	14.94	2.99	5.10	.0003
Duration (TTC)	1	14.28	14.28	32.1	.0001
Display, Speed and Duration	5	1.54	.31	2.84	.02

Display Type and Braking Decision Points

The results of the ANOVA suggested that there was a significant difference between display conditions ($F = 5.1$, $p < 0.01$). A plot of the mean braking scores for each display condition can be seen in Figure 1, which indicates that the above difference is largely due to the influence of the abstract/speech condition (C4) which produced higher braking scores than all other conditions.

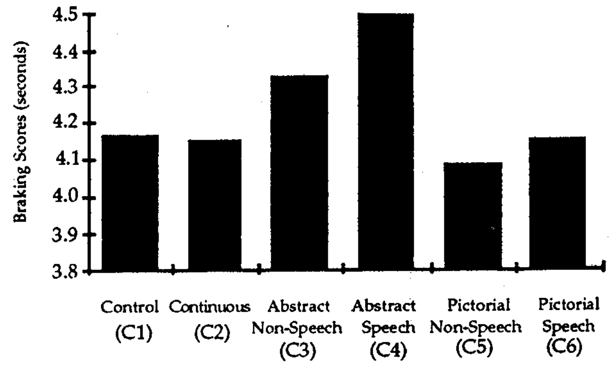

Figure 1. Mean braking point for each condition.

A subsequent Fishers Protected Least Significant Difference (PLSD) test indicated that there were several differences, significant at the 95% level, between the conditions. The only difference between the control condition (C1), where no display was presented and subjects made 'free' braking decisions, and the experimental conditions was between 'free' braking and the abstract/speech condition (C4): where subjects braked earlier with the abstract/speech display. The abstract/speech condition (C4) also produced significantly higher braking scores than all other experimental conditions other than the abstract/non-speech condition (C3). The scores produced for the abstract/non-speech condition (C3) were also significantly higher than those in the pictorial/non-speech (C5). This suggests that the abstract type display, particularly when paired with speech, leads to an earlier braking response. There appears to be no difference between the results produced by the other conditions and the non-display mediated response.

Approach Speed and Duration

The speed and duration of approach were varied during the trial in order to find out if these variables affected the subjects judgement of time-to-collision. The ANOVA showed no significant difference between the two speed conditions (30 and 40 mph). A t-test carried out to examine differences between the control and experimental conditions with regard to speed also failed to produce a significant result. However a significant difference ($F=32.1$; $p<0.01$) was shown to exist between braking scores pertaining to the two approach durations (ie initial TTC values of 8 and 12 seconds). A plot of the subjects braking scores for these two conditions is presented in Figure 2, where it can be seen that all subjects braked earlier in the longer approach condition (initial TTC = 12 seconds).

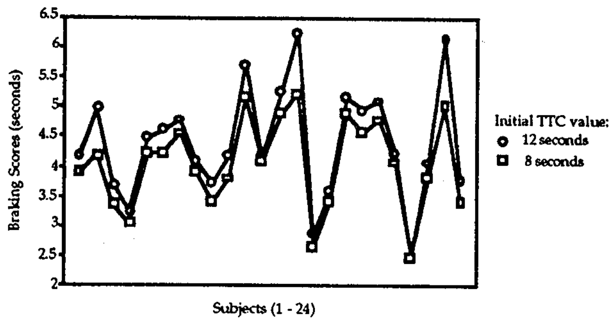

Figure 2. Subject braking scores for the two approach durations.

Display, Speed and Duration of Approach

The ANOVA also suggested that there was a significant interaction effect between the display conditions, speed and the duration of approach ($F=2.84$, $p<0.05$). The plot shown in Figure 3 illustrates this effect.

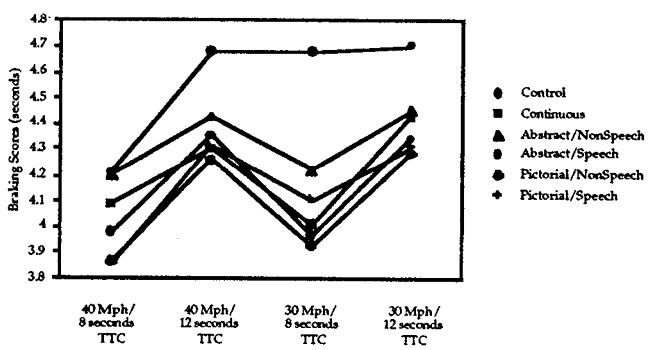

Figure 3. Mean braking scores by speed and duration of approach.

The abstract/speech condition (C4) produced higher braking scores than other display conditions in both of the 30 mph conditions and in the 40 mph condition at 12 seconds TTC, but there appears to be little difference between any of the scores produced in the 40 mph condition at 8 seconds TTC. The results of a post hoc one-way ANOVA and subsequent Fishers PLSD tests confirm this difference to be significant at the 95% level of probability.

Minimum Braking

In order to determine the number of braking decision points which in a realistic situation would have resulted in collision, minimum braking times based on a deceleration rate of $-7m/s^2$ were subtracted from the subject braking response times. For example at 30 mph, any braking response later than a TTC value of 1.92 seconds would have resulted in a collision. As shown in Figure 4 below, most 'collisions' occurred in the continuous display condition (C2), and less than half the number of 'collisions' obtained in the 'free' braking condition (C1) were produced in both the abstract/non-speech and the abstract/speech conditions (C3 & C4 respectively).

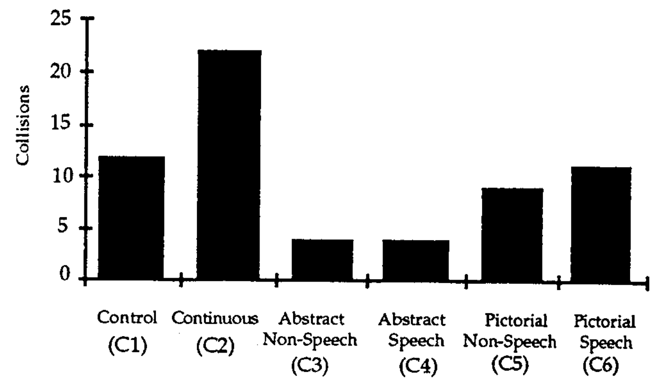

Figure 4. Number of 'collisions' in each of the display conditions.

Questionnaire Data

After completion of the trials subjects were given a final questionnaire where they were asked to rank their order of preference for displays. Figure 5 below shows the rankings of the individual conditions where the display attributes are combined. Here most subjects ranked the abstract/non-speech display (C3) as their first choice. The continuous display (C2) received more first choices than the other abstract display (C4) which had produced the best objective responses: ie earlier braking. A Wilcoxon Signed Rank Tests confirmed the abstract/non-speech display (C3) as the subjects first choice, but there was no significant difference between the rankings given to the abstract/speech and continuous displays (C4 & C2 respectively).

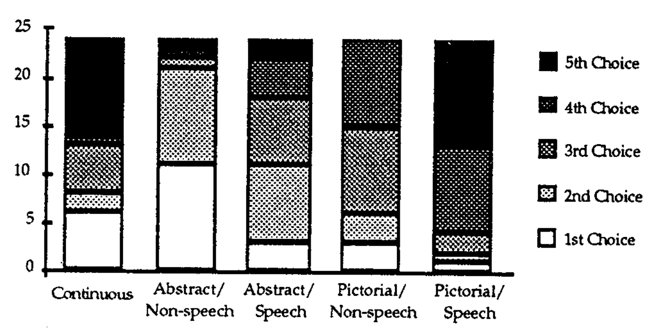

Figure 5. Subjects ranking of display preference.

DISCUSSION

It is apparent from the analysis of the objective and subjective data that the abstract visual warnings were superior to the pictorial variety. The abstract type display led to earlier braking responses, produced the least number of 'collisions', and was ranked first by most subjects. This finding tends to complement the conclusion of Gantzer and Rockwell (1968) that whilst improved performance in vehicle control can be obtained by the provision of supplementary visual headway information, drivers engaged in highly time critical situations are unable to benefit from such information because they are reluctant to divert attention away from the primary visual source. In the case of the abstract warnings, the visual display was available during the entire approach to the stationary vehicle, and so subjects were able to use the supplementary information to augment their braking judgements. The fact that the abstract/speech warnings gave rise to earlier braking responses than the non-display mediated control condition tends to support this rationale. In contrast, the pictorial warnings were only displayed when collision was imminent: at precisely the moment when the driver least needed a source of visual distraction.

With regard to the auditory displays, the results of the objective and subjective data analyses are less clear cut. Overall no significant difference was found between the braking scores for the speech and non-speech displays, but subjects clearly preferred the non-speech warnings. Whilst a few subjects specifically mentioned that they disliked the voice used, it may be that speech warnings are generally more irritating than discrete auditory tones. Whatever the case it appears that the speech warnings caused the greater annoyance, and several factors may have exacerbated the effect. First, subjects were unable to escape the presentation of the auditory warnings irrespective of when they activated the brake, and therefore were potentially exposed to a large number of 'false alarms'. Second, the fact that only one type of warning was displayed meant that in the case of the speech conditions the same speech warning was presented over and over again. Third, given that there were no response alternatives to braking, the actual informational content of the speech warning was largely redundant.

In contrast to the subjects preference for non-speech auditory warnings, the comparison of the individual conditions showed that the abstract display, especially when combined with speech warnings, led to earlier braking behaviour. A number of previous studies have indicated the superiority of speech displays over non-speech displays in terms of performance measures. Kemmerling et al. (1969) and Mellen (1983) both reported that visual displays combined with speech warnings resulted in shorter response times than the same displays when combined with non-speech warnings. However, in the current experiment subjects did not engage in a simple reaction time task where they were obliged to activate the brake on presentation of the warning. Rather, they were required to indicate the last moment at which braking must commence in order to avoid collision with the vehicle shown on video, and to use the displays provided to aid their decision. Also, speech warnings were not superior to non-speech warnings per se; it was the interaction between the components of the abstract/speech display alone which produced the beneficial effect of earlier braking. Therefore the legitimate explanation for this phenomenon must lie with the combined properties of the auditory and visual displays.

Intuitively, it seems plausible that the greater the stress experienced by an individual, the more likely they are to become irritated by an irrelevant speech warning. Haward (1977) has identified a number of stressors including cognitive stress: eg, that which is experienced due to the workload produced by concurrent task performance. Assuming that the speech warnings actually caused annoyance, subjects may have used feedback from the visual display to preempt the speech warnings and activate the brake before their occurrence. As stated above, only the abstract warnings were available during the entire approach sequence. Whilst the above strategy, employed in the abstract/speech condition, would not enable subjects to avoid the speech warnings altogether, it may have served to reduce the level of annoyance. Admittedly this interpretation of the results would be stronger had subjects been able to avoid the auditory warnings altogether.

An alternative explanation is that subjects were concerned that the speech warnings were 'too slow' to give them enough time to react in time to avoid 'collision', and compensated by braking earlier. As above, they were able to use the feedback from the visual display to preempt the speech warnings.

CONCLUSION

The implications of the above findings to the design of collision avoidance headway displays are as follows. First, given that only the abstract visual warning achieved better performance results than the non-display mediated control, and that in general it was liked by subjects, it is recommended that this type of visual warning display should be employed. The display should also provide continuously available feedback as the one used in this study. It should be noted that the visual displays used in the experiment were presented in head-up mode. The assumption was that if one display was more effective than the others, then it was certain to be apparent in this superior presentation mode. Of course, there is no guarantee that the above findings can be extrapolated to other modes of presentation, ie mid-head and head-down displays.

Second, in collision avoidance systems which are dedicated to a particular type of hazard, eg a headway warning system, the use of a discrete non-speech auditory warning combined with the above visual display is recommended. This conclusion is based on the grounds that subjects clearly preferred the non-speech warnings. Also, whilst this type of display was not shown to result in braking responses that were significantly earlier than the non-display mediated control, it incurred fewer 'collisions'.

Third, where an integrated collision avoidance system is to be designed the use of speech warnings is advisable. Bertone (1982) notes that speech warnings are more informative than simple auditory tones, and they not only alert the user to the problem but also provide more cues as to its nature. The fact that language is highly over-learned means that speech is likely to be more effective in conditions of high workload or stress, where the meaning of coded auditory tones may be forgotten (Edman, 1982).

As stated previously, a number of experimental factors contributed to the unpopularity of the speech warnings: ie, subjects were exposed to a large number of 'false alarms' where warnings occurred after a braking response, the same warning was presented repeatedly and its informational content was redundant. However, it is apparent that speech can cause irritation, and therefore it would be prudent to provide speech warnings as a 'default' option and make non-speech auditory warnings available as a user option. Of course, as in all cases where auditory displays are used, system designers must ensure that the it is possible to turn the displays 'off' and that false alarms are kept to a minimum.

One of the factors which influences the occurrence of false alarms is the activation criterion. The results of the experiment indicate that the criterion of TTC - 4 seconds may be too conservative and would result in a high number of false alarms, as most subjects thought they would brake at about the same time without a collision warning. Therefore, further research is necessary to investigate the effect of different TTC criteria on subjects' braking behaviour and acceptability.

ACKNOWLEDGEMENT

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Appendix 1: Visual Displays

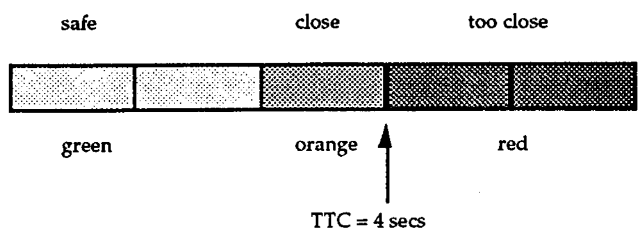

Figure 6. Abstract visual display.

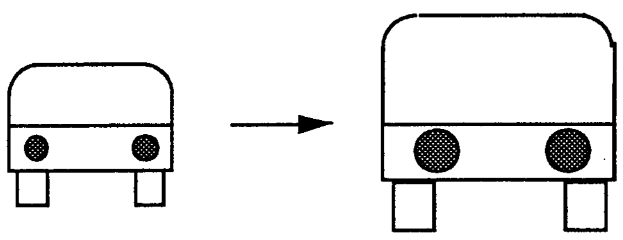

Figure 7. Pictorial visual display.

Figure 8. Informative visual display.

Safety Effects and Driver Acceptance of an Autonomous Distance Warning and Intervention System: Results From Field Trials

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94-S2-O-11

ABSTRACT

One of the main reasons for accidents especially on freeways is falling too short of a safe headway distance. This behaviour is often unintenional and caused by a lack of attention and the driver's inability for precise distance estimation.

Within TÜV Rheinland's PROMETHEUS project 'Integrated MMI-Solution for LOngitudinal COntrol (IMMIS-LOCO)' a driver assistance concept based on a visual display, an active gas pedal and an autonomous brake system (ITT Automotive Europe) is realized in an experimental vehicle. If the driver violates predefined distance limits, the assistance system presents a tactile warning (kick) on the active gas pedal combined with a visual explanation (pictogram) on the display. If the driver does not increase distance the gas pedal is pushed back and the autonomous brake system is activated. This intervention can always be controlled and overridden by the driver. Based on field trials on German motorways (Autobahn) with 'naive subjects' driver acceptance and safety consequences will be estimated. Layout of display, gas pedal and brake system and experimental results will be presented.

INTRODUCTION

Driving too close to the vehicle ahead for the speed the vehicle is travelling at is rated as the number one cause of accidents, at least on motorways (see Federal Department of Transport, 1992). Certainly some aggressive or reckless drivers simply disregard the need to maintain an adequate distance but, more often than not, man's limited ability to judge distances and relative speeds in particular is at the root of the problem. Another complication is that the driver's attention tends to wander as it is influenced by internal (cognitions) and external factors (e.g. working with the radio or mobile phone, see Becker, Bruckmayr, Krause & Wendland, 1994 ; Becker, Sonntag & Krause, 1994).

In view of these facts, it is only natural to start thinking about driver support systems which would warn the driver of critical situations, at least with regard to longitudinal control and which, by means of autonomous vehicle deceleration, could possibly help the driver to achieve a safe condition (see Janssen, 1989; Janssen & Nilsson, 1990). Although this approach is based on the same sensor and actuator engineering as the Autonomous Intelligent Cruise Control systems (AICC systems, see Bork, 1992; Nöcker, 1992), it offers a completely different concept for the driver. In the "classical" AICC system, the driver completely delegates longitudinal control to the system, at least within certain dynamic limits. In other words, although he has a supervising function, he is no longer directly and actively involved in longitudinal control of the vehicle ("out of the loop"). In the system presented here, the driver remains in partial control: He accelerates and the system decelerates as required. This means that he is actively involved in the control of his vehicle ("in the loop"). Both approaches have their advantages and disadvantages in respect of comfort, relief, safety and product acceptance and could be offered to the driver as alternative or supplementary systems depending on the situation.

The objectives of the project described here are to define the functional requirements to be fulfilled by such a support system, to produce a prototype and, in the course of driving tests, to determine its effects on the driver (comfort, safety, motivation to buy). At the same time, the results can be used for further development of the man-machine interaction in AICC systems (distance display and autonomous brake).

A brief initial outline is given in the following.

Concept of the Driver Support System

The warning and intervention system consists of the following three components (see figure 1):

- Display for presentation of distance and warnings

- Active gas pedal
- Autonomous brake system

The purpose of the system is to assist the driver with respect to longitudinal control by
1. keeping him informed of the actual distance (information function)
2. warning him if the distance drops below a critical limit or if a critical relative speed is exceeded (warning function)
3. assisting him with longitudinal vehicle control by means of a so-called active gas pedal (support function), and
4. intervening as required by activating an autonomous brake system (intervention function) until a safe condition is reattained.

Actuation of system activities 2 to 4 (warning, support and intervention) are governed by the distance to the vehicle ahead, the driver's own speed and the relative speed, additional assumptions relating to maximum possible vehicle deceleration and the driver's average reaction time. These elements are correlated in a formula EQ (1) for calculating the safe distance (d_S):

$$d_S = k_1 \bullet v_X + k_2 \bullet \mathrm{SGN}(V_{rel}) \bullet V_{rel}^2 \qquad (1)$$

$k1 = 0{,}8$ s : static distance term
$k2 = 0{,}11$ s²/m : dynamic distance term

The difference (Δd) between the safe distance (d_S) and the actual distance (d_X) ahead is compared by the system controller with distance limits given for each driver support component EQ (2).

$$\Delta d = d_S - d_X \qquad (2)$$

The purpose of the overall project, consisting of three successive work packages (display, active gas pedal, autonomous brake system) is to specify the functional layout of the individual components and to test them experimentally in driving tests.

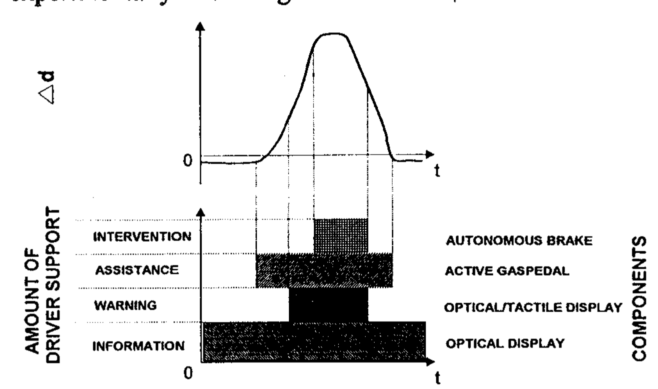

Figure 1. Relation between difference distance (Δd) and timepoints of system activities

RESULTS

Work Package 1: Display

The objective of this work package was:
- To develop different information and warning displays from the point of view of the information presented (what is displayed) and the way in which it is presented to the driver (how it is displayed).
- To test these displays in driving tests with "naive" subjects
- To evaluate motivation to buy and product acceptance of distance information and warning systems.

In order to evaluate the design versions obtained, four series of tests with a total of 48 subjects were performed on the A555 motorway (Cologne - Bonn). Each subject had to follow "in a safe distance" a target vehicle participating in the test. The different design versions were presented in a repeated measures design on a 5.5" TFT color display. This display was installed within the driver's primary field of vision, i.e. on the dashboard, in the TÜV Rheinland PROMETHEUS test vehicle. The display design of the final, best rated solution is presented in figure 2.

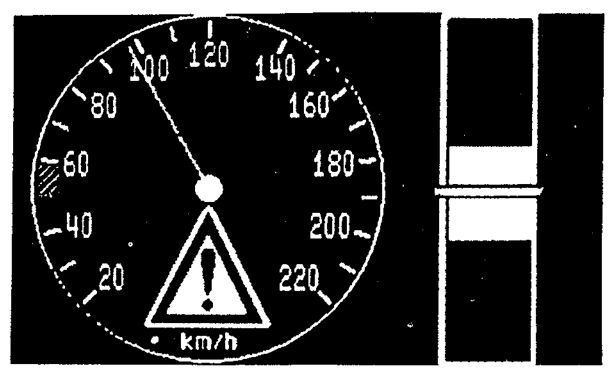

Figure 2. Distance information and warning display (final solution). Right side: bargraph with distance in seconds upper field: red, medium field: yellow, lower field: green

The subjects were asked to compare the design versions after the test. All parameters relating to longitudinal control were recorded as an objective criterion of the support function. These are still being evaluated. An analysis of the observations made by the subjects and their answers provided the following results:
1. Indication of the longitudinal distance in seconds was given preference over indication of the distance in meters or a difference distance (Δd) display as a permanent information feature. The subjects were of the opinion that this display best allowed them to maintain a safe, constant distance. However, the scale should be eliminated because some subjects had difficulty understanding it.
2. An additional distance warning (based on the difference distance criterion) was requested. This could be purely optical (e.g. flashing triangle) or a combined optical and

tactile signal (kick at active gas pedal). An acoustic warning was not favoured.

3. With reference to motivation to buy and product acceptance, a distance information and warning system was found to be advantageous and useful. The subjects were willing to buy the system but, on average, did not want to spend more than 413 DM. A representative classified survey of n=200 drivers at TÜV Rheinland's test centers confirmed this rather reserved result (between 230 DM and 358 DM depending on the product version; the results are presented in detail in Becker, S., Brauswetter, C., Hofmann, O., Mihm, J. & Sonntag, J., 1994).

Work Package 2: Active gas pedal

The objective of this work package is:

- To define the tactile characteristic of the active gas pedal
- To coordinate this with the optical display
- To establish product acceptance of this combined solution

Three series of each tests, are planned with 10 subjects. These will be carried out in June 1994 with the TÜV Rheinland PROMETHEUS test vehicle. An electrical lifting magnet connected to the gas pedal with a Bowden wire will serve as actuator. Advantages of this actuator development are the good controllability of force and position during gas pedal push-back and the short response times which permit tactile impulses with high edge steepness (kick). The active gas pedal is designed so that it can be overridden by the driver at all times.

Versions of the tactile characteristic which will be tested are as follows: Short impulse (kick) as a warning if the time distance from the vehicle ahead drops below a critical value of 0.8 s or if the difference distance (Δd) drops below a given limit. In comparison to this, the subjects will be asked to test a support function, in which the gas pedal is actively pushed back after the last actuation criterion until a safe distance is reached. The force required for this purpose will be defined and two versions will be tested, namely a first version in which the force can be set by the driver as desired, and a second automatic version in which the force is selected by the system itself.

In a second series of tests, the optimum versions of this tactile definition will be combined with the display versions from work package 1.

In a final field test, which will be designed on the basis of the AICC pilot study (Becker & Sonntag, 1993) for reasons of comparability, the optimum solutions from the two preceding test series will be subjected to a final acceptance test.

Work Package 3: Autonomous brake

The objective of this third work package is to carry out comprehensive driving tests in order to define the functions of an autonomous brake system which could considerably enlarge the control range realized by the engine braking performance (active gas pedal). A so-called research brake system designed by the company ITT-Automotive Europe was installed in the TÜV Rheinland test car for this purpose (Figure 3).

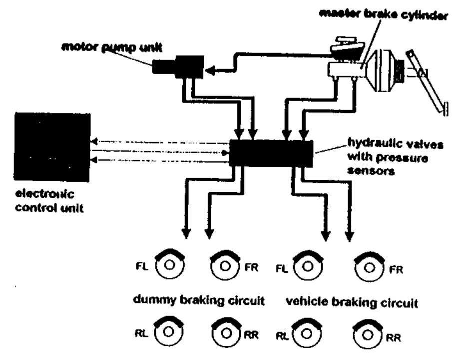

Figure 3. Schematic diagram of brake actuator

This brake system permits experimental manipulation of various influencing factors. In particular, the deceleration sequence which is acceptable to both driver and vehicle from the point of view of driving dynamics (comfort control versus intervention control) and the controllability of the system must be tested extensively. Furthermore the allocation of braking functions to the driver and automatic braking must be evaluated (Version 1: System off when driver brakes; Version 2: Summation of driver and system pressure; Version 3: Selection of maximum pressure (either driver or brake system). The tests will be carried out on motorways under real road traffic conditions (September 1994). The individual versions will be assessed on the basis of subjective evaluation (driver, observer), the driver's motor reactions (time and profile of brake actuation) and measurements of vehicle dynamics (deceleration and distance profile) as dependent variables.

In the last experiment, the interaction of all favoured functions of the three work packages will be checked.

DISCUSSION

Our own initial findings (Becker, 1992, 1993, 1994; Becker & Sonntag, 1993) and opinions put forward by other work groups (Minami, Yasuma, Okabayashi, Sakata & Muramoto, 1988; Nicklisch & Löffelholz, 1989; Farber & Paley, 1993; Godthelp & Schumann, 1993) lead one to expect that a longitudinal dynamic support system, like the "classical" AICC systems, will help to maintain a safe, constant distance between vehicles and will have a positive effect on the harmonization of motorway traffic. It is also very likely to enhance road safety, as assumed in various studies (e.g. Malaterre & Fontaine, 1992). Such support systems would also allow safety-related fluctuations of the driver's attention to be recorded, not directly in the sense of driver monitoring but indirectly by intercepting the negative consequences of such fluctuations. The classical AICC system, in which the driver delegates longitudinal control to the system at least within certain limits, and the support system described here, in which the driver remains in the loop, still have to be compared with regard to their effects on driver behaviour, the comfort they offer and product acceptance. However, there are first indications that the comfortable support and subjective feeling of safety ("the system will do it") given to the driver by an AICC system can lead him to take risks in certain situations which, in turn, could balance out any objective safety gain (Becker, Sonntag & Krause, 1994). Furthermore, the effects to be expected on driver behaviour and road safety if the control range is extended to include stop-and-go traffic and hence warning against and reaction to immobile obstacles (traffic jam) should be checked for both systems.

No clear findings are available on motivation to buy and product acceptance. Although positively assessed, a distance display as a stand-alone solution cannot be offered on the market at a profitable price. The price only reaches a realistic level if the warning function is combined with active control. These results were confirmed by a US marketing study (Turrentine, Sperling & Hungerford, 1991). The results also show that an experimental approach with the testing of prototypes must be selected for a valid estimation of driver-vehicle interaction and anticipated market chances.

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Mobility and Safety: The Mature Driver's Challenge

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ABSTRACT

As the numbers and licensure rates of older people increase, so does the need to focus on ways of ensuring the safety of all road users without unduly restricting the mobility of older drivers. The National Highway Traffic Safety Administration (NHTSA) is now conducting a coordinated research program designed to identify the safety and mobility needs of older people, with the intent of assuring that both can be satisfied.

Driving patterns and accident involvement of the elderly are reviewed, with emphasis on the role of medical conditions and functional limitations. Drivers who understand their own limitations tend to change their behavior to accommodate declining capabilities. Those unaware of limitations tend not to take corrective action, placing them at higher risk of crashes. Research under way to differentiate these groups and categorize their performance is presented. There is evidence that older drivers as a group are not a risk to others based upon their number of crashes per licensed driver.

INTRODUCTION

This paper is intended to give a better understanding of senior citizens as drivers. It presents a point of view that may be somewhat different from others. It hopes to show that by addressing the transportation issues of drivers with specific problems we can keep safer older drivers on the road.

Older Drivers as a Potential Problem

Extensive interest in the older driver issue started with the publishing of the Transportation Research Board (TRB) report: "Transportation in an Aging Society" in 1988. That report stated that there are going to be many more people over 65 after the second or third decade of the twenty-first century. Actually, this is going to be even more pronounced in other industrialized countries.

The TRB report indicated that older drivers were more likely to be involved in fatal crashes and crashes based upon the miles that they drove but that they have the same crash rate per licensed driver as middle age groups. The report noted that older people are much more likely to be killed in a crash; and that a driver who is over 80 is approximately 3 times more likely to die than a 20 year old because of his or her relative frailness (Fig. 1). This, however, is an occupant packaging problem, not a driver safety performance problem. The report went on to note that older people have declining capabilities that could influence their driving ability. The report indicated that current licensing examinations have limited ability to detect problem drivers.

The concern about older drivers was recently highlighted in the United States by two spectacular crashes. The crashes involved similar circumstances: an older driver inadvertently stepped on the gas instead of the brake, plunging the vehicle into a group of pedestrians, killing or injuring a number of people. Both crashes made national headlines. The inference was clear: older drivers pose a problem and perhaps we need to take them off the road. But, which age group actually kills more pedestrians? As Figure 2 shows, young drivers consistently kill more pedestrians than any other age drivers and older drivers kill the least number.

Older driver crashes are most often associated with failing to yield to traffic when merging, not responding properly to stop signs and traffic lights, or making unsafe turns. Behaviors that lead to older people's accidents seem more related to inattention or slowed perception and response than to deliberate unsafe actions, such as speeding, drinking and driving, and running traffic lights (NHTSA, 1993A).

Driving Patterns

There are those who say: "Let older drivers continue to drive, just not as much as before. Test them more frequently than younger drivers and gradually take away their driving privileges." This concept, called a "graduated license" (Malfetti and Winter, 1990). It would generally restrict older drivers to the non-rush hour times, which is when they drive and is when most older drivers crashes occur (NHTSA, 1993A).

What about their driving patterns? Most older people drive in familiar areas close to home on surface streets. This is where they experience most of their crashes. This exposes them to more dangers-per-mile than high-mileage drivers because they encounter disproportionally more intersections, more congestion, more confusing visual environments, and more signs and signals (Janke, 1991). Urban roads have a higher information load and require the driver to process more information and make faster decisions than do freeway driving situations. The changes in mental and physical abilities of older drivers places them at a distinct disadvantage for the denser urban situation (TRB, 1988).

We know, as Figure 3 shows, that as people get older they drive less - far less than do younger drivers (Foley et al., 1994A; Hu and Young, 1992). Older drivers are likely to be retired, so they can largely choose when to drive to the grocery store, the senior center, the doctor's office, or their children's or friends' houses. If they don't feel well or the weather is bad, they can usually put off the trip for another day.

Despite this decline in driving miles, most older people (as well as people in every age grouping) rely heavily on private vehicles for their transportation needs (Table 1). Dependence on these vehicles has increased over the past 20 years, while walking has decreased significantly, being roughly half of what it was in the 1970s. Public transportation, on the other hand, accounts for less than 3% of trips (Hu and Young, 1992).

We must exercise the greatest caution in imposing formal restrictions on drivers who have already adapted their driving habits to fit their changing capabilities.

Research on Driving Patterns

NHTSA and the National Institute on Aging (NIA) have joined in a study to measure changes in driving patterns of older people (Foley et al., 1990; Colsher and Wallace, 1993; Marottoli et al., 1993). The following paragraphs describe some of the findings.

As drivers age they become more conservative in driving habits. Men drive less at night, less on highways, almost never on unfamiliar roads. Men over 85 years old do no long distance driving and only a third drive after dark. Women echo these changes, only more so. They drive infrequently in unfamiliar areas and almost never on long trips. Night driving declines--in fact, only 8% of women over 85 drive after dark.

In related studies [California's Marin County (Satariano, 1993), Florida's Pinellis County (Stewart et al., 1992)], the licensing rates for women were similar to two of Iowa's rural counties (Colsher and Wallace, 1993) with approximately 80% of women in their 70's having a license, while only about 20% retained a license after age 84.

Men and women give up their licenses for different reasons (Foley et al., 1990). Vision problems, slowed responses, loss of confidence and license problems are the main reasons men quit. Almost a third of those over 75 have licensing problems. Women quit for somewhat different reasons. Loss of confidence was cited as the main reason in one study and cost in another. Licensing problems were not the major reason why women stopped driving.

We need to find out more about the basis for older drivers' lack of confidence. We will look at whether it is due to real or imagined incompetence, concern for personal safety (e.g., after breaking down), extensive medical conditions and frailty, or safety of others.

Mobility Issues

Many people recommend that older people use a public transit system in lieu of driving. But currently, public transportation accounts for less than 3% of trips (Hu and Young, 1992).

What do those who give up driving do? They stay home much more often. Foley et al (1990) found that in both rural (Iowa) and urban (New Haven) areas current drivers go out much more frequently than former drivers or people who have never driven. Of those who went out less than once a week, only 6 percent were licensed to drive. Inability to drive or ride in a car may preclude having a quality lifestyle. We need to determine why. Is it due to their declining functional abilities or due to lack of alternative transportation? If the latter is true, we need to determine what needs to be done to correct the problem.

Licensed Drivers

Based upon trends in current drivers' ages in the United States, there will be a marked increase in females over 70 licensed to drive. This increase will be about 12 percentage points a decade for the next four decades. As Figure 4 shows, the actual number of older drivers will jump from 13 million today to about 30 million in 2020. That's a lot of older drivers! At that rate, the rush hour in large retirement communities like St. Petersburg, Florida is likely to be at 12 noon! Not only will there be more older drivers but more of them are likely to be driving more miles than drivers today.

Safety Implications

Are older drivers an increasing threat to other drivers and pedestrians? During the years from 1980 through 1989 (Table 2; Barr, 1991)[1], the crash rate for drivers who were at least 65 fell from 11.6 per 100 drivers in 1980 to 7.9 per 100 drivers in 1989. This can be contrasted to the crash rate for all drivers of 21.0 in 1980 and 14.0 in 1989. Thus, older driver crash rates fell during the decade proportionally to that of all drivers, and their risk of being involved in a crash was much lower for both time periods. Thus, contrary to information in the press, older drivers do not constitute an undue risk to other road users. Clearly the consequences of a crash are more severe for older vehicle drivers and occupants (Fig. 1), than for younger vehicle drivers and occupants. During the years from 1980 through 1989, annual fatalities of motor vehicle occupants over 65 increased, the only age group to do so (Table 2). Therefore, the primary focus of the older driver program should be protecting older people in crashes.

Up to this point, we have been talking about the majority of older drivers - those who make appropriate adjustments to their driving patterns as their capabilities decline. There are, of course, some older drivers who do not make appropriate driving decisions and place themselves and others at risk of being involved in a crash. Our goals at NHTSA are to determine any characteristics that these problem drivers share and develop methods for regulating individuals who are likely to have problems driving.

RESEARCH PROGRAM

Based to a large extent on the 1988 TRB report, NHTSA developed a traffic safety plan for older persons (NHTSA, 1988). We then held a conference that took more of a medical approach than presented in the TRB report (NHTSA, 1989). This was followed by special editions of the Human Factors journal that synthesized the literature on older drivers (Barr and Eberhard, 1991 and Eberhard and Barr, 1992). Then a 1992 TRB Circular established priorities for the research and development needed to improve the safety and mobility of older drivers. These program development efforts, plus our ongoing research, served as a basis for the 1993 Report to Congress (NHTSA, 1993A) and an update of the NHTSA traffic safety plan for older drivers (NHTSA, 1993B).

Our program is on-going and encompasses research and program development activities. It will determine what the real issues are and what to do about them. Through epidemiological studies, direct observation, accident analyses and other sources it will determine which older driver groups are at higher risk and need assistance in regulating their driving. It will develop assessment techniques for use by state Department of Motor Vehicles (DMV), police, traffic courts, doctors and allied medical specialists, individual drivers and their lay caregivers. Wherever possible, it will design means to enable the older person to self regulate, because this is what they request to do (Yee and Melichar, 1992). Since not all older people will be able to self regulate it will identify those who are in the best position to assist them do it. Obviously, if an older person must stop driving, it is imperative that reasonable transportation alternatives be identified. These activities are being coordinated with the broader NHTSA research programs dealing with crash avoidance and crash survivability for older persons.

Medical Problems

Older drivers who have driving problems are suspected to also have medical problems -- but there is not enough data to be absolutely sure. The most serious of these medical problems are dementia, diabetes, depression, Parkinson's disease and visual pathology (Retchin, 1993).

There are a number of epidemiologically-oriented studies currently underway defining how older drivers go about changing their driving behavior (NHTSA, 1993B; Retchin, 1993). Among the studies are those in Marin and Sonoma Counties in California, and in Dunedin, Florida, as well as two studies at Yale and Iowa Universities. NHTSA is sponsoring these latter two studies. These studies are beginning to give us some objective data on how functional performance and medical conditions affect the driving decision and crash involvement. For the most part, the findings indicate that functional limitations are much more likely to be predictive of when individuals reduce or stop driving than they are predictive of crash involvement (Stewart et al., 1993). Generally, as people develop more physical restrictions, they are more likely to give up driving (Retchin, 1993; Stewart, et al., 1992; Marottoli et al., 1993). This bodes well for those who believe that the older person can be in charge of when he or she should or should not drive.

Some of the results of recent research are presented in the sections that follow.

Dementia

There is currently a lot of interest in dementia, particularly Alzheimer's disease (AD). There is a growing controversy about whether drivers in the early stages of dementia should be permitted to drive and, if so, how they can be monitored for continued safe driving.

Gilley et al. (1991) found that people with dementia do drive for a number of years after onset of the disease. Drachman and Swearer (1993) found that, based on caregiver reports, AD patients were 2.25 times more likely to be in a crash than age, sex and community matched individuals. Cooper et al. (1993) using official driving records in British Columbia matched controls on age, sex and location found a similar crash over-involvement rate: 2.4. Earlier, less well designed studies indicated much higher rates of crashes, while a more recent study by Waller et al. (1993) indicated that there were no elevated risks for demented drivers.

The real issue is when people with dementia should stop driving. Drachman and Swearer (1993) found that AD patients had more crashes per year than their controls but less so in the first three years. Additionally, demented drivers had fewer crashes per year than younger drivers (Table 3).
The Cooper study found rather different crash characteristics by AD patients as compared to other older drivers. They were much more likely to be responsible for the crash, had more night accidents and had fewer of their crashes at intersections.

Even if we were to agree that victims in the early stages of dementia could drive, do we have an adequate way to detect when they are no longer capable? Furthermore, how do they become known to the Department of Motor Vehicles?

Hunt, et al. (1993) found that caregivers are not currently in a very good position to judge when those with dementia should stop driving. If this is so, can caregivers be expected to either report them to the DMV or control them themselves? Research is needed to help identify problem older drivers, particularly those with dementia. The research will either help the community identify and regulate the problem drivers or to provide the DMV with input to re-examine and regulate them.

Visual impairments

Macular degeneration, paracentral scotomas (coincident blind areas in both eyes), glaucoma, and retinitis pigmentosis are among significant visual problems. In some of these conditions, the individual and close family members may be unaware of the problem until the driver has been involved in a motor-vehicle crash (Johnson and Keltner, 1983; Brown et al., 1993).

According to Johnson and Keltner (1983), those with overlapping scotomas had twice as many crashes in a year than age-matched drivers without the visual limitation. Those with glaucoma, another disease likely to affect peripheral vision, are also at higher risk (Wolfe, 1991).

Those with central visual acuity problems, the type of acuity tested for driver licensure, tend to reduce or stop driving if their conditions warrant it (Marottoli et al., 1993; Stewart, et al., 1993).

Perceptual/Cognitive impairments

Those with poor useful fields of view have been shown by Owsley et al. (1993) to be at much higher risk of crashes. However, a recent study (Brown et al., 1993) has not been able to confirm these findings. Performance on complex traffic sign tests have been shown to be difficult, particularly for those with dementia (Hunt et al., 1993).

Driver regulation

The key issue is whether older drivers are able to self-regulate or whether there is need for a graduated licensing system. Recent evidence indicates that if they are aware of their deficiencies and retain their cognitive ability, older drivers seem quite able to self manage (Colsher and Wallace, 1993; Marottoli et al., 1993; Stewart et al., 1992). Studies by Drachman and Swearer (1993); Hunt et al. (1993); Johnson and Keltner (1983), indicate that some older drivers are not as aware of their deficiencies. Those who are not as aware of their limitations, such as those with dementia, and parafoveal scotomas, tend to be at higher risk.

The American Association of Motor Vehicle Administrators (AAMVA) has developed a guideline (NHTSA/AAMVA, 1992) that addresses the older driver issues - with an emphasis on a graduated license. It would systematically reduce where and when an individual can drive based on his or her capability. Unfortunately the assessment tools needed to implement the program are not available. For example, DMVs for years have restricted some drivers to daytime only driving based upon the standard visual acuity test. This test basically measures photopic or daytime acuity but is not a test of mesopic acuity or the acuity needed for night-time driving.

There is concern about the extent to which current or proposed licensing procedures or medical, police or family reporting can identify those with problems. For example, most of the research on vision testing indicates that simple visual measures do not relate to crash involvement (Shinar, 1991; Owsley et al., 1991) and that the serious visual problems such, as blind areas in both eyes and glaucoma, cannot be detected by tests now being used in the DMV. And while the problems of older drivers appear to be related to inattention, we currently have no practical test for driver inattention. Current research indicates that the problems of older drivers are far more complex than things that simple, easy-to-measure and short-time frame tests can detect. Yet the practicality of examining thousands of people necessitates simple inexpensive measures.

Can the police identify demented drivers? Possibly, particularly if they have different types of crashes as the Cooper study indicates. McKnight and Urquijo (1992) studied police referrals of older drivers for license re-examination. Data from 5 states were analyzed to see what reasons police gave as the basis for their referral (Fig. 5). The most interesting finding of the study was that medical conditions were less frequently reported as the basis for referral as the age groups became older. The characteristic that did increase with age was sensory loss, which was primarily hearing loss. Since it is well known that there is an increase in medical conditions with older age, it is unclear why the oldest drivers were less frequently reported for such conditions. From the findings from Marottoli et al. (1993); Stewart et al. (1993); and Colsher and Wallace (1993), it may be that as multiple medical conditions occur, the driver simply reduces and eventually stops driving.

Can the DMV detect older problem drivers through the driver re-examination process? Possibly not under current procedures. Most states are trying to cut back on re-examination and renew by mail for those who have clean records. Furthermore, even for in-person re-examination, a study in British Columbia indicated that over 70% of people with dementia passed the standard road test (Tallman, 1992).

Can DMV personnel be trained to detect the symptoms of functional limitations likely to lead to unsafe driving in people who come in for re-examination? Can better tests be designed for use in the DMV? Since survey data indicates that they prefer to self manage (Yee and Melichar, 1992), can older drivers make their own decision on when and how much to drive? Our development program is addressing these issues and conducting studies to determine how to best assist older people regulate their driving.

Older drivers and their adult children and caregivers are becoming increasingly aware of the need for assessment. Generally, they do not know where to obtain help. Occupational therapists have indicated that they are beginning to see more clients who come for driver assessment based upon family concerns (Strano, 1993).

The American Association for Retired Persons (AARP) recently looked at the available assessment instruments that could potentially be used in AARP Evaluation Centers; however, the situation is much more complex and the number of validated tests is very limited (COMSIS, 1993). There are some simplified assessment tools available to older drivers but they seem to be too general to be of use to identify any complicated problems.

Develop Driver Assessment Procedures

In a recent conference on older drivers, the older driver panelists thought that there was a need for older drivers to be assessed but were not clear if it should be through periodic license examination or through private channels. They did indicate that the periodic license examination could be based upon the age of driver since they realized that many of the functional limitations that affect driving performance only begin to become prevalent in the upper sixties and seventies. In fact, surveys of general drivers, older drivers, physicians and others support more frequent re-examination of older drivers. The real issue is whether licensing examinations can fairly discriminate those people who need to have their license restricted or denied.

The current system in use in almost every state and Canadian province, brings drivers in for re-evaluation for some cause. The causes are an adverse traffic record, a physician report, a police officer referral after an accident or citation or a family referral.

What probably needs to be done is to improve that system and make certain that as many problem drivers as possible are detected **before** he or she gets into a crash. A clearer idea is needed about how older drivers go about performing the driving task and regulating their own driving. Otherwise, systems may be designed that either are not needed or cannot be used. Research into how older drivers, notably those with functional limitations, perform the tasks associated with intersection negotiation in familiar and unfamiliar areas is underway. If we find that drivers simply drive in their neighborhood during the daytime, knowing precisely where they are going, then developing elaborate night-time way-finding systems or night vision tests could be a waste of time and money.

If further research confirms that certain older drivers with extensive medical problems do not take themselves off the road, then developing elaborate, costly, time-consuming graded licensing systems may still not be necessary. A more pragmatic, acceptable, and successful way to control the riskier older driver may be to provide simple guidelines to the individual or his/her family or physician. The guidelines would enable the functionally disabled driver to judge the conditions under which they should or should not drive.

Before we can make recommendations to the states on detailed graduated licensing, procedures that identify and assess problem older drivers must be developed and rigorously evaluated. The evaluation should ensure that licensing agencies do not unnecessarily restrict capable drivers or permit drivers with real problems to slip through undetected. Unfortunately, it will be several years before the results are ready for implementation by the states. But as has been emphasized in this paper, the problem is not with all older drivers, just a select group who, comparatively speaking, are not involved with many crashes.

Alternative Transportation

If/there is a need to deny the older driver the right to drive, or restrain when they drive, then society must also be ready to provide alternatives. It is not fair nor in the best interest of society to remove someone's license without giving them alternatives. NHTSA, in conjunction with other government agencies and the private sector, needs to look into ways of maintaining the mobility of those who have to reduce their driving.

Public Information and Training

Because a lot of the pressure on DMV's to re-examine older drivers comes from the general public, the public needs to know that, as a group, they are causing far fewer crashes and are killing far fewer pedestrians than other age groups. They need to understand that older drivers are frail and, when involved in a crash, are more likely themselves to be seriously injured or killed. As research provides supporting evidence the general public needs to be told how they can help identify those older drivers who are at a higher risk and help in their regulation.

Training programs that assist older drivers and their caregivers are needed to facilitate correct driving decisions. For example, it may be necessary to look at the role confidence plays in driving decisions since our safest drivers, based on crashes per licensed drivers, are older women drivers, who quit before men. Since older women are likely to outlive their husbands by 8 to 10 years they may need to drive to maintain their mobility.

Working together, we can ensure that public safety is well served by identifying those older drivers who are truly too incapacitated to drive without infringing on the mobility that is so precious to us all.

ENDNOTES

[1] Crash data cited in Barr (1991) are from the National Safety Council's, Accident Facts, which contains trend data not available from NHTSA data. Discrepancies between similar data from different sources are attributable to differences in data-collection methodology.

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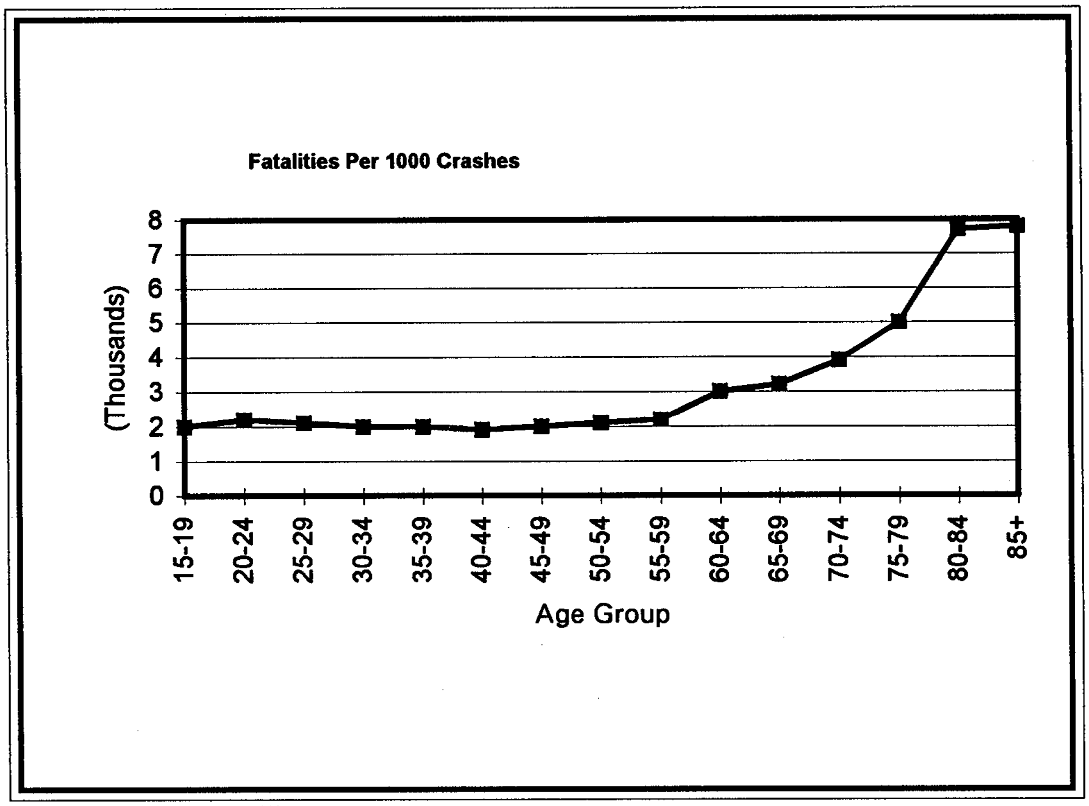

Figure 1. Driver Fragility

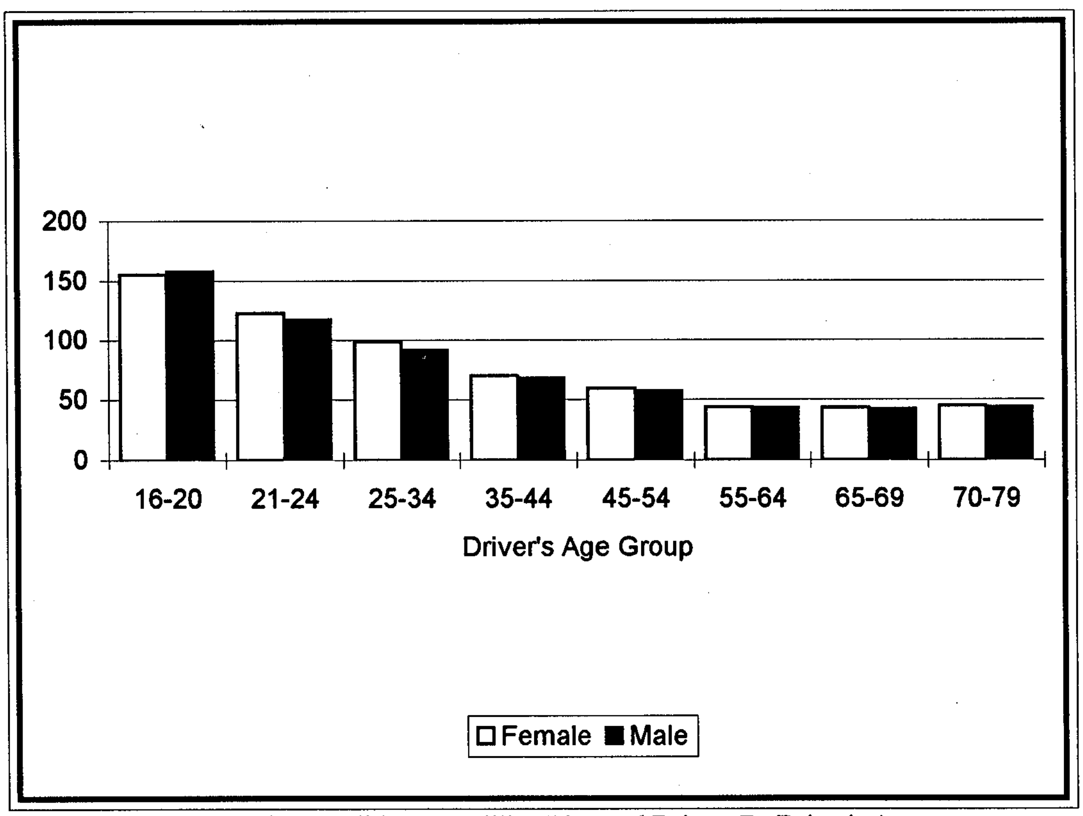

Figure 2. 1990 Pedestrian Fatalities Per Million Licensed Drivers By Driver's Age

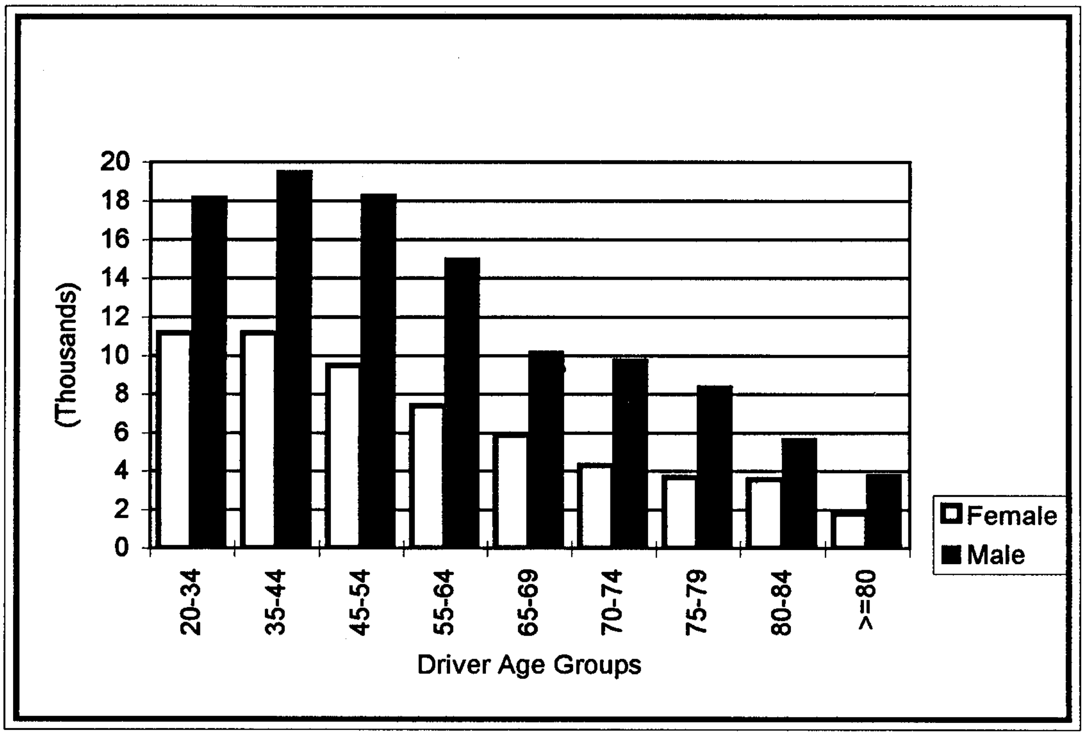

Figure 3. 1990 Average Annual Miles Driven

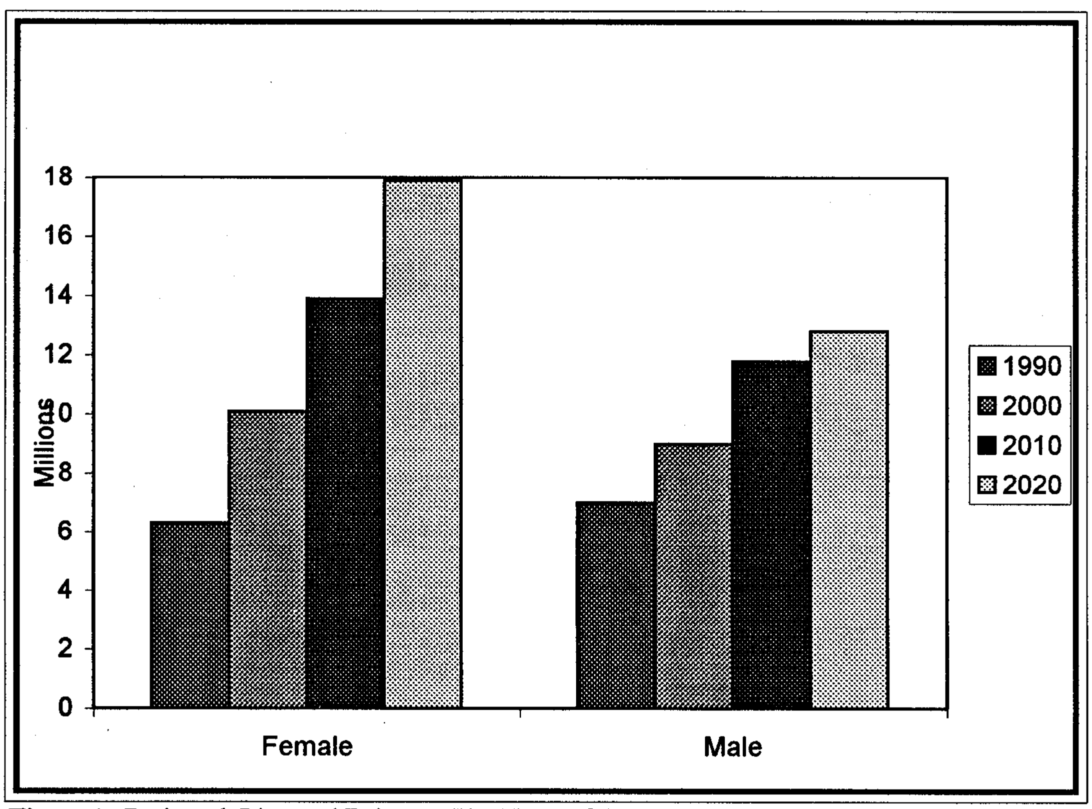

Figure 4. Projected Licensed Drivers - 70+ Years of Age

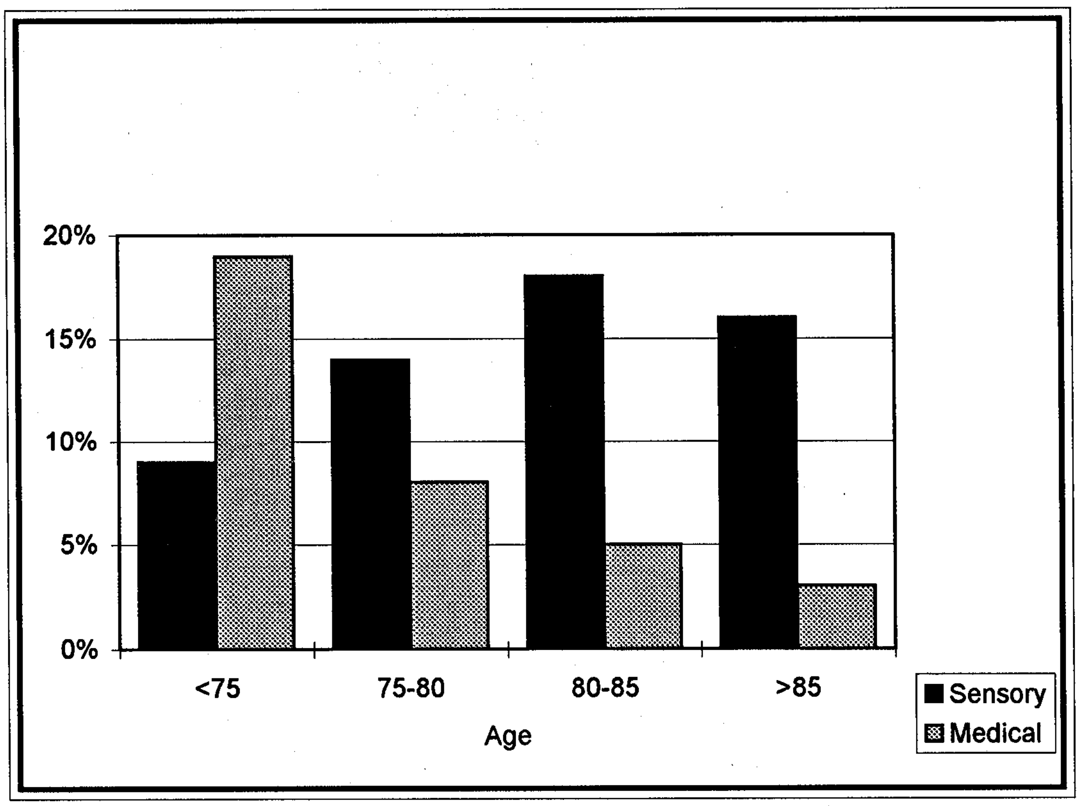

Figure 5. Change In Reason To Refer Drivers For Re-Examination By Police

Table 1
Percentage of Older Persons
in Urban Areas
Using Different Transportation Modes

	65-74		75-84		85+	
Mode	1983	1990	1983	1990	1983	1990
Private Vehicle	83	90	79	85	75	77
Public Transit	4	2	1	3	8	3
Taxi	0	1	1	1	0	3
Walking	11	7	17	10	18	16
All Others	1	0	2	1	0	1

Source: *National Personal Transportation Survey (FHWA, 1983 & 1990)*

Table 2

Fatality and Crash Statistics For Drivers Aged 65 And Older And All Drivers For 1980 and 1989

Measure	Drivers 65+		All Drivers	
	1980	1989	1980	1989
Total Fatalities	2,323	3,319	28,816	26,389
Deaths per 100 000 Population	9	10.7	16.7	13.8
Deaths per 100 000 Licensed Drivers	15.3	15.5	19.8	15.9
Crash Rate per 100 Licensed Drivers	11.6	7.9	21	14

Source: BARR 1991

Table 3
Crash Rate Per Year

Drachman and Swearer (1993) Data	
AD Group (n=83)	0.091
Control (n=83)	0.040
1990 National Data	
Drivers 65+	0.037
Males 16 - 24	0.148

The older driver problem: an epidemiological overview

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ABSTRACT

An overview of the risks drivers themselves face, and the risks they impose on other road users, is presented using the dependence on age and sex of various USA crash and fatality rates. While some measures of crash involvement increase with age, their values remain below those for drivers in their late teens and early 20's. If a 16-year-old male driver's crash risk declines by 7% throughout his life, his longevity increases by more than the longevity increase a 65-year-old driver obtains by reducing crash risk to zero. Reducing the younger driver's overall crash risk by 12% reduces the risk pedestrians face by more than reducing the older driver's crash risk to zero. Compared to the other risks of death as one ages, traffic risk plays an ever diminishing role; if an 18 year old dies, the probability that death is due to a traffic crash is almost 50%; for a 65 year old, it is under 1%. Much larger than any increase in driver risk with increasing age is declining driving. Thus the older driver problem may be more one of reduced mobility than of reduced safety. The above results are all based on cross-sectional analyses (examining rates of individuals of different age at the same time). A recent longitudinal analysis examined how the rates of a cohort of drivers changed as theses same drivers aged. This analysis showed that because older drivers had higher rates when they were younger than today's younger drivers, the increases with increasing age are in fact less than indicated by the cross-sectional analyses.

INTRODUCTION

The following three effects seem beyond dispute:

1. As drivers age, various physical (ability to rotate neck, muscle control), sensory (visual acuity, hearing), and cognitive (memory, information processing) capabilities relevant to driving decline.
2. As drivers age, their crash rates increase.
3. In the US in the future, because of changing demography, increased longevity, and increased universality of driving (especially by females), there will be enormously more older drivers than previously.

These three effects have generated concern that there is an impending major *older driver problem.* The purpose of this paper is to provide an epidemiological overview of the magnitude of this problem, relying mainly on material in [1], as recently presented in a similar format to the present in [2], and augmented by recent research [3]. Additional details and references are available in these sources.

The increase in driving risk with increasing age is best separated into two distinct components:-

Increased risks faced by older drivers,

and

Increased risks older driver impose on other road users

Legally and philosophically, 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.

INCREASED RISKS DRIVERS FACE AS THEY AGE

Figure 1 shows car-driver fatalities per million population in the early 1980's, as determined using Fatal Accident Reporting System (FARS) and census data. For males, it is clear that the rate increases steeply with age at older ages; at age 80 years, the rate approaches close to the peak value attained at age 19. Part of the reason for the increase in the rate at older ages for males but not for females is the lower fraction of older females who had driver licenses in the period covered by the data. Note that changes in the proportion of the population that is old, in the absence of other changes, is not expected to change Fig. 1 because the rate is already normalized with respect to population.

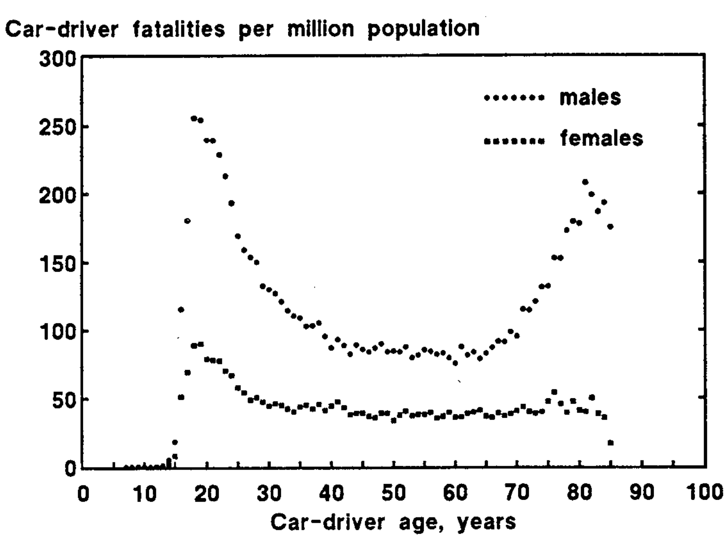

Fig. 1. Car-driver fatalities per million population versus age and sex (see [1], [2]).

Figure 2 shows the number of car-driver fatalities per licensed driver. The oldest age plotted, for drivers 70 or older, is the category used in the driver license data. Driver fatalities per licensed driver increase for drivers of both sexes at older ages. Male rates are considerably higher than female rates. Important contributors to this difference are that males traveled more, and when males and females traveled together, males were more likely to drive during the period covered by the data

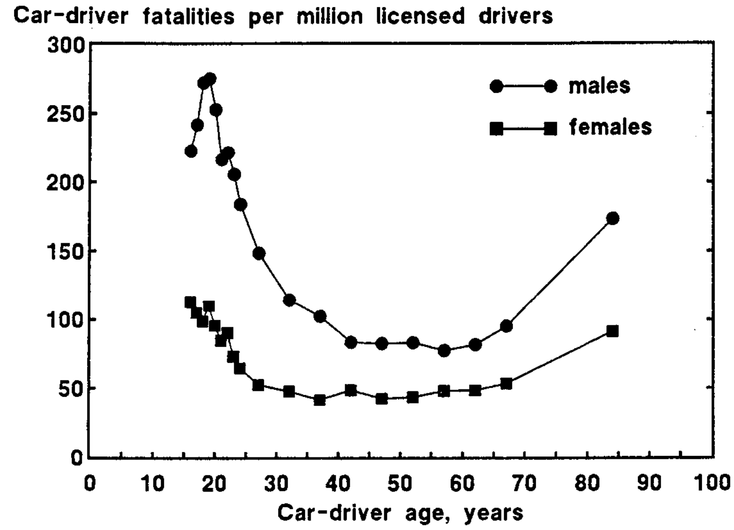

Fig. 2. Car-driver fatalities per licensed driver versus age and sex (see [1], [2]).

Because the patterns in Figs 1 and 2 depend directly on such changing social features as the number of persons obtaining licenses, amount of driving, and which occupant drives, it is preferable to look at the rate per unit distance of driving. This is shown in Fig. 3, computed using distance of travel estimates from the 1983 Nationwide Personal Transportation Study. The rate in Fig. 3 is not expected to change in any obvious way in response to increasing numbers of older drivers, increasing likelihood of obtaining a license, increasing travel, or increasing tendency for females to drive.

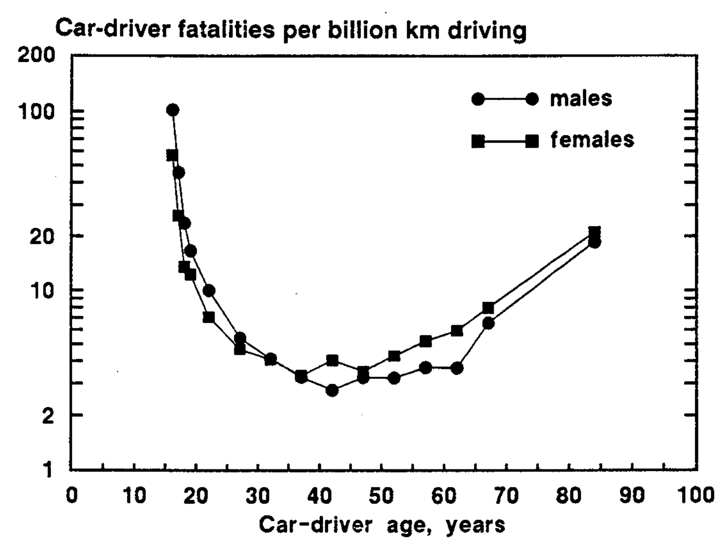

Fig. 3. Car-driver fatalities per billion km of travel versus age and sex (see [1], [2]).

The U-shaped patterns in Figs 1-3 contribute to general concerns about increasing crash involvement with age. Involvement rates in fatal crashes do not correctly reflect such changes because of the strong influence of age on fatality risk when a crash occurs. The number of drivers killed is the product of two factors:

The number of involvements in serious crashes,

and

The probability that involvement proves fatal.

The first factor reflects influences due to all use and behavioral factors, such as type of driving, driver capabilities, time of day, degree of intoxication, driving risks, etc.; it specifically includes all the factors likely to lead to declining driver performance. The second factor is primarily a physiological one. In order to examine separately the first of these factors, crash involvement, we require quantitative information about the second.

How does risk of death from the same impact depend on age?

This question was answered using data from over 80 000 vehicle occupants killed in crashes [1,4]. By focusing on vehicles containing two occupants of different age, at least one of whom was killed, and using the method described in [1], it is possible to extract the influence of age on relative risk of death for similar crash experiences. The results for 10 categories of male occupants are shown in Fig. 4; these occupants were killed by a wide range of impact mechanisms. For example, car-occupant fatalities usually are associated with impact on the vehicle interior, while motorcyclist fatalities come from impact with objects unrelated to the vehicle. The absence or presence of steering wheels, safety belts, helmets, cushioning effects of motorcyclist drivers in front, etc. all affect the details of the injury insult. Given these differences, the extent to which the 10 plots in Fig. 4 show similar features suggests that the effect displayed is due essentially to differences in basic susceptibility to trauma as a function of age, with the specific nature of the traffic crash being of secondary importance. That is, we expect that fatality risk would similarly depend on age for other types of potentially fatal physical insults, such as severe falls or blows from objects (including vehicles - the present method cannot be applied to investigate pedestrian fatality risk).

Figure 5 shows corresponding results for females; there are insufficient data to perform the analysis for motorcycle drivers, hence the 8 rather than 10 plots.

By collecting together data at common ages, the information in Figs 4 and 5 is summarized in Fig. 6. These data can be represented in convenient analytical form as

$$R_{males}(A) = \exp 0.0231\,(A - 20)$$
$$= 0.630 \exp(0.0231\,A) \qquad \text{Eqn 1}$$

and

$$R_{females}(A) = 1.3 \exp 0.0197\,(A - 20)$$
$$= 0.877 \exp(0.0197\,A) \qquad \text{Eqn 2}$$

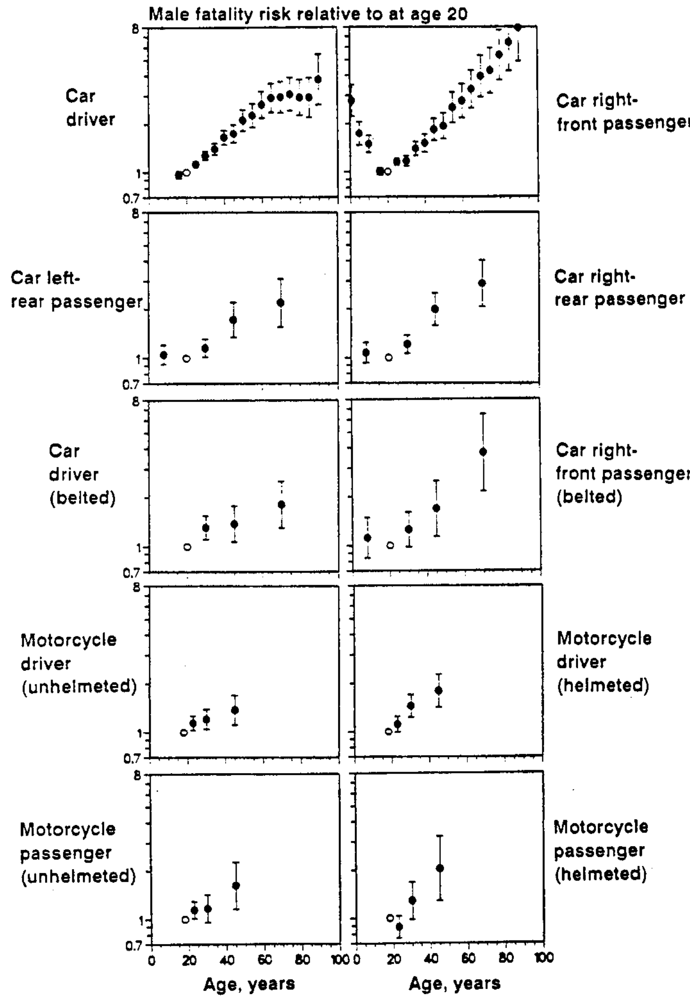

Fig. 4. Fatality risk from similar physical insults for males of different ages compared to that for 20-year-old males. Reproduced from [1].

for A ≥ 20, where A is age in years and R is the probability that a given impact will prove fatal relative to the probability that the same impact will kill a 20-year-old male. Once age exceeds about 20, fatality risk grows at an approximately uniform rate of (2.3 ± 0.2)% per year for males and (2.0 ± 0.2)% per year for females. At age 70 the risk is about three times what it is at age 20.

Involvement in severe crashes

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 kill 80-year-old male drivers, for which case R has a value of 4.0 (Eqn 1). Consider a set 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).

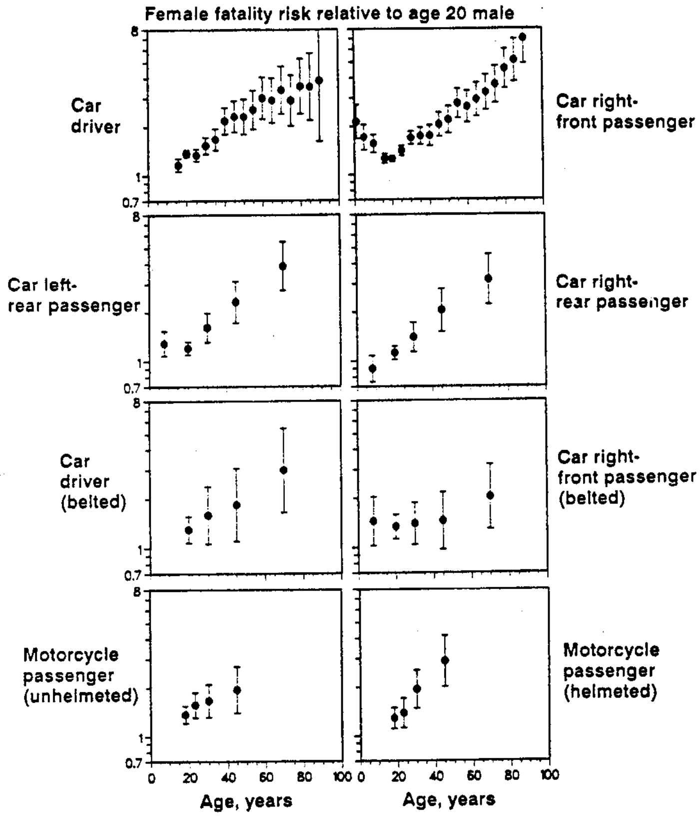

Fig. 5. Fatality risk from similar physical insults for females of different ages compared to that for 20-year-old MALES. Based on [4].

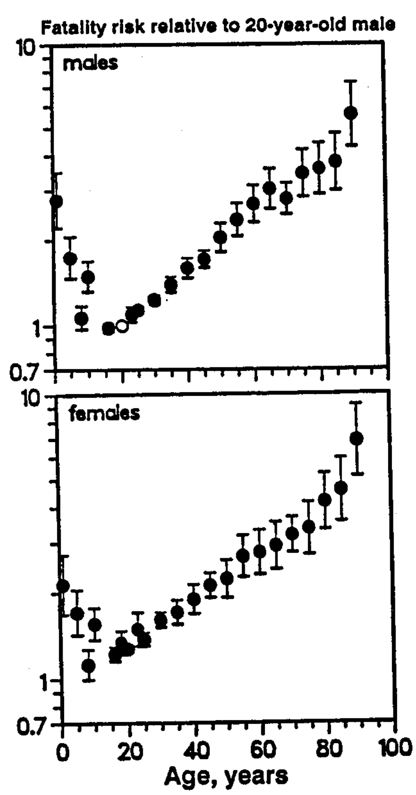

Fig. 6. Fatality risk from similar physical insult versus age for males and females. Synthesis of the information in Figs 4 & 5. Reproduced from [1].

In order to obtain the same number of fatalities, 4.0 times as many crashes by 20-year-old male 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 kill 80-year-old male drivers.

Figure 7 shows the number of involvements per capita in crashes in the severity range necessary to kill 80-year-old males versus car driver age and sex. In contrast to Fig. 1, there is now only a slight increase with age for older males. Note how much lower the rate at older ages is compared to at younger ages. Thus, a large mechanism generating the upward trend in Fig. 1 is the greater likelihood that a crash proves fatal, with an increase in crash involvement risk also contributing. Severe crash involvements per licensed driver (Fig. 8) barely exceed their minimum values as drivers age.

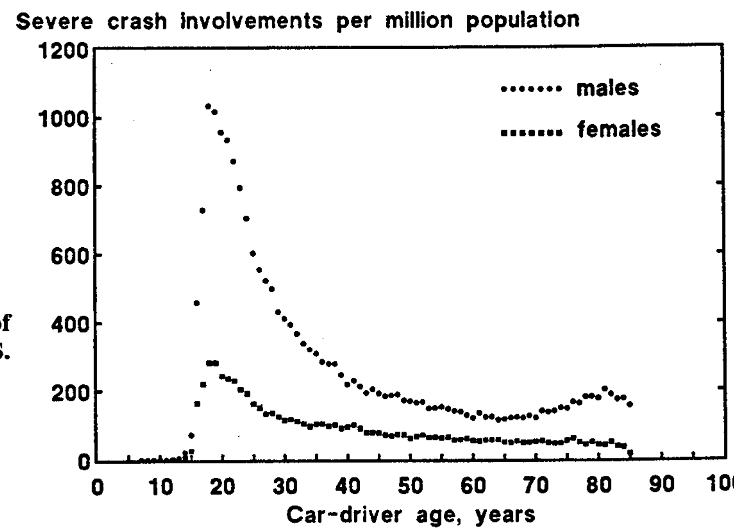

Fig. 7 Estimated car driver involvements per million population in severe crashes (those of sufficient severity to kill 80-year-old male drivers -- see [1], [2]).

The rate most indicative of driver behavior is severe crash involvements per unit distance of travel (Fig. 9), which shows an increase as drivers increase in age beyond 50 or so. For males and for females, the rate for the age 70 or older category is about a factor of three times the minimum rate (but still much less than the rates in the late teens and early 20's). This factor of three increase in rate likely reflects deteriorating skills important for safe driving. Indeed, the increase in the rate may underestimate the decline in performance because one of the most pronounced changes that occurs as drivers age is that they drive less, with the reduction in travel being preferentially higher risk travel, such as at night.

THREAT TO OTHER ROAD USERS

We investigate the threat to other road users by examining the number of crashes in which pedestrians (of any age) are killed as a function of the age and sex of drivers (of any type of motorized vehicle) involved in the crashes.

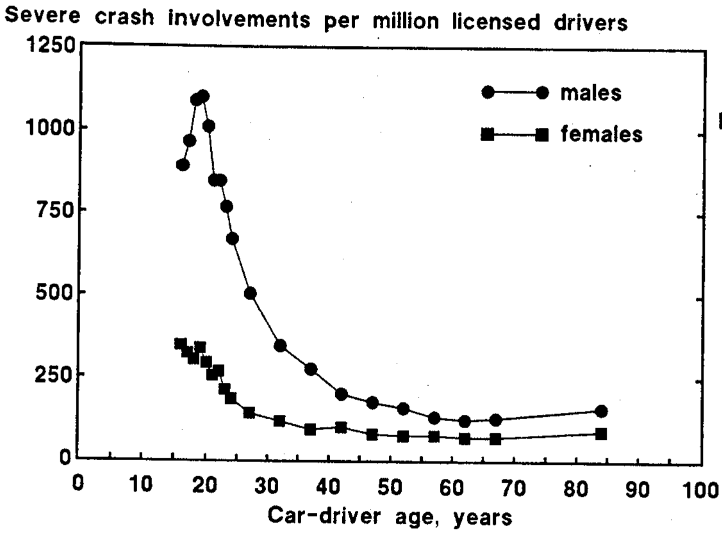

Fig. 8. Diver involvements in severe crashes per million licensed drivers. (see [1], [2]).

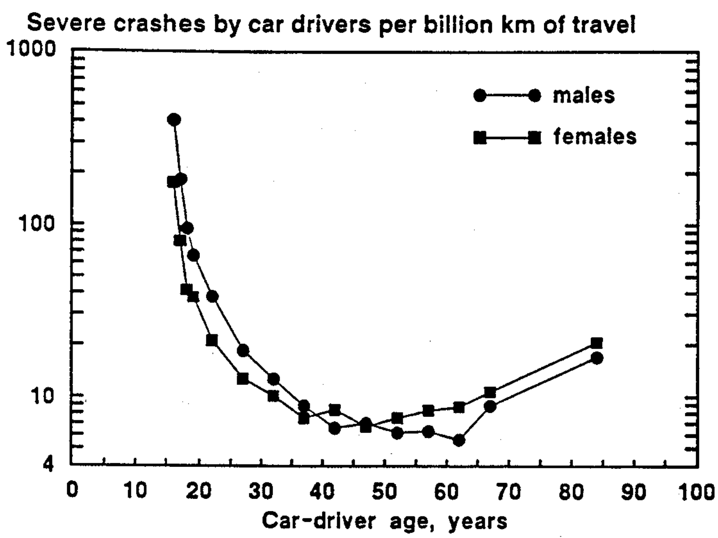

Fig. 9. Diver involvements per billion km in severe crashes (see [1], [2]).

Attention is confined to single vehicle crashes because when more than one vehicle is involved it is not always possible to determine 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 seriously injured. No assumption is made regarding responsibility in pedestrian fatality crashes; about one third of fatally injured pedestrians have blood alcohol concentrations in excess of 0.1%.

Figures 10 through 12 show the variables for crashes involving pedestrian fatalities corresponding to those for driver fatalities in Figs 1 through 3. The only curve that suggests any increase in threat to other road users as drivers age is Fig. 12, which shows pedestrian fatality crashes per unit distance of travel. Here the increase is small, and applies only at ages above about 60; it is quite overshadowed by the much greater values associated with young drivers of either sex.

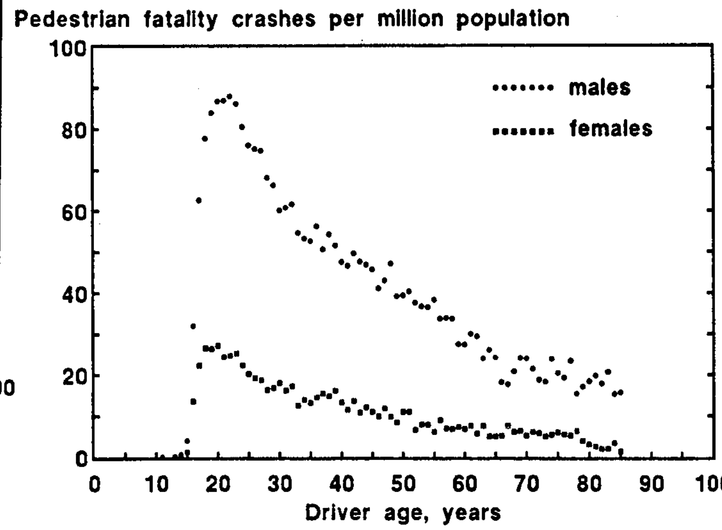

Fig. 10. Number of single-vehicle crashes per million population in which one or more pedestrians was killed. Reproduced from [1].

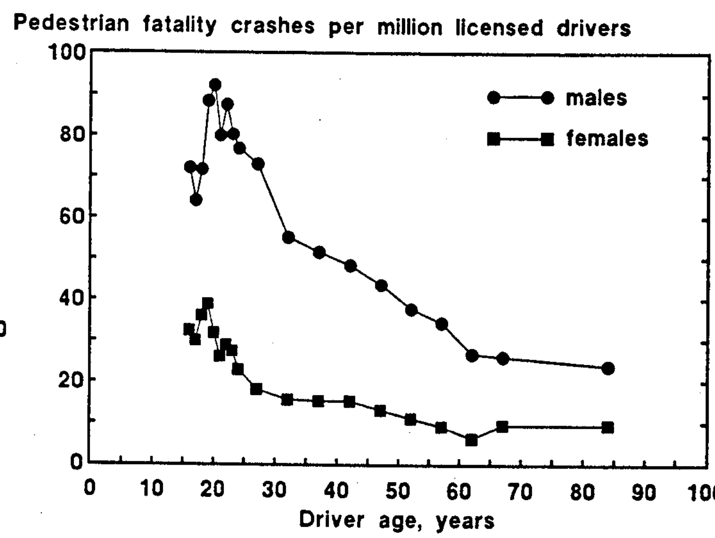

Fig. 11. Number of single vehicle crashes per million licensed drivers in which one or more pedestrians was killed. Reproduced from [1].

TRAFFIC RISKS COMPARED TO OTHER RISKS AS PEOPLE AGE

A large contributor to the increase in driver deaths per unit distance of travel as drivers age is increasing risk of death, given involvement in a crash. The increasing risk of death with increasing age from the same physical insult applies in general, and not just to traffic. Another traffic situation in which it is important is the risk that a pedestrian is killed; at age 80 pedestrian fatality risk per capita for males and females is more than twice its value at any age below 65.

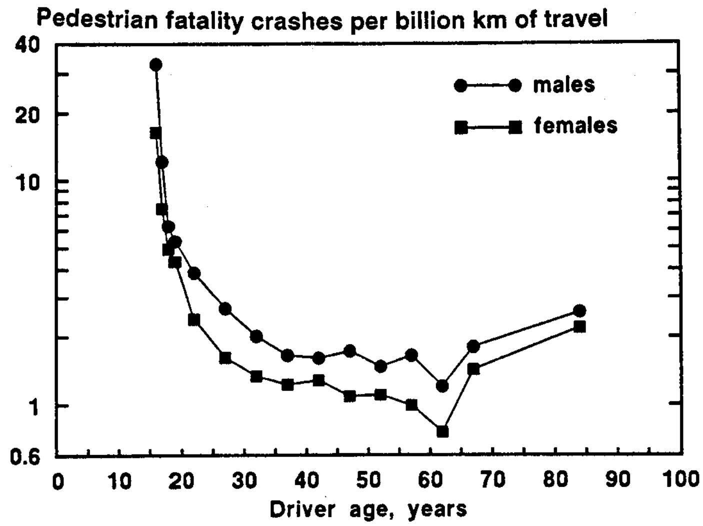

Fig. 12. Number of single vehicle crashes per billion km of travel in which one or more pedestrians was killed. Reproduced from [1].

Although risks in traffic increase with age, they do so much less rapidly than does the risk of death from all other causes combined. Figure 13 shows the probability that a given death is any type of traffic fatality versus age and sex. The peak at about age 10 is due primarily to pedestrian fatalities. The difference in Fig. 13 between the sexes is small because the increased risk males face in traffic (as pedestrians as well as drivers) is approximately in proportion to the increased risks to males from death from all causes; the greater risk of death to males from nearly all causes leads to male life expectancy at birth being a substantial 6 years less than for females. Given that an 18-year-old dies, the probability that death is due to a traffic crash is almost 50%. By age 65, given that death occurs, the probability it is due to a traffic crash is under 1%; by age 75 the probability drops to below half a percent.

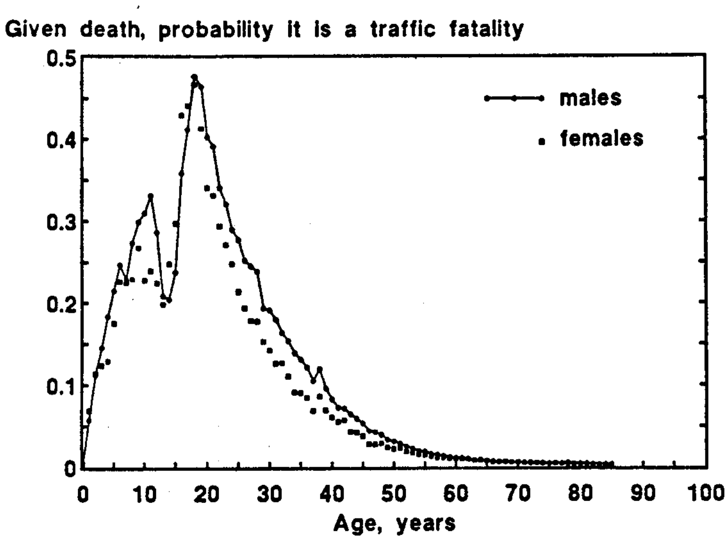

Fig. 13. The probability that a given death is due to a motor vehicle crash. Reproduced from [1].

EFFECTS ON LONGEVITY

Figure 14 shows increases in longevity calculated to result if all traffic fatalities were eliminated, without anything else changing. For boys at birth the increase is 242 days, or two thirds of a year; for girls 111 days. At age 65 the increases are 15 days for males and 12 days for females; at age 75, 9 days for males and 6 for females.

To place these longevity values in a different perspective, we use the data in Fig. 14 to perform some back of the envelope calculations based on assuming a make-believe intervention (say, a novel driver training program) which would permanently reduce an individual's risk in traffic by some percentage. Let us further confine the comparisons to male drivers, not only in the interests of simplicity, but also because males comprise a larger portion of the traffic safety problem, and are today nearly all licensed, thereby making present results more representative of likely future results. Let us ask the following question: If the intervention generated a life-long 1% reduction in traffic fatality risk for a 16-year-old male road user (that is, at every age his risk would be 1% lower than it would have been without the intervention), what corresponding reduction in older-driver risk would be necessary to provide that older road user an identical longevity increase? The answer is obtained by taking the ratios of the longevity increases in Fig. 14; for a 65-year-old road user it is 15%. That is, reducing a 16-year-old road user's risk by 1% provides that individual the same longevity increase as reducing his risk by 15% at age 65. Corresponding estimates for ages 70 and 75 are 19% and 24%, respectively. The longevity increase from eliminating entirely traffic fatality risk at age 65 (an unattainable goal) can be achieved by a reduction in traffic risk of under 7% for 16-year-old road users (a possible goal, at least in principle). Confining the analysis to drivers (of any vehicle) rather than to all road users shows that a 1% permanent reduction in

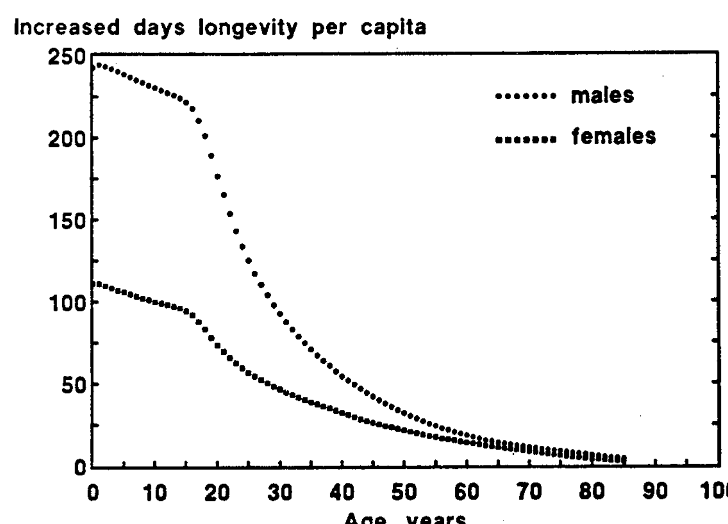

Fig. 14. Calculated increases in longevity per capita (days) assuming the elimination of all motor vehicle fatalities, using FARS 1983-1985. Reproduced from [1].

risk for a 16-year-old driver produces the same longevity extension as 16%, 21% and 28% risk reductions to 65, 70, and 75-year-old drivers, respectively.

We can apply similar calculations to examine how the risks faced by pedestrians are affected by reductions in the crash rates of older and younger drivers. From the data used to produce Fig. 10, we calculate that a 1% permanent reduction in crash risk for a 16-year-old male driver prevents the same number of pedestrian fatalities as a 9% reduction in crash risk for a 65-year-old male driver, an 11% reduction for a 70-year-old driver, and a 14% for a 75-year-old driver. The unattainable goal of eliminating entirely crashes by 65-year-old drivers into pedestrians is calculated to reduce pedestrian fatalities by a lesser amount than reducing by 12% the 16-year-old driver's crash rate into pedestrians.

The differences for female road users are generally similar to the corresponding differences for males, though in some cases smaller. A cursory examination of, say, Fig. 10 shows that eliminating the risks that older female drivers presently impose on other road users would produce modest benefits compared to reducing by even a small fraction the risks that younger male drivers impose on others.

The above calculations are on a per driver basis. Even with the demographic changes underway in the US, there are still going to be many more younger than older drivers into the foreseeable future. Hence, reducing the risk for **all** 16-year-old drivers compared to reducing the risk for **all** 65 year-old drivers will further increase the already substantially larger safety benefits shown above to be associated with reducing younger rather than older driver risk.

CROSS-SECTIONAL VERSUS LONGITUDINAL EFFECTS

All the above analyses, in keeping with nearly all prior analyses of age effects in traffic, have been cross-sectional. That is, people of different ages are examined at a given time. While the results have been discussed in terms of drivers aging, strictly speaking cross-sectional analysis cannot address what happens as individuals age. Apparent aging effects would be generated even if every driver had an unchanging risk, but drivers born a long time ago had higher rates than those born recently. There is indeed strong evidence that today's younger drivers were safer than younger drivers in years past [1]. In order to determine if the rate for a given group, or cohort, of drivers change as that cohort ages, it is necessary to monitor the cohort as it ages, rather than compare the rates of different groups of drivers who have different ages.

This was done in a recent study [3] which monitored driver fatalities per million population over the a 16 year period for which FARS data were available. The longitudinal analysis was therefore restricted to monitoring aging over a 16 year period; it is because sets of data are rarely collected in uniform ways over extended periods of time that most analyses are cross-sectional.

Data for drivers born in five-year intervals were combined to form 5-year birth cohorts. Drivers born 1967-1971 (inclusive) formed the first cohort, and those born 1892-1896 the last of 16 cohorts. The average fatality rate for each cohort was determined for each of the FARS calendar years. Fig. 15 shows results for half of the cohorts. (every other cohort is omitted to enhance clarity). The other half of the cohorts is displayed in Fig. 16.

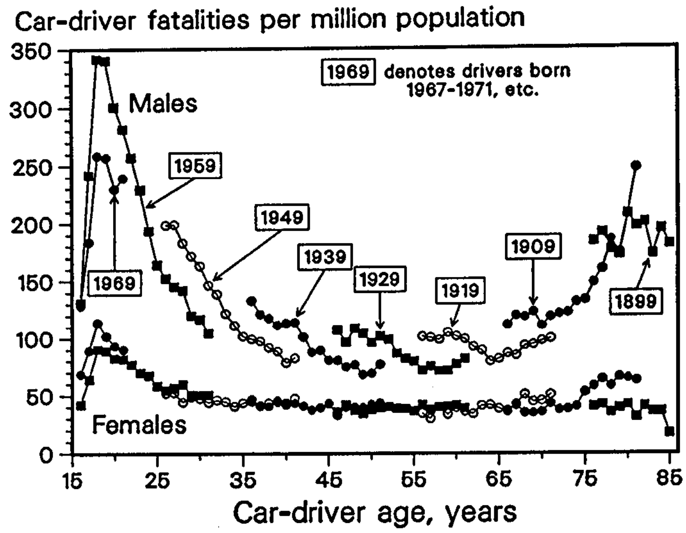

Fig. 15 Car driver fatalities per million population versus driver age for cohorts of individuals born in specified 5-year intervals. Reproduced from [3].

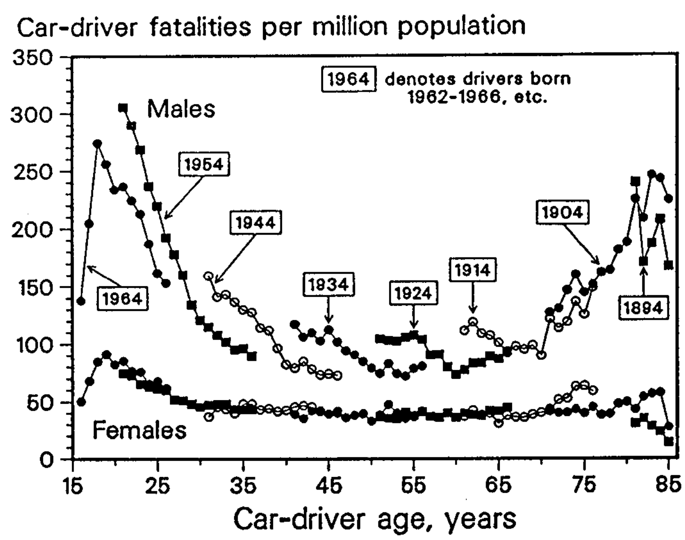

Fig. 16 Car driver fatalities per million population versus driver age for cohorts of individuals born in specified 5-year intervals.

The cohorts have different overlapping age ranges because knowledge about recently-born drivers when they become old will be known only in the future, whereas FARS, initiated in 1975, provides no data on today's old drivers when they were young. While nearly all the points plotted in Figs 15 and 16 reflect averaging over five individual rates, cases with three or more individual values were included in order to extend the age range to higher and lower values. For example, the point plotted for 21-year-old drivers born 1967-1971 is the average of three rates -- those for 21-year-old drivers born in 1967 and observed in 1988, born in 1968 and observed in 1989, and born in 1969 and observed in 1990. The rates for those born in the other two years defining the youngest cohort, namely 1970 and 1971, require data for 1991 and 1992, which were not available in [3].

A striking feature of Figs 15 and 16 is that when rates are available at the same age for male drivers from different cohorts, the more recently born drivers have lower rates. This effect is clear-cut and systematic for all drivers born in this century. As discussed in [3], the different results for female drivers reflects increasing licensure rates for female drivers over the period of data collection compared to essentially total licensure for the male population.

The near steady-state of the male driver population makes it possible to estimate how drivers' rates are expected to change as male drivers age from the late teens until old age, as shown in Fig. 17. It is found that the onset of increasing fatality rates begins at about age 70, rather than at age 65, as indicated by the cross-sectional analysis (Fig. 1). The magnitude of the effect is of substantially less magnitude than indicated by the cross-sectional analysis.

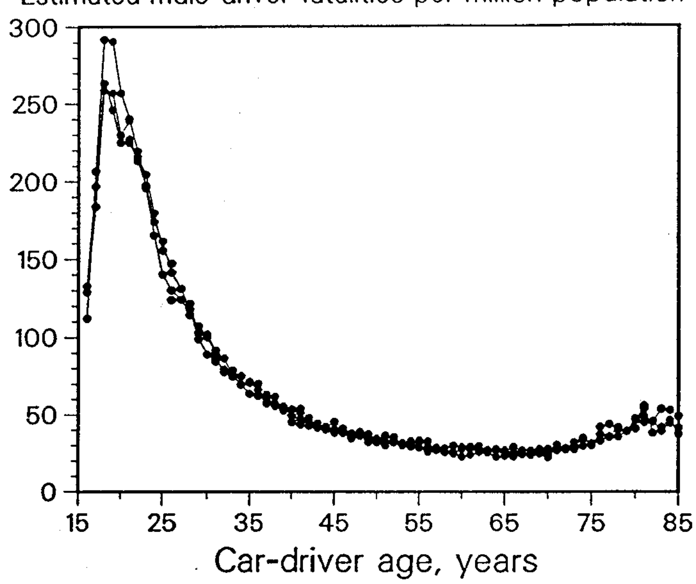

Fig. 17. Estimate of how the fatality rate of a group of present young male drivers will depend on age as they grow into old age based on longitudinal analysis. Reproduced from [3].

DISCUSSION AND CONCLUSIONS

While drivers over about 50 are increasingly more likely to be killed per unit distance of driving than 40-year-old drivers, a large factor contributing to this is not increased crash risk, but increased risk of death given that a crash occurs. That is, a physiological factor associated with aging plays a role comparable to that due to declines in driving performance (Figs 3 and 6 -- illustrative findings from these and other figures are summarized in Table 1). Although the risk of death from the combined effects of all traffic crashes increases at older ages, compared to the other risks of death as one ages, risk in traffic plays an ever diminishing role; given that an 18 year old dies in the US, the probability is almost 50% that the death is due to a traffic crash; given that a 65 year old dies, the probability is less than one percent that the death is due to a traffic crash.

Table 1. Comparison of risks at selected ages. The first entry indicates that in a year's driving, an average 70-year old licensed male driver is 51% as likely (that is 49% less likely) than is a 40-year old licensed male driver to be a driver in a crash in which a pedestrian is killed. Compared to the 70-year old, a 20-year old licensed male driver is 3.39 times as likely (that is 239% more likely) to be involved in a crash in which a pedestrian is killed.

VARIABLE	MALES Age 70 / Age 40	MALES Age 20 / Age 70	FEMALES Age 70 / Age 40	FEMALES Age 20 / Age 70
Risks drivers impose on others*				
Per licensed driver (Fig. 11)	0.51	3.39	0.62	3.36
For the same travel distance (Fig 12)	1.18	2.57	1.23	2.46
Risks car-drivers face themselves				
Driver fatalities per head of population (Fig. 1)	1.09	2.51	0.91	1.94
Fatalities per licensed driver (Fig. 2)	1.17	2.33	1.31	1.53
Fatalities for the same travel distance (Fig. 3)	2.78	1.75	2.71	1.08
Severe crashes per licensed driver (Fig. 8)	0.56	7.61	0.75	3.99
Severe crashes for the same travel distance (Fig. 9)	1.30	5.81	1.52	2.73

* As measured by involvements in crashes in which pedestrians (of any age) are killed

The graphs which best reflect the behavioral aspects of driving, namely, driver involvements in crashes in the same high severity range per unit distance of travel, and crashes in which pedestrians are killed per unit distance of travel (Figs 9 and 12) show similar features. Drivers from about age 30 to 60 have the lowest involvement rates. As age decreases below 30, rates increase at an increasing rate. For ages greater than about 60, rates increase somewhat, but much less rapidly than as one approaches the younger ages in the graphs.

Taking the most extreme crash rate comparison, Fig. 9 shows that, compared to driving at the age of minimum crash rate per unit distance of travel, drivers in the 70 and older age category experience a three-fold increase in risk to themselves. While this paper is based on US data, essentially similar effects are observed in data in Sweden [5], New Zealand [6], and Finland [7].

Although the factor of three difference in risk drivers themselves face as they age is substantial, it is of a magnitude common in many traffic situations, and should not be viewed as necessarily making a strong case for denying a driving license. If having an above average risk were sufficient grounds to deny a driving license, and if each driver's risk were known accurately, such a criterion would inexorably lead to only one driver being licensed, the one with the lowest risk.

The following examples place a factor of three difference in risk in perspective. A formula (given as Eqn 6-3 in [1]) indicates that traveling 80 km/h compared to traveling 60 km/h increases fatality risk by a factor of three. An unbelted driver in a small car is three times as likely to be killed in a crash as is a belted driver in a large car. In the US, the overall fatality rate was a factor of three higher 30 years ago than it is today, while many countries today have rates more than a factor of three times the present US rate. Driving 300 km generates three times the fatality risk that driving 100 km does. Driving with a blood alcohol concentration of between 0.05% and 0.99%, which is legal in most US states (the legal limit is 0.1% BAC) doubles crash risk. Driving with a just illegal level of 0.1% to 0.149% BAC increases risk by a factor of over 10.

Much more central to driver licensing policy is the harm that drivers may do to others. The data do not indicate that drivers pose any substantial increase in average risk to other road users as they age over the ages for which data are available. This finding offers additional support to the view that licenses should be denied on the basis of individual performance, but not on membership of any chronological age category.

Many of the figures presented (Figs 3, 4-6, 9, 12) are not dependent on demography or social custom in any large or direct way, so their broad qualitative features are expected to remain approximately invariant in time. The effects they represent seem more akin to laws of nature than to observations local to a specific time or place. Their broad features cannot be canceled by interventions -- there is no conceivable treatment which would render these figures straight lines parallel to the age axis. In any event, straightening the curves does not seem a more worthy societal goal than seeking safety measures which reduce risks to all ages in similar proportions if such measures generate greater net reductions in harm.

To acknowledge that the broad shape of Fig. 9 is close to being a law of nature is not to conclude that interventions aimed at specific ages cannot make important contributions. I believe that there are effective interventions that can reduce the degree of overinvolvement of young drivers, including changes in advertising and taxation of beer, and reduced fictional portrayal in movies aimed specifically at young people of the life-threatening use of vehicles as heroic, humorous, or harmless. Interventions focused on young drivers aim at reducing the magnitude of their overinvolvement relative to 40-year-old drivers. To expect young driver rates to drop to the same values as those for 40-year-old drivers in the same society at the same time is unrealistic. Present US rates for 20 year olds are less than those for 40 year olds at earlier periods in the development of US motorization, and are less than present 40-year-old rates in many countries.

Corresponding comments apply to older drivers. Research should aim to discover more specifically why crash risk increases with age with the goal of formulating specific countermeasures. However, it is unrealistic to expect rates for older drivers to become identical to minimum rates. While it might be a law of nature that the oldest age category drivers have rates well above the minimum, it is not a law of nature that they should be three times the minimum rate. Any measure which can reduce them to, say, 2.5 times the minimum, is of high importance. We already know that the mix of crashes in which older drivers are involved differs substantially from the mix for younger drivers; the older driver's crash is more likely to be multiple-vehicle, especially side impact, but less likely to be a rollover, to involve alcohol, or to occur at night. Such differences are relevant to where age-specific interventions (for young or old) might be focused.

Many measures aimed at improving older-driver safety (likewise younger driver safety) may improve safety for all ages in the same proportion. Any such change, no matter how much it reduces older-driver risk, will leave the shape of all the curves displayed in this paper unchanged. Consequently, if the focus is exclusively a comparison with drivers with the minimum risk (the usual metric), the *older driver problem* will remain unaltered independent of how much it really changes.

The information presented shows that the major contribution to traffic losses comes from young drivers; the younger driver component will remain overwhelmingly the major component even after major changes in the demographic composition of the population. Minor reductions in young-driver crash risk generate much larger safety benefits in terms of increased driver longevity or reductions in harm to others than do much larger reductions in older-driver crash risk. Thus, while there certainly are safety problems associated with driver aging, their magnitude is much less than the problems associated with younger drivers. If limited public resources are available for interventions to reduce driver risk, then the younger driver problem appears to have a substantially stronger claim. The question of using personal resources, or the resources of organizations supported by specific groups of drivers, to reduce the risks to specific groups of drivers is an entirely different matter.

Much larger than any proportionate increase in driver risk with increasing age is the decline in distance of driving. For example, male drivers 70 and over drive, on average, 9 300 km/year, compared to 31 000 km/year for 35 to 39-year-old drivers; the corresponding values for female drivers are 4 300 km/year and 12 600 km/year, respectively. As mental and sensory abilities decline, the dominant response is less driving, especially under conditions of elevated risk, rather than a net increase in risk from driving. Largely because of decreased driving, driver fatality risk per year increases only moderately with increasing age, while the threat to other road users declines. The transportation aspect of the problem of aging may thus be more one of reduced mobility than of reduced safety.

The above discussion, and most of the results presented, are based on cross-sectional analyses in which drivers of different ages are examined at the same time. A recent study [3] using a more appropriate longitudinal analysis, in which the rates of the same group of drivers are monitored as they age, suggests lesser increases in risk as drivers age.

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Technical Session 3

Intelligent Vehicle/Highway Systems: The Vehicle

Chairperson: William A. Leasure, United States

NHTSA'S IVHS Collision Avoidance Research Program: Strategic Plan And Status Update

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Paper No. 94 S3 O 01

ABSTRACT

Although crashes are relatively rare events, nearly 40,000 individuals are killed in motor vehicle crashes annually in the United States. Another 5 million are injured and the societal costs exceed $137 billion annually. These are unacceptable statistics that can be significantly reduced by improving the collision avoidance capabilities of motor vehicles. The maturity of advanced technologies provides the opportunity for major breakthroughs in assisting drivers to avoid crashes. This paper provides a status update on the National Highway Traffic Safety Administration's (NHTSA) program to facilitate development and early deployment of cost-effective, user-friendly collision avoidance systems. The program includes an expanding crash avoidance knowledge base; development of a vital set of research tools, including the National Advanced Driving Simulator; identification of crash avoidance opportunities; examination of key human factors and system design issues; and development of performance specifications for crash avoidance products and systems. These specifications will define performance characteristics in engineering and human factors terms and will help guide product development toward achievement of maximum safety potential.

BACKGROUND

Since the last ESV Conference in Paris in November 1991, NHTSA has prepared a strategic plan to describe and guide its Intelligent Vehicle Highway Systems (IVHS) program (NHTSA, 1992), has received significantly increased funding support for the program (Fiscal Year 1994 budget of $14.5 million), and is currently implementing this program.

The mission of NHTSA is to reduce traffic crashes and resulting injuries and death. Traffic-related deaths in the United States in 1992 declined to the lowest point in 30 years and the fatality rate fell to 1.8 deaths per 100 million miles travelled, down from 2.6 in 1983, and now at its lowest in history. Many people now walk away from collisions that would have killed or seriously injured them a decade ago. The improvements in the fatality rate reflect increased use of safety belts, greater availability of air bags, improvements in vehicle crashworthiness, a growing awareness that traffic casualties are a major public health problem, progress against alcohol-impaired driving, and improved road design.

Until recently, technology did not exist to make significant improvements in the crash avoidance capability of motor vehicles above that offered by existing countermeasures, such as antilock brakes and center high-mounted stop lamps. Recent advances in electronics, control systems, processors, and communications now allow for the design of collision avoidance systems with increased sophistication, reduced cost, and high reliability. In the United States, such technologies have been termed IVHS. With regard to IVHS, NHTSA is seeking to fulfill its mission by facilitating the development of safety products and systems and by evaluating the safety impact of introducing such systems into motor vehicles. This requires research into the science of crash avoidance.

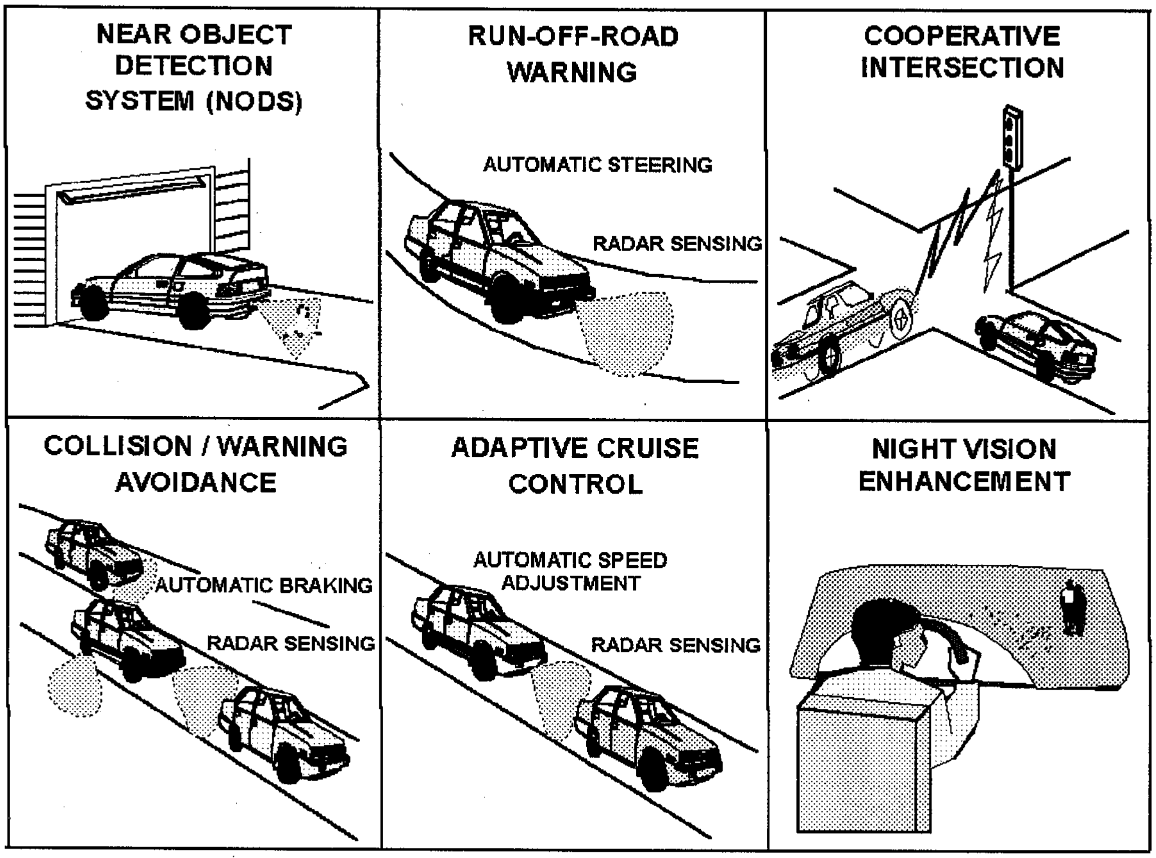


Figure 1. Examples of Potential IVHS Crash Avoidance Systems

In NHTSA's vision of the future driver-vehicle-highway environment, a wide variety of innovations will appear within and outside of the motor vehicle to supplement the driver's efforts at vigilance and control. Some example systems are illustrated in Figure 1. Such systems will ensure the driver's own state of fitness, enhance driver perception on a continuous basis, give warning of impending danger, and/or intervene with emergency control if a crash is imminent.

NHTSA is currently implementing a greatly expanded crash avoidance research and development effort following the five-thrust IVHS program illustrated in Figure 2. The agency is establishing safety targets for crash avoidance technology, developing performance guidelines for such systems, working with industry to demonstrate the most promising ones, and facilitating their deployment in the marketplace. NHTSA is also playing a major role in ensuring the system safety of IVHS initiatives other than collision avoidance, e.g., mobility and productivity enhancement systems. Through this process, NHTSA will facilitate and hopefully stimulate industry efforts which result in commercialization of safety-effective IVHS products. The NHTSA program will provide the engineering and human factors basis for achieving the potential safety benefits promised by IVHS.

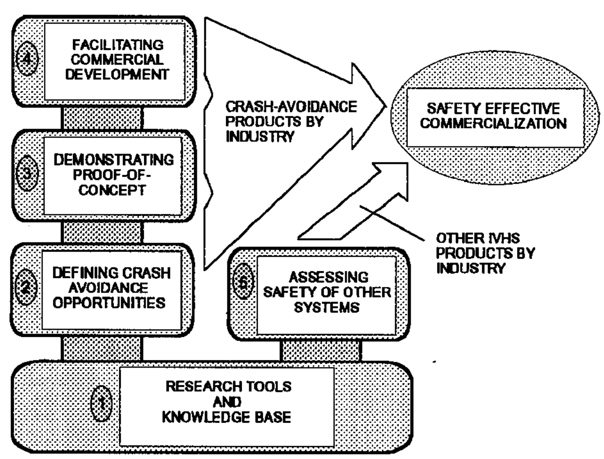


Figure 2. NHTSA's Five Thrust Program In IVHS

THRUST NUMBER 1: BUILD RESEARCH TOOLS AND COMPILE KNOWLEDGE BASES

Given the diversity and complexity of motor vehicle crashes, development of effective countermeasures can be realized only through a comprehensive understanding of crash antecedent events and relevant behavioral, vehicular, and roadway factors. The development of these countermeasures requires innovative research tools and analytical techniques. These research tools are vital to understanding and documenting the safety benefits and potential liabilities associated with new countermeasures and to define requirements associated with their design and implementation. Accordingly, the agency has defined goals for obtaining the research and analysis tools necessary to evaluate crash avoidance concepts and products and a more sophisticated and systematic knowledge base of driver-vehicle performance and behavior needed to support safety system development.

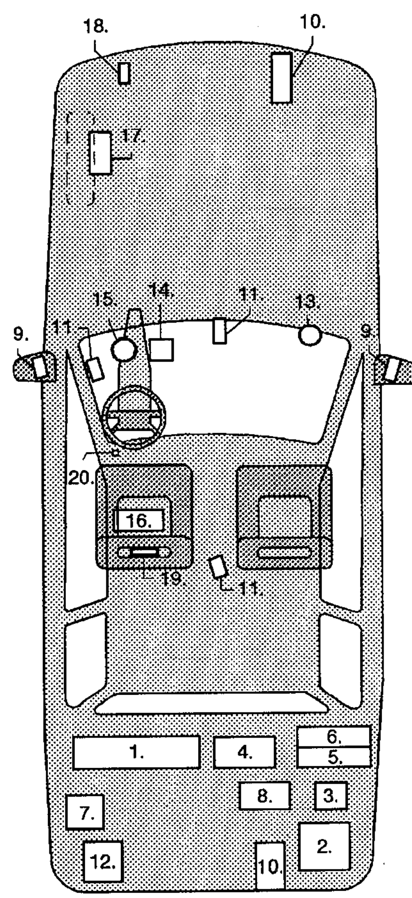
National Advanced Driving Simulator (NADS)

A critical research need relevant to crash avoidance is improvement in our state of knowledge about how drivers interact with the their vehicles and the roadway environment. This information is necessary for the development of advanced countermeasures and other vehicle components that are compatible with the performance capabilities and limitations of drivers. Simulators will be essential to this improved understanding of driver behavior since they provide a means for carrying out highly controlled experiments in crash imminent situations without putting subjects at risk. While many levels of simulation sophistication are possible, NHTSA is focusing on the development of a high-fidelity, moving base simulator. The state-of-the-art in highway vehicle simulation technology has progressed to the point where it is now possible to replicate, with impressive fidelity, the highway driving scenario. Emerging technologies in mechanical system dynamics and parallel computing, combined with high-speed computer graphics and motion base control technologies, have sufficiently evolved to support a national research facility for man-in-the-loop, real-time vehicle driving simulation, thus allowing researchers to present the antecedent events of a likely crash situation and then study the responses of both driver and vehicle. Most importantly, these simulated conditions can be presented in a precise and repeatable manner with complete safety for the human subject.

Two teams have recently begun a 13-month NADS design competition. At the completion of the design competition, the team with the winning design will carry out the actual construction of the NADS facility.

Portable Driver Performance Data Acquisition System for Crash Avoidance Research (DASCAR)

In addition to simulation, real-world, in-vehicle data are also important. To address the need for such data, this project is applying state-of-the-art technology and methods to develop an easily-installed, portable instrumentation package and a set of analytical methods/tools to allow driver-vehicle performance data to be collected using a variety of vehicle types (Figure 3). The instrumentation suite will be unobtrusive to subjects and inconspicuous to other drivers; thus, it will support "naturalistic" studies of driver performance/behavior on the road.



Major Hardware Components

1. Data Acquisition Platform
2. DC-DC Power Supply
3. 12V Battery System
4. 486DX2-66MHz Lap-Top Computer
5. Radio Telemetry
6. Satellite Uplink
7. Video Digitizer & Compression System

Sensor Suite

8. Six-Degrees of Freedom Sensor
9. Lane Tracking Unit
10. Headway/Tailway Measuring Device
11. Micro CCD Video Camera
12. Video Support System
13. Electronic Compass
14. Linear Position Transducer (Steering)
15. Pedal Force Tranducer
16. Accelerometer (Driver Motion)
17. Hall Effect Sensor (Speed)
18. Meteorological Sensor
19. Sound Level Meter
20. Photometer / Radiometer

* Various Psycho-Physiological Sensors will also be utilized

Figure 3. Portable Driver Performance Data Acquisition System for Crash Avoidance Research (DASCAR)

A prototype system is currently being fabricated and will be available for pilot testing in late 1994. Following validation of the prototype design, multiple units will be constructed and utilized to compile needed in-situ experimental or baseline human factors data.

Quantitative Characterization of Vehicle Motion Environment (VME)

This project is developing and validating a measurement system that can quantify the specific motions that vehicles exhibit as they move in traffic (Figure 4). The VME system will establish the locations and motions of all vehicles within the field of view relative to roadway boundaries, other features, and each other. The pertinent variables address vehicles in near proximity to one another, including spatial clearances, relative velocities, and angles of nominal attack vis-a-vis other vehicles and fixed objects. In operation, the VME will gather information on successful collision avoidance maneuvers. Information such as reaction to other drivers cutting in front, normal following distance, typical lane change trajectories, and response to inclement weather will be collected. This information will provide a geometric and kinematic data base which can be used to design IVHS countermeasures that intervene and/or provide collision avoidance warnings to the driver. That is, countermeasure parameters can be superimposed analytically on the vehicle motion record to assess their likely performance.

The initial VME measurement systems will be available for testing and validation in the fall of 1994. Once validation is complete, the units will be utilized to acquire baseline information on all aspects of driving.

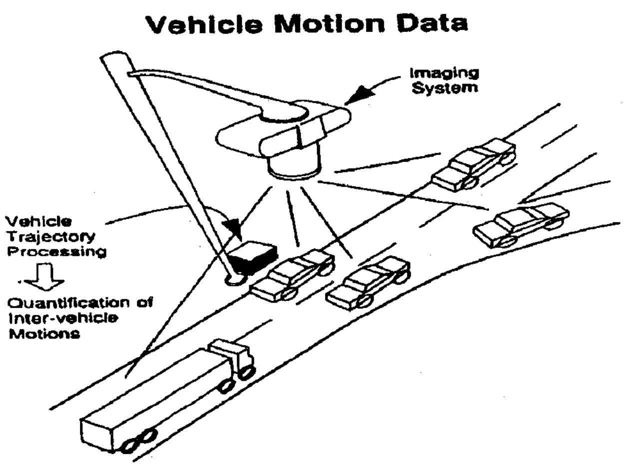


Figure 4. Vehicle Motion Environment (VME) Operation Concept

Variable-Dynamics Test Vehicle (VDTV)

Currently underway is a "needs" study and development of preliminary performance specifications for vehicle(s) with the capability to systematically vary vehicle control and handling characteristics. This phase will be completed in mid-1994. If the need is demonstrated, the VDTV will be constructed, tested, and validated in the second phase.

It would be used to establish the performance boundaries for IVHS systems that directly control vehicle motion, i.e., determine the vehicle-related limitations that should be placed on control algorithms. It will also allow determination of how drivers react to various proposed IVHS crash avoidance concepts, including the effect of vehicle characteristics on device effectiveness. The VDTV could also be used to validate NADS control algorithms and as a crash avoidance research vehicle to support the safety evaluation of automated highway system (AHS) concepts.

Driver Workload Assessment

In order to evaluate the effect on driver workload imposed by adding IVHS devices/systems to motor vehicles, a measure of today's workload is needed as a reference baseline. Since neither workload data nor a standardized approach for establishing such data exist, this initiative is (1) developing a capability to evaluate the effects of high-technology systems (e.g., crash avoidance systems, route guidance, and navigation systems) on driver safety performance, (2) developing standardized driver workload measurement protocols (including instrumentation), obtaining baseline workload data, and evaluating high technology systems that are currently being implemented, (3) identifying aspects of system design and operation that can compromise safety, and (4) obtaining data relevant to human factors guidelines for the driver-vehicle interfaces of these systems.

Table 1 shows sample results from the workload study. Video recordings of driver glance duration and frequency (taken during normal driving) indicate that, among conventional instrument panel controls and displays, the task of manually tuning a radio requires the greatest allocation of visual resources and, thus, creates the greatest workload for the driver. This is seen most vividly in the high number of driver glances required to carry out this task. New in-cab devices should be designed to create minimal visual or other workload demands on the driver. A new in-cab device causing a high visual demand--equivalent to manually tuning a radio--might cause excessive distraction to drivers and, thus, constitute a safety hazard.

Crash Avoidance and the Older Driver

Numerous physiological changes and related performance decrements relevant to driving are associated with aging. They include diminished ability for visual accommodation, decreased ability to see in darkness or diminished light, decreased accuracy of distance and closing speed estimation, longer glance times required to read instrument panel displays, decreased ability for selective attention, slower speed information processing and decision-making, and slower motor reaction times. Some deficits occur almost universally in older persons; others are not universal, but occur at a higher rate. This study is analyzing the traffic crash experience of older drivers, assessing their capabilities and limitations as drivers, and identifying and evaluating vehicle design features that will ensure the safety of their driving while accommodating their mobility needs.

This study is being coordinated with the broader NHTSA programs dealing with the safety and mobility of older drivers that are discussed in a paper in the IVHS Human Factors Session of this conference.

Table 1
Illustrative Visual Glance Data: All Subjects Combined

	Average Glance Duration (sec)	Mean Number of Glances	Average Time Off Road (sec)
Left Mirror-Detect	1.44	1.29	1.85
Left Mirror-Descrimination	1.77	1.58	2.79
Rear Exact Speed	1.50	1.45	2.18
Manually Tune Radio	1.33	11.31	15.10
Change CB Channel	1.18	3.93	4.63
Wipers On/Off	1.00	1.13	1.13

In-Vehicle Crash Avoidance Warning Systems - Human Factors Considerations

This project is attempting to identify driver requirements for effective warning system design and for evaluating the potential of warning systems to help drivers avoid crashes. The research is addressing the following human factors questions:

- What type of information should be presented to the driver - status or guidance? How should the information be presented (e.g., visual display, aural signal)? When should it be presented to provide the driver with enough time to take action?

- What system characteristics (e.g., location, display identification, information content) should be standardized to prevent problems for unfamiliar drivers?

- Will a vehicle equipped with multiple warning systems confuse or overload the driver? If multiple warnings are present, how should they be designed to minimize confusion? Should priorities be established in the event of simultaneous warnings?

The first product of this research was the development of a set of preliminary human factors guidelines for crash warning devices (Lyons, et al., 1994). These guidelines are intended to be sufficiently general so as to permit the use of various display technologies, from traditional automotive displays to CRTs, voice, or other formats.

Evaluation of Potential Health Hazards from Wide-Spread Usage of Collision Avoidance Systems

Widespread introduction of collision avoidance systems which utilize active sensor systems could result in a noticeable increase in the emittance of electromagnetic radiation. Example sensor technologies include radar, laser, and radio frequency transmissions. If any potential health or safety hazards could arise from the use of active sensors, NHTSA seeks to identify and quantify the nature of such potential problems as early as possible. The goal of this study is to provide design criteria that minimizes any potential health hazards to the population.

Vehicle-Induced Feedback Cues and Their Relationship to Driver Performance and Safety

Driving involves a continuous interaction of the driver with his or her vehicle and the roadway environment. Visual cues from the roadway are obviously of paramount importance to driver performance. Less obvious is the importance of cues and feedback from within the vehicle, such as kinesthetic, vestibular, and cues associated with certain vehicle response characteristics, e.g., body roll, tire screech, apparent oversteer/understeer. The role of these vehicle cues relative to driving performance needs to be better understood. IVHS technologies present the possibility that such cues may be radically changed in future generations of vehicles. The effects of such changes are largely unknown and could greatly influence how well drivers control their vehicles.

This project will develop guidelines for system designers to highlight the importance of vehicle cues to driver performance and system safety and to ensure that contradictory or counterintuitive feedback systems are not developed by different manufacturers. Lack of standardization could cause vehicle controllability problems for a driver operating an unfamiliar vehicle.

This project will also gather experimental data on the phenomenon of driver risk compensation, the possible tendency of drivers to drive faster or otherwise increase their risktaking in response to improvements in highway or vehicle safety, thereby partially or even fully negating the positive effects of crash avoidance countermeasures. Risk compensation has been hypothesized to be an attenuating factor in countermeasure effectiveness, but to date there is little empirical evidence to document its existence or significance to motor vehicle safety.

THRUST NUMBER 2: IDENTIFY PROMISING CRASH AVOIDANCE OPPORTUNITIES

The technological potential of IVHS presents an array of opportunities and challenges to the motor vehicle industry and to NHTSA in performing its mission to reduce traffic crashes and resulting injuries and death. One of the challenges is to effectively use the collision record with a new focus on crash avoidance. Looking carefully at the precrash circumstances associated with various crash types, the accident information must be analyzed to determine critical driving hazards. Countermeasures to address these hazards can then be specified in performance terms that match real needs. There is, however, a weak link in the logic chain between available technology and the prevention of target crashes. The mechanisms of intervention of IVHS devices in crash scenarios (and, in particular, driver actions) are not well understood. There is a pressing need for analyses of candidate technological solutions in relation to the parameters of target crash scenarios and the capabilities and limitations of drivers. This approach will identify the most promising countermeasure functions which, in turn, can lead to assessments of the most promising applications of technology and associated R&D needs.

The problem definition/analysis methodology being pursued by NHTSA incorporates the following key elements:

- o Quantification of the baseline crash problem size (in terms of numbers of crashes, injuries, and fatalities) and description of crash characteristics.
- o Description, analysis, and modeling of target crash scenarios in sufficient detail (i.e., clinical assessment) to permit understanding of the principal causes, time and motion sequences, and potential interventions.
- o Assessment of countermeasure mechanisms of action (countermeasure concepts) and technology status (sensors, processors, control and communication systems) to identify candidate solutions.
- o Assessment of relevant human factors and other "real world" factors affecting potential countermeasure effectiveness, e.g., vehicle response capabilities, driver reaction times, false alarm rates, driving behavior.
- o Modeling of countermeasure action to identify critical countermeasure functional requirements and where possible, predict effectiveness.
- o Identification of priority technological, human factors, and other R&D issues that need to be resolved to ensure that the countermeasure's safety enhancement potential is reached.

This approach recognizes that the mechanisms of intervention of IVHS devices in crash scenarios (and, in particular, driver actions) must be understood in order to predict potential device effectiveness and benefits, identify critical system performance goals, and guide agency and industry efforts along paths of greatest potential safety benefit. The analysis of collision records systematically guides NHTSA toward the key questions to be answered during countermeasure R&D efforts.

Figure 5 shows the distribution of crash types that provide the maximum opportunity for significant safety improvement through the introduction of safety-effective collision avoidance products/systems. Single vehicle road departure, rear end, and crossing path (intersection) crashes comprise nearly three-fourths of all crashes in approximately equal proportions. The remaining fourth is comprised of blind-spot, head-on and other crash types. Additional contributing factors such as reduced visibility, e.g., at night or in degraded weather conditions, and driver drowsiness, occur across the spectrum of crash types shown in Figure 5.

More detailed data specific to individual crash types are provided later in the paper as part of the discussion associated with the development of performance guidelines for collision avoidance countermeasures.

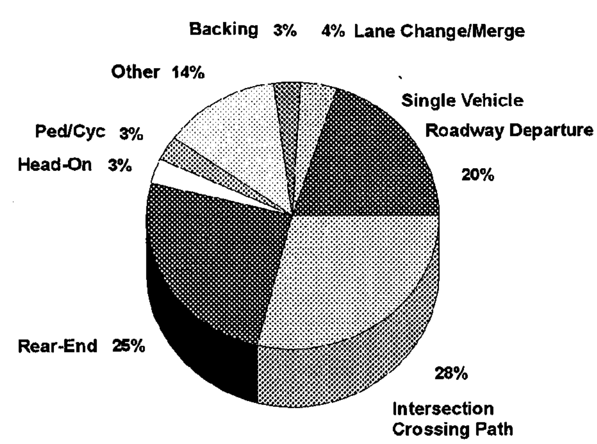


Figure 5. Distribution of Major Target Crash Types

THRUST NUMBER 3: DEMONSTRATE PROOF OF CONCEPTS FOR CRASH AVOIDANCE

NHTSA's goals are to see continual development of new products that provide enhanced information about the driving environment, instruct the driver to take immediate collision avoidance action, or take control of the vehicle and to develop guidelines that will help and encourage industry to develop and deploy such IVHS collision avoidance systems. Projects under this thrust have been specifically designed to help compress the time frame for product development. The early development of performance guidelines will also lessen the risk of hazardous side effects and help ensure that safety enhancement goals are achieved. Proof of the technical feasibility, operational practicality, and economic viability of crash avoidance systems is necessary for any concept to be commercialized.

There is a narrow margin between driver responses that do not result in collisions and those that do. Instances where a driver does not take appropriate collision avoidance action are opportunities for intervention by driver augmentation systems. Such systems fill the gap between "actual" and "needed" action.

To effectively prevent collisions, they must interact with the driver in a timely and effective way. They must also be designed to address specific collision circumstances.

To foster the development and use of a wide array of technologies for reducing or compensating for driver errors and limitations, NHTSA is establishing the functional requirements for various collision avoidance safety systems in performance terms. This will include performance parameters such as sensor detection range and sensitivity, signal processing capabilities, requirements for presentation of information to drivers, vehicle control modes, data architecture standards, and system reliability and durability. These specifications of functional requirements will serve as design targets for industrial development of IVHS hardware and as the basis for evaluation of the safety impact.

The development of performance specifications follows a systematic approach which includes the following key factors:

- o Thorough analysis of the crash problem,
- o Establishment of functional goals for system(s) to address the identified crash problem, including both engineering and human factors considerations,
- o Testing and evaluation of existing systems (commercially available and prototypes); including driver interfaces,
- o Development of preliminary performance specifications,
- o Evaluation of the state-of-the-art of enabling technologies needed to achieve particular collision avoidance safety performance,
- o Design and construction of a test bed for use in assessing concepts which can meet the preliminary performance specifications, and
- o Use of the test bed and other facilities to conduct vehicle and human factors testing to support finalization of the performance specification.

These projects are investigating the feasibility of equipping motor vehicles with systems to assist drivers in safely carrying out the maneuvers of interest. They will determine the performance required of one or more feasible countermeasure systems and define the specifications in performance terms without constraining the systems to particular devices or technologies. Although the major focus will be on systems which will be self-contained within the vehicles, cooperative systems which would require or would be improved by auxiliary equipment in the road or in other vehicles are also being addressed.

NHTSA currently has underway seven performance specification development projects:

Countermeasures Against Lane Change, Merging, and Backing Collisions

Approximately 400,000 police-reported collisions (and an even greater number of non-police-reported collisions) of these types occurred in 1992. This is about 7 percent of all collisions. These collisions are characterized by vehicles having low relative velocity and being in close proximity during normal operation.

Most lane change/merge crashes are angle or sideswipe collisions. Most lane change/merge crashes occur during dry, clear, daylight conditions. Just over half occur on divided highways. A large percentage of this type of collision involve recognition failure by the lane changing/merging driver, i.e., the driver "did not see" the other vehicle until the crash was unavoidable (Knipling, 1993).

Analysis of backing crash scenarios reveals two distinct subtypes - "encroachment" and "crossing path" crashes. Encroachment backing crashes involve slow closing speeds and a stationary (or slowly moving) struck pedestrian, object, or vehicle. In contrast, crossing path backing crashes generally involve higher closing speeds. For example, a vehicle backs out of a driveway and strikes (or is struck by) another vehicle moving at speed on the roadway. Approximately 43 percent of all backing crashes are encroachment crashes; the remaining 57 percent are crossing path crashes. Approximately 90 percent of drivers involved in backing crashes (as the driver of the backing vehicle) were unaware of the presence of what they hit (Knipling, 1993).

This project is investigating the feasibility of equipping motor vehicles with systems to assist drivers in safely carrying out lane change, merging, and backing maneuvers. A number of such systems have already been developed to improve the performance of drivers in situations relevant to these crashes. The ready availability of potential systems is a primary reason for including these collisions in the initial set of problem areas.

Countermeasures Against Rear-End Collisions

In 1992, rear-end collisions accounted for about 1.4 million police-reported collisions and perhaps more than 2 million non-police-reported crashes. Approximately two-thirds of the crashes are lead vehicle stopped crashes, while the remaining one-third are lead vehicle moving crashes. That is, most rear-end crashes do not involve "coupled" vehicles that collide due to a sudden deceleration by the lead vehicle. Rather, in most rear-end crashes a moving vehicle collides with a stopped vehicle in its forward travel path (Knipling, 1993).

The most common causal factor associated with rear-end crashes is driver inattention to the driving task. A second, and overlapping, major causal factor is following too closely. One or both of these factors are present in approximately 90 percent of rear-end crashes.

Systems to address rear-end collisions have been under serious development for about 2 years. Some of the concepts which have been investigated include intelligent cruise control systems which automatically maintain headway by throttle closure and/or downshifting of the transmission, systems which provide information about distance and speed of other vehicles, headway maintenance systems which rely on driver action, and automatic braking systems, In the future, there may be systems which provide full automatic control of longitudinal motion. These system concepts all rely on the ability to sense the relative velocity and distance of vehicles which are travelling in the same direction.

Countermeasures Against Roadway Departure Collisions

Single-vehicle roadway departure crashes represent a significant highway safety problem. There were 1.2 million single-vehicle roadway departure crashes in 1992, representing 20 percent of all crashes. Further, approximately 16,000 annual fatalities (36 percent of all traffic fatalities) are associated with these crashes.

Causal factors associated with single-vehicle roadway departure crashes include slippery road conditions, excessive speed/reckless maneuver, driver inattentiveness, evasive maneuver in response to an external crash threat, driver drowsiness, and driver intoxication. With so many diverse crash causes, multiple countermeasure concepts are likely to be applicable to this significant crash type (Knipling, 1993).

The requirements for the sensing element for these systems will include the ability to provide data on lateral lane position, presence of low coefficient-of-friction, and driver condition. It may be more efficient and practical to provide some of this information with sensors that are part of the highway infrastructure rather than in the individual vehicles. These capabilities are different than the primary need of determining speed and location of the vehicle which the preceding systems have. Thus, these systems may be complementary to the other systems and form a key component in an integrated collision avoidance system.

Countermeasures Against Intersection Collisions

Crossing path crashes at intersections represent a very large crash problem; nearly 30 percent of all crashes and 15 percent of all fatalities.

Figure 6 illustrates three major intersection crash scenarios. Below is a summary of principal causal factors identified for each:

o Perpendicular crossing path crashes at signalized intersections involve, by definition, a signal violation by one of the vehicles. Principal causal factors include: deliberately ran signal (ran red light or tried to beat signal change), inattentive driver (did not see red light), and driver intoxication.

o Perpendicular crossing path crashes at unsignalized intersections (e.g., controlled by stop signs) include cases where the at-fault driver ran the stop sign without stopping (42 percent) and those where the driver stopped but then proceeded against crossing traffic (58 percent). The principal causal factors for "ran stop sign" crashes include driver inattention and vision obstruction (e.g., sign obscured by foliage or parked vehicle). Principal causal factors for the "proceeded against crossing traffic" subtype include faulty perception ("looked but did not see"), misjudgment of gap/velocity, and vision obstruction.

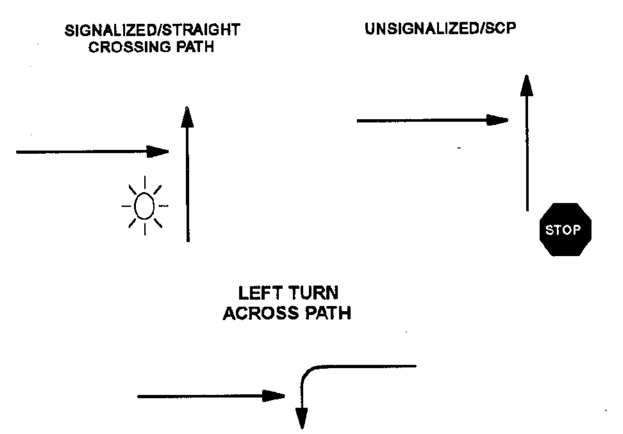


Figure 6. Intersection/Crossing Path Crashes: 3 Major Subtypes

- Left turn across path (from initial opposite direction) crashes involve similar causal factors whether they occur at a signalized or unsignalized intersection. These factors include "looked but did not see," misjudgment of gap/velocity, and vision obstruction (generally due to an intervening vehicle).

Intersection collisions generally involve vehicles which are moving at 90 degrees from each other and often at high relative speeds. This poses a tremendous challenge for the sensing and processing elements of any countermeasure to provide meaningful and timely collision avoidance assistance to drivers. The combination of two-dimensional motion, high relative speeds, large separation distances, and multiple vehicles with the potential for conflict make these systems potentially more complex than the preceding systems. For this reason, this project is addressing autonomous, vehicle-based systems, vehicle-to-vehicle communication systems, and/or cooperative highway-vehicle systems requiring instrumentation of intersections.

The potential role of cooperative vehicle-highway systems means that communication needs must be determined early in order to influence key system architecture decisions. Moreover, to efficiently incorporate collision management into the highway infrastructure, it will be necessary to begin developing functional and institutional interfaces, as well as the technology interface, as early as possible.

Vision Enhancement Systems for Nighttime and Inclement Weather

In 1992, approximately 44 percent of crashes (and 60 percent of fatal crashes) occurred during some degraded visibility condition, e.g., dawn, dusk, night, snow, rain, fog. The 2.6 million police-reported crashes and 23,472 fatalities represent target crashes for which visibility may be a contributing factor.

A number of interwoven factors contribute to the high crash rate at night, including alcohol, fatigue, and reduced visibility. Driver sensory impairments brought on by aging, glare, and loss of peripheral vision further degrade night vision/recognition tasks.

This project is investigating the feasibility of equipping motor vehicles with vision enhancement systems to help drivers avoid collisions at night and in inclement weather because of reduced visibility. It will address the visual information requirements for successful crash avoidance, as well as driver useability requirements, to ensure that supplementary vision enhancement systems do not distract drivers or otherwise degrade their overall driving performance.

Driver Status and Performance Monitoring

Agency statistics for 1992 indicate that there are approximately 50,000 police-reported crashes in which driver drowsiness/fatigue was cited as a potential contributing factor. Associated with these were approximately 1450 fatalities (4 percent of all fatalities). Due to underreporting, the actual involvement of driver drowsiness/fatigue in traffic crashes may be greater.

Research has shown that loss of driver alertness is preceded by measurable changes in performance and psychophysiological status. The NHTSA-supported research is addressing the concept of a vehicle-based device to unobtrusively monitor driver performance and potentially, psychophysiological status. The device will monitor driver status/performance, detect degraded performance, and provide an appropriate warning signal or other countermeasure to prevent its continuance. The current program is developing detection algorithms for reduced driver performance symptomatic of drowsiness/fatigue. Figure 7 shows a schematic of the envisioned vehicle-based drowsy driver detection system (Knipling and Wierwille, 1993; Knipling and Wierwille, 1994).

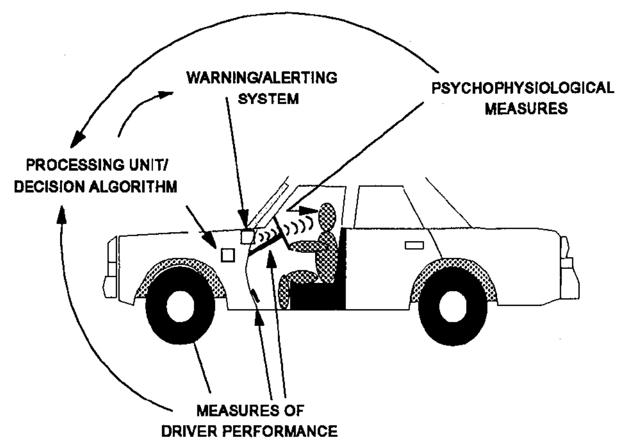


Figure 7. Vehicle Based Drowsy Driver Detection System Schematic

Enhanced Emergency Medical Service (EMS) Response

About 24 percent of collisions and 56 percent of fatal crashes occur in rural areas. Many of these crashes, especially single vehicle road departure crashes, occur in places where there are no easily-available communications facilities to alert emergency personnel of the need for emergency assistance. The objectives of this project are to investigate the feasibility of equipping motor vehicles with high-technology sensing and communications systems for automatically informing EMS dispatchers of the occurrence and location of a collision and to conduct an operational test in a rural area of systems to improve EMS response. The system tested would have the capability to automatically request emergency assistance.

Even in non-rural areas, these systems should speed EMS response by providing exact crash location, effectively reducing the injury consequences of the crash. The goal of this work is to provide improved notification and delivery capability that will help provide hospital-level medical care as early as possible following onset of the trauma. The patient's chances of survival decline rapidly with time. IVHS technologies should be able to reduce this time significantly.

THRUST NUMBER 4: FACILITATE DEVELOPMENT OF CRASH AVOIDANCE PRODUCTS TOWARD COMMERCIALIZATION

In order for safety to be improved, vehicle-based and/or cooperative collision avoidance systems must be available to, and purchased by, the motoring public, either as standard or optional equipment on new vehicles, or in the aftermarket. To facilitate product development and early deployment of IVHS-based, safety-enhancing systems, the agency is supporting industry initiatives by working cooperatively to accelerate development. NHTSA will also work with the industry to assess the performance, reliability, maintainability, failure modes/consequences, driver acceptance costs, and market readiness of promising systems under real world operating conditions.

In order to foster the development, evaluation and deployment of collision avoidance enabling technologies, products, and systems and to expand the knowledge base of collision avoidance, the agency has recently entered into cost-sharing, cooperative research efforts with five technology and product developers and research organizations.

Human Factors Aspects of Autonomous Intelligent Cruise Control

This project is addressing the range of human factors/driver acceptance issues associated with implementation of an autonomous intelligent cruise control (AICC) system. Industrial partners are Ford Motor Company and Systems Technology Inc.

Forward Crash Avoidance Systems

This project, being conducted by the University of Michigan Transportation Research Institute and Leica, is utilizing Leica's infrared-based AICC to evaluate varying levels of deceleration, through throttle closure, transmission down-shifting, and utilization of service braking as critical components of either AICC or crash avoidance systems.

Forward Looking Automotive Radar Sensors

The Environmental Research Institute of Michigan (ERIM) and TRW are contributing to the understanding of radar sensing in the roadway environment by collecting radar-cross-section data of representative motor vehicles and roadway objects, in both laboratory and freeway settings. Such data will assist developers of forward looking collision avoidance systems which utilize radar sensors.

Lane Detection

Lane tracking is a primary measure of driving performance; impaired drivers typically show increased fluctuations in lateral lane position. Inexpensive, reliable vehicle-based lane position detection is necessary for many of the prospective collision avoidance systems. No such devices currently exist. In this project, Rockwell International is evaluating a prototype machine vision lane detection sensor for this purpose.

Automatic Braking for Heavy Vehicles

Eaton is studying the issues associated with the automatic application of service brakes on heavy commercial vehicles. Results from this project will establish the feasibility of the concept of automatic braking for heavy vehicles, identify design requirements necessary to accomplish assisted braking through modification of existing ABS/traction control system components including associated costs/benefits for potential accident reductions, and provide an early indication of driver reaction to assisted braking under controlled conditions.

THRUST NUMBER 5: ASSESS THE SAFETY OF OTHER IVHS CONCEPTS

There are many IVHS concepts which entail functions other than crash avoidance, but nevertheless influence the driving task. Both for driver convenience and the avoidance of traffic congestion, driver information, and route guidance/navigation systems are likely to be marketed in substantial numbers by the mid-nineties. In Thrust 5, NHTSA fulfills its mission to ensure that such hardware is implemented in a safety-compatible manner by developing and applying evaluation protocols to assess the safety impact of introducing such systems into motor vehicles.

The fundamental safety questions being addressed in these evaluations are:

- o Do drivers drive more, or less, safely with the system than without it, in ways related to the system?
- o Do vehicles equipped with the system have fewer, or more, collisions than vehicles without the system?
- o If all vehicles in the fleet were equipped with the system, would there be a decrease, or increase, in the total number of collisions and collision-related deaths and injuries?

NHTSA is actively participating with the Federal Highway Administration (FHWA) in the safety assessment of such systems to ensure that protocols exist for evaluating the benefits of such technologies with regard to safety, and, most importantly, to ensure that safety is not inadvertently compromised by the systems. Of particular interest are those systems which pose unusual forms of driver workload and/or distraction. In addition, NHTSA is supporting FHWA in implementing the congressionally mandated program for automated highways demonstration by 1997. The agency will continue to be an active participant in this demonstration of automated highway technology addressing the safety and human factors implications of such systems.

NHTSA is currently involved in the safety evaluation of four operational tests. These are briefly described below:

Three of the projects are evaluating route guidance/navigation systems. For these systems there are two additional subquestions to be addressed:

- o Whether the system directs the driver to a route which has a lower likelihood of collision, and

- o Whether the driver interface enhances safety by providing information in a way that relieves the driver of some navigational workload or degrades safety due to distraction.

TravTek

TravTek is an operational test of an advanced motorist information system in 100 test vehicles which combines vehicle navigation and tourist information with up-to-the-minute traffic data to improve driver efficiency. TravTek is a joint venture of General Motors, the American Automobile Association, the State of Florida, the City of Orlando, and the U.S. Department of Transportation. The primary objectives of this demonstration project is to determine the technical feasibility of such a system, user acceptance, and reduction in travel times.

The 1-year test concluded in March 1993; evaluation of the test data continues. The final evaluation report is scheduled to be completed in June 1994.

Advanced Driver and Vehicle Advisory Navigation Concept (ADVANCE)

The Illinois Department of Transportation, Motorola, Inc., Illinois Universities Transportation Research Consortium, and the U.S. Department of Transportation are involved in a large-scale cooperative effort to evaluate the performance of a dynamic route guidance system. Up to 5,000 private and commercial vehicles in the northwestern suburbs of Chicago, Illinois, will be equipped with in-vehicle navigation and route guidance systems. Vehicles will serve as probes, providing travel time data to a traffic information center. This information will then be transmitted to the equipped vehicles and used to develop a preferred route. The routing information will be presented to the driver in the form of dynamic route instructions.

The safety issues in ADVANCE are substantially the same as those addressed in TravTek. ADVANCE differs from TravTek in that it involves a much larger population of equipped vehicles and the in-vehicle equipment is installed in existing vehicles rather than engineered into a new vehicle. The use of existing vehicles raises additional ergonomic/human factors issues such as the effect of various locations in or near the instrument panel and ease of use.

Faster and Safer Travel Through Traffic Routing and Advanced Controls (FAST-TRAC)

This operational test in Oakland County, Michigan, is evaluating the Australian SCATS traffic adaptive control system, Autoscope video-image processing technology for traffic detection in support of real-time traffic control, and vehicles equipped with the Siemans Ali-Scout route guidance and driver information system. Infrared beacons will be installed at critical locations in the network to provide for a continuous exchange of real-time traffic and route guidance information. Partners in this endeavor include the Michigan Department of Transportation, Siemans Automotive, General Motors, Ford, Chrysler, Road Commission for Oakland County, the University of Michigan, and the U.S. Department of Transportation.

TravelAid

The Washington State Department of Transportation, Farradyne Systems, Inc., and the U.S. Department of Transportation are evaluating the effectiveness of variable message/speed limit signs and in-vehicle communication equipment to improve the safety along a 40-mile stretch of heavily travelled I-90 across Snoqualmie Pass, a rural area of Washington State that is prone to snow, ice, and poor visibility. Electronic sensing and equipment will be installed to monitor traffic, speeds, and road/weather conditions. This information will be the basis for determining appropriate speeds for conditions. Variable message/speed signs will broadcast warnings about road conditions, accidents, or slow-moving equipment, as well as appropriate speeds. In addition, the use of a relatively simple, low cost in-vehicle device which will display to the driver a text message similar to that displayed by the variable message signs will also be evaluated. Up to 200 vehicles will be equipped with the in-vehicle devices.

The in-vehicle equipment will be available for testing in the winter of 1994; the variable message signs a year later. Key safety questions to be addressed in this operational test are the safety impact of the in-vehicle information system and the effect of the information provided on reducing vehicle speed.

SUMMARY

Although extensive research, development, test, and evaluation programs will be necessary to produce reliable, cost-effective intelligent collision avoidance systems, it is believed that effective systems can be developed without the need for major technological breakthroughs. The major challenge will be to ensure the characteristics of the IVHS systems match the capabilities and limitations of the drivers who must use these systems. If the systems are not "user-friendly," the potential safety benefits will likely not be fully realized. The NHTSA IVHS program described in this paper is providing the engineering and human factors research necessary to accelerate the development and deployment of collision avoidance systems by the industry and to achieve the potential safety benefits promised by such systems.

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Automatic Distance Keeping: A Vehicle Comfort System for Improving Safety?

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94-S3-O-02

INTRODUCTION

Today conventional cruise control systems are only well accepted in the North-American countries. A reason may be the steady increase in traffic density in Western Europe together with a continuous change of speed. This makes it almost impossible to drive with a fixed speed for a longer period of time.

ABSTRACT

This paper describes the structure of Adaptive Cruise Control (ACC) systems. To find out how driving with ACC systems will effect safety a simulation experiment was designed. To achieve the amount of realism needed this experiment uses a moving base driving simulator. During a 60 min. journey with an ACC vehicle and with an standard vehicle test subjects are exposed to several hazardous situations. Besides the subjective evaluation, done by psychologists, analysis of recorded data allows also to assess safety effects objectively.

Bearing this in mind, the European car manufacturers started, embedded into the PROMETHEUS research framework, a project called "Autonomous Intelligent Cruise Control (AICC)". The objective is by adding an automatic distance keeping function to the ordinary speed keeping function of a current cruise control system to enlarge the operating envelope of these systems. Although being a research topic for more than twenty years automatic distance keeping has now become attractive for automotive industry because of the availability of forward looking sensors which can be produced with acceptable cost.

In North-America the same function is called "Adaptive Cruise Control (ACC)" and is evaluated within the IVHS activities. This is also the name under which it will be standardized, therefore we will call them ACC systems.

3 years ago we had our first ACC vehicle driving on public roads. Meanwhile we have driven thousands of kilometers and the enhanced comfort provided by these systems cannot be denied.

Also first results from traffic simulation show that probably these systems will increase traffic safety by reducing the potential that a traffic jam will occur with its hazardous traffic situations [Mau, 92].

On the other hand there is an ongoing discussion what effect these systems will have on driver's safety, i. e. what will happen if he is exposed to a real critical situation. ACC systems are no collision avoidance systems, so they will fail to handle these situations. Will we have a negative side effect from these systems because the driver expects more than it can provide?

In order to get first results to answer this question we decided to setup a driving experiment in a simulator.

SYSTEM DESCRIPTION

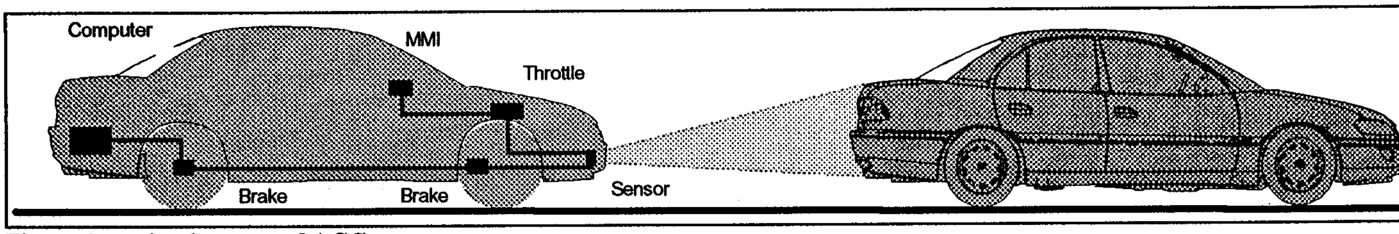

Figure 1: main elements of ACC systems

Man-Machine-Interface

In order to ease the transition from standard cruise control to intelligent cruise control systems for the driver, we introduced only very little changes to the driver system interaction. The same lever used in standard cruise control the driver now sets his desired maximum speed he wants to travel. The Tap Up or Tap Down Function changes the desired speed in steps of 10 km/h accordingly. This stepsize allows a convenient adaptation of the set speed to prevailing speed limits.

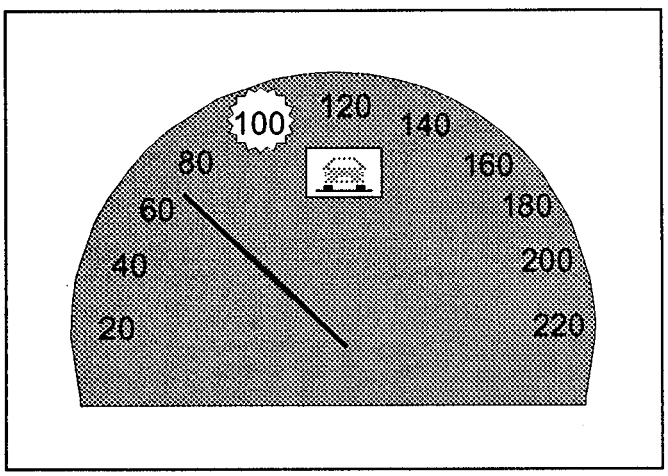

Figure 2: ACC display structure

LED's are installed in the outer speedometer circle every 10 km/h. When the system is switched on a green LED related to the set speed is illuminated. With introduction of ACC this feed back is mandatory because in case a slower vehicle is driving in front of you the ACC vehicle will automatically slow down and now the driver needs to know to what speed the car will accelerate again. All other functions remained unchanged, particularly we are convinced that the system has to be disengaged by brake pedal activation.

Throttle

For throttle control we use in our vehicle an electronic throttle control. However, this job could also be done by a ordinary cruise control actuator. On the other hand there is a high probability that electronic throttle control will become standard in the near future because of the lower emission limits issued by authorities. Then the cruise control function is degraded to *software only.*

Brake

For performing the active braking, we see two concurrent developments. So called "Smart booster" systems or modified ABS/Traction Control systems. The advantage of "Smart booster" systems will be their quietness which will be difficult to achieve with ABS/Traction Control system. But especially in car lines where ABS/Traction Control is already standard it might be more cost effective to go in this direction.

Currently we use a discrete additional brake system, consisting of its own pump, pressure storage and a plunger to feed this into the vehicle's brake circuit just before the ABS block.

Computer

The control algorithms for speed and distance control currently reside in a separate computer. Nevertheless, when it comes to production this part is only a logical module which could be placed for instance in the engine management control.

In our ACC vehicles we implemented a two-step approach. First we created a vehicle independent algorithm to calculate the desired acceleration. Input variables are the distance to the preceding vehicle, the desired headway and the relative speed. This is done by using fuzzy control techniques. In a second step the desired acceleration respective deceleration is then transformed into a butterfly valve angle and a brake pressure using a dynamic model of the specific car.

Sensor

The most innovative element is definitely the forward looking sensor required for detecting the preceding vehicle. The minimum required output is range and range rate. Additionally the lateral position of the detected vehicle is needed in systems with active braking. Here the acceptable false alarm rate has to be significantly lower than in systems without active braking.

For proper system function particularly on highways with its highspeed driving, we consider a minimum range capability of 150 m. Our requirements for relative speed accuracy are driven by our demand for a comfortable car following control. A value of circa 0.5 m/s with an overall latency of 200 - 300 msec seems sufficient. The update rate should be at least 10 Hz.

Two different technologies are currently competing on the market, infrared and microwave radar, both having their specific advantages. Microwave radar can make use of the Doppler effect to measure the range rate whereas infrared systems have to derive this from a sequence of distance measurements. This can generate virtual targets when you are driving through a bend. On the other hand infrared technology still seems to be the cheaper solution.

SIMULATION LOOP

When we were planning to study the safety effects of ACC systems by a simulator experiment, we had to look for a simulator which could give the amount of realism needed. It became obvious that only a moving base driving simulator could fulfill our requirements.

Several reasons facilitated our decision to conduct this study at the driving simulator of the Swedish Road and Traffic Research Institute (VTI) at Linköping, Sweden.

Firstly, due to its unique graphics system, the VTI driving simulator is one of the fastest in the world. The picture update rate is 20 milliseconds, which is also the update rate of the video system. Therefore it is not sensible to be faster than that. This very high update rate is responsible for the convincing sensation of realism this simulator provides.

Secondly, we took advantage of the fact that SAAB had already conducted a different study with this simulator at the beginning of this year. So basically the simulation loop existed, only the ACC function had to integrated and a forward looking sensor had to be simulated.

For this study the following sensor characteristics were chosen:

Range:	3 - 130 m
Field of view:	± 4 °
Update rate:	10 Hz

For simplicity the range-rate values will be accurate, because both, the speed of the preceding vehicle and the speed of the ACC vehicle are calculated in the simulator. Also, within these limits the sensor will work perfectly, as it was beyond the scope of this study to evaluate false alarms generated by the sensor module. However, these

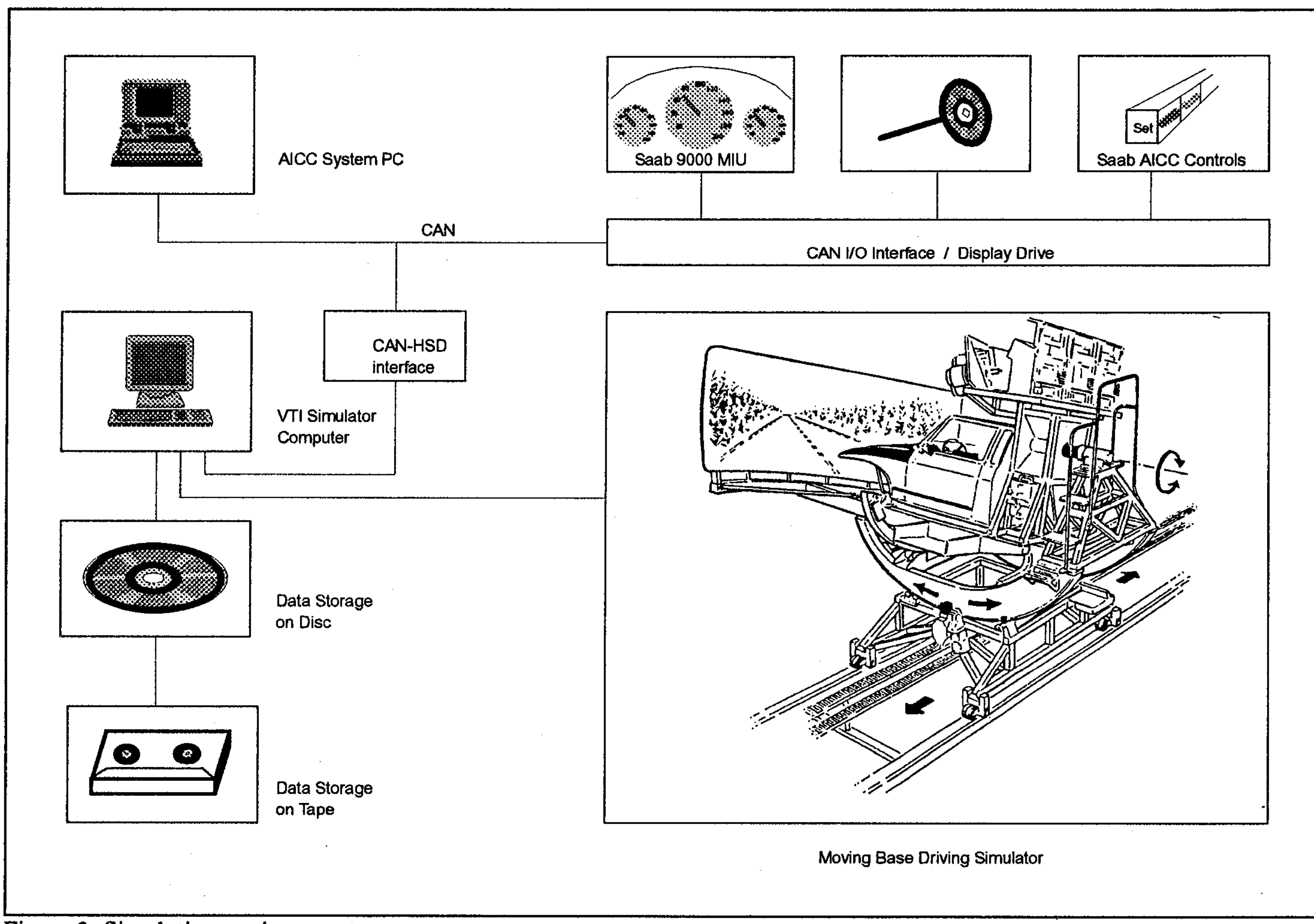

Figure 3: Simulation environment

will happen in reality.

Another problem which had to be resolved was to improve the sensation of deceleration. As you can see on Fig. 3, it is not possible to move the simulator along the longitudinal axis in order to provide a real acceleration/deceleration feeling. However, up to a certain extent this can be induced by a pitch movement of the vehicle cabin. Additionally we produced a noisy jerk during the start of braking to give a even more noticeable sensation of deceleration.

During the simulation all scenario data like road position, curvature, road sign appearance and type, appearance of vehicle ahead and performance data like speed, lateral position, headway, reaction time, pedal use are recorded. Also the complete ACC status is made available to the simulator computer.

Naturally the complete test ride is recorded on video including the driver behavior.

TRAFFIC SCENARIOS AND STUDY SET UP

Potential candidates for traffic scenarios which may cause critical situations are always those when the system state changes from *automatic* to *manual,* unless it was initiated by the driver. This can happen both, on demand of the system and without any notice.

Scenarios belonging to the first category are:

a. While braking automatic the system reaches its minimum allowed speed for ACC. In this case the system will inform the driver by an acoustic signal. At the same it will continue braking until the driver takes over or the ACC controller wants to accelerate the vehicle again. At that moment ACC will switch off itself and brake and throttle control is at the driver.
b. ACC has reached its maximum braking capability, but it is not sufficient to handle the situation. Also in this situation ACC will ask the driver to take over control by using the same acoustic signal.

Scenarios of the second category are:

a. The ACC vehicle is approaching a stationary object, for instance the rear end of a traffic jam. Although these objects might be detected by sensor, the post-processing will remove them, because they are not considered valid targets in ACC systems. Consequently there won't be any reaction of the vehicle. Here the driver himself has to identify the situation and has to react properly.
b. failure of the sensor to detect preceding vehicle
c. loss of preceding vehicle. Here the ACC vehicle will react with a sudden acceleration, if the set speed is higher than the current speed.

To prevent frustration of the subject we selected only three of these scenarios. Both of the first category and the first of the second category. These scenarios will be generated by the following traffic situations:

Subject stuck:

The subject catches up a car driving with subject's speed - 20 km/h. At the same time another car has overtaken and is positioned in the left lane "between" the subject's car and the car in front: The subject is locked in, and all 3 cars are driving with the same speed. Then the two cars in front brake harder than 0.3 g.

Subject overtaken:

The subject catches up 8 vehicles driving with a speed 20 km/h below his/her own speed. In seven cases everything goes well and the subject overtakes the car in front. For the eighth case the car in front starts overtaking another car in front when the subject has changed lane in order to overtake.

Slow traffic:

Vehicles in both lanes, slowing down to a very low speed (25 - 30 km/h) due to a traffic jam ahead. Then the cars ahead accelerate and disappear.

Traffic standing still:

Vehicles in both lanes ahead standing still due to traffic jam.

"Subject stuck" and "Slow traffic" are considered non-critical. They will appear announced and without announcement. The announcement will be done by displaying a red square in the image which has to be confirmed by the pressing a button on the steering wheel. These situations will be integrated into a 80 km long journey on a standard motorway with two lanes in one direction with the most critical situation "Traffic standing still" at the end. As this study is done in Sweden we have speed limit signs of 110 km/h along the road. The sight is slightly hazy with a range of visibility of 400 m. The subjects task is to drive as they usually do under similar road, environmental and traffic conditions. They are allowed to set there ACC speed themselves and to overtake if they like. Two groups of subjects are formed one driving with and without ACC respectively. All drivers will have at least five years experience in driving. In order to establish a good confidence level into ACC, we will not have critical situations within the first third of the test ride.

METHODS AND RESULTS

In the first run we will have at least 10 subjects in each group. They will be guided by an instructor. Besides an subjective evaluation done by an psychologist, we will record for an objective analysis the following data:

Number of crashes
Crash analysis
Preceding vehicle inside the Brake-to-Stop distance
Improper speed according to traffic situation

Particularly we will analyze whether the safety margin you can possibly gain by the early reaction of the ACC system is later on ruined by the take over control action of the driver.

Unfortunately first results won't be available before End of May. An amendment will be given at the conference.

CONCLUSIONS

will be included in the amendment

REFERENCE

[Mau, 92] Vito Mauro, "Effectiveness of AICC: outline of an assessment" in Proc. of the AICC-Workshop, Dudenhofen, November 25/26, 1992, pages 193 - 207

Using the REAMACS Model to Compare the Effectiveness of Alternative Rear End Collision Warning Algorithms

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94-S3-O-03

ABSTRACT

This paper presents the results of an analytical study of alternative rear end collision-avoidance algorithms using the Ford REAMACS simulation. REAMACS (Rear End Accident Model And Countermeasure Simulation) models rear end collision situations in freeway traffic and estimates the benefits of collision avoidance systems. Previously reported applications of the model indicate that rear end crash warning system has the potential for a 60% reduction of the number of serious rear end crashes in freeway traffic. The present study confirmed and extended those findings to a broader range of conditions. Two different collision warning algorithms were analyzed: (1) a Closing Rate algorithm (CRA) which provides a warning only if the following vehicle has a positive closing rate with the lead vehicle, and (2) a Stopping Distance algorithm (SDA) which provides advanced warning of a potential hazard. The Stopping Distance Algorithm was more effective than the Closing Rate algorithm, with effectiveness rates approaching 100%, but gave 440 to 1100 times more warnings than the Closing Rate Algorithm. Whether or not drivers would comply with such warnings is an issue.

INTRODUCTION

A previous paper (1) described a model for studying the genesis of rear-end collisions in freeway traffic and estimating the potential benefits of collision warning systems in such crashes. The model is known as REAMACS (Rear-End Accident Model And Countermeasure Simulation). REAMACS uses a quasi-Monte Carlo routine to generate the initial conditions that determine whether or not a crash occurs. The model was used to estimate the benefits of a collision-avoidance algorithm which provides a warning when the distance to the vehicle ahead is less than a threshold distance determined by the closing rate, i.e., the speed with the following car is overtaking the lead car.

These initial applications of the model indicated that a collision warning system with a range of about 250 feet (75 meters) has the potential to reduce the number of all rear-end collisions by 50% and the more serious ones by over 60%. Further, the impact speeds of crashes that do occur are reduced by up to 38% with a 250-foot range system.

This paper reports the results of further REAMACS applications in three areas:

1. the sensitivity of the results to some of the fundamental assumptions in the model, in particular, driver response time and braking deceleration levels,
2. consistency of results across different traffic data sets,
3. a comparison of alternative collision warning algorithms.

THE REAMACS MODEL

REAMACS is a quasi-Monte-Carlo simulation which uses data recorded from freeway loop detectors as a source of realistic information on vehicle speeds, closing rates and headways in traffic. The simulation also incorporates routines to represent the effect of a rear-end collision warning system on the driver's response time and hence on the outcome of a potential crash. REAMACS thus "creates" a large number of following situations in freeway traffic. The model determines (1) which of these scenarios will lead to rear-end crashes if the lead vehicle brakes to a stop, and (2) the effectiveness of some collision-avoidance countermeasure in preventing or ameliorating the crash. A detailed description of the model is provided in Reference 1.

The REAMACS Scenario

The simulation begins with a lead and following vehicle travelling in the same lane. At t_0, the lead vehicle commences braking and slows to a stop. After some response time delay, the driver of the following vehicle begins to brake. (Braking is the only avoidance maneuver considered in the model.) The t_0 parameters that determine whether or not a rear-end collision ensues are:

1. the lead vehicle's speed,
2. following vehicle's speed,
3. the closing rate (determined by the lead and following vehicle speeds),
4. the gap (front to rear) between the lead and following vehicles,
5. lead vehicle's deceleration,
6. the response time of the following vehicle driver to:
   - the onset of lead car braking,
   - the collision warning system signal,
7. the following vehicle's deceleration.

The lead vehicle's braking level and the following driver's response time are random variables, sampled from appropriate distributions. The following vehicle's deceleration level is fixed at 0.7g to represent emergency braking on a dry surface. The speeds of the lead and following vehicles and the gap between them are taken from a vehicle pairs data base created from traffic data files provided by the Federal Highway Administration. These files contain data recorded from a pair of loop detectors on Interstate 40 in New Mexico near Albuquerque. Each record in the file contains the speeds of the lead and following vehicles of a "following pair" and the front-to-rear gap between them. This file is not randomly sampled. Rather, every vehicle pair record in the data file is used in a given "run" of the model.

For a given vehicle pair REAMACS calculates whether or not, given these initial conditions, a collision occurs and, if so, the speeds of the vehicles at the moment of the crash. If a crash occurs, REAMACS recalculates the kinematics to reflect the effect of whatever collision-avoidance countermeasure is under investigation.

The simulation proceeds in this manner until all of the vehicle pairs in the traffic data base have been exhausted.

Countermeasures

The accident-avoidance countermeasure evaluated in this simulation is a front collision warning system employing a simple warning algorithm. The assumptions about this system are as follows:

1. the following vehicle is equipped with a sensor for measuring the distance to the lead vehicle directly ahead and the speed difference between them,

2. the system always works perfectly up to its range limitation, i.e., it never fails to detect the lead vehicle, never detects the "wrong" vehicle and provides accurate speed and distance information,

3. when the warning criterion is met, the system signals the driver, for example, with a warning tone,

4. the following driver always responds to the warning by braking after some response time. In particular, if the following vehicle is in a warning state at t_0 (i.e., inside the warning distance), its position and speed at t_0 are recalculated under the assumption that the driver would have responded when the warning threshold distance was reached at some time prior to t_0.

5. the system has a 0.2 second lag, which is added to driver response time.

THE "EXPERIMENT"

Traffic Data Files

Two different traffic data sets were used in these analyses. One data set was recorded on September 25, 1991 and consists of 36,919 pairs of following vehicles. The results published earlier (1) were based on this file. The second set was recorded on July 11, 1993 and consists of 31,612 vehicle pairs. The distributions of time gaps (headway measured from the front of the following vehicle to the rear of the lead vehicle) for the two files are given in Table 1. Note that in both distributions about 1/4 the vehicles were following at time gaps of one second or less and about 6% at time gaps of 0.5 seconds or less. The September 25 traffic was somewhat heavier than the July 11 traffic with median time gaps of 1.67 and 1.97 seconds, respectively.

The speed distributions are given in Table 2. The mean speeds were 54 and 61 mph (87 and 98 kph) respectively for the September and July files.

Changing Standard Assumptions about Response Time and Lead Car Braking

REAMACS makes certain "standard" assumptions about (1) the response time of drivers to the onset of braking by the lead vehicle and (2) lead vehicle braking levels. One purpose of this study was to determine the sensitivity of both the base accident rate and the effectiveness of the collision warning algorithms to changes in these assumptions.

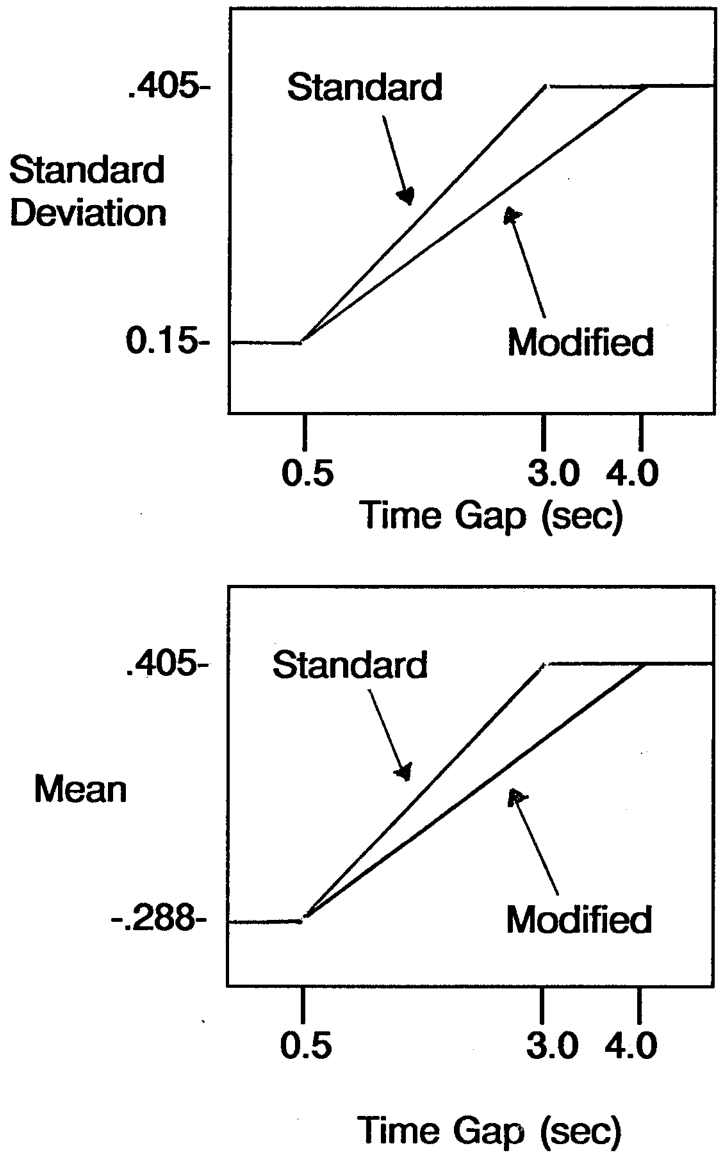
Table 1
Cumulative Time Gap Distributions
September and July Data Files

Time Gap (sec) (Front to Rear)	Cumulative Percent	
	Sept. 25	July 11
0.25	0.9	0.7
0.50	6.4	5.5
0.75	16.8	14.2
1.00	28.3	23.5
1.50	46.0	39.5
2.00	56.6	50.6
2.50	64.1	59.3
3.00	69.5	65.7
4.00	77.2	77.8
8.00	90.1	93.1
12.00	94.5	98.1
16.00	96.4	99.3

Table 2
Cumulative Speed Distributions
September and July Data Files

Speed mph (kph)	Cumulative Percent	
	Sept. 25	July 11
10 (16)	0.01	0.0
20 (32)	0.40	0.0
30 (48)	3.2	0.0
40 (64)	11.1	1.6
50 (81)	27.2	6.0
60 (97)	77.6	58.3
70 (113)	99.0	98.4
80 (129)	99.9	100.0

<u>Following Driver Response Time to Lead Car Braking</u> In REAMACS, driver response times are represented by a log-normal distribution whose mean and standard deviation depend on the gap time between the vehicles. These relationships are shown in Figure 1. In the "standard" version of the model, the distribution parameters are based on the surprise reaction time data reported by



Note: 0.405 = ln(1.5)
0.150 = ln(1.16),
-0.288 = ln(0.75)

Figure 1. Assumptions for a Log-Normal Response Time Distribution: Mean and Standard Deviations as a Function of Time Separation Between Lead and Following Vehicles

Olson et. al. (2) when the time gap is 3 seconds or greater. At shorter gap times, drivers are assumed to be more alert. Accordingly, both the mean response time and the variability are reduced at the shorter headways.

In the present application, this relationship is modified by increasing the time headway at which the maximum parameter values are reached from three seconds to four seconds. This is shown as the "modified" line in Figure 1. The effect of this change is to curtail the overall distribution and reduce the probability of drawing long response times.

Lead Vehicle Deceleration Level In the baseline condition, lead vehicle deceleration values are drawn from a normal distribution reported by Farber et al. (3) with a mean of 0.17g and a standard deviation of 0.1. To test the sensitivity of the model to deceleration level, runs were made with the mean reduced to 0.13g.

The standard and modified assumptions are summarized in Table 3.

Table 3
Standard and Modified Assumptions Regarding Response Times and Deceleration

Assumption	Time Headway for Maximum Response Time Mean and SD	Mean Lead Car Deceleration
Standard	3 seconds	0.17g
Modified	4 seconds	0.13g

Countermeasure Algorithm

Two collision warning algorithms are compared in this study. For convenience, they are termed the "Closing Rate" (CRA) and the "Stopping Distance" (SDA) algorithms and are given in Equations 1 and 2, respectively. The base algorithm used in the previous study (1) was Closing Rate. The Stopping Distance algorithm is so termed because the warning distance is defined as the difference between the stopping distances of the lead and following vehicles. The form of the algorithm and the parameter values shown in Equation 2 were taken from a U.S.Department of Transportation study of rear end collision countermeasures (4). With either algorithm, the assumption is that when the actual distance between the vehicles is less than D_w, a warning is provided to the driver of the following vehicle.

Equation 1
Closing Rate Algorithm

$$D_w = \frac{(FCS - LCS)^2}{2a_w} + (FCS - LCS) \bullet RT_w$$

Where:
D_w is the warning distance
FCS is following vehicle speed
LCS is lead vehicle speed
a_w is the deceleration of the following vehicle, and
RT_w is the response time of the following driver.

and
a_w = 10 feet/sec^2 (0.31g)
RT_w = 2.5 seconds

Equation 2
Stopping Distance Algorithm

$$D_w = \frac{(FCS)^2}{2aF_w} + (FCS) \bullet RT_w - \frac{(LCS)^2}{2aL_w}$$

Where:
D_w, FCS, LCS and RT_w are as defined above
aF_w is the deceleration of the following vehicle,
aL_w is the deceleration of the lead vehicle

and
aF_w = 19.3 feet/sec^2 (0.6g)
aL_w = 11.3 feet/sec^2 (0.35g)
RT_w = 2.05 seconds

It should be noted that the CRA establishes no minimum following distance. No warning is provided unless the following vehicle is closing on the lead vehicle, i.e., FCS - LCS > 0. The SDA, on the other hand, does establish a warning distance even when there is no closing rate because of the different deceleration levels assumed for the lead and following vehicles. Also, the warning distances produced by the SDA are much more sensitive to the difference in the speeds between the two vehicles than is the CRA. That is because with the SDA, the warning distance increase as the difference between the squares of the speeds, whereas with the CRA, the warning distance increases as the square of the difference.

The difference in the warning distance produced by these algorithms is shown in the example in Table 4.

Table 4
Warning Distances with CRA and SDA Algorithms for Two Cases

	LCS=FCS=55mph (90 kph)	LCS = 55mph FCS = 65mph (105kph)
CRA	No warning	47 feet (14m)
SDA	46 feet (14m)	143 feet (44m)

RESULTS

Table 5 defines the conditions of the REAMACS exercises conducted for this analysis and also provides baseline data on crashes and warnings.

The warning data refer to the number of vehicle pairs that were in a warning state (i.e., inside the warning distance) at t_o. This is the only set of results in Table 5 that is dependent on the warning algorithm.

The crashes shown are those that occurred as a result of initial conditions and lead car braking in the absence of any countermeasure. "Police Crashes" represent a subset of crashes in which the impact speed (difference between lead and following car speeds at impact) was 10 mph (16kph) or greater.

Relative harm is the squared sum of the impact speeds divided by the total sample size and is arbitrarily scaled so that the value is 100 for the September standard baseline data (first data column). Crash energy increases with the square of the impact speed. The relative harm parameters thus reflects both the crash rate and the seriousness of the crashes.

Each data column of the table represents a separate run of the model. Each run consisted of multiple samples of each of the vehicle pairs in the data base. That is, for each record in the data base, the calculations were repeated 100 or 200 times, each time with different random values of response time and lead vehicle deceleration.

The first four data columns of the table represent runs under standard conditions, that is, the standard driver response time assumptions shown in Figure 1 and the mean lead vehicle braking level is 0.17g. The last three columns represent runs in which these assumptions were modified: Reduced RT refers to the modified assumptions shown in Figure 1 and Reduced a_L means that the mean lead car deceleration was 0.13g. (It is important to note that these response time and deceleration conditions pertain to the assumed response of a following driver to lead car braking, and to lead car braking levels in traffic; they do not pertain to the warning algorithms.)

Data File Effects

The first four data columns of the table provide a comparison of the two different data bases. There were about 1/3 more crashes and almost 40% more warnings with the July data than the September data, despite the fact that the traffic was heavier in the September file. The July data also produced a higher percentage of police crashes, and relative harm was greater with the July data. The mean speed was seven mph (11 kph) higher in the July file which might account for the difference.

Modified Response Time and Deceleration Assumptions

The effect of reduced response times and lead car braking levels is to significantly reduce the number of crashes, especially in combination, as would certainly be expected. Reduced response time also drastically lowered the relative harm. Reducing lead car deceleration also resulted in a reduction in relative harm.

Algorithms and Warnings

As shown in the second and fourth data column, the SDA produced many times more warnings than the CRA. In fact, 18.4% of the vehicles in the September data base and 9.8% of

Table 5
Baseline Results - No Countermeasures

Algorithm/Conditions ========>	Closing Rate Algorithm Standard Assumptions		Stopping Distance Algorithm Standard Assumptions		Closing Rate Algorithm Modified Assumptions		
					Reduced RT	Reduced aL	Reduced RT & a_L
	September	July	September	July	September		
File size (vehicle pairs)	36,671	31,479	36,671	31,479	36,671	36,671	36,671
Number of iterations	100	100	100	100	200	200	200
Total sample size	3,667,100	3,147,900	3,667,100	3,147,900	7,334,200	7,334,200	7,334,200
Warnings at t_o per million vehicle pairs	436	604	183,551	97,875	436	436	436
Crashes per million vehicle pairs	167	223	167	222	103	75	39
Police crashes per million vehicle pairs	68 (41%)	104 (46%)	62 (37%)	106 (48%)	15 (15%)	28 (37%)	5 (13%)
Relative Harm	100	145	95	168	14	53	5
Warnings per crash	2.6	2.7	1098	441	4.3	5.8	11.1

the vehicles in the July data base were within the SDA's warning distance at t_0.

Effects of Warning Countermeasures

Results are summarized in Tables 6 and 7 which show the effect of the warning algorithms on crash frequencies and impact speeds, respectively.

Table 6 shows percent reductions in the number of all crashes and police crashes for each of the seven runs. A primary variable of interest in the table is the range limitation of the crash warning system. The important results were as follows:

- Under standard conditions (first four data columns), the effectiveness of the warning increases with range and peaks at 250 or 300 feet (75 or 90 meters). (Previous work (1) has show that there is almost no improvement in performance with ranges greater than 300 feet.) However, under the reduced Response Time assumption, there is little or no improvement in performance beyond 150 feet (45 meters). At 250 feet, the CRA reduced the number of police crashes from between 60% to 75%, depending on the assumptions.

- The SDA produced much larger crash reductions than the CRA, approaching 100% for a 300-foot (90m) range system. At 250 feet (75 meters) this algorithm eliminated 94% to 96% of the police crashes.

- In general, the CRA was more effective against the more severe crashes than against crashes with impact speeds less than 10 mph (16 kph).

- The CRA was more effective with the July traffic than the September traffic.

- Changing the assumptions about response times and braking levels had a strong effect on the number of crashes. However it had much less effect on the performance of the warning system. The magnitude of the reductions in police crash rates for the CRA is of the same general order over the range of conditions studied.

Table 7 shows the total reductions in relative harm brought about by the warning systems, and reflects both reductions in the number of accidents and reductions in impact speed in crashes that occurred despite the warning. As with crash reductions, relative harm decreases with increasing system range, with useful improvements out to 300 feet (90 meters) with the SDA. The SDA generally produced greater reductions in harm than the CRA.

The effect of the reduced lead car deceleration assumption was to reduce the base (no-system) level of harm by about half. Relative harm decreased with system range at about the same rate as under the standard assumptions.

The effect of the reduced response time assumption on the base crash rate and level of harm is so great that it tends to mask the effect of the warning system. Nevertheless, viewed as a percentage of the base rate, the reduction in relative harm produced by the warning (57%) was significant and the maximum effect was achieved with a system range of only 200 feet (60 meters). Combining reduced response time and reduced lead car deceleration had an even more radical effect on the base level of harm. Still, the warning reduced the level of harm by 60%, this level being achieved with a system range of only 150 feet (45 meters).

DISCUSSION

Closing Rate vs. Stopping Distance Algorithms

The most striking result of these analyses is the difference between the CRA and SDA. Where the CRA eliminated roughly 2/3 of the police crashes, the SDA eliminated from 95% to 100% of them. At the same time however, the SDA produced many more warnings. In the September 25 traffic, 18% of the drivers were in a warning state at any given time. It must be kept in mind that REAMACS assumes perfect compliance by drivers to the warning system. This means that when REAMACS recalculates crash kinematics after a warning, any following vehicles that are in a warning state at t_0 are moved back to the warning distance. As Table 4 shows, the warning distances are generally much longer for the SDA than the CRA. In particular, the SDA establishes a minimum, speed-dependent following distance.

Table 6
Effects of Countermeasures - Reductions in Crashes as a Function of System Range

		Closing Rate Algorithm Standard Assumptions		Stopping Distance Algorithm Standard Assumptions		Closing Rate Algorithm Modified Assumptions		
						Reduced RT	Reduced a_L	Reduced RT Reduced a_L
System Range	Crash Type	September	July	September	July	September		
		Number of Crashes and Police Crashes per million vehicle pairs with no Countermeasure (from Table 5)						
No System	All	167	223	167	222	103	75	39
	Police	68	104	62	106	15	28	5
		Percent Reduction of Crashes and Police Crashes Due to Warning						
150 feet (46m)	All	29	39	78	71	39	39	46
	Police	34	46	49	48	58	37	71
200 feet (61m)	All	37	62	92	88	39	48	47
	Police	53	69	82	79	60	63	76
250 feet (76m)	All	41	66	98	97	39	53	47
	Police	63	77	96	94	60	73	76
300 feet (91m)	All	42	66	99	99	39	54	47
	Police	65	78	99	99+	60	75	76

Table 7 Effects of Countermeasures on Relative Harm							
	Closing Rate Algorithm Standard Assumptions		Stopping Distance Algorithm Standard Assumptions		Closing Rate Algorithm Modified Assumtions		
					Reduced RT	Reduced a_L	Reduced RT & a_L
System Range	Sept	July	Sept	July	September		
No System	100	145	95	168	14	53	5
150 ft (46m)	62	92	50	96	7	34	2
200 ft (61m)	34	36	19	36	6	17	2
250 ft (76m)	24	23	4	9	6	10	2
300 ft (91m)	22	21	1	0	6	8	2

The SDA provides drivers with advance warning of potential hazard whereas the CRA provides last-moment warning of actual hazard. In the end, the willingness of drivers to accept and respond to frequent warnings, the great majority of which will be false alarms, will determine whether or not the SDA represents a feasible approach.

Modified vs. Standard Assumptions

The seemingly modest alteration in the standard response time assumption resulted in a very large decrease in the crash rate and demonstrates once again how important driver reaction time is in accident causation. Reducing the mean lead car deceleration level by 0.04g's also produced a significant reduction in crashes.

What is more important for the purpose of this analysis is that these modifications to the standard assumptions had little effect on the overall effectiveness of the crash warning. At 250 feet (75 meters), the CRA resulted in 60% to 75% reductions in police crashes under standard and modified assumptions.

An analysis reported in the earlier paper (1) estimated that the number of police crashes per million vehicle stops predicted by REAMACS (standard assumptions, no countermeasures) was from 1.6 to 16 times higher than the actual rate. When the modified assumptions are factored into the analysis, this range changes from 0.4 to 16 overall. *This range of assumptions thus produces a range of crash rates that likely encompasses the real world rates. This attaches some additional validity to the REAMACS predictions, in particular with regard to the CRA warning countermeasure.

One important effect of the reduced response time assumption is that with this modification, the warning (CRA) reached maximum effectiveness at shorter system ranges, i.e., 150 or 200 feet (45 to 60 meters) instead of 250 feet (75 meters).

Traffic Data Files

There was enough difference in the outcome of the simulation between the two different traffic data files (e.g., 63% vs. 77% effectiveness for September and July at 250 feet (90 meters) to warrant further analysis. In particular, the simulation needs to be run with a wider range of traffic data.

SUMMARY AND CAVEATS

It is important to keep in mind that the findings in no way demonstrate the feasibility or practicability of an actual collision warning device. The analysis assumes that the system always works perfectly up to its range limitation, i.e., it never fails to detect the lead vehicle, never detects the "wrong" vehicle and always provides accurate speed and distance information. Moreover, the model assumes 100% compliance with the warning alarm even under conditions that drivers may not regard as alarming. The performance figures should thus be regarded as upper bounds on the safety benefits of the particular collision warning algorithms studied here. With this caveat in mind, the major findings can be summarized as follows:

1. Rear end collision warning systems have the potential to eliminate 60% or more of crashes with impact speeds over 10 mph (16kph) in freeway type driving.

2. The Stopping Distance Algorithm was more effective than the Closing Rate algorithm, with effectiveness rates approaching 100%, but would result in from 440 to 1100 times more warnings than the Closing Rate Algorithm.

3. The collision warning system (Closing Rate Algorithm) was effective at roughly the same level under all conditions studied. It was generally more effective against police crashes than lesser crashes.

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Active counter-measures testing on actual accident sites

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Paper No. 94 S3 O 04

ABSTRACT

In the frame of the European Safety Program PROMETHEUS, PSA Peugeot Citroën had since 1989 a common action with INRETS-MA (*) and L.A.B. (**), aiming at the specification and development of active counter-measure systems likely to help drivers to avoid the accident in the most frequent road fatalities circumstances.

The first part of this program, presented at the 13th ESV conference held in Paris in 1991 (S4 W 15), consisted in the in-depth analysis of a selection of representative accidents and in the reflexion on possible prevention strategies.

The second part of this program, presented here, is the validation of two of the counter-measures developped by PSA : *Interactive road Signalling System*-ISIS-and *Automatic Guidance System*, through experiments at actual accident sites, under the conditions of the accidents in question.

Three typical accidents : loss of control in curve, collision in curve and at a crossroad, are selected for detailed presentation, theoritical kinematic reconstruction and actual counter-measure testing, in the conditions of the initial accident.

The results (illustrated during the conference by a video) show adequation of the systems to selected cases.

A partial impact study of *Automatic Guidance System* application effects on curve severe accidents breakdown concludes this presentation.

AVOIDANCE OF ACCIDENTS. WHY ? HOW ?

During the previous ESV conference (1) we recalled that the fatal consequences in accidents exceeding a certain level of impact energy could not be avoided by realistic secondary safety measures ; this required us to try to prevent these accidents, in order to improve global road safety level (2).

The manner in which the accident avoidance procedures are conceived and validated has been established by PSA in liaison with LAB and INRETS-MA and it is shown in figure 1.

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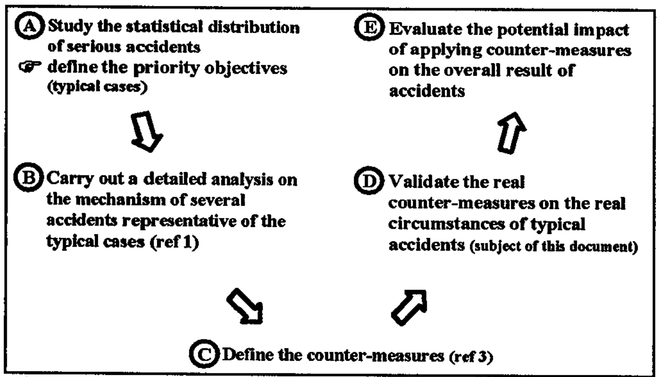

Figure 1. The PSA/LAB/INRETS accident avoidance procedures

The conclusions of phase A may be resumed as follows :

Typical cases of serious accidents	
Intersections	16.8%
Loss of control on a bend	12.8%
Collision on a bend	15.2%
Other circumstances	-

The values above are modulated by the circumstances (ligthing, humidity) and by the type of vehicle implicated (passenger car, truck).

The conclusions of phase B concern the identification of the typical dysfunctions of the drivers' behaviour :

- at an intersection :
  - misunderstanding of the infrastructure
  - lack of information acquisition (or lack of information up-date, particularly at re-starting time) on the surrounding traffic.
- on a bend
  - underestimation of the real difficulty (first difficulty of an itinerary, poor visibility, negative camber)
  - late turn-in on bends, without any apparent difficulty, leading :
    - on right-hand bends, to an excursion on the opposite lane
    - on left-hand bends to an off-road excursion, then destabilisation due to inadequate corrective manoeuvre (too ample or too long).

The remainder of this document describes, for three real accidents representative of the three chosen cases how the active safety counter-measures developed by PSA were applied experimentally at the site and under identical conditions to the accident. For each case, a preliminary presentation of the accident analysis justifies the choice of counter-measure.

ACCIDENT AT AN INTERSECTION

Presentation of the real accident

It took place during the daytime, at the intersection of the busy trunk road RN 113 and the secondary road CD 569. The RN is crossed by means of an overpass, whereas the bifurcations to the right and left consist of access roads controlled by STOP panels, preceded at 150 m by preparatory signs (see figure 2).

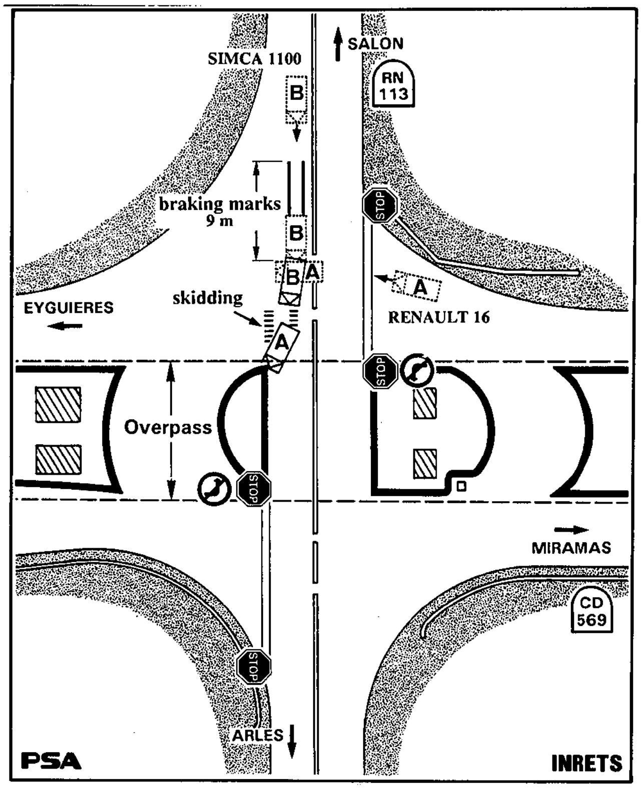

Figure 2. Plan of the accident at the RN 113/CD 569 intersection with both impact positions and final positions of the Renault 16 and Simca 1100

The driver of the Renault 16, responsible for the accident, was coming from Miramas by the CD and wished to go to Arles. So he had to turn left onto the RN.


Figure 3. The two vehicles in their final positions after impact

Having badly interpreted the indication sign preceding the intersection, he thought he was on a slip-road of the intersection and did not notice either the preliminary signal or the STOP sign. Coming from his direction, the RN, slightly sunken in level, is masked by the vegetation. Due to this, he advanced at low speed onto the RN to find himself in front of a Simca 1100 coming from his right. Despite both vehicles braking, the Simca 1100 hit the Renault 16 on the right hand front door and spun it onto a concrete central reservation (figure 3).

Kinematic reconstruction

The braking marks with wheel locking (3 m by the Renault 16 and 9 m by the Simca 1100) as well as the estimated energy of the impact, as used in a method developed by INRETS-MA (4) and (5) to establish the chronological order of the accident (table 1).

Time(s) before impact	Event	R16 distance to point of impact (m)	R16 speed (kph)	S1100 distance to point of impact (m)	S1100 speed (kph)
-2.0		15.0	28	39	75
-1.5	R16 visible to S1100	11.0	28	28	75
-1.0	R16 passes STOP sign	7.0	28	18	75
-0.9	S1100 brakes	6.0	28	15	75
-0.6	S1100 skidmarks start	3.6	28	9	66
-0.5	R16 skidmarks start	3.0	28	8	64
0	Impact	0.0	16	0	50

Table 1

The estimated reaction time of the Simca 1100 driver (0.6 s) represents a good attention level and his choice of strategy (straight-line braking) is the only one possible due to the infrastructure and the proximity of the two vehicles. The only dysfunction apparent here is that of the Renault 16 driver not having seen the STOP sign.

Choice of counter-measure

The functions to be achieved are :

- reinforce the regulatory "STOP Obligatory" sign by a message (visual and/or vocal) inside the passenger compartment.
- automate the stop in case of absence of driver reaction.

This is the objective of the *ISIS plus automatic stop system* presented in detail in the document (3) at this ESV conference.

Real test of choosen counter-measure

Installation of the ISIS beacon

Placing the ISIS beacon at 150 meters from the STOP line allows a stop after a deceleration of $2 m/s^2$ from the initial maximum authorised speed of 90 k.p.h. (figure 4)

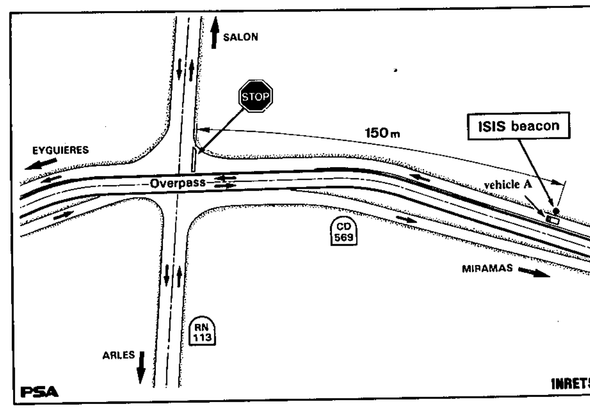

Figure 4. Plan of the intersection and of the position of the ISIS beacon

The *obligatory STOP* message must only be transmitted to those vehicles which take the lower approach road towards the RN and not to those which cross on the fly-over or which come from the opposite direction. This is done by using the difference in level between the two roadways, as well as by the direction and narrowness of the ISIS infra-red beam (figure 5 and figure 6).

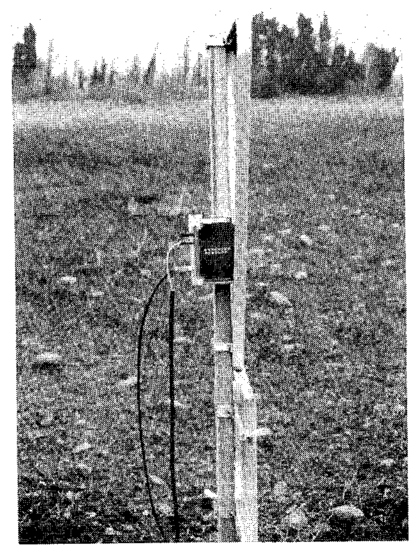

Figure 5. ISIS beacon on the initial signal post

Experimental application

The on-site test, presented by a video film in the oral session of the ESV congress, shows how the driver is warned, then how the PSA ISIS vehicle is automatically

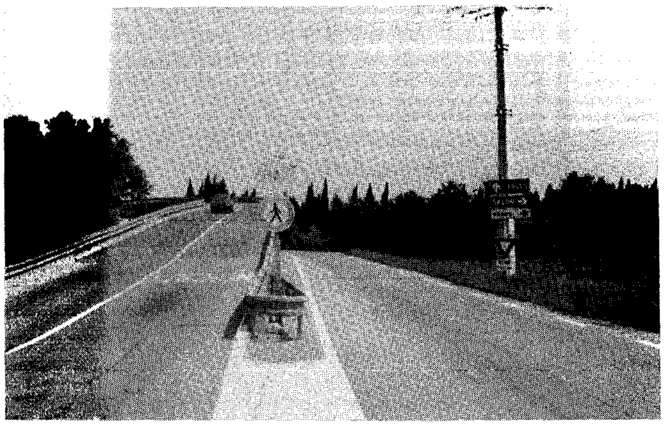

Figure 6. Relative altitude of ISIS beacon and upper roadway

stopped, if necessary, at the STOP sign, with a precision better than one meter from the range of all practical initial speeds at this site. The only limiting factor is the intrinsic maximum braking performance of the vehicle.

Conclusion on the intersection accidents.

This experiment illustrates the possibility (if the costs of specific vehicle equipement and infrastructure were payed) of how accidents at intersections, due to the driver not seeing or not understanding the stop signs may be avoided. The demonstration is made in completely realistic environmental conditions.

The case where one or several vehicle were already stopped and waiting at the STOP sign has not been investigated in this experiment as it did not correspond to the reference accident ; this case could be treated with the help of the AICC system, as tests have shown on a protected site.

The accidentoloy studies show that it is also necessary to find counter-measures appropriate to the other circumstances, such as restarting phases and for complex intersections with multiple possible trajectorie. Some solution concepts for this kind of problem are found but the products do not exist yet.

ACCIDENTS ON BENDS

The "detailed accident analysis", B part of the PSA-INRETS study (see figure 1) has shown two typical dysfunctions in driver behaviour during accidents in bends :

- firstly, inappropriate application of steering lock in a bend without particular difficulties at the speed employed (lateral accelerations of 2 to 3 m/s^2), then followed by loss of control due to a late and inappropriate corrective action.
- secondly, underestimation of the real difficulty (resulting in lateral accelerations above $5m/s^2$, so exceeding the driver's capacity to control).

The two following examples will describe the application of counter-measures adapted for each of the two cases.

Collision on a bend : Peugeot 104/semi-articulated truck.

This accident was the subject of a detailed study presented during the 1991 ESV congress (1). It took place on a narrow secondary road existing from the village of Pelissane, during daytime and on a wet road, on a right-hand bend of 95 metres average radius. The driver of the Peugeot 104, approaching the bend on the inside lane, was late in seeing the truck arriving in the opposite direction, and his steering and braking manoeuvre, too late, could not prevent him from hitting the left front of the truck, which was almost stopped on its side of the road. (see photo figure 7 and plan figure 8).

Figure 7. Peugeot 104 and semi articulated truck at point of impact

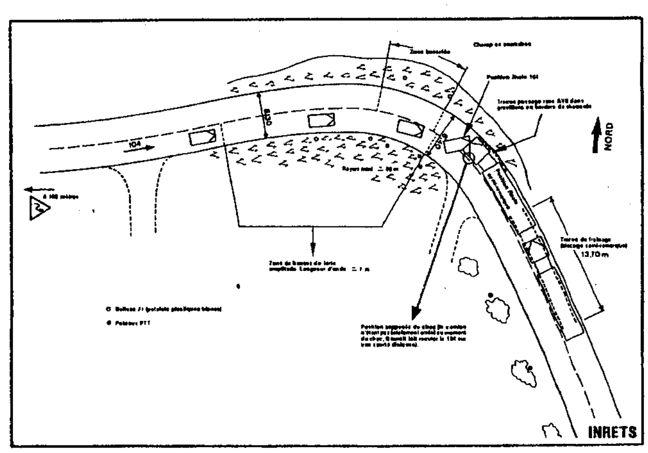

Figure 8. Peugeot 104/semi-articulated truck : plan of the accident

Kinematic Reconstruction

Using the deformation of the Peugeot 104, the tyre skid-marks from the truck braking before and after the impact, we have obtained the results shown by figure 9, concluding in a irreprochable reaction by the truck driver (braking 0,5 s after having seen the Peugeot 104) and in an inappropriate reaction by the 104 driver (start of braking 1 s later than the truck, and inappropriate steering action).

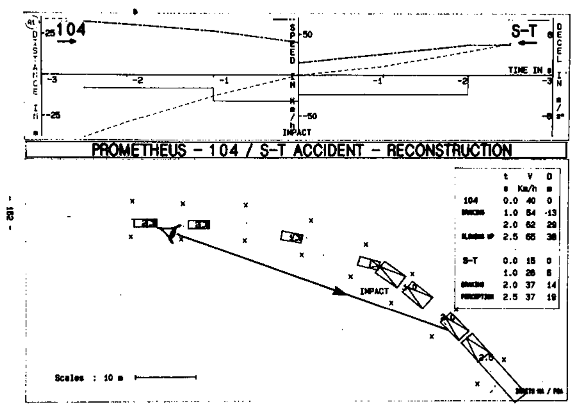

Figure 9. Time diagram of the progress of the Peugeot 104/semi articulated truck accident.

Choice of counter-measure

The speed calculated for the Peugeot 104 at the entry to the bend should have allowed it to negociate the bend without difficulty, if it had followed the axis of its lane normally ; this is the function carried out by the autonomous *Automatic Guidance System* (3) which links together an on-board camera, a system of image analysis observing the longitudinal road markings lines and an automatic steering mechanism.

Experimental application

The PSA *Automatic Guidance System* vehicle has been tested at this bend on automatic operation up to 40 k.p.h. demonstrating a trajectory regulation quality compatible with open road traffic conditions. This is shown on video film during the oral session of the ESV congress.

Loss of control in a bend

The accident chosen to illustrate this case took place during the daytime, in dry weather, on a small sloping secondary road on the exit from Salon de Provence. The right-hand bend in question is the first difficulty encountered on leaving the town, its radius tightens from 70 to 32 metres, and the visibility at the entry considerably reduced due to the relief (40 metres).

The Renault 12 concerned in the accident entered the bend at 70 k.p.h. (declared by the driver), and left the road on the outside of the bend, leaving skid marks on the road (see photo figure 10), then rolled over into the ditch below the road (see plan figure 11).

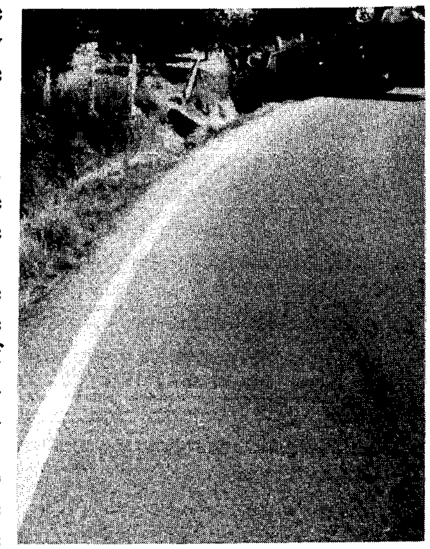

Figure 10. View on skidmarks

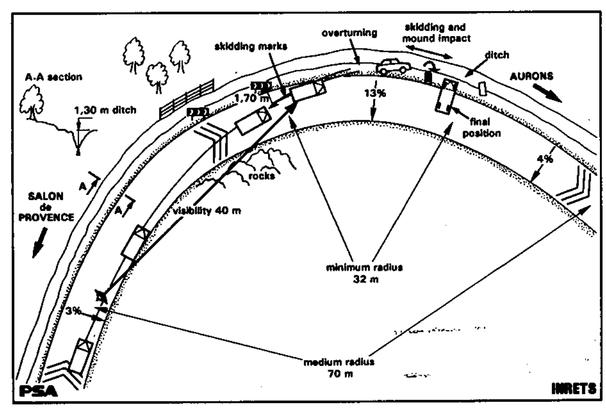

Figure 11. Plan of the accident : loss of control in a bend

The complexity of the impact makes the estimation of the energy dissipated impossible, and because of that, the strict kinematic reconstruction of the accident could not be made. The analysis of the mechanism of the accident has therefore been made, starting from the initial speed declared by the driver, by measurements made on site with an instrumented vehicle, and by numeric simulation. Figure 12 shows the results of a simulated drive through the bend at 60 k.p.h. , showing a lateral acceleration greater than 6 m/s^2 on all the section of minimum curve radius. It is at the start of this zone (point 1 on the figure 12) that one finds the beginning of the Renault 12 off-road excursion.

The driver has therefore committed two errors during the accident :

• he entered the bend at a speed too high with respect to the capacity of control.

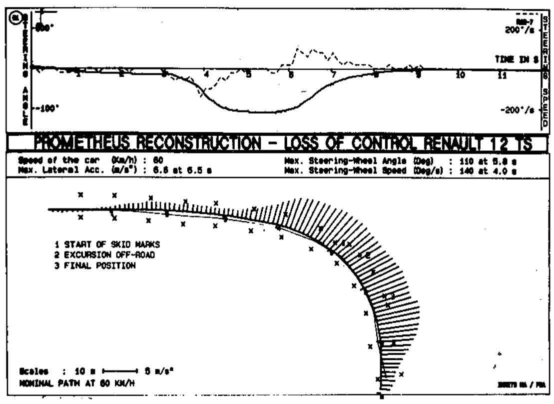

Figure 12. Numerical simulation of the loss of control in a bend

• he reacted too late on the steering in response to the tightening of the curvature of the bend.

Definition and application of the counter-measures.

The action of two systems is needed to prevent this accident :

■ *ISIS, plus automatic braking.*

The ISIS beacon was installed on the preliminary sign post for the sinuous zone, more than 200 metres before the bend. As the vehicule passes in front of it, the distance to the bend and the advised speed are communicated. The driver is first warned by visual and vocal messages, then the vehicule is automatically shown if the driver does not react.

■ *Automatic Guidance System* provides the steering command needed by the vehicle to negociate the bend within the inside line. During the real experiments, shown on the video film at the oral session of the ESV conference, it was proven that the consecutive use of these two systems allowed the vehicle to be flowed, from the maximum possible initial speed at the ISIS beacon, down to 40 k.p.h. speed to which the *Automatic Guidance System* was able to provide autonomous steering control needed to keep the vehicle in its driving lane.

TECHNOLOGICAL EVOLUTION OF THE *AUTOMATIC GUIDANCE SYSTEM*

The speeds employed in the bend during the experiments presented above were limited, not by the intrinsic performance of the guidance system (tests on a closed track were conducted up to 3 m/s^2 lateral acceleration and at more than 100 k.p.h.) but by the safety margin it was necessary to observe on these narrow roads, with a system where the steering wheel was physically disconnected during the automatic operation phase.

PSA is now working on solutions where the steering column is not interrupted, and where the steering command is the result of an arbitrage in effort between the automatic mechanism and the driver.

A simple level of definition of the *Automatic Guidance System* associates an alert (audible, visual or tactile) with the detection of the vehicule's position relative to the road markings.

ACCIDENTOLOGY POTENTIAL OF THE *AUTOMATIC GUIDANCE SYSTEM*

Figure 13 illustrates an analysis, still partial, carried out by LAB on fatal accidents (at least one person killed inside a passenger car) arising in France in the second quarter of 1990.

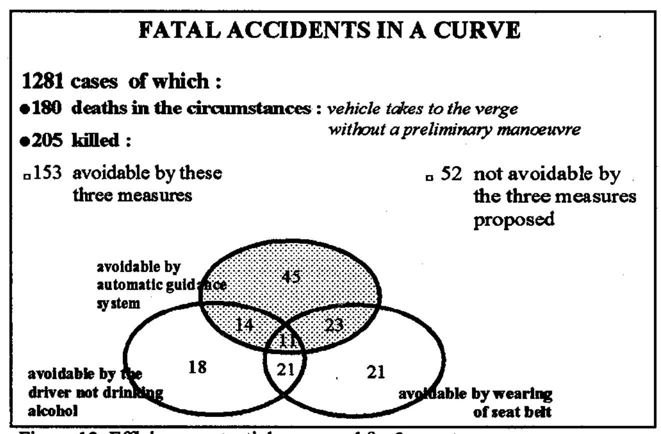

Figure 13. Efficiency potential compared for 3 counter-measures

Remarks

• This analysis is based on an efficiency hypothesis of 100 % of the proposed counter-measures.

• In the case of *Automatic Guidance System*, the counter-measure was supposed efficient if the lane had two-side markings (continuous or discontinuous). The case where the performance of the system would be inadequate have to be substracted from the total (taking into account particularly the radius of the curve and the speed). On a reduced sample, a PSA experiment showed a success expectation of more than 50%.

• Among the 1101 cases not considered, *Automatic Guidance System* may still find applications (collisions due to uncontrolled excursions on the left-hand lane).

This analysis, still partial, shows that the application of *Automatic Guidance System* can contribute to avoiding a significant number of fatal accidents (93 in 205, in the efficiency hypothesis of 100 %, of which 45 are not susceptible to other existing counter-measures). The effect in the case of less serious accidents will be of the same nature.

It is intended to complete the study during 1994 by examining the levels of performance required and by analysing the cases not so far treated, but these preliminary results demonstrate already the important efficiency potential of *Automatic Guidance System*.

CONCLUSION

This series of experiments has allowed PSA to test active safety systems in real accident situations, in completely real road environnements (road geometry, visibility, markings quality, surroundings traffic), where these systems were previously tested only on closed sites.

Without being exhaustive demonstrations, they have allowed us to show the strong points of the systems and to orient their further development.

ACKNOWLEDGEMENTS :

Fondation MAIF and CEESAR (Centre Européen d'Etudes Socio-Economiques Accidentologie des Risques) for their help to the Laboratoire d' Accidentologie et de Biomécanique L.A.B. for the analysis of Fatal Accident Report Forms.

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A Study of Self-Reliant Cornering Speed Control System
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94-S3-O-05

ABSTRACT

Recently in Japan, there is an increasing tendency of serious traffic accidents while negotiating curves. A major cause of such accidents is excessive vehicular speeds due to the driver's incorrect recognition or misjudgement for curvature of the road, the vehicular performance or road conditions. Some papers have been published on the systems which prevents such accidents by means of limiting vehicular speed before entering a curves. However, most such systems rely on informations given by local facilities along the road, so that various problems to be solved are still left for practical use. From this view-point, we are now studying a self-reliant cornering vehicular speed limitation system without using outside facilities along the road . This paper presents the base technology of such a system which forecasts the curvature of the oncoming road based on the map information integrated in car navigation system which has already been installed in production vehicles in Japan.

INTRODUCTION

According to traffic accident statistics[1] compiled in Japan, the number of deaths resulting from accidents in cornering comprise 20% of total traffic accident deaths, and in recent years this percentage has been showing an increase. (See Fig. 1) The some causes of such accidents seem to be errors in steering wheel operation, however, the main reason seems to be overspeeding, largely brought about by factors such as driver's overconfidence, mis-reading for the curvature of the roads, or driver's carelessness and lack of concentration. Under this background, proposals have been set forth for systems which can control the vehicular speed based on the curvature informations obtained from road-vehicle communication system along the road or image processing technology to deduce the curvature of the road. However, both types of system have some subject to be solved such as the required time and cost to set up facilities, in the case of the former, and the fitness for the varying environmental conditions, for example, fog, rain, snow and glare, in the case of later.

Considering above situation, we have been investigating the possibility of a "self-reliant cornering speed control system" which uses a car navigation system. The investigations results indicate that it is possible to judge whether the vehicular speed is appropriate or not on cornering based on the built-in map data which is used in existing car navigation systems. This paper describes the judging method of the cornering speed appropriateness, then, proposes the self-reliant cornering speed control algorithm rely on the car navigation system.

SYSTEM CONCEPT

Purpose

The purpose of this study is to eliminate or reduce the traffic accidents while cornering by controlling the vehicular speed at a curve to a level which is at or below an appropriate value. However, the system explained here is intended to prevent overspeeding resulting from the mis-recognition or erroneous judgement for the road curvature due to driver's carelessness or lack of concentration, who is attempting to drive safely, but skilled driver's hard driving is out of consideration.

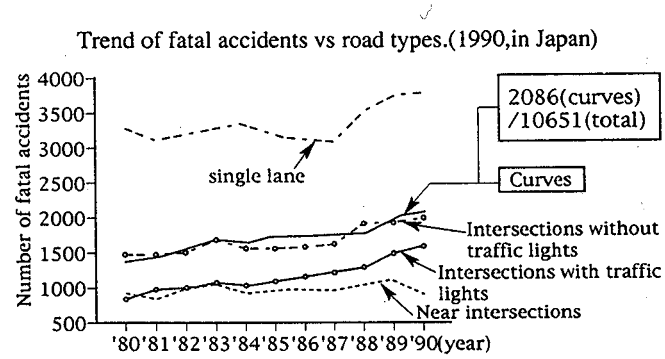


Figure 1. Result of traffic accidents investigation.

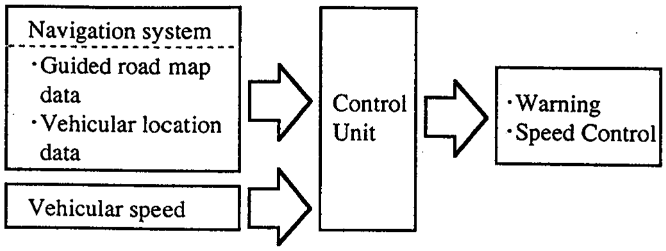


Figure 2. Basic system configuration.

Configuration

The appropriateness of the vehicular speed is judged from the vehicular position and data on the contour of the road which are obtained from a car navigation system equipped with a route guidance function, and warning is originated or the vehicular speed is automatically controlled if necessary. The basic system configuration is shown in Fig. 2.

METHOD OF JUDGING APPROPRIATENESS OF VEHICULAR SPEED

In general, maps which are used in car navigation systems provide the coordinates for points which are plotted on the road at appropriate intervals (hereinafter referred to as "nodes"). As shown in Fig. 3, accordingly, the orthodox method of implementation for this system can be easily considered, which calculates the curvature of the road from three of these nodes which lie ahead of the current vehicular position, and finds the amount of lateral acceleration which will be generated when the vehicle travels through the curve based on estimated curvature and vehicular speed, then judges the appropriateness of the vehicular speed. This is referred to as the "curvature judgenent method". However, the results of investigation show that the plotting error which should be included in the map data has a large affection on the results of such calculation, and this prevents the correct judgements for the appropriateness of the vehicular speed. We propose a new method named as the "zone judgement method" which judges the appropriateness of the vehicular speed without directly calculating the road curvature. The affection of the plotting error on the judgement result for the vehicular speed appropriateness is explained below for both the curvature judgement method and the zone judgement method.

Summary of the Curvateure Judgement Method and Associated Problems

As shown in Fig. 3, the position of the road is indicated by means of three nodes (a, b and c), and if the road is assumed to be a arc, the radius of curvature can be expressed

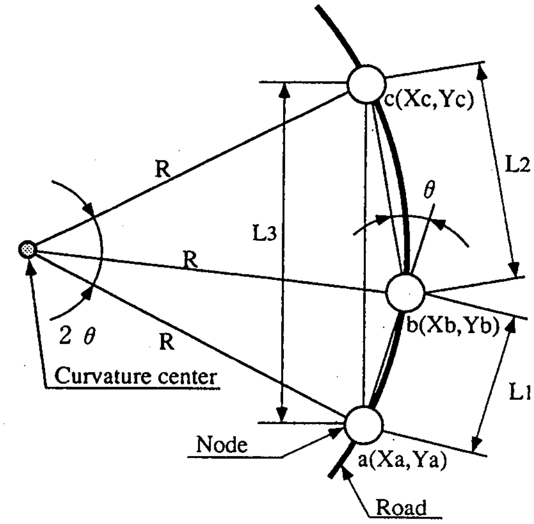


Figure 3. Concept of the curvature judgement method.

by the following formula;

$$R = L_3 / 2 \sin \theta$$

Where, L_3 is the length of chord ac, and θ is an angle of intersection formed by chords ab and ac. On the other hand, if the vehicular speed at node b is represented by V_0 and the maximum degree of lateral acceleraion permissible is represented by G, the minimum radius of curvature (Rc) which is possible to handle the curve is:

$$Rc = V_0^2 / G$$

Accordingly, the judgement as to the appropriateness of the vehicular speed is made according to the magnitude of the relationship between R and Rc.

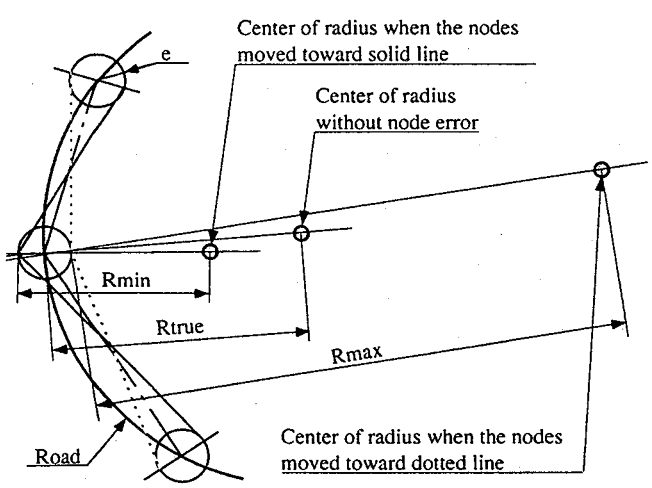
The problem associated with this method, however, is that the node coordinates always contain a plotting error which is inherent in the map data, and this inevitably limits the accuracy of judgement as to whether the vehicular speed is appropriate or not. This is illustrated in Fig. 4. The circled areas in the illustration indicate the ranges of plotting error which the node coordinates contain. That is to say, the radius of curvature R can extend from Rmax, the radius of the arc when the nodes follow the dotted line in the illustration, through to Rmin, the radius of the arc when the nodes follow the solid line. This results in judgement errors.

The Zone Judgement Method

Assuming the normal line at the hypothetical vehicular position P_0 on the road in front of the current vehicular position, the two arcs which contact with the road at the point P_0 and have arc centers on above normal line and which have a permissible minimum turning radius Rc as determined by the estimated vehicular speed V_0 at the point P_0 and the predetermined permissible degree of lateral acceleration G, are superimposed to the left and right of the road on the map. As a result, the road map is devided as two sections, as shown in Fig. 5. In this Figure, it is clear that the vehicle can pass thrugh the curves with permissible lateral acceleration, if the road is in only the zone with diagonal-line. So that it is possible to judge the appropriateness of the vehicular speed by refering whether no nodes are out of above diagonal-line zone without calculating the road curvature directly. In this method also, the judgement for appropriateness of the vehicular speed is affected from the plotting error for the judgement nodes and changes in the normal line due to the plotting error. In this case, however, the appropriateness of the vehicular speed is judged based on the relationship of numerical value between the above-mentioned Rc and the distance D between the hypothetical turning center and the judgement node. So that the error for the distance from the true center of turning radius Rc to the judgement node should be only considered. A graphical illustration of this is shown in Fig. 6 and the range obtained for the distance D thus becomes the range between Dmin and Dmax, which are the distance from the turning center to the judgement node when the nodes follow the solid line and the distance when the nodes follow the dotted line respectively.

Judgement Reliability

First let us consider the case where the vehicular speed appropriateness judgement is carried out for the curve with the curvature Rtrue (the true value for road radius R). In Fig. 7-1 and Fig. 7-2, the horizontal axis represents the turning radius Rc as determined by the vehicular speed and maximum degree of lateral acceleration permissible. The vertical axis represents the radius of the curvature R calculated by means of the curvature judgement method, and



R ; Radius of curvature which passes through 3 nodes

e ; The maximum permissible node plotting error

⊗ ; Center of curvature which passes through 3 nodes

Figure 4. Error of the curvature judgement method.

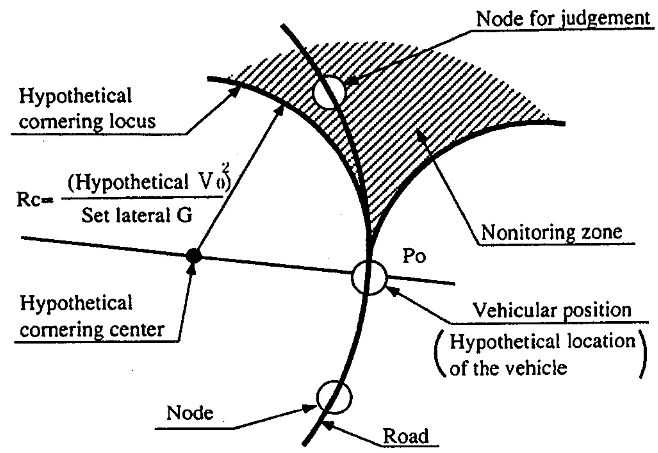
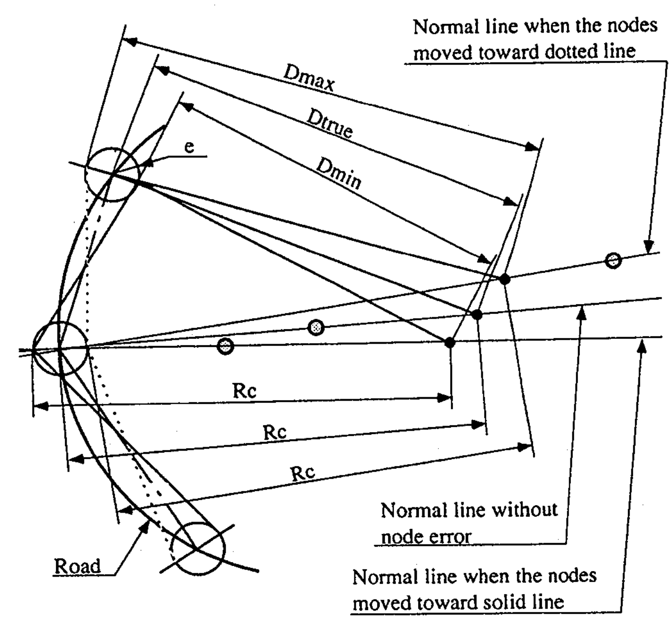


Figure 5. Concept of the zone judgement method.



D ; Distance between center of turning radius corresponding to vehicle speed and node for judgement

Rc ; Turning radious corresponding to vehicle speed and set lateral acceleration

e ; The maximum permissible node plotting error

⊗ ; Center of curvature which passes through 3 nodes

● ; Hypothetical cornering center

Figure 6. Error of the zone judgement method.

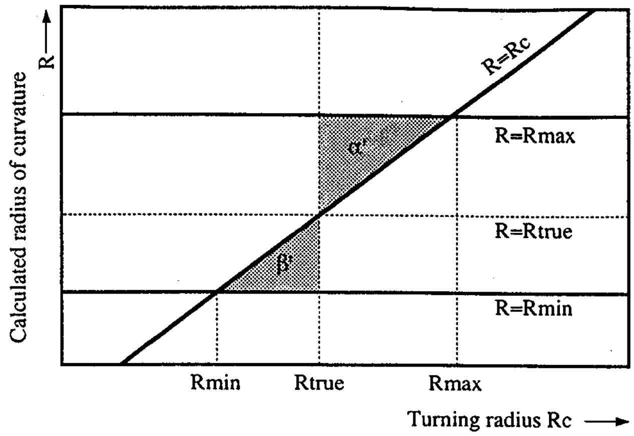


Figure 7-1. Affection of plotting error on judgement with the curvature judgement method.

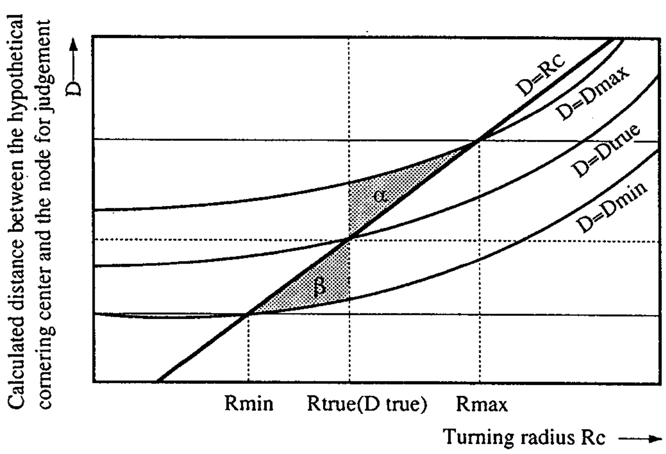


Figure 7-2. Affection of plotting error on judgement with the zone judgement method.

Table 1
Probability of Erroneous Judgement

Method \ area	Rmin<Rc<Rtrue	Rtrue<Rc<Rmax
Zone judgement	$\Pr[\beta]=\frac{Rc-Dmin}{Dmax-Dmin}$	$\Pr[\alpha]=\frac{Dmax-Rc}{Dmax-Dmin}$
Curvature judgement	$\Pr[\beta']=\frac{Rc-Rmin}{Rmax-Rmin}$	$\Pr[\alpha']=\frac{Rmax-Rc}{Rmax-Rmin}$

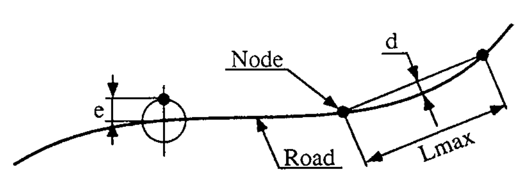
Table 2
Lmax & Lmin

Node pitch L	General expression
Lmin	$\sqrt{4eRtrue}$
Lmax	$\sqrt{4d(2Rtrue-d)}$

also the distance D obtained from the zone judgement method respectively. In the case of the curvature judgement method (See Fig. 7-1), Rmin, Rmax and Rtrue have constant values which are independent from Rc, whereas in the case of the zone judgement method (See Fig. 7-2), Dmin, Dmax and Dtrue vary in accordance with Rc, and when Rc=Rmin then Dmin=Rmin, and when Rc=Rmax then Dmax=Rmax. (For the method of calculating Rmin, Rmax, Rtrue, Dmin, Dmax and Dtrue, refer to equations (1)~(6) at the end of this paper.)

Assuming that we project the straight lines R=Rc and D=Rc onto Fig. 7-1 and Fig. 7-2 respectively, areas of misjudgement can be seen, that is to say, passing through the curve is judged as not appropriate even though it is in reality appropriate within areas β and β', and passing through the curve is judged as appropriate even though it is in reality not appropriate within areas α and α'.

Accordingly, the probability of erroneous judgement Pr when passing through the curve defined by Rtrue will vary with respect to Rc, and if the value for R is uniformly dispered between Rmin and Rmax, the results are shown in Table-1. This probability of erroneous judgement Pr will also vary greatly depending on the pitch between the nodes and the ratio between the pitches of adjacent pairs of nodes, in addition to the plotting error for the node coordinates. That is to easy, if ϕ 2e is the node error range and chords ab and bc in Fig. 3 are designated as L_1 and L_2 respectively, then the probability of judgement error Pr can be expressed as a function of e, L_1 and $L_2 / L_1 = k$. However, for the node pitch L, the maximum and minimum values are estimated as shown in Table-2 as a function of Rtrue, e and d, as shown in Fig. 8, based on the engagement in creating the map. In Table-2, the value for Lmin here is assumed to be the shortest node pitch in order to avoid any inversion occurring due to the plotting error, and Lmax is set as that the difference d between the straight line connecting the pairs of nodes and actual line of the road would be the maximum permissible value.



d ; The maximum permissible difference between actual line of the road and straight line which connects nodes
e ; The maximum permissible node plotting error

Figure 8. Plotting data on the map.

The general form of the probability of erroneous judgement Pr when e, L and k are constant can be expressed as a function of Rc as shown in Fig. 9. Accordingly, when Rc is Rmin < Rc < Rtrue, thenPr [β] > Pr [β '] and curvature judgement method is the more reliable, but if Rtrue > Rc > Rmax, then Pr [α] < Pr [α '] so that zone judgement method is the more reliable.

Fig. 10 shows the maximum permissible error rates for the curvature R according to the node pitch ratio k under the most severe condition L_1=Lmin within the limits for the node pitch L in Table-2. From this, it can be seen that the error rate for Rmin is relatively smaller than that for Rmax. This means that the affection from an erroneous judgement will be comparatively small. And the probability of erroneous judgement will also small because Rtrue - Rmin << Rmax - Rtrue. From the view point of suppressing the overspeeding also, it should be emphasized that the probability of erroneous judgement is smaller in the range Rtrue < Rc < Rmax. Because a higher vehicular speed will be allowed in above range.

Furthermore, when one of the node pitch is Lmin, the change of the probability of erroneous judgement Pr can be specifically calculated and is shown in Fig. 11 also. In this figure, Pr[α] is always less than Pr[α '] regardless of the node pitch ratio k so that the zone judgement method is always superior to the curvature judgement method. Where in Fig. 11, Rc is estimated 1.2 times Rtrue. This value corresponds to an about 10% increase in the maximum appropriate vehicular speed, but it is a value which will be built into the system configuration as an allowance value.

In addition, it can be conjectured from Fig. 11 that: (1) the node plotting error is distributed uniformly within ϕ 2e, and (2) the smallest pitch is the worst conditions, so that the probability of erroneous judgement for actual road conditions should be even lower.

SPEED CONTROL ALGORITHM

Fllowing is a description of the cornering speed control algorithm which uses the zone judgement method.

Basic Algorithm

First, two reference values for the lateral acceleration G_1 and G_2 ($G_1 < G_2$) are predetermined. Then, assuming that when the driver perceives the curve ahead, an uniform normal amount of deceleration 'a' is applied. And when the forecast lateral acceleration in a definite section ahead of the vehicle $S_1 \sim S_2$ in Fig. 12, will become higher than that of the first reference value G_1, a warning sounds, and when it exceeds the second reference value G_2, the vehicle is automatically decelerated at a uniform rate 'a' untill the forecast lateral acceleration reaches the first reference value. Concretely, for each node in a section $S_1 \sim S_2$, the arcs which radii R_1 and R_2 determined by the forecast vehicular speed at each nodes and reference lateral acceleration are superimposed onto the map as shown in Fig. 13. So, the map

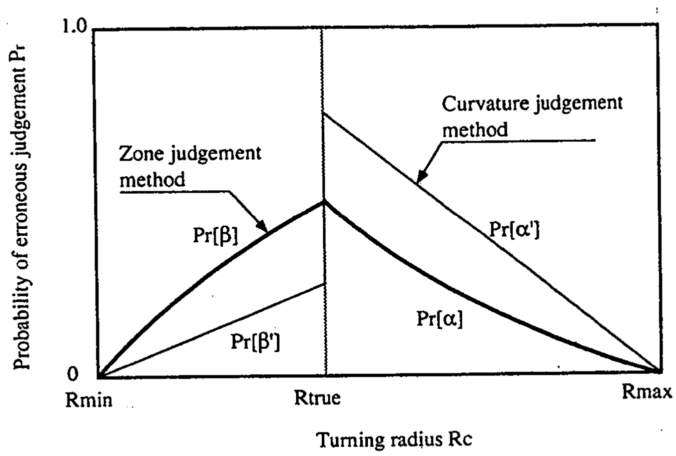


Figure 9. Probability of erroneous judgement Pr when Rc is between Rmin and Rmax.

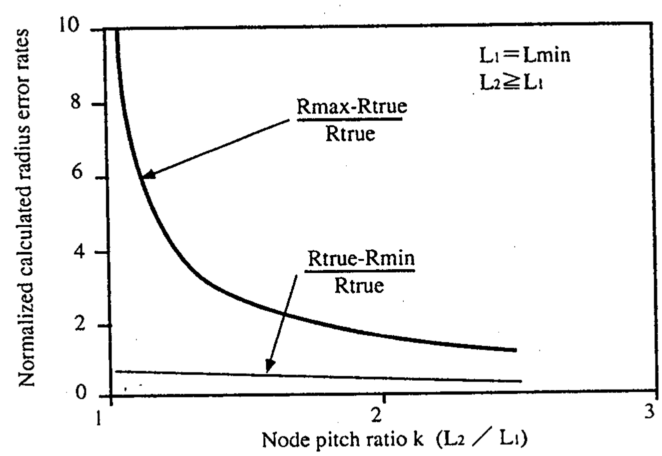


Figure 10. Maximum error of calulated radius error with the node pitch.

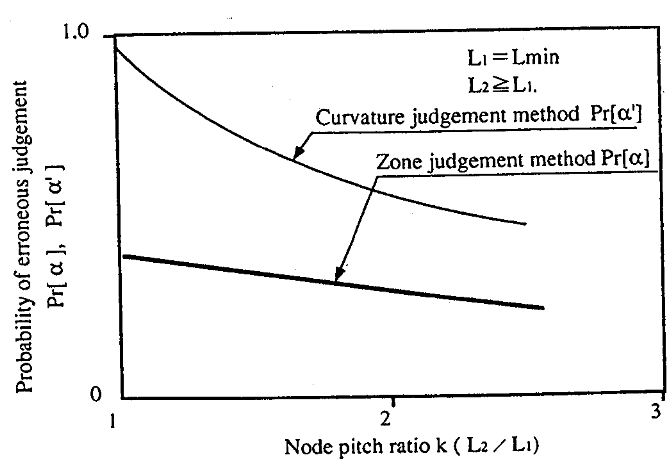


Figure 11. Probability of erroneous judgement Pr with the node pitch (Rc = Rtrue×1.2).

is divided into zones (1), (2), and (3). And if each foward nodes falls within zone (2), the warning sounds, and if they fall within zone (3), the vehicle is automatically decelerated. If every nodes fall within zone (1), the vehicular speed is judged to be appropriate, and so in this case no warning is given and no control is carried out.

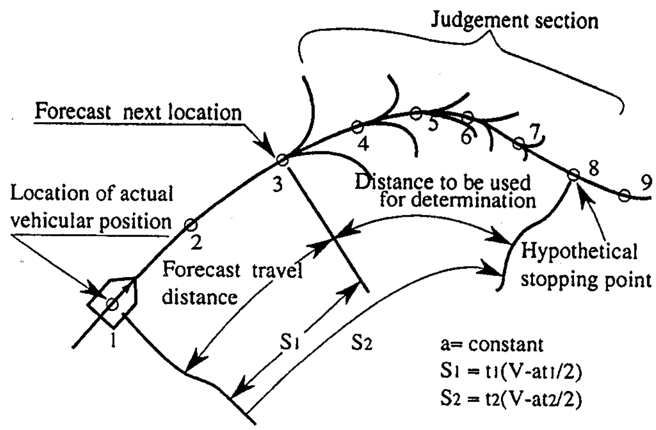


Figure 12. Control strategy.

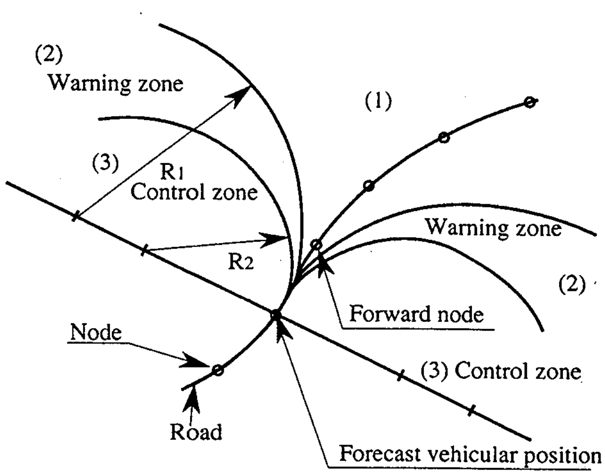


Figure 13. Judgement with the zone judgement method.

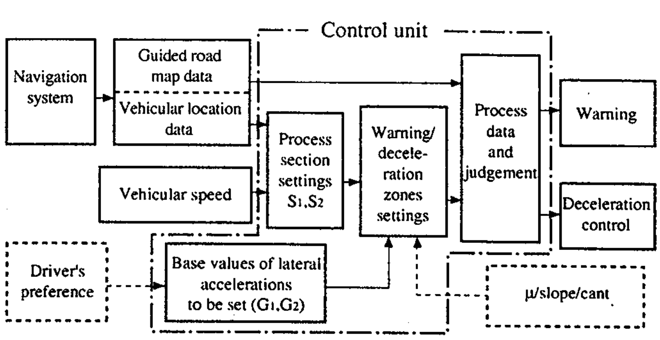


Figure 14. System block diagram.

Parameters

a : This parameter represents the rate of deceleration when normal driver decelerates before entering a curve during normal driving. It is set fairly high (2~3 m/s^2) to prevent excessive warnings.

S_1 : Represents the look-ahead distance, the distance from the current vehicular position to the estimated vehicular position when the vehicle is decelerated with above-mentioned deceleration "a" over a constant time t_1. It is calculated by the following formula.

$$S_1 = t_1 (V - a * t_1/2)$$

V is the current vehicular speed and t_1 is the driver's look-ahead time. It will be to be within 2~3 seconds based on experimentation.

S_2 : Ideally, this is the distance it takes for the vehicle to stop when it is decelerating at the rate "a". However, the judgement section becomes so large and processing time become insufficient, so it is set by the following formula, with t_2 being three times the value of t_1.

$$S_2 = t_2 (V - a * t_2/ 2)$$

G_1 : This parameter is set to be a slightly higher value (2.5 m/s^2 or less) than the lateral acceleration generated when a normal driver pass through a curve during normal driving.

G_2 : This parameter correspond to the lateral acceleration generated when a normal driver pass through a curve during hard driving. It is set fairly high (5.0 m/s^2 or less) to prevent excessive contorol.

Summary of System Configuration

A block diagram of the overall processing section for this system has been shown in Fig. 14. The signal processing block consists of a road data processor, a zone setting block for setting the judgement execution zone from the map data, vehicular position and vehicular speed, a judgement block to judge whether the vehicular speed is appropriate or not, and a vehicular speed control block.

Accurately, the appropriate values for the reference lateral acceleration will vary depending on not only the curvature but also the frictional resistance and gradient of the road. So in the future, it will be desirable to be incorporated these other values to fine-tune the reference lateral acceleration.

In addition, as mentioned at the beginning of this paper, this system is intended to prevent the driver from perception and judgement errors who is attempting to drive safely, and thus the standard lateral acceleration values have been set fairly low. So that in more hard driving by skilled drivers, warnings and speed control operations may occur a little frequently. Thus, we are also investigating that it will be better to make the standard lateral acceleration variable within an appropriate range in accordance with driver's preference.

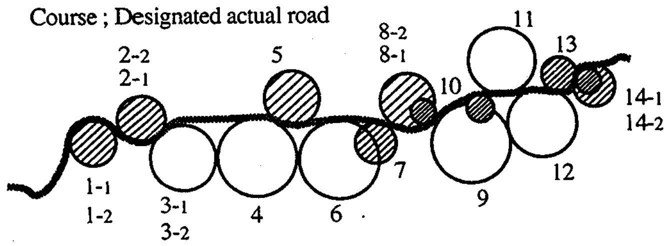


Figure 15. Actual measurements.

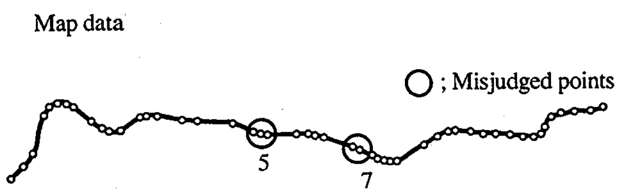


Figure 16. Result of simulation.

SYSTEM VERIFICATION

The functioning and performance of this cornering speed cotrol system was evaluated by means of a computer simulation and actual road tests.

Simulation

A simulation which followed the algorithm mentioned before was carried out using an already-existing map data base.

Conditions -

(1) Vehicular speed : 80 km/h

(2) Standard lateral acceleration (G_2) : 4 m/s^2

(3) Test course : Designated actual road (Total length : 3.6 km, refer to Fig. 15.
The actual test run was carried out, and each curve radius was obtained from the vehicular speed and the yaw rate.)

The size of the curve radii is indicated by a circle in the Fig. 15. The curves with the circles which shaded with diagonal lines represent curves where lateral acceleraion exceed the standard value under the above conditions. The numbers given to each curve indicate each curve in order from the starting point for convenience.

Out Put - Output signals was generated when the lateral acceleration becomes larger than that of standard values.

Results - As shown in Table-3, the simulation results indicate that erroneous judgements, such as even though output signal should have originated but should not, or vise versa, were given at 2 among the 20 curves. (Refer to Fig. 16)

Table 3
Judgement Result from the Simulation

Curve No.	1-1	1-2	2-1	2-2	3-1	3-2	4	5	6	7	8-1
Actual measurement data	ON	ON	ON	ON				ON		ON	ON
Map-data	ON	ON	ON	ON							ON

Curve No.	8-2	9	10	11	12-1	12-2	13	14-1	14-2
Actual measurement data	ON		ON				ON	ON	ON
Map-data	ON		ON				ON	ON	ON

ON:Warning be generated

However, detail examination was carried out for these places, and it became apparent that because there were other roads joining a road at these curves, the nodes have been misplaced. If nodes such as these are dismissed as the peculiar points, it could be considered that judgement with a high degree of precision is possible.

Actual Vehicle Test

Conditions -

(1) First reference value (G_1) : 2 m/s^2 (Warning level)

(2) Second reference value (G_2) : 4 m/s^2 (Automatic deceleration level)

(3) Standard rate of deceleration (a) : 2 m/s^2

(4) Look-ahead time (t_1) : 2 sec

(5) Designated vehicular speed : 60 km/h
(Without decelerating from the designated vehicle speed until the second warning below occurred at every points on the curves.)

(6) Test course : Designated actual road (Total length 14.6 km)

Output - The first warning sound was generated when the lateral aceleration at the look-ahead point exceeded the first standard value, and the second warning sound was generated when the lateral acceleration exceeded the second standard value.

The two sounds emitted as the first and second warnings were different so that they could be distinguished by the drivers. (In this test, automatic control of vehicular speed was not carried out. Instead, only the appropriateness of the warning time was evaluated.

Result - The six test drivers involved in the test were given questionnaires, and from these it could be confirmed that almost drivers felt no sense of any incompatibility for the first and second warning timing. (Refer to Fig. 17) Furthermore, in order to evaluate[2] mental work load on the driver, heart rate variability, variations in the driver's

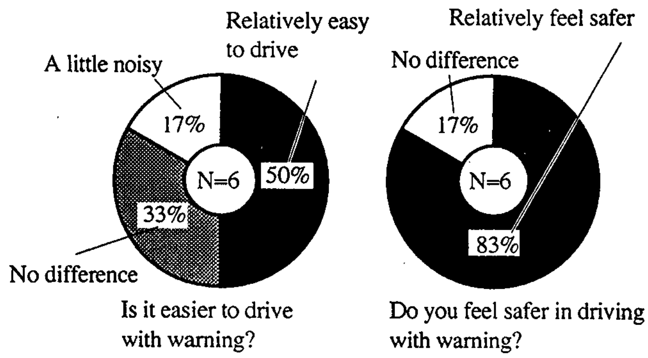


Figure 17. Subjective evaluation.

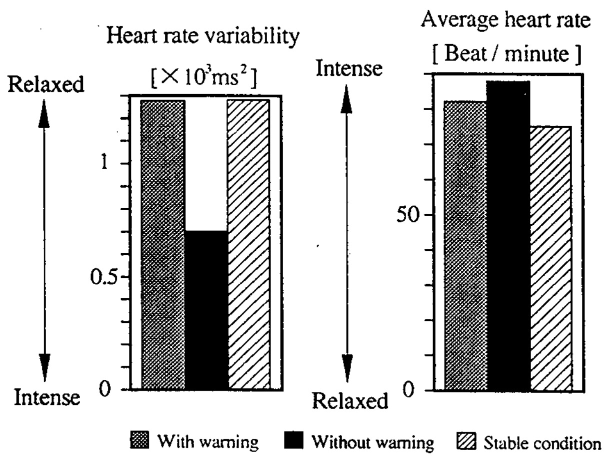


Figure 18. Evaluation of mental work load.

heartbeat were measured, and the results of this are shown in Fig. 18. From these results, it could also be confirmed that the warning for the possibility of overspeeding during cornering relieved some of the mental work load on the driver.

CONCLUSION

A new method of judging the appropriateness of vehicular speed while cornering has been proposed. This method is called the "zone judgement method". By using this method, it is possible to contorol the vehicular speed on entering a curve with practical precision even using existing map data bases.

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1) Traffic Accident Statistic Yearbook (Japan), 1991 Edition, issued by the Traffic Division of the Metropolitan Police Office.
2) Atsumi, Sugiura et, al,: Evaluation of Mental Work Load in Vehicle Driving by Analysis of Heart Rate Variability: TOYOTA Technical Review Vol. 42 No. 2 Nov. 1992.

APPENDIX

If the three nodes are designared as P_1 (x_1, y_1), P_2 (e, 0) and P_3 (x_3, y_3) respectively, Rmin, Rmax, Rtrue, Dmin, Dmax, Dtrue are calculated by means of the following formulas. The node error is given as ϕ 2e.

(1) $$R_{min}=\sqrt{(X_{dmin}-X_{2a})^2+(Y_{dmin}-Y_{2a})^2}$$

(2) $$R_{max}=\sqrt{(X_{dmax}-X_{2b})^2+(Y_{dmax}-Y_{2b})^2}$$

(3) $$R_{true}=\sqrt{(X_d-e)^2+Y_d^2}$$

(4) $$D_{min}=\sqrt{\left\{X_{2a}-\left(X_{3b}+\sqrt{\frac{Rc^2}{1+M_4^2}}\right)\right\}^2+\left\{Y_{2a}-\left(Y_{3b}+M_4\sqrt{\frac{Rc^2}{1+M_4^2}}\right)\right\}^2}$$

(5) $$D_{max}=\sqrt{\left\{X_{2b}-\left(X_{3a}-\sqrt{\frac{Rc^2}{1+M_5^2}}\right)\right\}^2+\left\{Y_{2b}-\left(Y_{3a}-M_5\sqrt{\frac{Rc^2}{1+M_5^2}}\right)\right\}^2}$$

(6) $$D_{true}=\sqrt{\left\{X_3-\left(e+\sqrt{\frac{Rc^2}{1+M_3^2}}\right)\right\}^2+\left(Y_3-M_3\sqrt{\frac{Rc^2}{1+M_3^2}}\right)^2}$$

$$X_{1a}=X_1-\sqrt{\frac{e^2}{1+M_1^2}} \qquad X_{2a}=e-\sqrt{\frac{e^2}{1+M_3^2}} \qquad X_{3a}=X_3-\sqrt{\frac{e^2}{1+M_2^2}}$$

$$Y_{1a}=Y_1-M_1\sqrt{\frac{e^2}{1+M_1^2}} \qquad Y_{2a}=-M_3\sqrt{\frac{e^2}{1+M_3^2}} \qquad Y_{3a}=Y_3-M_2\sqrt{\frac{e^2}{1+M_2^2}}$$

$$X_{1b}=X_1+\sqrt{\frac{e^2}{1+M_1^2}} \qquad X_{2b}=e+\sqrt{\frac{e^2}{1+M_3^2}} \qquad X_{3b}=X_3+\sqrt{\frac{e^2}{1+M_2^2}}$$

$$Y_{1b}=Y_1+M_1\sqrt{\frac{e^2}{1+M_1^2}} \qquad Y_{2b}=+M_3\sqrt{\frac{e^2}{1+M_3^2}} \qquad Y_{3b}=Y_3+M_2\sqrt{\frac{e^2}{1+M_2^2}}$$

$$X_d=\frac{Z}{2(M_2-M_1)}$$

$$Y_d=M_1\left\{\frac{Z}{2(M_2-M_1)}-\frac{(X_1+e)}{2}\right\}+\frac{Y_1}{2}$$

$$Z=M_2(X_3-e)-M_1(X_1+e)+Y_1-Y_3$$

$$X_{dmax}=\frac{1}{2(A'-B')}\left\{A'(X_{2b}+X_{1a})-B'(X_{2b}+X_{3a})+Y_{3a}-Y_{1a}\right\}$$

$$Y_{dmax}=A'\left(X_{dmax}-\frac{X_{1a}+X_{2b}}{2}\right)+\frac{Y_{1a}+Y_{2b}}{2}$$

$$X_{dmin}=\frac{1}{2(A-B)}\left\{A(X_{2a}+X_{3b})-B(X_{2a}+X_{1b})+Y_{1b}-Y_{3b}\right\}$$

$$Y_{dmin}=A\left(X_{dmin}-\frac{X_{2a}+X_{3b}}{2}\right)+\frac{Y_{2a}+Y_{3b}}{2}$$

$$M_1=\frac{e-X_1}{Y_1} \qquad M_2=\frac{e-X_3}{Y_3}$$

$$A=\frac{X_{2a}-X_{3b}}{Y_{3b}-Y_{2a}} \qquad B=\frac{X_{2a}-X_{1b}}{Y_{1b}-Y_{2a}}$$

$$A'=\frac{X_{2b}-X_{1a}}{Y_{1a}-Y_{2b}} \qquad B'=\frac{X_{2b}-X_{3a}}{Y_{3a}-Y_{2b}}$$

$$M_3=\frac{Y_d}{X_d-e} \qquad M_4=\frac{Y_{dmin}-Y_{2a}}{X_{dmin}-X_{2a}} \qquad M_5=\frac{Y_{dmax}-Y_{2b}}{X_{dmax}-X_{2b}}$$

Drowsiness of the Driver: EEG and Vehicle Parameters Interaction

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94-S3-O-06

ABSTRACT

Three factors are involved in car accidents : the road, the vehicle and the driver. Of these, the first two have recently received considerable attention; the third factor, the driver behind the wheel, is probably the most important. Attention have been paid to the last two factors. The present study characterizes low vigilance periods relative to driver's drowsiness by simultaneous analysis of the recorded EEG, steering wheel movements and vehicle speed signals during six hours driving period. The mechanical parameters thresholds of the vehicle have been discussed.

This paper examines firstly the state of the art in monitoring driver states. It reviews and discusses empirical studies that assessed the relationship between EEG indices and measurements of car mechanical parameters which are used as a criteria of vigilance impairment. We have secondly compared EEG indexes with the absolute fluctuations of the mechanical settings and we have evaluated thresholds of the steering wheel movements relative to physiological impairments. We have examined their variation during the trip versus theta and alpha rhythms. Their changes are used to define thresholds and to quantify driver impairments in real traffic. We have defined two and seven degrees thresholds for the steering wheel movement fluctuations. For the vehicle speed fluctuations, the results show that it's impossible to obtain some significant threshold value. We also noted that some periods where $\Delta\Phi \geq 2°$ and theta energy is not predominate, alpha bursts last 1.5 seconds or more. We have also found that amplitude of the alpha waves only is unable to define the steering wheel movements low thresholds. Sometimes, "delay effects" between EEG and vehicle variables have occured.

INTRODUCTION

Human physiological functions and mechanical variations ordinarily show a certain range of fluctuation as well as a number of distinguishing characteristics. A full understanding of the true nature of these functions and measures to compensate their weak points are indispensable to safe driving. The principal reason why drivers are the cause of more than 90 % of all traffic accidents lies in the limited reliability of human physiological and mechanical functions.

Recent analysis of spectacular accidents and catastrophes suggest that drowsiness at the wheel may play an important role in such events (Mitler et al., 1988). Systematic investigation of such links requires some objective measurements of drowsiness.

The way in which drowsiness is perceived by the subject varies with circumstances. Defining drowsiness is the most problemtic part of studying or discussing it. It can be either pleasant when it progressively comes over the traveller sitting in a train or in a plane, making the fastidious hours of the journey shorter, or unpleasant when it suddenly invades the driver behind the wheel. It is best defined in terms of eye movements, and the reliable recognition of drowsiness in the EEG depends on adequate eye-movement recordings and a full knowledge of eye-movement patterns awake, drowsy, and asleep (Santamaria and Chiappa, 1987; Torsvall and Åkerstedt, 1988; Ogilvie et al. 1988, Hiroshige, 1990). It is responsible for many of the driving and industrial accidents reported each year and constitutes a major health problem with a serious socio-economic impact (Guilleminault et al., 1993). For driving, we usually associate drowsiness with a loss of vigilance. The three main states of vigilance (waking, quiet sleep with EEG synchronisation and REM (rapid eye movements), sleep with EEG desynchronisation) can be objectified by a set of three physiological signs that include EEG rhythms, muscular tone, and eye movements associated with sharp waves in brainstem-thalamocortical systems (Steriade and McCarley, 1990). More subtle features have to be used for the transitional epochs between waking and quiet sleep or vice versa and between quiet sleep and REM sleep, when most dramatic neuronal changes are expected to occur. Such neuronal activities may shed light on the mechanisms or, various physiological aspects of awakening, falling asleep, and entering REM sleep.

Over the last few years, the additional and complementary effects of this are driver's stress and sustained attention. They have became a major focus of research (Hancock, 1989; Fakhar et al. 1992). The relation between intensity of sustained attention of the driver and safe driving was determined a long time ago, in particular on studying collision-free accidents. Tarrière (1960), observed that half of the accidents of this type occurred on straight sections of road. The road system has been the subject of a lot of development since this time and accident studies carried out by Lafont (1987) have revealed the effects of drowsiness and fatigue in the case of trips undertaken on motorways during the period from 1982 to 1986. Thus for a yearly sample of about 300 killed, a loss of vigilance was the prime cause (34%) of lethal accidents compared with (12%) due to burst tyres, (12%) due to a failure to make proper allowance for the weather conditions, (11%) due to a failure to keep a safe distance from the vehicle ahead and (9%) due to a loss of control of the vehicle because of excessive speed, these statistics being based on the assumption that there was a single cause for each of these accidents. It should be noted that these statistics were derived from police reports of the accidents. No statistics for driver's experience have been reported.

Our experimental investigation permitted to identify the factors influencing driver behaviour under real driving conditions. It was performed to clarify the role of the interaction between car mechanical activities and drivers vigilance during monotonous and prolonged driving so as to draw some recommendations for conception of security systems.

Driver vigilance monitoring, recognition, warning ...

Driver impairment detection under real traffic holds now a strategic place : to prevent and to reduce the road crashes rate. Until now, it doesn't exist any reliable system that yields the precocious detection or prediction of driver impairment. Technology improvements of sensors and data treatments tools could provide vigilance experiments a new growth.

The vigilance disorders of healthy drivers, are presently known only by the crashes they cause. In view of improves stagnation in this field since 1985, objectives and a renewed approaches become necessary, from which the necessity to work out some physiological and mechanical approaches able to assess vigilance levels in interaction with external environment (traffic, basic equipment, ...).

Actually, the main problem is precisely identified, it lies in :

* the most reliable critera of vigilance

* the choice of good(s) parameter(s) susceptible(s) of giving a precocious assessment of vigilance fluctuations in car driving and of becoming integrated inside an "intelligent" system

* the research of the best dynamical model able to give driver behavioural actions and simultaneousely to diagnose the behavioural characteristics against driver basic levels

* the choice of the method which could become integrated in a hybrid system of acquisition and of information treatment

* the appropriate warning systems

Problems appear under several aspects : data acquisition, theoretical concepts, practical carrying out, results use and their interpretation

A number of devices are available (or in their intermediate steps) which claim to monitor driver states, but none is without serious deficiencies. Nevertheless they show that the development of a workable device should be feasible. Until now, scientists haven't found any precise correlation between physiological behaviour and mechanical car parameters. Then, we are still asking questions about what phenomena have to be regarded as a base in this correlation and which mechanical settings of the vehicle that may indicate the beginning of drivers drowsiness. We have finally noticed that psychological and behavioural studies obviously permit to take part in vigilance's understanding, but none of them are able to be enclosed in vigilance levels detection's subsystem. The difficulty lies in the quantification of the psychological and behavioural evaluated settings.

In this paper, whenever we have summoned vigilance levels, they are certainly synonymous with driver impairment states.

CURRENT RESEARCH

Vigilance and/or drowsiness

Different terminology has been cited in the literature regarding vigilance and vigilance test situation. Hundreds of studies had been published with a profusion of methods and types of task, asked whether all of them are really studing the same phenomenon. This undefined terminology alone appears to evoke diverse opinions. Almost no everyone is speaking about the same sort of task. There is no universality of task definition. In the light of old or recent studies, we have tried to summarize in this section some few necessary findings. We should like so much to summarize all the results done in this topic, otherwise the goal of our paper will be unfortunately overshooted in the case. We have presented only some appreciated findings. In this contribution, we haven't tackeled the identification of certain inappropriate driving behaviours which sometimes result in unsafe driving conditions and increased accident potential (specifically, high-risk driver groups).

Papers are a welcome addition to the literature on driver vigilance because it raises some important issues with respect to the general psychphysiological theory. Largely due to the influence of Mackworth (1950), the word of "attention" have been replaced by the term of "vigilance". These words -attention, vigilance- by no means refer to the same things, but they have common origins in class of psychological problems, and it is a fruitless and arbitrary task to attempt to distinguish clearly between them.

In the first case, vigilance was defined by Head (1923) as a "state of high efficiency of the central nervous system" which ensures that there are prompt adaptation responses. Macworth (1950 and 1957), redefined it as a "state of readiness in detecting and responding to short-lived and randomly occurring changes in the environment". He also analyzed activation or arousal and identified the performance failures with impaired attention (in Deese, 1955). Both of these definitions implicate the presence of inhibitory processes during the active and the adaptive behavioural state of wakefulness. The expression "sustained attention" is more commonly used in current psychophysiology studies (O'Hanlon and Kelly, 1977; Gale, 1977; Warm, 1984; Parasumaran, 1984). Thus a distinction is made between the basal vigilance of the nervous system and an operational vigilance concerned with the behavioural readiness of the subject.

In the second case we have the work of Lecret (1976) and Lecret-Grillon (1985) on driver fatigue. It appears to this author that the "best approach in dealing with road problems is to consider the vigilance of drivers with respect to the prevention of accidents" which calls for the conduct of research concerned with the use of electrophysiological techniques rather than monotonic performance tasks. However Mackie (1987), considered that studies of vigilance under actual or simply realistic conditions are not yet sufficiently advanced for us to be able to propose effective means for ensuring the maintenance of driver vigilance.

It is already clear that subjective vigilance and objective vigilance are not exactly parallel. Subjective vigilance should approach physiological one. If vigilance has an objective, psychological dimension, what are its specific substrates ? Santamaria and Chiappa (1987), thought that psychological and observational features of drowsiness (a lower state of vigilance) are unreliable. Perhaps the most important issue from a pratical point of view is the degree of driver impairment. As have been described, there is several factors hypothesized useful. The partial listing of variables that may influence decrement of drivers have been suggested by Mackie (1987). Actually, some of them have not yet been rationally examined.

A decrease in vigilance is undoubtedly associated with different states of the car mechanical fluctuations that need to be identified before making a detector of the vigilance levels. A low level of vigilance gives rise to particular types of driving that need to be identified in term of specific actions (steering wheel movements, deviation from the normal trajectory along a traffic lane, speed variations, ...). In this paper we have briefly described the state of researches on this subject without including the influence of alcohol, drugs, medications, ... which have a considerable negative effect on driver vigilance and on traffic safety (see O'Hanlon et al., 1982; O'Hanlon, 1984; Volkerts et al., 1987; Smiley and Brookhuis, 1987; ...).

Diagnosis of the Driver States : EEG activities reflect vigilance

The EEG recorded from the human scalp is the most useful physiological indicator of central nervous system activation and alertness (Lindsley, 1987). Its measure is naturally the first choice as measurements of drowsiness (Fruhstorfer et al., 1977; Belyavin and Wright, 1987). Analysis of Belyavin and Wright (1987), showed that periods of low vigilance were marked by an increase of theta (4-7 Hz) activity. Further analysis suggested that it was the increase in theta and the decrease in beta activity. Great care should be taken with respect to artifact control. Many studies have led to a better understanding of the mechanisms involved in a decreased wakefulness (Autret, 1985; Jones, 1989). The EEG is still the best parameter for vigilance levels' detection and their changes during real driving experiments. Many authors have used this physiological indicator to identify the period of drowsiness. The relation between EEG and alertness has also been demonstrated outside the laboratory. Torsvall and Åkerstedt (1987) measured continuous EEG spectra in eleven train drivers. They showed that lapses of attention were preceded by increased low frequency EEG activity. Significant increases of alpha and theta activity were present. After prolonged driving, a driver vigilance tends to diminish rapidely, such as can be measured by means of spectral analysis of the EEG (Åkerstedt and Torsvall, 1984 and 1985; Torsvall and Åkerstedt, 1985; Åkerstedt and Gillberg, 1990; Åkerstedt et al., 1991, Sauvignon, 1992). Before closing this short review, we could notice that analysis of Hjorth (1970, 1973) remains usefull in this domain. Hjorth findings, that concern the derivation of quantifying EEG parameters, show that the time domain descriptors (outstandingly, the graphical characteristics of EEG trace in terms of amplitude, slope and slope spread) obviously convey all informations which could be obtainable from conventional frequency analysis.

Thus, there is considerable evidence that spectral patterns may reflect central nervous system alertness under conditions requiring sustained attention. Under such conditions, increases in theta activity are related to impaired vigilance. Another approach to studying the neurophysiology of vigilance examines the responses of the peripheral nervous system to task-relevant stimuli. This line of research is not our first priority.

In this literature review, we don't tackle the discussion linked to the technical aspects of measurements or differences between analysis methods which are mostly important in this area. Sometimes, these discussions have involved to engage investigators to a polemic. Along our contribution, the result and discussion presented here have used three alpha wave indicators as ones of EEG indexes to analyze vigilance states. For this, we have appreciated that some cautions must be drawn. They are briefly described below.

The alpha waves interpretation : caution is advised - The definition of alpha wave most widely accepted is that proposed by the Terminology Commitee (in Markand, 1990) of the International Federation of Societies for Electroencephalography and Clinical Neurophysiology : "rhythm at 8-12 Hz occuring during wakefulness over the posterior region of the head, generally with high voltage (alpha waves occur at amplitudes varying from 20-60 µV) over the occipital areas. Best seen with the eyes closed and under conditions of physical relaxation and relative mental inactivity. Blocked or attenuated by attention, especially visual and mental effort. Both the view that alpha reflected relaxation and the view that it was controlled by visual stimulation were challenged when visual control processes (e.g. fixation, tracking, ...) were found to be the critical variable in the generation and inhibition of alpha activity. Much evidence now indicates that the activation of these visual control processes blocks alpha activity. For example, alpha desynchronization during mental tasks, such as mathematical problem solving or imaging an event, may occur because these activities stimulate oculomotor processing, which in turn causes alpha to block (Lorens et al., 1962; Antrobus et al., 1964; Wertheim, 1974). After 60 years of research, investigators are still divided on neurophysiological substrates of alpha rhythm. Based on findings that thalamic rhythmic activity is similar to barbiturate spindle activity in animals and persists after destruction of the cortex, it's suggested that alpha rhythm is driven by presynaptic input to cortical neurons from the thalamus. This motion was challenged by Lopes de Silva et al. (1974), who suggested that the genesis of alpha is cortical rather than subcortical. Still others suggested an extracerebral genesis for the alpha rhythm. For example, Lippold (1973) argued that alpha is caused by extra-ocular motor activity brought about by translational eye tremor modulating the position of the corneo-retinal potential. Although each hypothesis has some evidence in its favor, there still no neurophysiological theory that has found general acceptance. A hyperaroused or alert mental state was accompanied by fast frequency beta activity, where as a hyperaroused, sleep state was accompanied by slower theta activity. Alpha activity became associated with relaxed experience during which, attention was unfocused. Traditionally, alpha was considered an autonomic-like response which was optimally produced under conditions of relaxed awaking. Another long-standing belief was that visual stimulation played a role in alpha production. This belief was supported by the observation that alpha activity was reduced under eyes-open versus eyes-closed conditions.

Diagnosis of the Steering Wheel Movements and the Vehicle Speed

Practical observations and analysis of accidents suggest that inexperienced drivers tend to oversteer in the event of accidents. This reaction can also be observed in the case of drivers who had too much of alcohol and thus are not able to synchronize their driving operations. This suggests that the correction of the trajectory of a vehicle could be the subject of instruction and could be taught to learner drivers although this latter possibility would be controversial.

For many years, experiments have been carried out to determine the physical parameters characterizing driving, which could be correlated with EEG parameters that revealing the driver vigilance state. The most often measured parameter is the frequency of steering wheel movements. This characteristic decrease with longer driving times (Macfarland and Moseley, 1954). Conversely, when the subject's attention is distracted by a rich environment, steering wheel movements are often frequent (Maclean and Hoffmann, 1972 and 1973).

Some parameters derived from steering wheel movements are accordingly indicators of a change in driver strategy with longer driving times. We have noted that no reference frequency shift is established over the time of use. The most used token is the SWRR : Steering Wheel Reversals Rate. This one can be gotten by accounting for oscillation numbers of the steering wheel when the amplitude is lower or equal to a certain maximum value. This later value is different according to the authors and varies from .5 to 10 degrees. It's often not precised. This type of steering behaviour has been used in many studies as measurements of driving task requirements, driving difficulty, or driver's experience. It leads to reduce when the driving time lenghtens, either in real driving conditions or in simulated driving. Maclean and Hoffmann (1972, 1973), have shown that the SWRR is higher when the road width is decreased. It can be supposed that the SWRR is connected with the requested task. This hypothesis is strenghtened by the works of

MacDonald and Hoffman (1978). According to the authors a driving effort increase, by a secundary task adding, induces a SWRR increase.

Kahneman (1973), show that effort and SWRR are linked by a physiological activation increase. He also show that a SWRR increases with subjects having absorbed some increasing activation substances. In the same way, the SWRR decreases under the influence of substances (as alcohol) which diminue the activation level (Mortmer and Sturgis, 1975).

Now a decrease of vigilance is going with an activation drop, therefore it's probable that vigilance variations have an important impact upon steering wheel movements. In literature it's established that steering wheel movements have been studied to examine performance variations bound to traffic conditions, driver's experience, road type, etc.

Riemersma et al. (1977) recorded vehicle speed during a night driving experiment. The standard deviation of speed variations, calculated on 45 minutes periods during 8 hours, increases a lot from 3 hours driving.

O'Hanlon and Beaty (1977) recorded vehicle speed during a 4 hours on different routes with two drivers' groups, good and less good. Drivers are classified according to their performance in the ability of keeping the vehicle in position on the road, good drivers being these who do less corrections of their trajectories. The authors established that standard deviation (calculated per 17 minutes periods) tends to diminish for "less good" drivers and to be stable for "goods" ones. For trips, standard deviation doesn't show any big variation on all individuals.

Mackie and O'Hanlon (1977) recorded speed on a 6 hours driving experiment on subway (with a 45 minutes pause after 3 hours driving). The authors noticed a regular increase of standard deviation from the third driving hour. Though they emphasized that this increase might be due to either driver's fatigue or traffic growth. As described by Fuller (1984), feelings of fatigue sampled included drowsiness, exhaustion, awareness of what doing, daydreaming, hallucinations, physical comfort, boredom, awareness of time and irritation.

Chaput et al. (1991) show that there is some correlation between micro steering wheel movements and vigilance drop. On high vigilance periods small amplitude of steering wheel movements are frequent, and great corrections predominate during low vigilance states.

The precedently mentioned works display the steering wheel movements interest in detection of low vigilance periods. Several car manufacturers undertook research in this field (Renault : Tarrière et al. 1988; Nissan : Yabuta et al. 1985). Since ten years, their plans are not yet beginning to take shape with no tangible results.

Vehicle speed and steering wheel movements variations show a notable interest in the driver's fatigue study. Then, it's necessary to take in account that they are very perceptible to road features and traffic conditions.

Mackie and Wylie (1990) have treated in their general paper, a review of patterns of steering wheel movements and vehicle speed. They have affirmed the complexity of the analysis of these two tokens which are often perturbed by the environmental factors. These factors could highly affect principally the steering precision.

Khardi et al. (1993) have introduced some empirical formula which unify mechanical car parameters with EEG rhythms. Combining these settings, they proposed a newly established indicator named "K-factor". They have examined its variation during the drive which indicates the three common vigilance levels (high, medium, low). Along the trip, this factor varies between a minimum (High Vigilance) and a maximum (Low Vigilance).

<u>**A critical review**</u> - Although there are confirmatory reports of such a relationship, these findings have not been corroborated in repeated attempts at replication. The research is characterized by poor design and statistical procedures that fail to control for various extraneous factors. Although a few positive findings have been tentatively identified, they await replication.

METHODS

Subject design

Twelve healthy subjects from 25 to 45 years old voluntarily participated in our experiments (eight males and four females), with no neurophysiological problems. Subjects had normal driving habits and were not on any medications. All had normal or corrected-to-normal vision. They can be typically considered as a part of the driving population, having experience of more than five years in driving and have been driving constantly until now. Subjects had to drive normally without exceeding the legal "speed-limit" in France : 130 km/h. The driving task is diurnal and prolonged. The experimenter noticed during the trip some observations on driver behaviour, and on traffic conditions. All investigations were performed with remunerated subjects. Before the experiment began, subject were asked to fill out the handedness questionnaire. Once the questionnaire was completed, the electrodes were attached.

Experimental set up

The experimental vehicle used was a left-hand-drive car. Temperature inside the car is balanced with air conditionning system and the window's opening is not allowed during the highway trips. This environmental factor added to external noises can have a great influence on vigilance levels (Hancock, 1989). The trip on the motorway running between Lyon and Vittel (France) is approximately 700 kilometers long. During experimental runs, EEG, EOG, steering wheel movements and vehicle speed signals were measured.

The experimental arrangement is illustrated schematically in figure 1a. A continuous EEG recorded from the human scalp (the most useful physiological indicator of a central nervous system activation) was obtained from electrodes glued on the head (it's a nontraumatic and a noninvasive method). EEG were recorded with standard Ag/AgCl electrodes. The recording sites were the traditional Jasper ones : Fz , Cz, T5, T6, O1 and O2 (Jasper, 1958; Nuwer, 1987) (see figure 1b). Subjects are equiped in the laboratory. After electrode's fixing, some tests are carried out with open close eyes in order to evaluate the basic level of EEG. The signals delivered by the sensors are tested so as to detect eventual anomalies. The physiological parameters recording is made in bipolar mode.

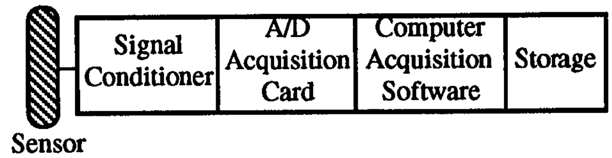

Figure 1a. Experimental set-up

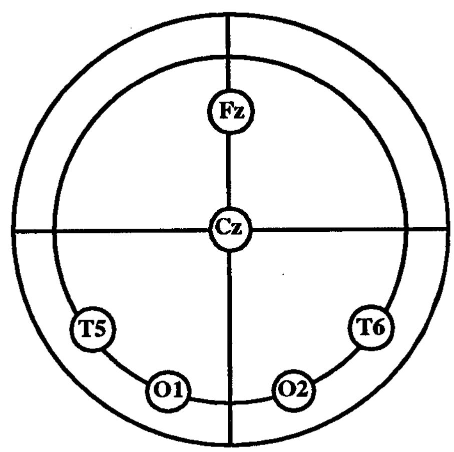

Figure 1b. A single plane projection of the head, showing the standard positions. The outer circle was drawn at the level of the nasion and inion. The inner circle represents the T5, T6, O1 and O2 sites. This diagram provides a stamp for the indication of electrode placements in routine recording.

The optimal electrode positions for EEG detection in automatic vigilance analysis could be used to analyze slow EEG waves diffusion.

There are 8 registered signals :

- 4 EEG derivations
- 2 EOG derivations
- steering wheel movements
- vehicle speed

For the whole signals (4 EEG, 2 EOG, steering wheel movements and vehicle speed), taking into account the spectral width of their bands, the sampling frequency has been fixed at 100 Hz. For EEG, the upper frequency limit was 45 Hz. All signals were amplified and filtered. On-line A/D-conversion is controlled by a Personal Computer. The card is piloted by a software who allows acquisition and storage of data. The elements of our acquisition system met the essential requirements of immunity to noise and vibration, of robustness and of durability for one-board installation.

The arrangement of the signal processing board employed gave rise to a particular design of the system in our laboratory. It has been done by Fakhar et al. (1992).

The recorded data were analyzed with the help of the digital computation facilities in INRETS-LEN Laboratory and by spectral analysis. Prior to analysis, the EEG was visually edited to remove all portions associated with eye movements (identified from the EEG channel) or other artifact (sometimes the removal of the ocular artifact algorithm (Semilitsch et al., 1986; Kenemans et al., 1991) has been used alone or in combination with our proper method (Khardi et al., 1994)). The procedures for visually inspecting and editing data are highly reliable as described by Åkerstedt et al., (1991). The EEG was analysed over 1.5 second periods as a function of the frequency concerned. We have then determined the total energy of alpha and theta bands. The estimation of the power spectral densities of the EEG indicators is based on procedures employing the modified Fast Fourier Transform. This approach is computationally efficient and produces reasonable results for a large class of signal processes (Antoniou 1979; Lawrence and Gold 1975; Gibson et al. 1979). The steering wheel movements and vehicle speed signals were also analyzed over 1.5 sec periods. To define steering wheel movements thresholds, we don't agree with the authors that analyzed vigilance or drowsiness by large temporal steps.

Each subject was filmed by two cameras (lateral and facial) which are fixed inside the car during the motorway trips. The EEG, EOG and car mechanical parameters were recorded simultaneously with the behavioural ones.

In this paper, we do not treat nor discuss our experimental results on the ocular manifestations of drowsiness which include the disappearence of waking eye movements and the appearence of drowsy eye-movement patterns (Torsvall and Åkerstedt, 1988). This study will be tackeled in an other paper. We have no intention here to analyze vigilance levels recognition using behavioural components which remain alone in a state of uncertainty to assess degraded driver states. Nevertheless, we have used the global behavioural state that obviously shows driver drowsiness by lateral and facial imagery analysis. We aren't in a position to show that behavioural components are enough sensitive indicators to reflect the earlier fluctuations of the cortical vigilance. Many papers are actually available in several areas but none of them is able to give proof of one's ability in vigilance level classifications. It's a reason why we have used the only global behavioural effect or the most macroscopic behavioural phenomenon which explicitly appears in real driving conditions. This study was strictly controlled with respect to head and body position. The presented EEG and car mechanical parameters have been analyzed during periods where the characterized behavioural effects have been occured. We have also broadened out physiological and mechanical indicators for the whole experimental time. Our analysis doesn't take into account the last part of the drive (≈ 15 minutes) where theta and alpha indexes rapidly increased, indicating driver fatigue. The calibration of drowsiness effect during the initial parts by studying slow EEG productions has been done.

RESULTS AND DISCUSSION

The aim of our experiments is to detect the steering wheel movements (angle, speed, number and amplitude of the movements), the vehicle speed (mean and instantaneous variation) and the subject electroencephalography responses during the trip. We search to study the relationship between car parameters (minor and major directional corrections and speed variations made by the driver) and the physiological signals of the cerebral activity describing the low state of vigilance.

Analysis of theta and alpha emissions show that almost every subject have produced more or less important hypovigilance peaks. These two parameters reveal themselves to be complementary in the assessment of driver impairment periods. The neurophysiological parameters appreciated to be the most promising in the pseudo quantative study of these periods, are theta and alpha energetical ratio (Daniel, 1967; Steriade and McCarley, 1990; Sauvigon, 1992), and the appearance frequency of alpha bursts (Khardi et al., 1993 and 1994). The every alpha burst duration have provided a supplementary information with the aforementioned analysis.

We have presented (figure 2) an example of the EEG activity for approximately nine and eleven seconds periods. It illustrates the alpha emissions which power spectral distribution is centered at the vicinity of 10.5 Hz. This agrees with the Garma's polygraphic study (Garma, 1984) and Khardi et al. (1994) one. This analysis consequently permits to show the interest of narrow bands studies to improve the information research concerning subject low vigilance states. Recently, a subdivision in three alpha frequency bands ($\alpha 1$ [8-9.5]; $\alpha 2$ [9.5-10.5]; $\alpha 3$ [10.5-11.5] in Hz) have been introduced (Khardi et al., 1994) to show the frequency variation effect. The choice of 1 Hz step is quite arbitrary and analysis done by a lower 1 Hz value could be considered.

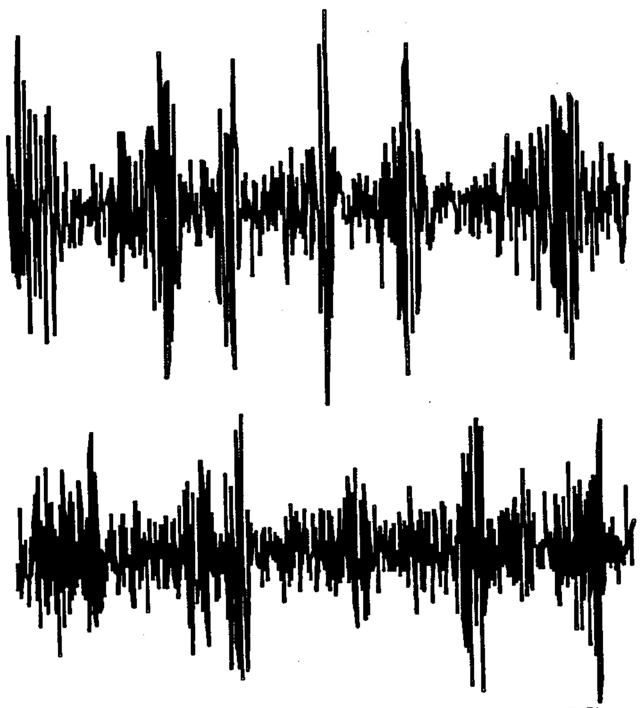

Figure 2. Example of two successive EEG periods. Alpha bursts are shown and clearly identified

Alpha oscillations appear during the transitional period between "waking" and "beginning of drowsiness". It permits to quantify "selectively" drowsiness (optimization of the EEG emission). Naturally, the strong alpha activity could be explained by what it's called " subject relaxation effects" (Khardi et al., 1994). This kind of analysis is indispensable for driver impairment phenomena understanding which will allowed to determine a positive or negative correlation with car mechanical parameters.

As part of this research, we have examined the "time-frequency" evolution of the EEG activity between 1 and 45 Hz. This type presentation permits to obtain a total view of the power spectrum within the most electroencephalogram frequency bands (≥ 1 Hz). As an example, figures 3a, 3b, 3c and 3d (Intensities in A.U.) show axonometric plots of the EEG power spectrum between 1 and 45 Hz versus an evolution on a timescale of about 7 minutes and 30 seconds for the EEG activities ($\Delta t = t_{final} - t_{initial} = 7$ mn 30 sec) [the software have been developped by Khardi, 1994 (unpublished work)]. The axonometric plots (horizontal shift factors are 5. and 7. (the default values are 3. and 5.); .65 is a scalar that is used to control the span of the z-axis (decreasing this value will compress the plot. Values should typically range between 0 and 1. (the default value is .5))) are used to produce graphical of two dimentional data arrays. They can often reveal much more information about variations in the data than can be seen from cartesian plots of array cross-sections. The following table tells the driving periods on motorway which have been shown in figures 3a, 3b, 3c and 3d (the all trip time on motorway is 6 hours) :

Figures	Initial time	Final time
3a	1 H 22 mn 30 sec	1 H 30 mn
3b	1 H 45 mn	1 H 52 mn 30 sec
3c	2 H 15 mn	2 H 22 mn 30 sec
3d	2 H 37 mn 30 sec	2 H 45 mn

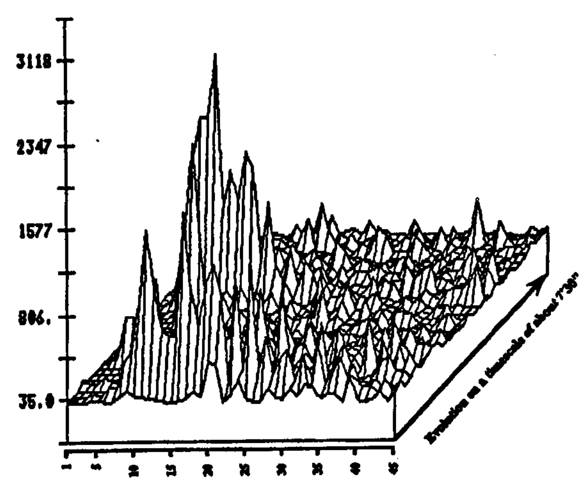

Figure 3a.

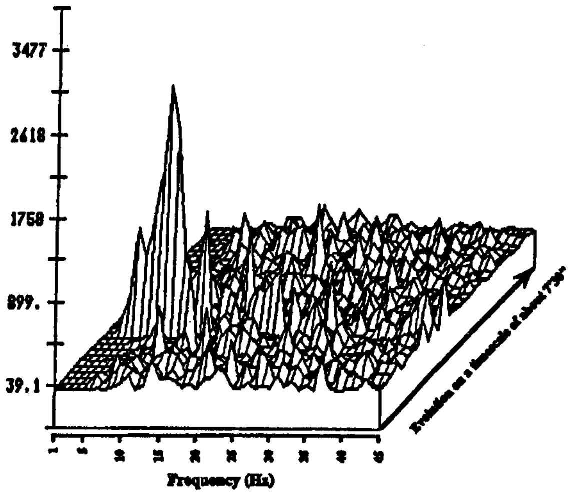

Figure 3b.

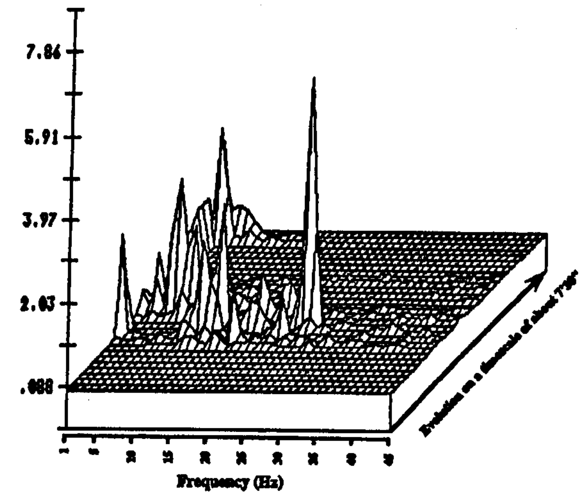

Figure 3d. (Y-axis; ordinates * 10^6)

The shift phenomena have been obviously shown in the fourth figures. In the figure 3a, the most predominate activities are alpha and beta. The percentage of the two activities are nearly in the same ratio. Fifteen minutes later, we have observed (figure 3b) the frequency shifts toward the alpha and theta activity frequencies. The shift does dramatically square with driver impairment. At this time, the alert system (if it exists !) would be profitable for the driving safety.

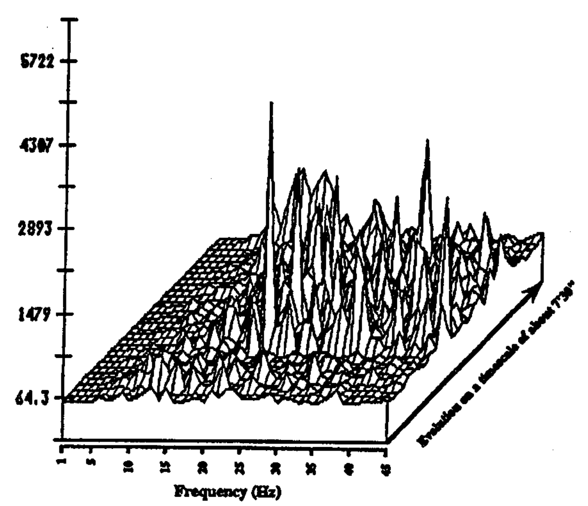

Figure 3c.

Few time later (figure 3c), low frequency activities are going out compared with the last case; subject is awakened in this period. Finally (figure 3d), in the period [2 H 39 mn 30 sec - 2 H 41 mn 15 sec], driver's vigilance level fluctuates between awakening and impaired states. These states are followed by a continuous emergence of very low frequency activities which are dangerous for driver's safety. Intensities of slow EEG activities which occured at low frequencies are dramatically increased between the two first driving hours and the last of the third ones (see figures 3a and 3d) and are in the ratio of 1895. It's naturally explained by the damage of driver vigilance with prolonged driving. This ratio almost stayed constant between first figures 3a. and 3b.; it's due to their short separated time. To conclude, two empirical aspects have been briefly tackeled : frequencies shift and the ratio of slow EEG activity intensities of two driving periods. They must be taked into account in the interpretation of the driver Central Nervous System impairment and for the classifyied vigilance states. The produced axonometric plots which are exceedingly rich in carried informations show their ability to analyze driver EEG activities under real driving conditions. The aforementioned analysis is a definite advantage to watch the electroencephalogram frequency variation during the trip. A lack of the relevance findings which would be able to predict the exact vigilance states allows this anlysis to be in the lead with regard to the used traditional methods. During a trip, the shift phenomena toward the low frequencies, by their duration and their distribution, could be so dangerous that it gives rise to a deep drowsiness at the wheel. The interference between driver's impairment states and environment (traffic, climatic conditions, type of run, ...) can dramatically disturb the driver's safety and the users one.

Car mechanical thresholds

The litterature explains that there are considerable disagreements in the definition of vehicle parameters thresholds, which are characteristic of the beginning of the drowsiness (low vigilance states). So, we realized here an introduction of two parameters which represent a compromise between EEG responses and car mechanical fluctuations (steering wheel movements and vehicle speed). This analysis type permits to identify and to objectify the role of the car mechanical settings in vigilance level detections. The precise control over all the situational items, such as traffic, is necessary for the assessment of low mechanical thresholds. We have looked for the minimum and the maximum values of the experimental input array of steering wheel movements (in degrees) and vehicle speed (in km/h). The result is two scalars which are called $\Delta\Phi$ and ΔV, and they are written by :

$$\Delta\Phi = |\Phi max - \Phi min|$$
and
$$\Delta V = |Vmax - Vmin|$$

$\Delta\Phi$ and ΔV are the absolute value fluctuations of Φ and V over each 1.5 seconds epoch.
The global energetic ratio of theta and alpha waves, named R, was employed as an indicator of the degree of vigilance. Analysis suggested that periods of low vigilance were characterized by the highest values of this ratio. Peculiarly, this situation occured when R was up to one and oscillates between this value and its maximum.
In this paper, the ΔV is used as a monitoring parameter. Their optimum thresholds have not been found because they require to introduce a smattering of the vehicle spontaneous deceleration (in Khardi et al., 1994).

Analysis of collected data (steering wheel movements, vehicle speed fluctuations and a thresholds evaluation) are based on the R ratio. We have carried two strategy to define empirically the optimum threshold values of the car mechanical parameters in the aforementioned context. The first one is used in the aim to define the high-threshold value (maximum) and the second one to approach roughly the low-thresold value (minimum). These two thresholds would be in the closed interval in which driver degraded states were generally noticed. Of course, because the difficulty of the problem, the relative low value that's observed here must warily used in the future and it'll leave to the scientist's summing up.

The following example treats the adopted first strategy for defining a high threshold value of the steering wheel movements. During some 34 minutes and 15 seconds trip where driver impairment have been observed (the global behavioural state that obviously shows driver's impairment at the wheel; see experimental set up section), the ΔV absolute limits have weakly varied (table 1).

table 1 : The optimum ΔV values

limits	Minimum	Maximum
ΔV	0.08	4.04

During these weak variations, the R ratio and the steering wheel movement fluctuations vary between their optimal values : .004 to 30 (in arbitrary units) for R and .2 to 11 degrees for the second parameter. Figure 4 show the breakdown of the two variables. As shown in this figure, the maximun of the distribution is confined between s1 and s2 : 98.94 % of the global population. These two values are selected to fulfil the logical conclusions that we may observe in the below contingency table (see table 2 and 3) (Maurin).

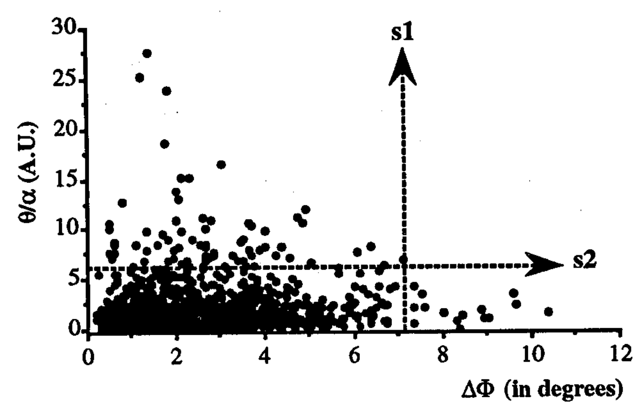

figure 4. R ratio versus $\Delta\Phi$

The logical conclusions which are used to define the high threshold value are :

$\{\Delta\Phi > s\,1\} ==> \{R < s\,2\}$

and its negation

$\{R \geq s\,2\} ==> \{\Delta\Phi \leq s\,1\}$

To look for threshold values , we have divided the distribution of the figure 4 into the following six regions :

1- (X1, Y1),
2- (X1, Y2),
3- (X2, Y1),
4- (X2, Y2),
5- (X3, Y1),
6- (X3, Y2),

where the boundary values are shown in table 2 and their observed frequencies inside each region are in table 3. On the one hand, this empirical division is done to establish principally the minimum $\Delta\Phi_m$ which is stayed - as mentioned - debatable. On the other hand, it's done to simplfy and to solve in part the problem of this threshold. Because the pair of variables ($\Delta\Phi_m$, s1) is not unique, we took some liberty of picking the one which seems to give the higher density inside the definite region. We have chosen the following values : $\Delta\Phi_m$ = .5°, s1 = 7.2° and s2 = 6 (A.U.). The global counting for the first column X1 is 1.67 % against 97.33 % for X2 and 1% for the last one. The observed frequencies in the region (X2-Y1) represent 97.18 % of the total density (table 3) where all information is almost impacted. For some cases, the choice of the couple ($\Delta\Phi_m$, s1) could be defined with 90 % of the total density without changing the aim of the goal. For this, we think that the error of the high threshold value is approximately around 1°.

Table 2 : Values which delimited the six regions of the figure 4

X 1	0 to 0.5 degree
X 2	0.5 to 7.2 degrees
X 3	7.2 to 12 degrees

Y 1	0 to 6 units (A.U.)
Y 2	6 to 30 units (A.U.)

Table 3 : The observed frequencies table

	X 1	X 2	X 3
Y 2	0	81	0
Y 1	25	1377	15

We can't definitely conclude about the reliability of the measurement error of the .5° low threshold value. Some driver impairment have been selectively occured with some $\Delta\Phi$ values lower than .5°. But, as described above, it has been happened with distribution density lower than 1 %.

The final step is done to examine the two remainder following cases which are necessary for understanding the uncertainty of the low threshold assessment and for clarifying the case where $\Delta\Phi \geq 2°$ and $R \leq 1$:

1- we are uncertain of the best low threshold value and of its measurement errors. Despite of this, we have examined some states where steering wheel movements fluctuations are between .5 and 2 degrees ($.5 \leq \Delta\Phi \leq 2$), and simultaneously R ratio shows a low state of vigilance (the theta energy is more important than the alpha one) (see table 4). We have observed that periods which preceed these ones show a $\Delta\Phi$ greater than 2°. This result can be explained as a delay effect. It means that a low threshold value could be shifted to 2°. We have observed that this phenomena occurs in nearly all the trip (at constant speed periods on motorway). This analysis stage constitutes the second announced strategy.

Table 4 : It shows point number, the absolute variation of the steering wheel movements and R ratio

N°	ΔΦ	R (A.U.)
1	0,5	8,6
2	2	5,3
3	1,7	5,2
4	0,6	5,1

2- in this investigation, we have noted some periods where $\Delta\Phi \geq 2°$ and theta energy is not greater than alpha one ($R \leq 1$). In this case, we observed that alpha bursts last more than 1.5 seconds (see figure 5a). Perceived Drowsiness was closely reflected in increased alpha activity.

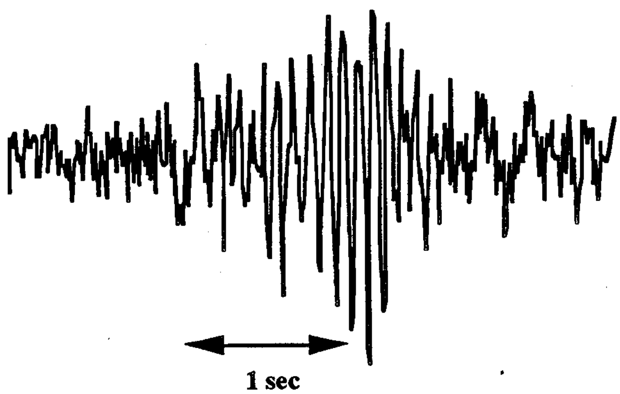

Figure 5a. The 3.5 seconds EEG activity. It shows more than 1.5 seconds of alpha burst

The examination of these cases show that during increased drowsiness, subject started to oscillate between alertness and drowsiness, leading to an oscillation in the EEG between alpha (lasting in time) and theta activity. This result agree with the one done by Åkerstedt and Gillberg (1990) in their analysis of the EEG changes due to sleepiness in the active individual.

We have also found that the amplitude of the alpha waves only is unable to assess the steering wheel movements low-threshold which is corresponding to the beginning of drivers drowsiness. Figures 5a and 5b normalized at the same amplitude, illustrate this behaviour. In the first case, (figure 5a) $\Delta\Phi = 4.7°$ (with $\Delta V = .2$ km/h) and alpha burst duration τ # 1.5 seconds, then later give place to the EEG with generalized slowing. What happens when you are in this state (1.5 seconds alpha bursts duration) ? This event characterized the state where consciousness is clouding and the brain is losing contact with reality. In the second one (figure 5b), $\Delta\Phi = 0.4°$ (with $\Delta V = .4$ km/h) and $\tau \leq .75$ second with a higher alpha burst amplitude against figure 5a. A state of reduced vigilance is induced by a decline in cerebral function as described above. It is not frequently related to a driver's degree of fatigue.

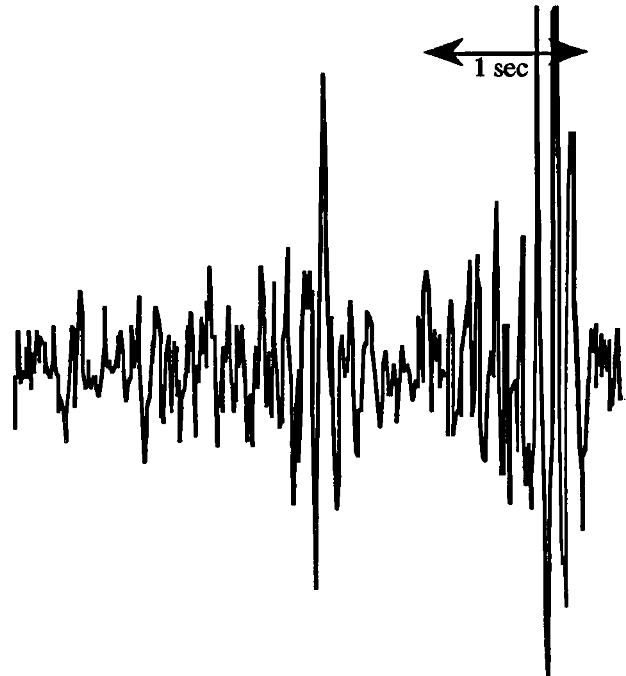

Figure 5b. The 3.5 seconds EEG activity. The alpha burst last less than 0.75 second

A subject who drives under the 1.5 seconds alpha burst duration is more apt to be involved in a collision, due to a drop in his ability to precess information. For example, as studied by Kobayashi (1988), in such reduced vigilance state a driver takes about 3-4 seconds to depress the brake pedal, whereas the requires only about .7 second when fully alert. Under this state, the driver's visual field becomes constricted, making him incapable of reacting quickly, and he fails to notice most road signs. When the judgment time is added to this, it can be assumed that about 2.5 seconds are usually required from the time a braking request is made until the brakes begin to take hold. The distance required for braking varies greatly depending on the performance of the vehicle itself as well as on the vehicle speed, load weight, road surface condition (whether wet or dry) and other factors. We consider the total time of 4 seconds (1.5 seconds of the alpha burst duration and the 2.5 seconds for the judgment time) while driving at 130 km/h could drastically delays the execution of emergency manoeuvres.

To conclude, on the one hand, only alpha bursts which last in time are the most important finding in the case where theta energy is lower than the alpha one and on the other hand the two degrees low threshold value proved true.

It is apparent from the above result that our indicators are most reliable, and vary most consistently with the experimental variables. Our result under real driving conditions fits with the one done by Wierwille and Muto (1981) in their sudy on the vehicle measures for extended duration simulated driving tasks. They observed a decrease in small movements of the steering wheel (.5° to 2°) with time, whereas movements larger than 2° tend to become more numerous. Our low threshold value of $\Delta\Phi_m = 2°$ agree with the higher value of the interval [.5°, 2°]. But as described above, we can't definitely conclude about the reliability of the .5° as the minimum low threshold value. Wierwille and Muto (1981) had not define the high threshold value but they only concluded about the movement frequencies of $\Delta\Phi$ greater than $\Delta\Phi_m$. McLean and Hoffman (1975) found that the minimum gap size vary between .5 and .7 degree, and the maximum is possibly of 10° or greater. Their measurements of driver performance and steering task difficulty have been fundamentally used to distinguish differences between drivers or driving conditions in tracking experiments but can not to interpret the nature of the differences. Our estimated high threshold value is approximately $\Delta\Phi_M = 7.2°$. The error on this value is around 1°. To a certain extent, we consider that our high threshold value agrees with the finding of McLean and Hoffman because the methods and the experimental conditions are different between simulated driving task and real driving conditions. In real-world driving studies, thresholds can be valid criteria for detecting differences. As explained since the start of this paper, caution is required in using the low threshold value.

CONCLUSION

The present investigation is concerned with a particular aspect of car mechanical parameters and driver interaction in real traffic. It describes the general findings in this area during the last few years and sometimes attempts to clarify the rout of some topics. We tackle the problem of vigilance states assessment governing the success of the future state detection and alarm devices when driver impairment occurs on the road.

The general and the most obvious conclusion to be drawn from the results of this research is that physiological indicators provede an important approach to the experimental study of vigilance. The judicious use of this finding may make significant contributions to understanding vigilance specially a car mechanical settings behaviour. The precise control over situational variables, such as steering wheel movements, necessary for the assessment of thresholds, is the most important finding for the vigilance studies. Analysis of the R ratio and the alpha bursts duration permit to assess the steering wheel movements thresholds which are equal to 2° and 7.2 (± 1°) in the case of low vigilance states or the beginning of driver drowsiness. We noted in the case where $\Delta\Phi \geq 2°$ and theta energy is not predominate than alpha one, that alpha bursts duration is about 1.5 seconds or more. Sometimes, a delay effect between EEG and steering wheel movements happens. We have also found that the only amplitude of the alpha waves is unable to define the steering wheel movements low threshold.

We have not defined any threshold for the car speed fluctuations by way of the analysis of the EEG indexes. We have only observed an increase of ΔV in high density traffic, and critical situations. Under these conditions $\Delta\Phi$ increasingly fluctuated. These factors varied with anticipation difficulties on section of junctions. Evaluated on the whole trip, our indicator quickly increased during the last parts of the drive, it indicates driver's fatigue.

Simultaneously with this kind of experiment, we are beginning to think about what useful integrated-apparatus would be able to adequately alert drivers at their first impairment periods, which kind of messages and on which manner it will be sent to drowsy-drivers. Somehow or other, reducing road-crashes, must start by a serious understanding of the global behavioural manifestations and by using intelligent and intelligently equiped vehicules.

Remarks :

i) we have briefly discussed the proliferation of parameters and analyzed the ones which are more likely to be unable to assess vigilance states or the impairing properties. A distinction has been drawn between some typical indicators of implicit or explicit vigilance states. Some findings are behind the drivers impairment detector race and the others are still in the running. All scientific works differences carried out on both sides of the Atlantic show the difficulty of the problem, specially the first and low vigilance states appraisal.

ii) it is appropriate to review some knowledge about vigilance as carefully and comprehensively as possible. Amalgation of several research topics in this issue is the first such attempt and is a priority to reduce crashes due to driver vigilance failures.

iii) as pointed out previously, the investigations reported here represent an initial approach under real driving conditions to examine some relations between different aspects of driver impairment. In addition and complementarity to this, we intend to study the R's microanalysis which shows a so called "beat phenomena" (Khardi, Olivier and Vallet, to be published in 1994). The simplex calculation which clarify the role of the sharp analysis of the electrophysiological signals (especially EEG and EOG) to understanding and to simplifying the automatic analysis of drowsiness in real driving conditions or in clinical experimentations will be introduce.

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OVERVIEW OF RESEARCH ON DRIVER DROWSINESS DEFINITION AND DRIVER DROWSINESS DETECTION

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ABSTRACT

A major cause of vehicle accidents is driver impairment due to drowsiness. Further research is needed on drowsiness definition and its countermeasures. Four studies were recently undertaken, two of which have dealt with problems of drowsiness definition while two have dealt with on-line drowsiness detection. The first definitional study involved observer rating and the second involved prediction of reductions in task performance based on combinations of physiological measures. Both approaches appear promising. These definitions, as well as others, could then be related to measures taken from the vehicle itself (e.g., measures of steering, lane position, and lateral acceleration), which could be combined to form drowsiness detection algorithms. The first detection study involved algorithm development and expected accuracy, and the second involved validation of typical algorithms. This paper provides an overview of the four studies and an assessment of the feasibility of on-line detection of drowsiness.

INTRODUCTION

A significant cause of single- and multiple-vehicle crashes is driver impairment due to drowsiness (Knipling and Wierwille, 1993). Such crashes appear to peak in the early morning hours and occur most often on higher speed roads. Drowsiness-related crashes are probably more common than accident statistics indicate, because of difficulties of attributing drowsiness as a cause. Tilley, Erwin, and Gianturco (1973), for example, found by means of questionnaires administered to 1500 drivers receiving license renewals that sixty-four percent had at one time or another become drowsy while driving. Seven percent of the drivers in the survey indicated that they had had a crash involving drowsiness and another seven percent indicated that they had had a near miss resulting from drowsiness. Because of the hazard that drowsiness presents in transportation systems, methods need to be developed for operationally assessing and counteracting its effects.

This paper describes four studies directed at advancing the understanding and feasibility of operational detection of driver drowsiness. Two of the studies deal with definitional issues and two deal with detection issues. The four studies are described in subsequent sections of this paper, with conclusions drawn thereafter.

Before describing the studies, it is important to note that definitional issues have not received adequate attention in the past. Unless researchers deal with such issues, accuracy evaluations cannot be carried out. It is also important to point out that for a drowsiness detection system to be feasible, it must provide high detection capability with a low false alarm rate, and it should not encumber the driver.

DEFINITIONAL STUDIES

As indicated, two definition studies were conducted. Each study was directed at developing a usable measure, the numerical value of which would serve as an "accurate" indicator of the level of drowsiness of any driver. The measure need not be operationally feasible, since other measures could be used to estimate it.

Previously, two promising measures of eye closure have been used as definitional measures (Dingus, Hardee, and Wierwille, 1985):

EYEMEAS: the mean square value of percent eye closure of the driver, and
PERCLOS: the proportion of time that the driver's eyes are 80 to 100 percent closed.

These measures assess so-called "slow closure," as opposed to blinks. Slow closure appears to occur in almost all drowsy individuals (Erwin, 1976) and represents a reasonably accurate predictor of sleep onset as well as degraded task performance. Thus, these measures can serve as definitional measures.

To expand the range of possible definitions and to insure that at least one definition would prove effective, research was directed at developing two alternative definitions of drowsiness, based on what appeared to be reasonable approaches. These research studies used the concept of observer ratings of drowsiness and the concept of physiological correlates of drowsiness with task performance.

Observer Rating Experiment

This experiment is more fully described in Wierwille and Ellsworth (1994), and is summarized here for completeness. The study involved assessing the level of drowsiness based on a rating system. Recently, while performing simulator experiments on sleep-deprived drivers, it was found that the experimenters conducting the experiments could estimate the level of drowsiness based on characteristics such as facial tone, slow eyelid closure, and mannerisms (rubbing, yawning, nodding, etc.). Sufficient promise existed that it was decided to conduct a formal experiment in which observer ratings of drowsiness would be assessed. The observer-rating approach to definition of level of drowsiness has been largely overlooked by researchers.

Six informed observer-raters were requested to give ratings on a variety of one-minute segments of videotaped facial images. These images had been obtained from previous drowsy-driver experiments using the moving-base computer-controlled simulator at Virginia Tech. Segments were transcribed to new tapes and showed drivers at all levels of "apparent" drowsiness.

The raters in this experiment used the continuous rating scale shown in Figure 1. They were also given a "Description of drowsiness continuum," that is, a one-page description of the stages of drowsiness and what to consider (see Wierwille and Ellsworth, 1994). This description indicated that facial tone and length of eye closures were important indicators. It also indicated that mannerisms usually occur in the intermediate stages between alertness and extreme drowsiness.

Analysis of the data from the experiment showed that ratings do in fact exhibit a high degree of consistency and

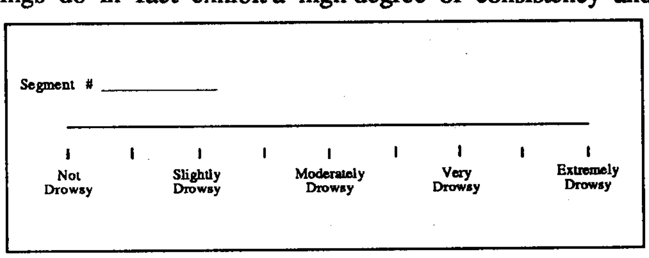

Figure 1. Drowsiness rating scale.

reliability. Figure 2 shows the degree of consistency among ratings. The ranking of the ratings in the graph is according tothe means taken from the six raters. Note that raters were willing to ascribe ratings across the entire scale, based on what they observed, and also that ratings do cluster with only moderate variance at any given point on the abscissa. Table 1 shows a matrix of interrater correlations, which average to $\bar{r} = 0.81$. This again indicates good agreement among raters. Furthermore test-retest reliability was relatively high, with an average of $\bar{r} = 0.81$ also.

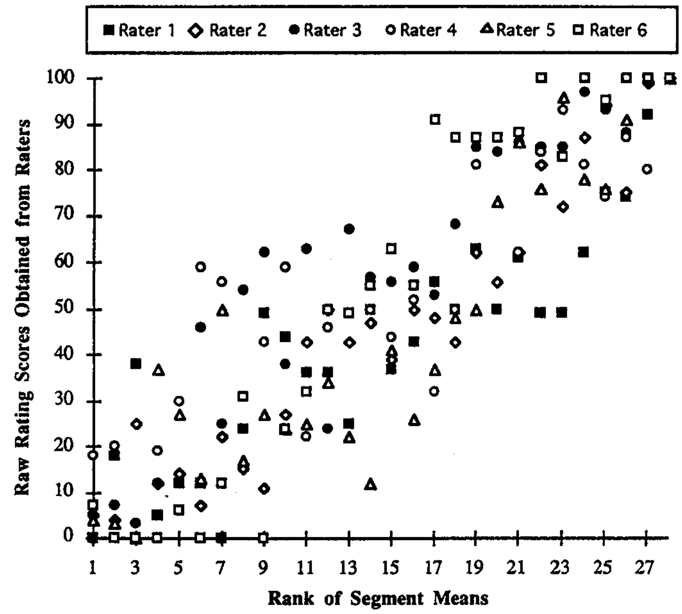

Figure 2. Raw rating scores as a function of segment mean rank.

Table 1. Interrater Correlation Matrix.

		RATER NUMBER 2	3	4	5	6
	1	0.87	0.81	0.68	0.72	0.81
RATER	2		0.85	0.79	0.85	0.91
NUMBER	3			0.84	0.80	0.86
	4	$\bar{r}$ = 0.81			0.84	0.76
	5					0.80

These results (as well as others presented in Wierwille and Ellsworth, 1994) suggest that observer rating of drowsiness using the scale shown in Figure 1 and the description of drowsiness continuum can serve as a definitional assessment of drowsiness. Furthermore, averages of the results of two or more observer-raters may provide even greater stability. The observer measure used to assess level of drowsiness (in subsequent experiments) is as follows:

AVEOBS: average of the ratings given by three independent observers, using the drowsiness scale, for each one-minute interval of videotaped facial image.

Physiological Correlates Experiment

In this experiment an attempt was made to relate physiological measures with task performance measures (Ellsworth, Wreggit, and Wierwille, 1993). The basic concept was to enhance the eyelid closure measures by "blending" or otherwise including physiological measures believed from previous research to be related to drowsiness. Accordingly, an enhanced definition might result that would be more comprehensive than eye-closure by itself.

Eight sleep deprived subjects performed two interleaved tasks, one being a lower level cognitive task (simple detection task), the other being a higher level cognitive task (mental arithmetic). By exposing the subjects to these two tasks, it was possible to determine performance decrements in both lower-level cognitive functions as well as in higher-level cognitive functions.

The Virginia Tech driving simulator was used for the experiment, however, the subjects in the experiment did not drive. Instead, the subjects performed the two tasks, which were presented on the simulator display. Pushbuttons on the steering wheel were used by the subjects to respond to the two tasks.

The detection task consisted of a group of random-letter characters that were displayed on the screen. If the subject detected one of the two target characters, the subject pressed the "yes" pushbutton on the steering wheel. If none of the target letters was present in the field, the subject pressed the "no" pushbutton.

For the arithmetic task, each problem had a numerical integer for an answer. The subject pressed the "even" pushbutton if the answer to the problem was even and pressed the "odd" pushbutton if the answer to the problem was odd.

Twenty-one performance, eye closure, and physiological measures were gathered in this experiment. Included were measures of task errors, task response latency, eye closure, heart rate, EOG, EEG, EMG, and skin potential. Thus, performance could be examined in relation to eye closure and physiological variables.

Two types of analyses were performed on the data collected in this study. The purpose of the first type (correlation analysis) was to determine which eye closure and physiological measures covaried with performance deterioration. The purpose of the second type of analysis (multiple regression analysis) was to determine linear combinations of the eye closure and physiological measures that would best predict performance deterioration.

The results of the analyses indicated that performance impairment due to drowsiness could be reliably predicted with linear combinations of eye closure and physiological measures. Regression models of a global performance measure (composed of standardized values of errors and response latency for each of the two tasks) showed multiple correlation values (R) ranging from 0.76 to 0.86 depending on the data and the variables used (all significant measures or a reduced set of significant measures). The results also indicate that using fewer variables in the regression models does cause a decrease in the multiple correlation value (R), however, the decrease is not substantial. Furthermore, the results suggest that using baselined data is a more efficient method than using non-baselined data. (Baselining is the subtraction of an initial mean value of a measure from all subsequent values of the measure, performed on a per-subject basis.) Baselining can be used to produce similar values of R with fewer measures.

The most important result of the study is that a good definitional measure of drowsiness can be obtained using a combination of eye closure, EEG, and heart rate measures. If the measures are first computed over moving six-minute averages, they can be used to predict global performance with reasonable accuracy.

Table 2 shows the outcome of a regression analysis using PERCLOS combined with three EEG measures and one heart rate measure to predict global task performance for the eight sleep-deprived subjects. In this table, the additional measures are defined as follows:

Table 2. Regression model summary for the global task performance measure.

Regression Statistics

Multiple R	0.821551
R Square	0.674946
Adjusted R Square	0.663814
Standard Error	0.579816
Observations	152

Analysis of Variance

	df	*Sum of Squares*	*Mean Square*	*F*	*Significance F*
Regression	5	101.9168	20.38336	60.63114	6.36E-34
Residual	146	49.0832	0.336186		
Total	151	151			

	Coefficients	*Standard Error*	*t Statistic*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	2.151302	0.056569	38.02996	3.09E-79	2.039503	2.263101
PERCLOS	0.939449	0.08067	11.64561	9.06E-23	0.780018	1.098881
MNALPHA	-0.66039	0.10233	-6.45351	1.4E-09	-0.86263	-0.45815
MNBETA	-0.25655	0.07469	-3.43482	0.000766	-0.40416	-0.10893
MNTHETA	0.345228	0.080706	4.277585	3.34E-05	0.185725	0.504732
MNSQHRT	0.128913	0.054767	2.353869	0.019867	0.020676	0.237151

MNALPHA: mean of the detected amplitude of the output of a filter of the EEG having a passband from 8 to 12 Hz.

MNBETA: mean of the detected amplitude of the output of a filter of the EEG having a passband from 12 to 24 Hz.

MNTHETA: mean of the detected amplitude of the output of a filter of the EEG having a passband from 4 to 8 Hz.

and

MNSQHRT: mean square of the instantaneous pulse rate in beats per minute.

The column of coefficients in the table shows the relative weightings of standardized values of the component measures. As can be seen, PERCLOS is most heavily weighted, but the other measures contribute significantly. Note in particular that a multiple R value of 0.82 is achievable with this set of measures. This indicates that approximately two-thirds of the variance in the task performance measure is attributable to measures known to covary with drowsiness. Based on these results, it would be possible to define the level of drowsiness as

$$\text{NEWDEF} = 0.94\ \text{PERCLOS} - 0.66\ \text{MNALPHA} + 0.345\ \text{MNTHETA} - 0.257\ \text{MNBETA} + 0.129\ \text{MNSQHRT}$$

where it is assumed that the measures on the right have been standardized.

Figure 3 shows how well the above definition reflects global performance on the subjects' tasks. In this figure there are 152 values on the abscissa corresponding to 19 non-overlapping six-minute averages for each of the eight subjects (that is, 19 times 8). As the plot shows, the output of the regression model does a credible job of determining performance deterioration (increases in value on the ordinate). Therefore, NEWDEF represents a reasonable alternative definition of the level of drowsiness.

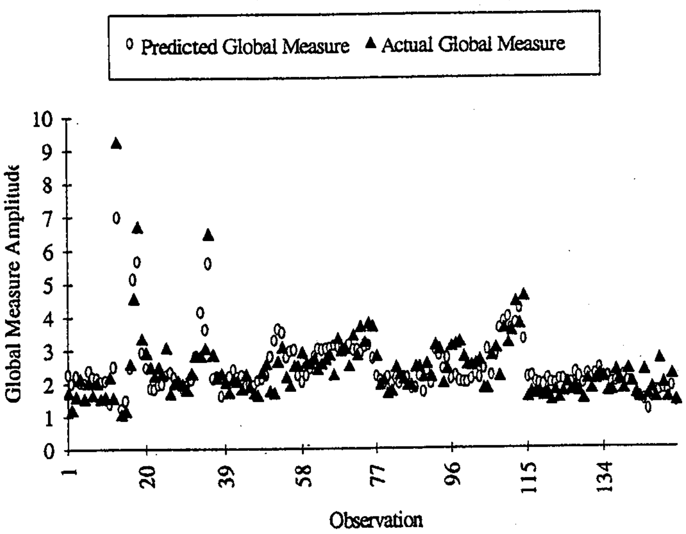

Figure 3. Actual global measure vs. predicted global measure.

DETECTION STUDIES

The definitional measures just described are considered promising for use in driver drowsiness research. However, such measures cannot at present be operationalized. Thus available measures must be used for on-line drowsiness detection systems. This section describes two studies, one directed at determining practical algorithms for drowsiness detection and associated expected accuracy, and the other directed at validation of typical algorithms. The term validation is used here to describe the application of detection algorithms to new driver subjects, that is, subjects other than those for whom the algorithms were derived.

Algorithm Development Study

As indicated, one approach to drowsiness detection is to use the available measures in combinations that best mimic the definitional measures. Techniques of statistics can then be applied to develop optimized algorithms for drowsiness detection. Figure 4 depicts the concept just described. A variety of measures may be operationally obtainable and are shown on the left. Definitional measures obtained from observer ratings, eye closures, and physiological measures are shown on the right. (The definitional measure, MASTER, is defined as the sum of the standardized values of the other four definitional measures.) Statistical techniques are applied to subsets of measures on the left to mimic (predict or estimate) one of the measures on the right. It should be noted as shown in Figure 4 that heart-related measures might possibly be available operationally from a plethysmograph sensor or from an unobtrusive system. Also, the A/O task-related measures are associated with a secondary task the driver might be asked to perform, once initial indications of drowsiness occur. This task is described later.

Twelve volunteer subjects (six male and six female), with an age range of 18 to 40 participated in this experiment (Wreggit, Kirn, and Wierwille, 1993; Wierwille, Wreggit, and Knipling, 1994). Young subjects were used because accident statistics indicate they are most likely to have accidents resulting from drowsiness.

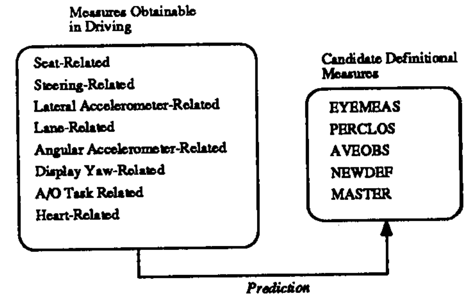

Figure 4. Concept of using obtainable measures to mimic (predict) a definitional measure.

The simulator used for this study was the computer-controlled, moving-base simulator at Virginia Tech. The simulator had been validated by Leonard and Wierwille (1975) with regard to driver-vehicle performance measures by comparing it with an actual automobile. It had similarly been validated in regard to visual glance times for in-vehicle tasks (Kurokawa and Wierwille, 1990). A good deal of peripheral equipment was added to the simulator so that it would be possible to obtain the many measures that had to be computed.

Subjects drove the simulated automobile at a speed of 60 mph (97 km/hr) and were instructed to drive (in the right lane) as if they were on a lonely U.S. interstate highway. Four of the twelve subjects simply drove, that is, they were given no additional duties. A second group of four subjects was asked to also manipulate various controls on the dash board. These tasks involved following auditory commands to adjust radio controls, push buttons, and operate vertical slide controls. This dashboard manipulation task was used simply to distract the driver from the driving task as would happen in an actual on-the-road setting. The third group of four was asked to perform an auditory search task while driving. This consisted of a subsidiary task that involved an auditory presentation of various words. If the presented word contained an "A" or "O", the subject was to press the button labeled "YES" located on the steering wheel. If the presented word did not include an "A" or "O" the subject was to press the button labeled "NO" located on the steering wheel. A new word was presented verbally every 15 seconds by means of an audio track on a pre-recorded videotape. The letters "A" and "O" were chosen as target letters because words could be found that include the letters "A" and "O" and are easily distinguishable from other words. All simulator runs took place between 12:30 a.m. (0030) and 3:00 a.m. (0300). Subjects had been up since 7:00 a.m. (0700) the previous day and had not been permitted to ingest stimulants after 6:00 p.m. (1800) the previous day.

The measures obtained from the twelve subjects were first computed over one-minute intervals. Thereafter, six-minute averages were computed using six consecutive one-minute intervals. This procedure provided the statistical stability of the six-minute averages while at the same time making it possible (in an application) to update each minute. All of the operationally obtainable (independent) measures were baselined using the first two six-minute intervals. After the baselined six-minute averages were computed, the measures were used in multiple regression and discriminant analyses to develop the best estimations of the definitional measures (as depicted in Figure 4). Analyses were performed using data for all twelve subjects, and separately for the four subjects involved with the A/O task. Only the multiple regression results will be described here, because the discriminant analyses were more complex and did not produce any improvement over the regression models.

The multiple regression procedure began with all selected measures, followed by systematic removal of nonsignificant measures as shown in Figure 5. Subsequently, measures were re-introduced to insure that the best available models were obtained.

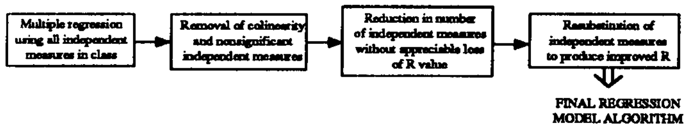

Figure 5. Steps in the regression algorithm development procedure.

The regression equations that resulted generally contained four to six measures. Average multiple regression correlation coefficients (R-values) for each definitional measure were as follows: Master, 0.878; PERCLOS, 0.856; AVEOBS, 0.830; EYEMEAS, 0.815; and NEWDEF, 0.752. Since these are averages, it is clear that some of the regression models had higher R-values. Obviously, such models could be selected, assuming the operational measures could be made available. In any case, these R-values indicate that operational measures are capable of providing a reasonably high level of accuracy in drowsiness estimation.

To obtain a better understanding of the quality of algorithms, algorithm (multiple regression) output was plotted over the dependent (definitional) measure for typical cases. Figure 6 shows the results of one of these plots. It corresponds to prediction of PERCLOS using steering, lateral-accelerometer, and several lane-related measures. Note that each interval on the abscissa represents a six-minute average. Thus, Subject 1 contributed the data from 1 to 25, Subject 2 from 26 to 50, etc. Increasing drowsiness is denoted by increasing values of the ordinate. The plot shows that the algorithm follows the major trends in PERCLOS and should be quite effective in detecting drowsiness.

A summary specification of the algorithm producing the results of Figure 6 is given in Table 3. The measures included in the algorithm appear in the left column. BETA weights represent the equivalent contribution of each measure to the algorithm and B weights represent the actual coefficients that would be used in computing the algorithm. The column at the right indicates that all measures that have been included in the algorithm are highly significant contributors.

The operational measures appearing in Table 3 are defined as follows:

INTACDE: standard deviation of the lateral velocity of the vehicle.

LANDEV: standard deviation of lateral position relative to the lane.

LNERRSQ: mean square of the difference between the outside edge of the vehicle and the lane edge when the vehicle exceeds the lane. When the vehicle is in the lane, the contribution to the measure is zero.

STEXED: proportion of time that steering velocity exceeds 150 degrees per second.

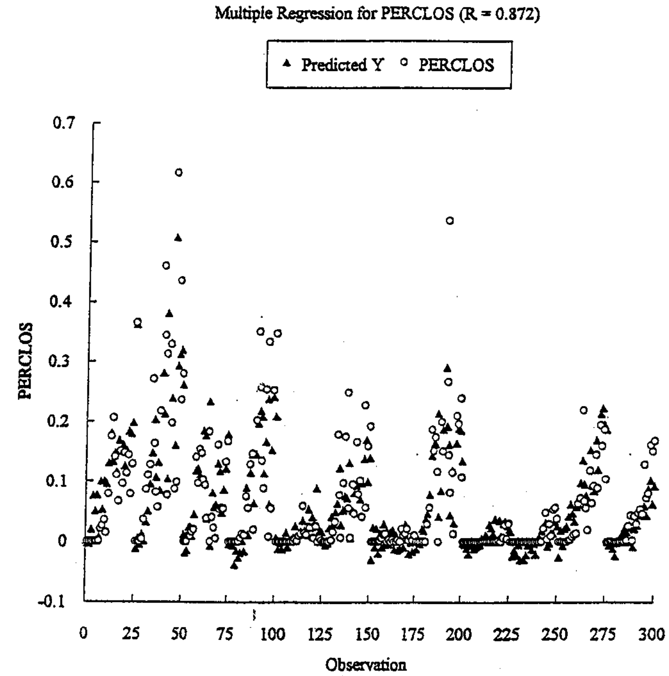

Figure 6. Plot of PERCLOS data — predicted vs. observed.

Table 3. Regression summary for dependent variable: PERCLOS.

R= 0.87159526 R^2≤= 0.75967830 Adjusted R^2≤= 0.75475703
F(6,293)=154.37 p<0.0000 Std.Error of estimate: .04849

	BETA	St. Err. of BETA	B	St. Err. of B	t(293)	p-level
Intercpt			-0.003	0.004053	-0.694	0.488
INTACDE	-0.109	0.030	-0.069	0.019114	-3.603	0.000
LANDEV	0.873	0.063	0.066	0.004763	13.798	0.000
LNERRSQ	-0.258	0.054	-0.002	0.000410	-4.820	0.000
STEXED	0.090	0.033	45.740	16.818827	2.720	0.007
NMRHOLD	-0.204	0.045	-0.004	0.000785	-4.494	0.000
THRSHLD	0.250	0.041	0.231	0.037904	6.098	0.000

NMRHOLD: number of times the hold circuit output on the steering exceeds a threshold value (corresponding to holding the steering wheel still for 0.4 second or longer).

THRSHLD: proportion of total time that the hold circuit on the steering exceeds a threshold value.

As can be seen, all of these measures could be computed with instrumentation on steering and the output of a lane tracking device.

To obtain a better understanding of the estimated accuracy of the various algorithms, thresholds were specified for the definitional variables. These thresholds, when applied to the corresponding algorithm outputs, could then be used to determine the number of misclassifications. For the example in Figure 6 and Table 3, the two thresholds were specified as follows:

questionable/drowsy: PERCLOS = 0.15
alert/questionable: PERCLOS = 0.075

Thus, the three defined levels of vigilance were: Alert: PERCLOS < 0.075; Questionable: 0.075 ≤ PERCLOS < 0.150; Drowsy: PERCLOS ≥ 0.150. The resulting classification matrix is shown in Figure 7. It shows the results of dual-thresholding the algorithm output into the three categories of wakefulness/drowsiness. As an example of how to interpret this matrix, find the "18" in the cell located under the predicted category of "Questionable" in the classification matrix. This cell contains 18 misclassifications due to the fact that those 18 data points were classified as "Questionable" by the multiple regression equation but were actually in the "Awake" category. The figure shows that there were only 6 large misclassifications out of 300, that is, 3 indicating the driver was awake when the driver was actually drowsy and 3 indicating the driver was drowsy when the driver was actually awake. These values are circled in the figure.

			Predicted		
	Group	Percent Correct	Alert	Questionable	Drowsy
Observed	Alert	89.76	**184**	18	3
	Questionable	47.27	7	**21**	16
	Drowsy	62.75	3	16	**32**
	Total	79.00	194	55	51

PERCLOS (R = 0.872).

Apparent Accuracy Rate (large misclassifications): 0.98

Apparent Accuracy Rate (all misclassifications): 0.79

Figure 7. Classification matrix generated from multiple regression analysis of PERCLOS data.

Algorithm Validation Study

Recently, an additional study was undertaken for the purpose of validating typical algorithms obtained from the study just described. Validation in this case is defined as application of the algorithms to data taken from driver-subjects other than those for whom the algorithms were derived. The main question to be answered by such a study is the degree of accuracy that can be expected from the algorithms when they are applied.

To answer questions of accuracy, twelve new driver subjects were tested in the Virginia Tech driving simulator. In this case, however, eight males and four females were used, because young males are now known to be much more likely to have drowsiness-related accidents than females (Knipling and Wierwille, 1993). The subjects performed the same types of tasks, however, and in some cases they had cruise control engaged and in other cases they did not. The idea was to have similar, but not identical driving conditions, thereby testing the robustness of the algorithms.

The results of the validation study are expected to be reported in the late summer of 1994 in a NHTSA (U.S.) report under Contract No. DTNH 22-91-Y-0266. It is anticipated that there will be a slight degradation in algorithm classification accuracy when applied to new data because the algorithms will be used on drivers other than those for which the algorithms were "trained." However, only the actual analysis will determine the level of accuracy with certainty.

CONCLUDING REMARKS

The results of the various studies completed thus far suggest that on-line detection of driver drowsiness is feasible. The number of misclassifications for many of the algorithms is relatively small, particularly when a two-threshold model and large misclassification errors (only) are considered. Insofar as the definitional measures are concerned, all of them can be predicted with reasonable accuracy by the regression models, with MASTER and PERCLOS producing slightly better results than the others.

Although feasibility has been demonstrated, it must be recognized that a few serious misclassifications will remain, and attention must be paid to such errors. False alarms in particular are likely to reduce driver acceptance. To overcome the false alarm problem, it is proposed that a two-stage detection system be used. The first stage would detect probable drowsiness based on driver and vehicle related measures, and the second stage would further discriminate by requesting the driver to perform the auditory (A/O) task. A system for implementing the two-stage approach is shown in Figure 8. Sensors on the vehicle would provide signals through an interface to a dedicated microcomputer. The computer would condition the incoming signals, determine their validity where necessary, and then perform one-minute measures computations. Subsequently it would average six consecutive one-minute values of each measure, pass the results through a stage-one algorithm, and determine whether or not threshold had been exceeded. It would continue to perform the test using the algorithm each subsequent minute, by deleting the oldest one-minute of data and inserting the newest one-minute of data. Such a procedure would produce current testing while taking advantage of the improved statistical stability associated with six-minute averages.

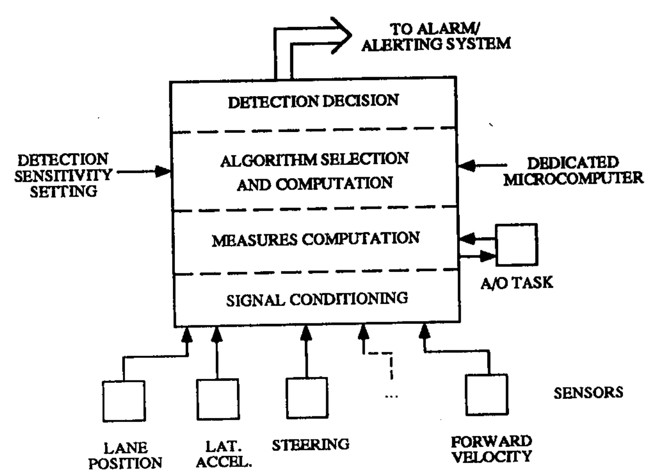

Figure 8. Envisioned on-board detection system.

Whenever the threshold is exceeded by the stage-one detection process, the computer would switch to stage two in which it would implement the A/O task using a "sound board" to produce previously recorded spoken words. It would score the task, and it would compute the stage-two algorithm output to determine if threshold had again been exceeded. If so, it would output an indication to an alarm/alerting system. If not, it would eventually revert to the stage-one algorithm.

It should be remembered that the results of this study would only apply to highway driving at speeds above, say, 50 MPH (80 km/hr). However, studies of accident data bases suggest that most serious drowsy driver accidents do in fact occur at such speeds, particularly in low-volume traffic. Thus, the envisioned system should be capable of providing a measure of protection where it appears most needed.

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The opinions expressed are those of the author.

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Development of a Drowsiness Warning System

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ABSTRACT

The development of technologies for preventing drowsiness at the wheel is a major challenge in the field of accident avoidance systems. Preventing drowsiness during driving requires a method for accurately detecting a decline in driver alertness and a method for alerting and refreshing the driver. As a detection method, the authors have developed a system that uses image processing technology to analyze images of the driver's face taken with a video camera. Diminished alertness is detected on the basis of the degree to which the driver's eyes are open or closed. This detection system provides a noncontact technique for judging various levels of driver alertness and facilitates early detection of a decline in alertness during driving. When a diminished state of alertness is detected, the system issues a signal that first activates an audible warning and then generates a menthol scent. Compared with the stimulative effect of an audible warning alone, experimental results show that the provision of an audible warning combined with a menthol scent is more than twice as effctive in keeping the driver alert.

INTRODUCTION

The growing number of traffic accident fatalities in Japan in recent years has become a problem of serious concern to society. Based on the results of accident analysis, the authors are engaged in research and development work on active safety systems that are intended to reduce the number of accidents causing death or injury. The key to driving safety and the prevention of accidents before they happen lies with the driver. For this reason, eliminating situations in which the driver is insecure is essential to accident prevention. Accidents due to drowsiness at the wheel have a high fatality rate because of the marked decline in the driver's abilities of perception, recognition and vehicle control when sleepy. The prevention of such accidents is a major focus of effort in the field of active safety research.

DROWSINESS-RELATED ACCIDENTS

Drowsiness can be caused by various factors such as fatigue, lack of sleep and the use of medication. In addition, another factor that can be considered is the monotony of driving on expressways or in congested traffic. The continued construction of highways and improvement of vehicle performance have made it possible for drivers to enjoy pleasant, comfortable motoring. On the other hand, drivers are more apt to operate their vehicles under monotonous driving conditions. This observation is substantiated by the findings of various surveys, which indicate that approximately 70% of the respondents said they have experienced drowsiness while driving.

In many instances, drivers are not conscious of becoming drowsy while driving. A consideration of the psychology of drivers suggests that a slight feeling of sleepiness is not regarded as a sufficient reason for stopping to rest. As a result, it is not unusual for drivers to subsequently fall asleep while continuing to drive. An active safety system that could effectively prevent drowsiness at the wheel would contribute to a large reduction in fatal and injury-causing accidents.

SYSTEM IMPLEMENTATION TECHNOLOGIES

A drowsiness warning system must incorporate a technology for detecting drowsiness in the driver and a stimulation technology for refreshing the driver. The process of falling asleep at the wheel can be characterized by a gradual decline in alertness from a normal state due to monotonous driving conditions or other environmental factors; this diminished alertness leads to a state of fuzzy consciousness followed by the onset of sleep. There are two critical issues that a drowsiness warning system must address. The first is the question of how to accurately detect drowsiness at the initial stage. The second is the issue of how to refresh the driver when drowsiness is detected. In addition, the stimulation device used to relieve drowsiness should also be designed such that drivers can easily operate it and comfortably refresh themselves whenever they become conscious of a decline in alertness.

Drowsiness Detection

Techniques for detecting drowsiness in drivers can be broadly divided into five categories, as shown in Table 1. Among these different methods, the best detection accuracy is achieved with techniques that are based on physiological signals, which are currently used as indices for evaluating alertness. However, this detection approach has the drawback of not being very practical because it requires the attachment of electrodes directly to the driver's body. Detection methods that are superior in terms of practicality are ones that sense driving behavior or vehicle behavior that is distinctly characteristic of a sleepy driver. Since these techniques allow noncontact detection of drowsiness, they do not give the driver any feeling of discomfort and provide high detection accuracy. On the negative side, they are subject to numerous limitations depending on the vehicle type and driving conditions. It would also be necessary to tune each system separately for different types of vehicles. Still another problem with these techniques is that detection would not be possible at low speed.

Table 1
Drowsiness detection techniques.

Detection techniques			Description
(1) Sensing of human physiological reactions	Physiological signals		Detection by changes in brain waves, blinking, electrocardiogram, pulse rate, skin potential, etc.
	Physical changes	Contact	Detection by changes in inclination driver's head, posture, grip on steering wheel, etc.
		Non-contact	Detection by changes in frequency at which eyes close
(2) Sensing of driving operation			Detection by changes in driving operations (steering, accelerator inputs, braking, shift Lever changes, etc.)
(3) Sensing of vehicle conditions			Detection by changes in vehicle conditions (speed, lateral G, yaw rate, lateral position, etc.)
(4) Response of driver			Detection by periodic request for response
(5) Traveling conditions			Detection by measurement of traveling time and conditions (daytime or nighttime driving, weather, speed, etc.)

This research focused on an investigation of a system for detecting changes in the degree of openness of the driver's eyes, which has a high correlation with drowsiness and allows noncontact detection. This approach falls under the category of detection of physical changes in physiological phenomena. This particular method was selected because it was felt that a practical drowsiness detection system would have to assure a high level of detection accuracy equivalent to that of methods based on physiological signals. Moreover, the system should be able to detect drowsiness in the driver by means of a noncontact technique.

Technology for Refreshing the Driver

The stimulation device used to refresh the driver must be capable of providing the following two effects.

- Immediate refreshment: It should be capable of relieving drowsiness immediately whenever the driver feels sleepy.
- Sustained refreshment: It should be capable of keeping the driver alert for a period of time after relieving drowsiness.

A buzzer or some other audible warning can provide enough of a stimulus to achieve immediate relief from drowsiness. When driving on expressways or in other situations, however, it is not possible to stop and rest except at certain designated places. In such cases, it is important to provide a sustained refreshing effect until the driver reaches a place where it is possible to rest. To meet this requirement, a stimulation technology has been developed which uses an optimum combination of an audible stimulus and a scent stimulus to effectively relieve drowsiness and maintain a state of alertness.

DROWSINESS DETECTION BY IMAGE RECOGNITION

Detection Method

An investigation of the human eyes under a condition of reduced alertness indicated that the eyes are narrower than in a wide-awake state and that there are times when the eyes actually close.

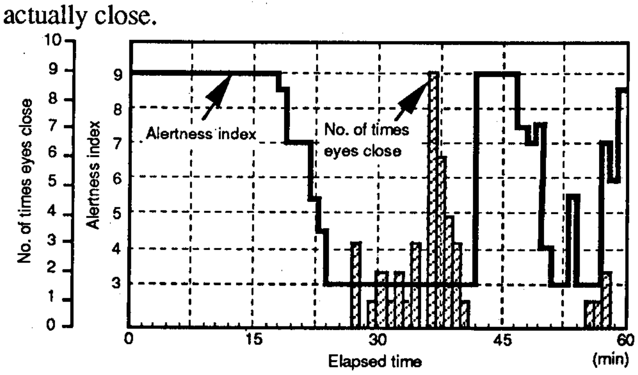

Figure 1. Number of times eyes close and alertness level.

Figure 1 presents experimental results showing the alertness level and the number of times the driver's eyes closed for two or more seconds while driving on a test course. Good correlation is seen between the two sets of data. This result indicated that a reduced level of alertness could be detected with good accuracy by monitoring changes in the degree of openness of the driver's eyes.

System Configuration

A small CCD camera positioned in front of the driver takes images of the driver's face. The facial image data are converted to binary images one frame at a time and sent to the frame memory of the image processor. The frame memory stores each image in a 512x432 pixel format, with eight bits of memory capacity used for each pixel. A personal computer connected to the image processor controls the image processing procedure and judges the processed results. An infrared lamp is provided in the instrument panel to facilitate the recording of facial images during nighttime driving.

Basic Algorithm

Flowchart of Major Functions - A flowchart of the major functions of the drowsiness detection system is shown in Figure 2. The functions of the system can be broadly divided into an eyeball detection function, comprising the first half of the processing routine, and a drowsiness detection function, comprising the second half.

Eyeball Detection Function - A brief explanation is given here of the eyeball detection procedure. After inputting a facial image, preprocessing is first performed to binarize the image and remove noise, which makes it possible for the image to be accepted by the image processor. The maximum width of the face is then detected so that the right and left edges of the face can be identified. After that, the vertical position of each eye is detected independently within an area defined by the center line of the face width and lines running through the outermost points of the face. On that basis, the area in which each eye is present is determined. Once the areas of eye presence have been defined, they can be updated by tracking the movement of the eyes. The degree of eye openness is output simultaneously with the establishment and updating of the areas of eye presence. That value is used in judging whether the eyes are open or closed and also in judging whether the eyes have been detected correctly or not. If the system judges that the eyes have not been detected correctly, the routine returns to the detection of the entire face. The following explains the eyeball detection procedure in the order of the processing operations.

(1) Preprocessing

The preprocessing operations include the binarization of a facial image to increase the processing speed and conserve memory capacity, and noise removal.

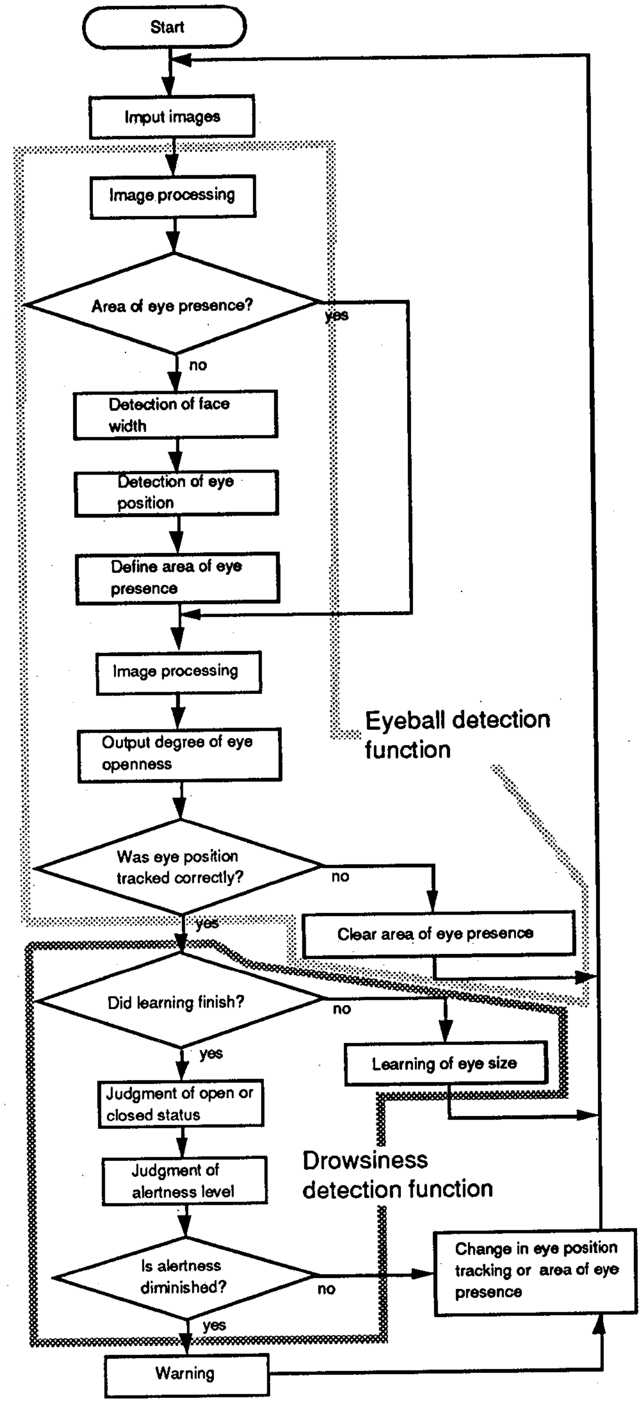

Figure 2. Flowchart.

The noise removal procedure involves a general expansion processing method combined with the use of a median filter. These preprocessing operations are sufficient to support detection of the vertical positions of the eyes. However, following identification of the eye positions, the size of the eyes must be converted back to the original image format at the time the degree of eye openness is output. To facilitate that, data compression is performed in the latter stage of preprocessing. The image processor developed for the drowsiness detection system performs the expansion and compression operations on the white pixels, and processing for noise removal is performed on the small black pixels of the facial image.

(2) Face width detection

The maximum width of the driver's face must be detected in order to determine the lateral positions of the areas in which the eyes are present. Face width is detected by judging the continuity of white pixels and the pattern of change in pixel number. On that basis, the outer edges of the face are recognized and determined.

(3) Detection of vertical eye positions

Each vertical eye position is detected independently within an area demarcated by the center line of the face, which is found from the face width, and straight lines running through the right and left outer edges of the face. In a binary image, the eyes become collections of black pixels along with the eyebrows, nostrils, mouth and other facial features. These collections of black pixels are recognized on the basis of a labeling operation, and the position of each eye is extracted by judging the area of each label along with its aspect ratio and relative coordinate positions in the facial image. Through this process of detecting each vertical eye position, the central coordinates of each eye are recognized. The coordinates serve as references for defining the areas of eye presence, as indicated in Figure 3.

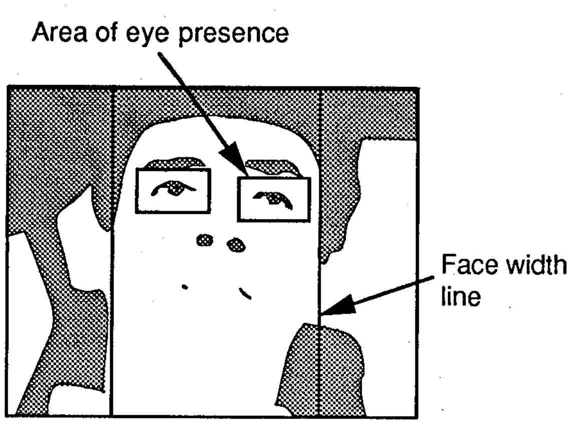

Figure 3. Image of face and objects of detection.

(4) Eyeball tracking

A function for tracking the positions of the eyeballs is an important capability for achieving high-speed processing because it eliminates the need to process every frame in order to detect each eye position from the entire facial image. This function consists of a subroutine for updating the areas of eye presence and a subroutine for recognizing when tracking becomes impossible.

The basic concept of eyeball tracking is to update the area of eye presence, in which an eye search is made in the following frame, according to the central coordinates of the eye in the previous frame. The following is an explanation of the specific processing procedure.

The updating process involves defining an area of eye presence on the basis of the coordinates (xk,yk) at the point of intersection of center lines running through the Feret's diameter of the detected eye (Figure 4-a). The area thus defined becomes the area of eye presence in which the system searches for the eyeball in the image data of the next frame. Owing to movement of the driver's head or other reasons, the center point of the eye detected in this area in the next frame changes relative to the center point (point A) of this area of eye presence (Figure 4-b). In relation to this change in eye position, the area of eye presence is updated in reference to the center point (point B) of the eye detected in this frame, and then the facial image data of the next frame are input. Similar to the previous step, the system then searches for the eyeball in the updated area of eye presence (Figure 4-c). This process of using information on eye position changes to define the eye position for obtaining the next facial image data makes it possible to track the position of the eyeball. As is clear from this description, the size of the area of eye presence can be defined so as to correspond to these eye position changes.

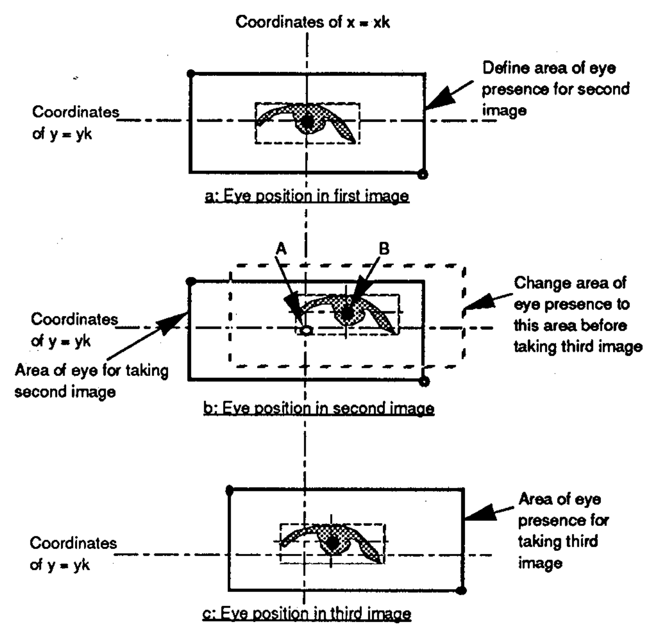

Figure 4. Tracking of eye position.

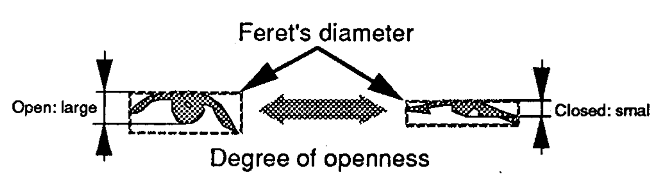

Figure 5. Degree of eye openness.

If the eyes are tracked correctly, their degree of openness will always vary within a certain specified range for each individual driver, as illustrated in Figure 5. Consequently, if the value found by the system falls outside that range, it judges that the eyes are not being tracked correctly. The process of detecting the position of each eye from the entire facial image is then executed once more.

Drowsiness Judgment Function

(1) Alertness index

An alertness index has been devised for making quantitative judgments of a driver's state of drowsiness. This index is based on the assignment of points to brain waves, blinking and facial expression, which are known to vary according to a person's level of alertness. The point total provides a quantitative measure for judging the alertness level. The specific procedure for rating these three elements is outlined in Figure 6.

As a person's level of alertness drops, a large number of a2 waves appear and their amplitude becomes larger. Points are thus assigned according to the number and amplitude of the a2 waves detected. Blinking is rated by evaluating the measured waveforms for the upper and lower electric potential of the eyes. In a normal state of alertness, blinking appears as sharp spikes in the waveform. As the level of alertness drops, the spikes appear more frequently and subsequently lose their shape to become a gentle waveform when a person becomes drowsy. Eventually, the waveform shows trapezoidal shapes indicating that the eyes close for long intervals. In terms of facial expression, a drowsy-looking appearance can be determined from the slackness of the face muscles and the drooping of the upper eyelids. Each of the three elements is rated in this way using a three-point scale and the points are totalled to indicate the alertness level, which ranges from a wide-awake state (9 points) to a fuzzy state just prior to falling asleep (3 points).

Ranking	Brain waves	Blinking	Facial expression
3	No α2 waves	Continuous rapid blinking	Rigid face muscles (Alert expression)
2	Clusters of small-amplitude α2 waves	Appearance of slow blinking	Drooping of upper eyelids (Vacant expression)
1	Continuous appearance of large-amplitude α2 waves	Eyes close for long intervals	Eyes half-closed (Drowsy expression)

Figure 6. Evaluation criteria for brain waves, blinking and facial expression.

(2) Judgment of whether eyes are open/closed

A window is defined on the basis of the Feret's diameter of the eyes. The maximum number of black pixels along the vertical axis of the window indicates the degree of eye openness and is used as the basis for judging whether the eyes are open or closed (Figure 5).

(3) Criterion for judging eye open/closed state, and learning function

A standard value is established for each driver for judging whether the person's eyes are open or closed. That criterion is based on the degree of eye openness observed for the individual when the eyes are open and closed. The system also learns the size of each person's eyes in order to cope with variation in eye sizes due to individual differences or to differences in the distance between the camera and the driver's face at the time facial images are filmed.

(4) Method of judging alertness level

As shown in Figure 7, the method of counting the number of times the eyes close begins with the second consecutive closure. This is done to avoid including instances of eye closure due to blinking. In the figure, the numbers in the middle of the interval for judging the alertness level indicate the eye closure count. In this example, the system judged that the eyes closed four times. The specified interval for judging the alertness level with this system has been set at one minute.

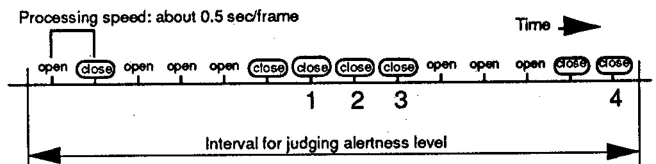

Figure 7. Method of totaling no. of times eyes close.

Criteria for judging the alertness level on the basis of the eye closure count have been determined according to the results of driving tests in which drowsiness at the wheel was investigated (Table 2). The table shows the correlation between the alertness level, based on the alertness index, and the eye closure count found from the driving test data. Three levels of alertness are indicated here: a wide-awake state (an alertness index of 9.0-8.0), a slight decline in alertness accompanied by a little drowsiness (7.5-6.5) and a large decline in alertness, a state ill-suited for continued driving (6.0-3.0).

Table 2
Relation between alertness level and no. of times eyes close.

	Alertness index	No. of times eyes close
Wide-awake	9.0 ~ 8.0	0
Slight decline in alertness	7.5 ~ 6.5	2 ~ 5
Large decline in alertness	6.0 ~ 3.0	10 ~ 31

DROWSINESS DETECTION PERFORMANCE

Evaluation of Detection Performance

The drowsiness detection performance of the system was evaluated in laboratory tests and actual driving tests. In these tests, the subjects were asked to perform a simple task or to drive under monotonous conditions in order to induce drowsiness.

Laboratory Tests - Figure 8 shows the laboratory test setup used to simulate a condition of driving while drowsy. A CRT monitor was positioned in front of the driver's seat of a trimmed body, the interior of which was darkened by covering the windows. A subject sat in the driver's seat and performed a simple task while watching the CRT screen. The task involved using a ring to pursue a target point that moved at a constant speed in a circular pattern on the screen. The subject moved the ring laterally by turning the steering wheel and vertically by operating the accelerator. Because of the monotonous simplicity of this task, it soon made the subject drowsy. The subject's alertness level was judged by the methods explained earlier for detecting drowsiness from physiological signals. The performance of the drowsiness detection system was evaluated on the basis of the degree of correlation between the alertness level provided by the system and the alertness level obtained from the physiological signals.

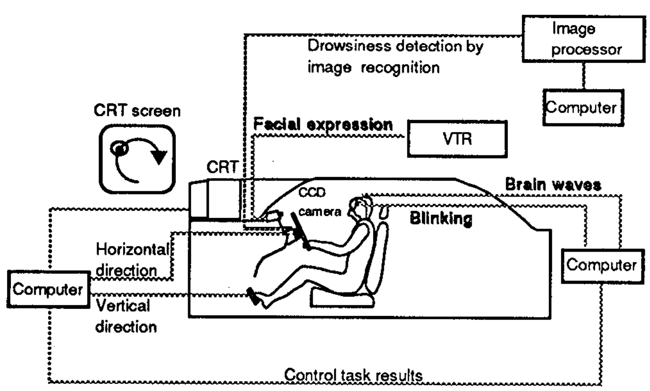

Figure 8. Schematic diagram of test setup.

Driving Tests Using an Actual Vehicle - The subjects were asked to drive at a constant speed on a circuit around the periphery of a test course, and this monotonous driving served to induce a natural state of drowsiness. Similar to the laboratory tests, a data recorder was used to record the subject's brain waves and eye electric potential in order to facilitate judgment of the alertness level on the basis of physiological signals. A CCD camera was installed on the steering column in the same position as in the laboratory tests. The camera recorded the facial image data used to facilitate drowsiness detection by means of image recognition. Just as in the laboratory tests, drowsiness detection performance was evaluated by comparing the degree of correlation between the alertness level indicated by image recognition and that based on the physiological signals.

Evaluation Results

Laboratory tests were conducted several times with multiple subjects and comparisons were made of the alertness index scores found from the physiological signals and the alertness levels obtained by image recognition. An example of the results obtained is given in Figure 9. It is seen that the method of detecting alertness on the basis of image recognition accurately traced the changes that occurred in the alertness level with elapsed time.

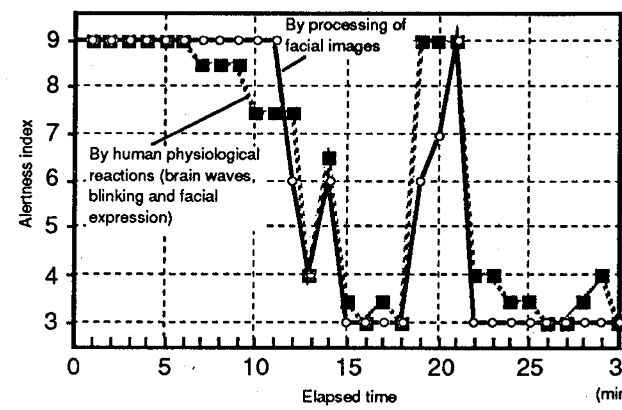

Figure 9. Evaluation of drowsiness detection.

Using the method of counting the number of eye closures, alertness levels were determined for 17 facial image records obtained in laboratory tests involving five subjects. The results were then subjected to a correlation analysis and the correlation coefficients obtained are given in Table 3. These data also indicate that an exceptionally high level of detection performance was obtained with the system in these multiple tests involving a number of subjects.

Table 3
Correlation coefficients.

Subject	No. of trials	Correlation coefficient (individual)	Correlation coefficient (average)
A	4	0.79	0.77
B	3	0.74	
C	3	0.83	
D	3	0.73	
E	4	0.78	

The foregoing results thus confirmed that the drowsiness detection system based on image recognition can provide detection performance close to that of techniques using physiological signals, even though it is a noncontact method. This indicates that the system is capable of detecting the initial stage of drowsiness without causing false alarms to be issued.

Various factors can be considered as possible causes of a decline in the degree of correlation. One factor might be subjective variation on the part of the test engineers in judging intermediate levels of alertness from the physiological signal data. Another factor might be discrepancies between the timing for changes in alertness levels and the time when alertness judgments are made. In order to obtain better correlation with alertness levels based on physiological signals, further studies are needed, including possible altenation of the criteria for judging the alertness level.

REFRESHING EFFECT

Evaluation of Refreshing Effect

Evaluations were made of the refreshing effect of different scents using the same laboratory test setup as in the assessment of detection performance. The reduced alertness of the subject was first confirmed on the basis of the control task results and physiological signals. At that point, an interior odorizer was used to supply a particular scent to the subject under a variety of conditions and the refreshing effect was measured. A comparison was made of the refreshing effect of several types of scents by quantifying their intensity, which was accomplished by controlling the mass flow rate and velocity of the discharge from the odorizer. It was found that the greatest refreshing effect was obtained when peppermint was introduced (Figure 10). This effect is attributed to the menthol content of peppermint.

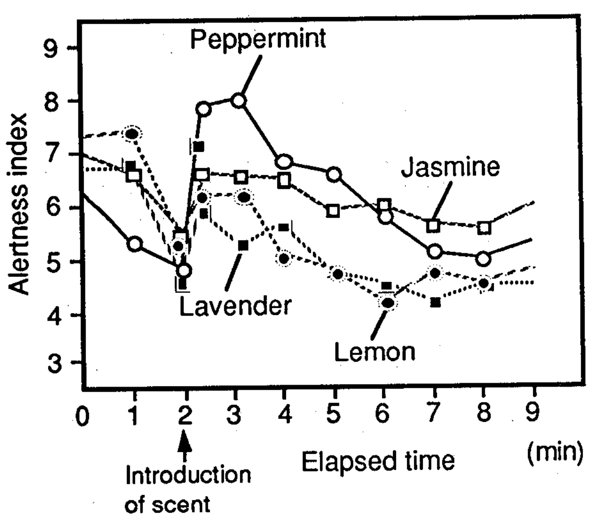

Figure 10. Refreshing effect of various scent.

Evaluation Results

Timing for Scent Introduction - Using peppermint, which showed the strongest refreshing effect among the various scents examined, a comparison was made of the refreshing effect obtained for different scent introduction timings. Typical results are shown in Figure 11. The solid line indicates the effect obtained when the scent was introduced in the early stage of the decline in alertness, and the dashed line shows the effect obtained when it was supplied after a considerable drop in alertness. The results indicate that the refreshing effect was not sustained when the scent was supplied at a later timing, i.e., when the subject was in a state of reduced alertness.

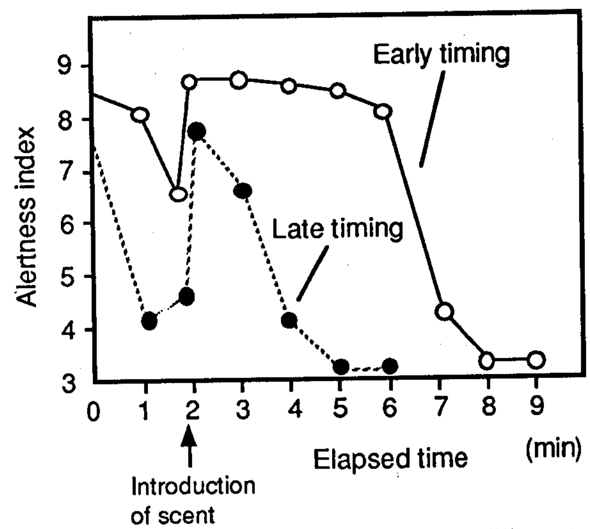

Figure 11. Refreshing effect for different scent introduction timings.

Self-Consciousness of Reduced Alertness - Tests were conducted to ascertain the subjects' level of alertness when they themselves were conscious of being drowsy.

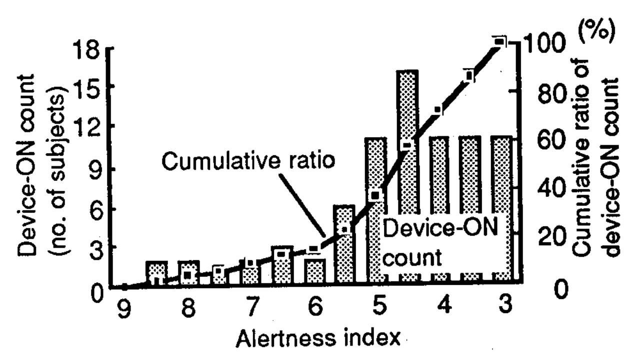

Figure 12. Use of refreshing device vs. alertness index.

Figure 12 shows the alertness level at the time the subjects switched on the refreshing device based on their own judgment of feeling sleepy. The bar graph indicates the number of subjects who turned on the refreshing device at each alertness index level. The closed squares show the cumulative ratio of the subjects who switched on the device. Down to an alertness index of 5, which represents a considerable decline in alertness, only about 40% of all the subjects switched on the device. This result suggests that people are not aware of being drowsy until their alertness level has declined considerably. When this observation is considered together with the results in the previous section showing that the refreshing effect was not sustained with a late supply timing, it is clear that an effective warning system must be able to detect a decline in alertness at an early stage and provide a suitable refreshing effect.

Refreshing Effect of Combined Stimuli - An investigation was made of the refreshing effect obtained by providing a combination of stimuli. With the combined stimuli, a buzzer was first sounded to give the subject an immediate refreshing effect and a scent was then introduced once the subject's alertness had risen to a certain level. Typical results are shown in Fig. 13. When either the scent or the buzzer stimulus was provided alone, the refreshing effect was sustained for approximately three minutes. In contrast, when a scent containing menthol was provided after the buzzer was sounded, the refreshing effect was maintained for approximately 11 to 16 minutes. These results indicate that the combined use of a scent and a buzzer is more effective in obtaining a greater refreshing effect than when either of the two is applied in isolation.

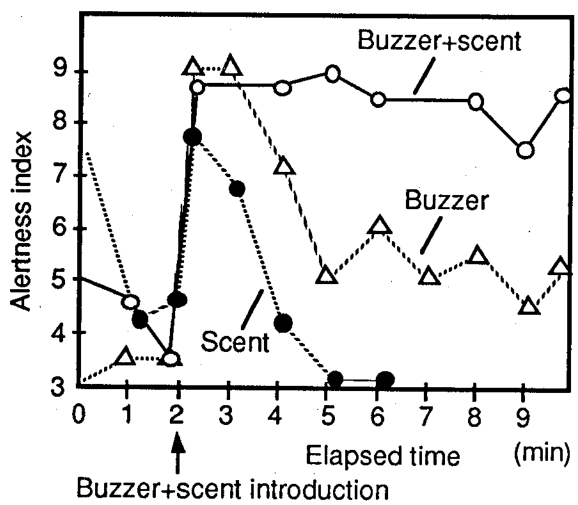

Figure 13. Comparison of refreshing effect of different approaches.

CONCLUSION

The results of tests conducted under a drowsy state in the laboratory and on a test course with an actual vehicle have made the following points clear.

(1) Image recognition offers a noncontact approach to detecting drowsiness in drivers and it achieves highly accurate detection.

(2) A drowsiness detection system developed around the principle of image recognition judges the driver's alertness level on the basis of a continuous time history and provides early detection of reduced alertness.

(3) Applying a stimulus in the early stage of a reduction in alertness is effective in prolonging the refreshing effect. Since the drowsiness detection system is capable of detecting and providing a stimulus in that early stage, it has a high potential for preventing drowsiness at the wheel.

(4) A combination of audible and scent stimuli is more effective in refreshing the driver than the sound of a buzzer alone. It has been shown that the sounding of a buzzer to achieve an immediate refreshing effect following by the provision of a scent stimulus with a large menthol content is more effective in keeping the driver alert for a longer period of time.

There are a number of issues that remain to be addressed in the drowsiness detection system. These include improvement of its adaptability to changes in ambient brightness, assurance of reliability and attainment of a more compact system design. Further studies must also be done on the system for refreshing the driver, including an examination of the human body's adaptation to the scent refresher and its effect on a person's physical condition.

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Safe Manoeuvers in Adverse Weather Conditions
A Simulation Study of Entering a Motorway

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ABSTRACT

This paper describes an analysis of microscopic traffic behaviour when entering a motorway. The study is part of the DRIVE II project ROSES, in which an integrated infrastructure based and on-board road and weather monitoring system is developed and tested.
A simulation model has been built, which incorporates the characteristics of vehicle performance and the driver control. For the subsequent phases of the entering procedure, a driver behaviour model has been designed.
One specific road lay-out is investigated, while traffic situation and road friction are varied in a number of scenarios. Simulation results show that in slippery conditions a reduction of the mainstream traffic speed is required in order to maintain a proper safety level.
The results of this study can be used in advanced traffic control and in-vehicle safety systems.

INTRODUCTION

Road safety enhancement systems

Road and weather conditions are important factors in the capabilities of both driver and vehicle to participate safely in traffic. To support drivers and traffic-operators to cope with these influences, information is needed to give an accurate estimate of the traffic risk level and an advice has to be given on how to control the risk to stay within a safe range.
The DRIVE II project ROSES (ROad Safety Enhancement System) aims to improve traffic safety under adverse weather conditions. Operational goal is the implementation of a fully integrated monitoring system for traffic, weather and road condition, to support drivers and traffic management.

Microscopic traffic behaviour

Within the ROSES project, microscopic traffic behaviour is investigated to increase the understanding of the processes that determine traffic safety. Previous studies concentrated on lateral vehicle behaviour in cross-wind in combination with reduced road friction [1] and on longitudinal behaviour in adverse visibility and low friction conditions [2].
As a part of this work the safety aspects are investigated of the manoeuvres needed to enter a motorway and to merge into the main traffic stream. The method applied is to perform computer simulations of the road traffic process on a microscopic level using and extending existing models of driver and vehicle behaviour.
When traffic volume on the main road increases, the available inter-vehicle distances decrease. This means that the task of the driver to be performed is more and more a combination of lateral control to move from one lane to another and control of the longitudinal movements relative to the vehicles in front and behind. The proper realisation of the manoeuvre is influenced by both the perception of the surrounding traffic situation, the manoeuvring capabilities of the vehicle and the control actions (speed, distance and course control). The simulation model concentrates on the longitudinal behaviour, while the lateral behaviour is only taken into account for as far as it influences longitudinal control. In this study an exploratory analysis is made of the influence of traffic and road conditions.
The available criteria to assess the merging situation are the headways and speed differences at the moment of merging. The simulation results can be evaluated in terms of the distance needed before merging and the reserve of vehicle capabilities i.e. the margin to the maximum tyre-road friction.
The safety increase potential of both driver support and traffic control measures (such as speed control and flow control) are discussed.

ROAD AND TRAFFIC SITUATION

There is a great variability in entering situations due to differences in road lay-out as well as differences in traffic situation.
For this study a specific road situation was chosen in order to be able to concentrate on the effects of traffic and road surface conditions. A fixed scenario for the road configuration and the mainstream traffic situation is assumed.
Figure 1 gives an overview of the situation.

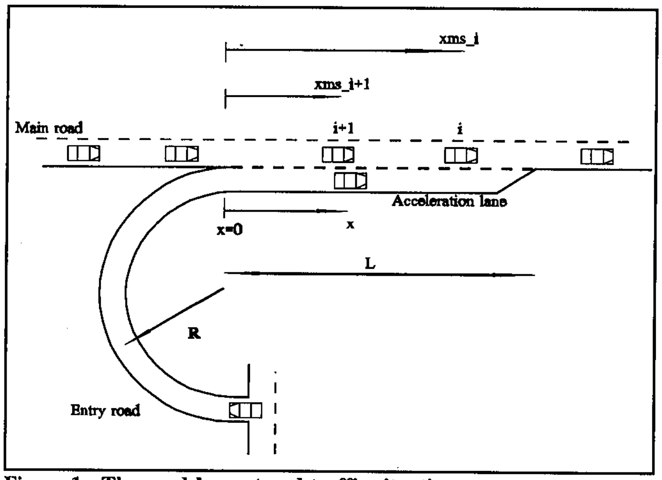

Figure 1. The road lay-out and traffic situation.

Road lay-out

The simulations start at the beginning of a semicircular entry road which has a radius R, set at 50 m. At the start of the entry road, vehicle speed is zero. The entry road leads to an acceleration lane of length L = 400 m, parallel to the main road. It is assumed that the acceleration lane has a definite end, without the possibility to proceed on an emergency lane. The reference point for the location of a vehicle is the start of the acceleration lane.

Traffic scenario

The traffic stream on the main road is considered to have a stationary speed, vms. This means that the vehicles on the main road do not dynamically interact with each other, nor do they respond to the merging vehicle. Different traffic situations can be created for the entering vehicle by varying the intervals between the mainstream vehicles. The intervals are prescribed by an input file, which lists the time each vehicle is passing the reference point x = 0.

DESCRIPTION OF THE SIMULATION MODEL

The microscopic traffic simulation model consists of sub-models for the merging vehicle and the driver. For each timestep the model calculates the vehicle acceleration, speed and position of the merging vehicle, as well as the new positions, xms_i, of the vehicles in the main traffic stream.

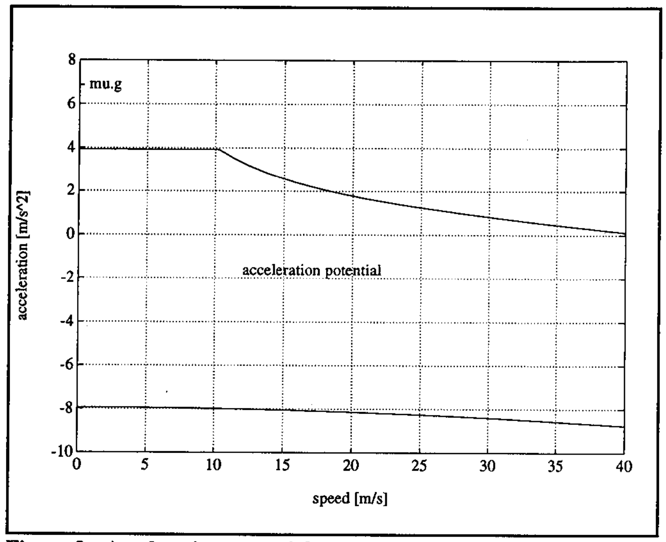

Figure 2. Acceleration potential versus speed.

The vehicle model

The merging vehicle is an average passenger car.
The characteristics the vehicle are described by the following parameters:
- vehicle mass, M = 1200 kg;
- rolling resistance coefficient, $f_r = 0.01$;
- aerodynamic coefficient, $C_{aerodynamic}$ (= ½$\rho C_w A$) = 0.625 kg/m;
- maximum effective engine power, P = 50 kW;
- the ratio between the load on the driven wheels and the total vehicle mass, $M_d = 0.5$.

The acceleration performance, a_{max}, of the vehicle is limited by the friction between the vehicle tyres and the road (friction coefficient μ), as well as by the limited engine power:

$$a_{max} = \min\,(a_{friction}\ ,\ a_{drive}) \tag{1}$$

in which:

$$a_{friction} = M_d \mu g \tag{2}$$

$$a_{drive} = \frac{(\frac{P}{v} - f_r\, M\, g - C_{aerodynamic}\, v^2)}{M} \tag{3}$$

The extreme deceleration, a_{min}, is the result of the limited friction and the resistance forces:

$$a_{\min} = -\mu g - f_r g - \frac{C_{aerodynamic} v^2}{M} \tag{4}$$

Figure 2 indicates the resulting acceleration potential.

The limited engine torque and the characteristics of the transmission are not taken into account.

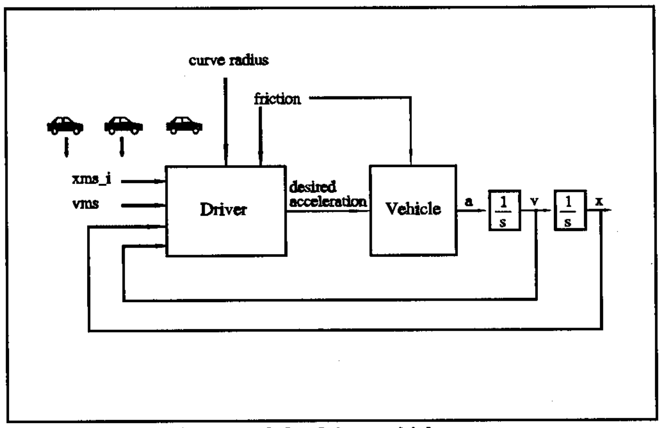

Figure 3. Block diagram of the driver-vehicle system.

The driver model

The driver controls the acceleration and deceleration of the vehicle, based on his perception of speed, lateral acceleration and the surrounding traffic. The block diagram in Figure 3 indicates the control structure.
The behaviour model assumes that there are a number of subsequent phases:

1. Approach of the acceleration lane via the entry road
2. Acceleration to approximately the speed of the main traffic stream
3. Orientation on the most suitable gap to merge
4. Control of position relative to a vehicle in front and behind in the chosen gap
5. Lane change

There is a gradual transition from one phase to the next.
In case there is no opportunity to merge in time before the end of the acceleration lane, the procedure may be aborted and the driver starts to brake in order to stop in time for the end of the acceleration lane (in this scenario it is assumed that there is no possibility to proceed on an emergency lane beyond the acceleration lane).

A behavioural model corresponding to each phase is designed:

1. In the scenario situation the possibility to start accelerating to the mainstream traffic speed is limited by the road curvature of the on-ramp. The model is a pure speed control. A proportional feedback loop with gain K_{curve} produces the acceleration based on the error signal between desired speed and actual speed. The determination of the desired speed is based on a comfortable and safe level of lateral acceleration:

$$v_{curve} = \sqrt{S_F \mu g R} \tag{5}$$

in which S_F is the factor that determines the margin between the centrifugal force and the maximum lateral friction force, μg.

The desired acceleration in the curve becomes:

$$a_{desired} = K_{curve} (v_{curve} - v) \tag{6}$$

2. On the first part of the acceleration lane the driver uses the speed of the mainstream as his setpoint for a proportional speed control with gain K_{vms}.
3. When the speed difference with respect to the main traffic stream is below a certain threshold, the driver checks whether the nearest gap is large enough. In case the nearest gap is too small, the driver scans the gaps further away and adjusts his target accordingly.
4. Once the driver has chosen a suitable gap, the situation becomes similar to a car following situation. The desired acceleration is a combination of two feedback loops for the speed difference and the deviation from the desired distance to the preceding vehicle. In a previous study a relationship between the feedback gains and road friction was derived, based on optimal control theory [3].
5. In order to be able to actually merge, two criteria have to be satisfied:
   - the speed difference has to be below a certain threshold;
   - the time headways relative to the preceding vehicle $T_{preceding}$ and the vehicle behind T_{behind} have to be sufficient. In the simulation the thresholds are set at 0.5 seconds.

The driver is assumed to maintain a margin between his acceleration use and the maximum available acceleration under the prevailing friction condition.

The dynamic response of the driver-vehicle system is modelled as a combination of a pure time delay, τ_d, and a first order response with time-constant, τ_1.

Optimal merging strategy

In case intelligent vehicle systems are able to determine the position of the vehicle relative to the surrounding traffic, it is possible to determine an optimal strategy at time t when the vehicle is at the start of the acceleration lane.

The two requirements to merge behind a certain predecessor at time t_{merge} are:

$$x\,(t_{merge}) = xms_{predecessor}(t_{merge}) - distance_{safe} \qquad (7)$$

$$v(t_{merge}) = vms \qquad (8)$$

if this situation is to be realised by a constant acceleration, $a_{constant}$, this yields:

$$t_{merge} = t + \frac{2\,(xms_{predecessor}(t) - x(t) - distance_{safe})}{v(t) - vms} \qquad (9)$$

$$a_{constant} = \frac{-\,(vms - v(t))^2}{2(xms_{predecessor}(t) - x(t) - distance_{safe})} \qquad (10)$$

For each vehicle of the main traffic stream these equations can be evaluated. The optimal merging position is a trade-off between use of the available acceleration potential and the available acceleration lane length. This trade-off can be quantified by minimizing the weighting function:

$$J = Q_1\, a + Q_2\, x_{merge} \qquad (11)$$

SIMULATION RESULTS

Different scenarios are simulated to study the effect of traffic and road conditions.

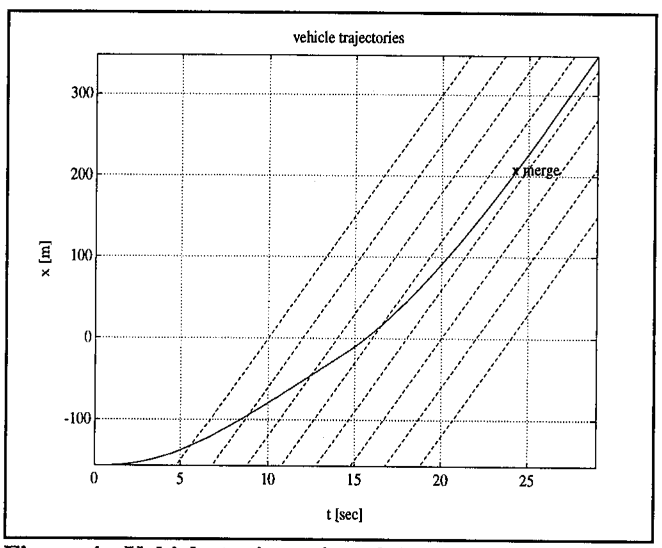

Figure 4. Vehicle trajectories of the reference scenario.

Reference situation. Scenario A is the reference situation with a homogeneous traffic situation (headway = 2 seconds) and normal friction. In Figure 4 the results of the reference case are plotted as trajectories in the distance-time plane (conform [4]). The straight lines (dashed) indicate the trajectories of the mainstream vehicles. The curved line (solid) is the trajectory of the merging vehicle.

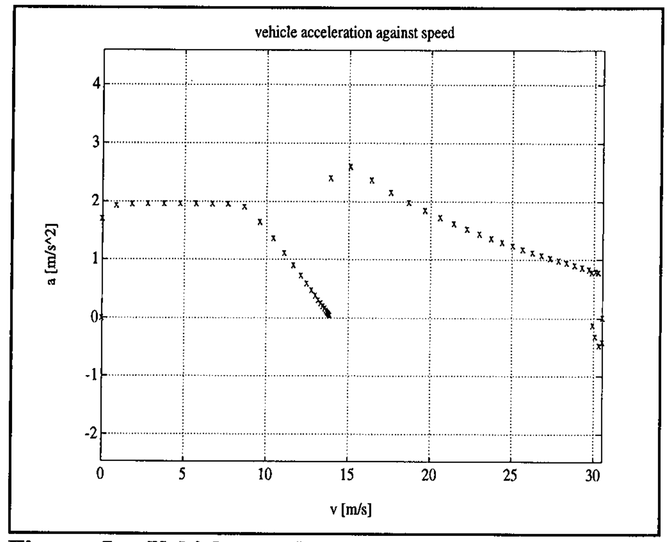

Figure 5. Vehicle acceleration against speed for the reference scenario.

The vehicle merges behind the fourth vehicle in the mainstream. The optimal merging strategy confirms that this is the best gap. The optimal procedure would be a constant acceleration of 2.12 m/s^2 and a merge procedure at x = 139.1 m. Due to the limited vehicle performance, this acceleration level can not be maintained up to the mainstream speed. This is illustrated by the acceleration against speed plot in Figure 5. Figures 6 and 7 show the time histories of respectively acceleration and speed for the simulation. The maximum acceleration during the simulation is 2.6 m/s^2, while merging takes place at x = 198 m.

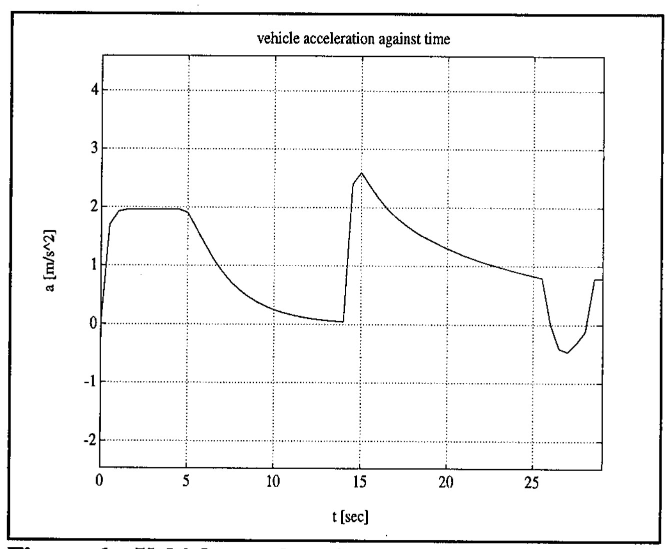

Figure 6. Vehicle acceleration history of the reference scenario.

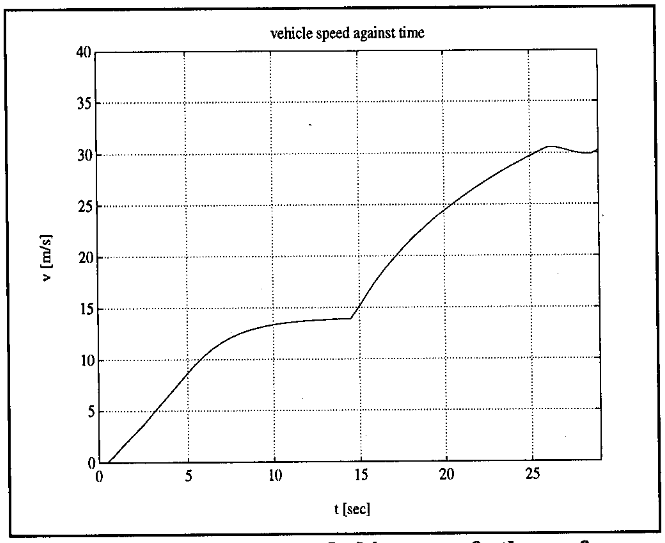

Figure 7. Vehicle speed history of the reference scenario.

High traffic density. The trajectories of scenario B in Figure 8 illustrate how the merging procedure is broken off when the mainstream traffic is too dense (headway = 1 second) to find a gap large enough to merge safely. The vehicle starts braking when the distance left to the end of the acceleration lane approaches the vehicle braking distance.

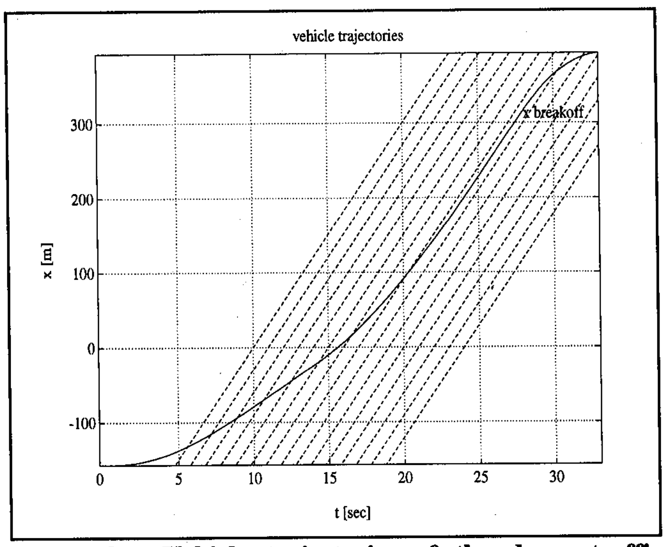

Figure 8. Vehicle trajectories of the dense traffic scenario.

Reduced friction. In scenario C the friction coefficient is reduced from 0.8 to 0.4. If the driver maintains the same friction safety margin (never exceeding 70% of the available friction potential), the merging manoeuvre has to be broken off. Only if the driver reduces his acceleration safety margin below 30%, he can be sure of a successful manoeuvre in this scenario. Especially with a rear-wheel driven vehicle, instability may occur when the friction potential is exceeded. This may lead to an uncontrollable spin-out of the vehicle.

Reduced friction and adapted mainstream speed. In scenario D the speed of the mainstream is reduced from 30 m/s to 20 m/s, while the same headways of 2 seconds are maintained. The friction coefficient is 0.4. In this situation the vehicle is able to merge safely, even if the driver maintains a proper friction safety margin.

CONCLUSIONS AND FUTURE STEPS

The results that can be obtained with this simulation model can be employed in two ways:

Traffic control. Using the data from road condition sensors and traffic detectors as an input, a traffic control system can determine a proper speed advice for the main road, in order to allow the entering vehicles to merge safely.

In-vehicle driver support. An on-board system can advise the driver about a proper acceleration level for a safe merging strategy. This requires input data about general traffic conditions (speed and density) and friction conditions. A vehicle-infrastructure communication link, as used in the ROSES concept [5], can transfer this information to a vehicle.
If, in case of an advanced traffic system, the relative positions of the surrounding vehicles are measured, the model can be used to execute an automatic merging procedure.

Calibration and extension of the model. A first calibration of the model was based on observations (timing, distances and evolution of speed) in a real situation. Further validations can be done using the results of a driving simulator experiment.
In a next phase the model can be combined with a dynamic model for the mainstream traffic.

NOMENCLATURE

a	[m/s^2]	Acceleration
$C_{aerodynamic}$	[kg/m]	Aerodynamic factor
$distance_{safe}$	[m]	Safe following distance
f_r	[-]	Rolling resistance coefficient
g	[m/s^2]	Gravity
K	[-]	Feedback gain
L	[m]	Acceleration lane length
M	[m]	Vehicle mass
M_d	[-]	Ratio between load on driven wheels and the total vehicle mass
μ	[-]	Friction coefficient
P	[kW]	Effective engine power
Q	[-]	Weighting factor

R	[m]	Curve radius
S	[-]	Safety factor
t	[sec]	Time
T	[sec]	Time headway
τ_d	[sec]	Delay time
τ_l	[sec]	Time-constant
v	[m/s]	Vehicle speed
vms	[m/s]	Mainstream speed
x	[m]	Vehicle position
xms_i	[m]	Position of mainstream vehicle i

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Intervehicle Communication System

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Paper No. 94-S3-O-10

ABSTRACT

In the framework of PROMETHEUS, Renault, Thomson et PSA have launched with the support of the French Government, the study and the development of a communication system allowing data transmission between a cluster of vehicles.

After having described the traffic circumstances where such transmission migth improve driving safety, the paper will describe the main features of the system, which can accomodate up to one hundred vehicles without any need of central management or synchronization, and will give the first results of experiments.

INTRODUCTION

Framework of the Study

The Prometheus program started in 1986 and brings together almost all the European car manufacturers, equipment suppliers and some Companies working in advanced technology, institutes and laboratories.The goal of this program is to combine the leading technologies in order that the automobile industry may realize a significant progress in the fields of pollution, safety, and traffic efficiency. Amongst all the techniques able to the achievement of these objectives, one of them, telecommunications has been acknowledged as very promising. What can we expect from them ? Indeed one can realize as a driver, that one is often caught by sudden changes in traffic conditions, traffic jams, works, bad road surfaces, weather conditions, unexpected manoeuvres create stress, tiredness, and sometimes late reactions which can lead to an accident. This is confirmed by detailed studies about accidents, which were carried out in particular in France and which show that a lot of accidents would have been avoided if the drivers were informed of the special driving conditions from 1 to 2 seconds earlier.

The investigations about data transmissions between the vehicle and the outside world have been undertaken by the working group Copdrive (Cooperative Driving), whose the objective at the beginning was to deal with data transmissions between vehicles, either directly or through beacons on the roadside, linked by a transmitting network. In a wider field, this group has worked on applications using transmissions between vehicles and infrastructure by creating a sub-group Short Range Communication.

Therefore the Copdrive group identified some applications using communications between vehicles which are likely to improve the driving safety. These applications are recalled hereafter.

The Copdrive Functions

The Cooperative Driving has been divided into 4 main functions :

- Intelligent Cruise Control (figure 1)

  To support cooperative longitudinal control between interdependent vehicles on single lanes for harmonizing speeds and distances and reacting to significant events ahead.

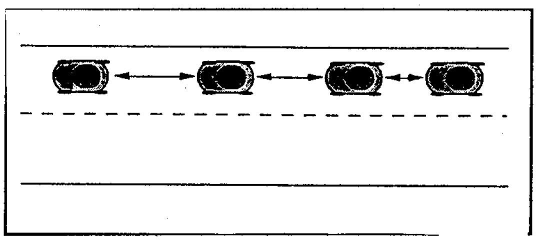

Figure 1

- Intelligent Manoeuvring and Control (figure 2)

  To perform cooperative manoeuvring in order to safeguard lane changes and overtakings.
  To recommend proper behoviour to the driver/system in order to improve safety and traffic efficiency.

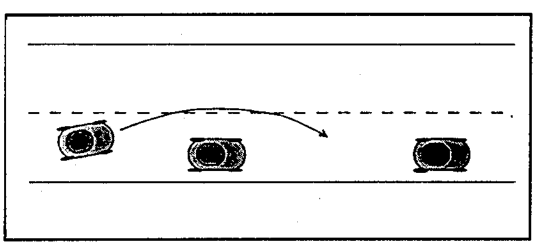

Figure 2

- Medium Range Pre-Information (figure 3)

  To supply driver and vehicle system information well in advance with relevant static and dynamic data on safety and traffic related occurences and situations between interdependent vehicles.

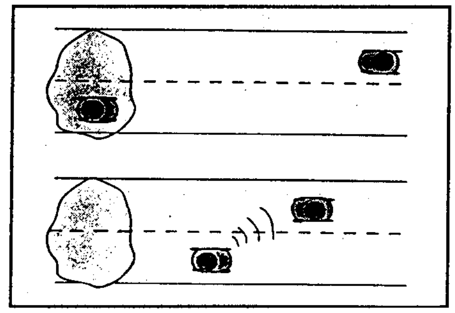

Figure 3

- Emergency Warning (figure 4)

  Warning about occurence of an emergency/incident case to road users in the vicinity of the location.

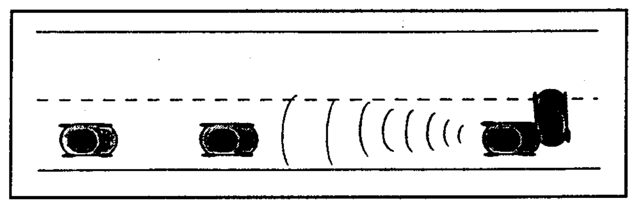

Figure 4

The main data which are needed to be exchanged are: speed, position (if it is accurate enough), running lane number, light indicators, warning indicator, braking, ...

Whatever may be the benefit of these applications, they cannot be considered without having a "dynamic" communication network, which until recently did not exist. Therefore in the framework of the program Prometheus, Renault, PSA Peugeot-Citroën and Thomson-CSF, with the financial support of the French Government, have defined, developped and tested such a communication network. After having described the functionalities and the system itself, we give the results obtained from the first experiments.

COMMUNICATION SYSTEM DEFINITION

Objective

The problem is the following one: how to build and to manage a communication network which is mainly unstable, with a variable number of participants in a period of time, which is mobile in space, with low reconfiguration time (about 1 sec.), high transmission reliability for reason of safety, high resistance to saturation, and with a range of roughly 500 m. There are some additional constraints the system must be autonomous (it is not considered that the system is managed or synchronised by infrastructure means), the system must use a frequency authorized by regulation bodies, or at least which will be authorized in a near future.

Technical requirements of the transmission chanel

Number of bytes in a message :	26
Message frequency :	10 Hz
Transmission range, nominal :	250 m

Probability of not receiving 2 successive messages from the same transmiter : $<10^{-3}$

Technical requirements of the system

Every vehicle must send its messages to all surrounding vehicles and reciprocally, every vehicle must receive all the data sent by all surrounding vehicles.
System management: autonomous and automatic
Minimum number of vehicules before network saturation : 100
Maximum stabilisation time of the network after a disturbance (one or several vehicules joining the network): < 1 sec.

Problems Identified

Amongst problems to solve, we can mention :

- the building of the network
- the merging or the meeting of two networks
- the behavior when there are interferences
- the synchronisation between vehicules
- masks and multipaths
- collisions
- smooth degradation of network performances in case of saturation

All these problems have been studied and a lot of work has been done, but eventually, only experiments in open fields permit us to know exactly the system behavior.

Realizations

Still in the framework of PROMETHEUS, a first system, called Manet, has been developped by Matra and permit to perform the Copdrive functions. This system has been used in the Drive project TESCO, which aims at performing endurance tests of Cooperative Driving functions with a fleet of six vehicles on a private track in Nardo, Italy. An second one has been developped by Thomson-CSF, with another protocol and working at a closer frequency to 63 GHz allocated by CEPT, and this last one forms the subject of this detailed publication.

THOMSON 'S SYSTEM PRESENTATION

Main characteristics

The main 2 features of the sytem developed by THOMSON-CSF are the choice of the 60 GHz frequency band and of the channel access protocol.

Frequency band

The 63-64 GHz band is allocated to vehicle communications by CEPT. Besides the avaibility of suitable bandwidth, the main reason for this allocation is no doubt the atmospheric absorption band centered at 60 GHz. Actually, when large numbers of vehicles are to transmit in the same area, signals originating from remote vehicles may prevent the reception of closer ones. Atmospheric attenuation helps limit the jamming effect of undesirable remote transmissions on expected receptions as explained in the next paragraphs. However THOMSON-CSF built its experimental system at a center frequency of 57 GHz because of the availabily of technology. This discrepancy does not matter very much in an experimental system, because the frequencies 57 and 63 GHZ are very close and similar regarding atmospheric attenuation since they are symetrical about 60 GHz.

The standard propagation attenuation is 6 dB in signal strength when distance doubles. The atmospheric absorption at 60 GHz adds an extra attenuation of 15 dB per Km.

Figure 5 shows the ratio of expected signal to undesirable signal versus the distance of the undesirable signal transmitter, when the receiver is 250 m away from the expected transmitter and both expected and undesirable transmitters are using the same frequency.

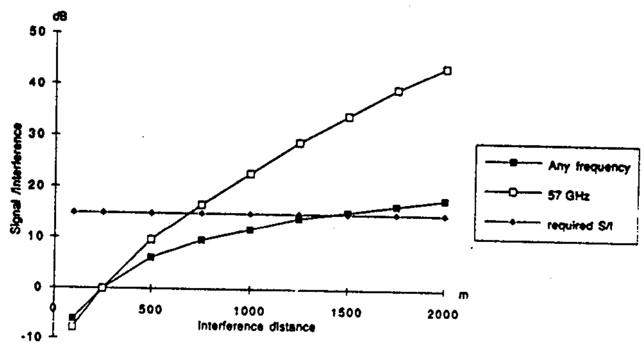

Figure 5. Atmospheric absorption effect

One can see that the undesirable transmitter must be further than 1500m, at any frequency outside the 60 GHz band, to get the 15 dB ratio, or thereabouts, of expected signal to undesirable signal required for proper demodulation. At 60 GHz the minimum distance of the undesirable transmitter is shortened to 700m. In addition, at 2000 m, more than 300 sources are bearable at 60 GHz and only a few at any other frequency.

As very few experiments were run in this band, the propagation characteristics are still to be investigated, namely multipaths, diffraction...

Channel access

The main constraints in choosing a channel access protocol were no master station, fast responsiveness and high reliability (very low lost-message rate).

As no standard protocol quite fulfilled these requirements, an original one was designed and proposed by THOMSON-CSF.

It is a sort of TDMA (Time Division Multiple Access) which can operate with or without synchronization procedure. In either case, after a short stabilization while there is no message loss, even if vehicles out of specified range transmit toward common vehicles in range.

Figure 6 compares a CSMA protocol and the protocols proposed by THOMSON-CSF, referred to as A-TDMA or S-TDMA depending on whether the synchronization procedure is on or off.

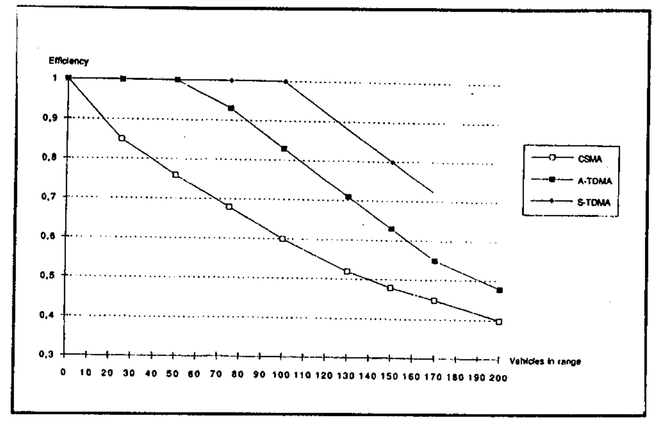

Figure 6. Comparison of CSMA, A-TDMA, end S-TDMA Performance

What is called efficiency is the ratio of actually received messages to those that should have been from vehicles in specified range. One can see that both A and S-TDMA feature absolutely no message loss as long as the number of vehicles in specified range does not exceed a given threshold, unlike CSMA. Synchronization provides a higher threshold.

Radio characteristics

They are summarized as following:

- frequency transmission 56,4 GHz
- modulation DPSK
- modulation rate 1 Mbaud
- power amplifier 20 mW
- EIRP 200 mW
- noise figure 10 dB
- antenna gain 13 dB
- sensitivity 12 dBHz, [Eb(energy per bit)/No(noise power per Hertz)] for a BER (bit error rate)of 10^{-3}.

The antenna is made of a forward and a backward horn, the diagrams of which are:

- elevation beamwidth (-3 dB) 17 degree
- azimuth beamwidth (-3 dB) 90 degree

These characteristics should provide a range of 400 m according to the propagation and atmospheric attenuation, multipaths and other disturbances aside.

Ground reflection

One disturbance that is virtually sure to occur is the multipath generated by the reflection on the ground.

It is interesting to evaluate the ensuing fading characteristics as a reference model.

So one calculates that received signal power goes from a minimum to a maximum if the antenna is moved by 8 cm in the vertical plane and by 25 m in the horizontal plane, for a link range of 200 m and antennas heights of 1,5 m. If the relative speed between the transmitter and the receiver is 50 m/s, the time necessary to go from a maximum to a minimum is 0,5 sec. Hence the multipath configuration seems unlikely to change during the millisecond necessary to transmit a message. That would mean that a message is either fully lost or fully received.

Protocol

Principle

Each vehicle counts time in 1 ms slots. A given vehicle normally transmits a message every 100 th slot, i.e. every 100 ms.

For a given vehicle, a slot is stated as free if it can infer that no transmission occurs in it, busy if a single transmission occurs, collided if more than one transmission occurs.

When a station is switched on, the channel is listen to for 100 ms. During this time it receives messages originating from vehicles in range. Each of these messages carries information indicating if the source vehicle deemed that the previous 100 1 ms-slots were free, busy or collided. From that information and its own receptions the station calculates an occupation index associated with each slot. That index is calculated for each slot by dividing the number of vehicule claiming that this slot is busy or collided by the overall number of vehicles taken in account. Then the local station will transmit in a slot randomly chosen among the slots the index of which are 0 or the lowest values. The value beneath which a slot can be used is called the transmission threshold.

A station keeps on transmitting every 100 th slot unless too many received messages indicate that the slot being used is collided. In that case a new slot is chosen the same way.

Message structure

Messages begin with bits alternating 0 and 1 and a unique bit pattern for presence detection and clock synchronization purposes. They end up with another unique bit pattern.

A message is made up of 2 parts: user information and technical information.

The user information is the part containing the data useful for the application, and which can contain up to 26 bytes per message.

The technical information is the part containing all the data useful for the management of the transmission protocol and in particular to indicate if the last 100 slots were deemed free, busy or collided 20 bytes are used for that.

Moreover some bytes are added to allow receiving stations to correct errors and detect residual errors. In this application, Reed-Solomon coding is used.

Then the whole message includes 824 bits and hence its 824 µs duration fits in a 1 ms slot.

Transmission time jitter

Since a station is either transmitting or receiving, if 2 isolated stations happened to start transmitting in the same 100 µs they would never receive each other. The probability is about 10^{-3} and does not meet the requirement. A 100 µs random jitter in the transmission time provides for that possibility. So a station is likely to detect the start or end unique sequence of the other one as soon as the random draw shifts the transmissions by 100 µs.

Collision detection

A station infers that there was a message collision :

- no start or end unique sequence is detected even though the power received in the channel exceeds a threshold,
- more than one start or end sequence is detected within a 1 ms interval.

Slot synchronization

To use the channel capacity completely, the messages must be transmitted without idle time. This implies that all vehicles slot clock are synchronised. To achieve this synchronisation, each vehicle measures the time shift (gap) between the beginning of every received messages and its own slot clock. The algebrical mean and the standard deviation of these times are calculated and are used to correct the local time.

PERFORMANCES

Simulations

Many static and dynamic simulations were carried out in order to design and fine-tune the protocol.

Figure 7 shows results when 100 stations are randomly scattered in a square of 700mx700m and switched on at the same time. Protocol performance is mainly represented by the efficiency against time curve, other curves are technical information. Steady state efficiency is 100%. Slot-shift rate corresponds to the percentage of message transmissions which are postponed following a collision indication. It boils down to zero in the steady state of a static scenario. The mean time error tends toward 0 with a maximum error of 10 μs.

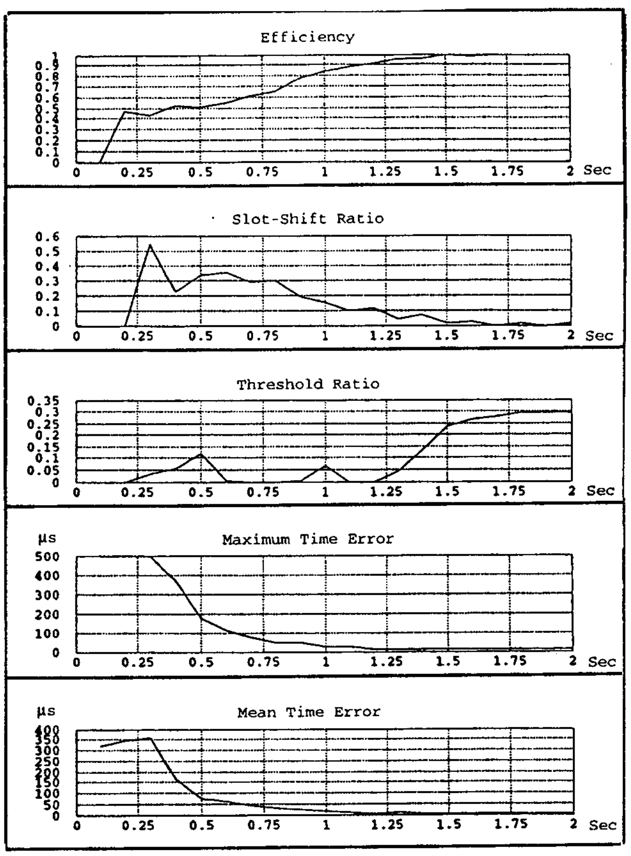

Figure 7. 100 Vehicles scattered within a 700x 700 m square

Figure 8 shows an overcrowded scenario where 150 stations are scattered on the same square.

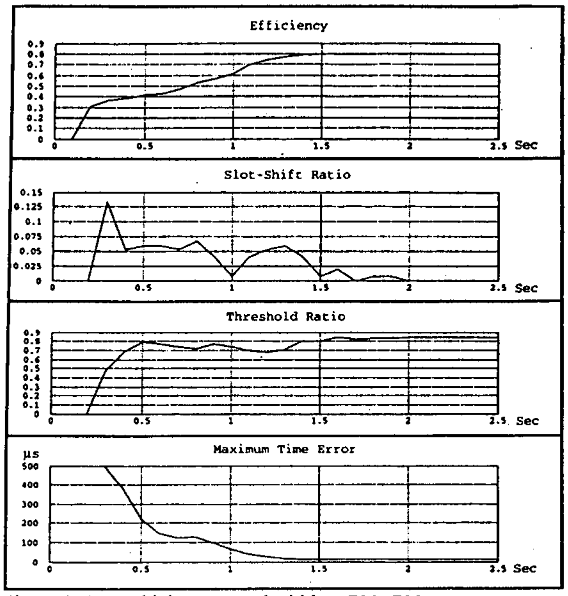

Figure 8. 150 vehicles scattered within a 700x700 m square

The overall steady state efficiency is no longer 100%, but figure 9 shows that efficiency is still 100% for the nearest stations.

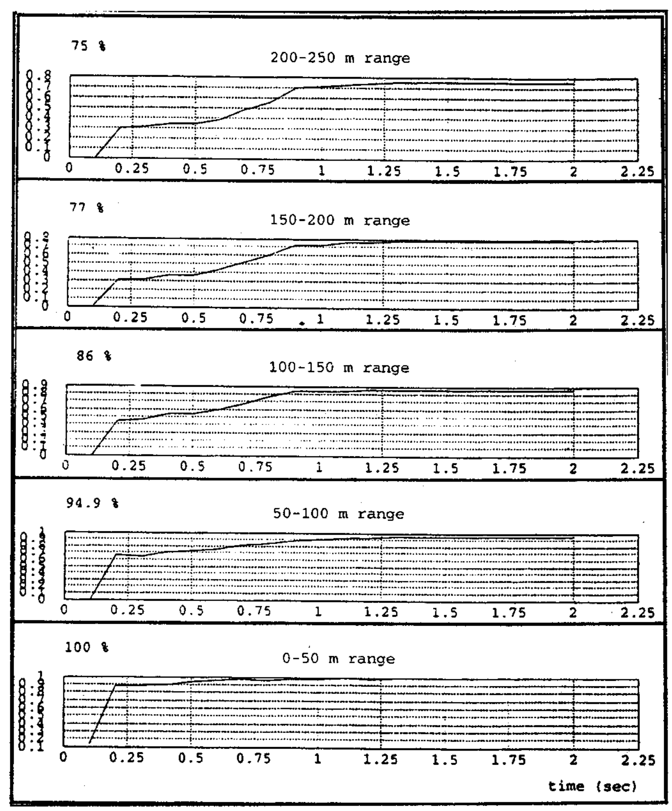

Figure 9.150 vehicles scattered within a 700x 700 m square : efficiency versus range.

Figures 10 and 11 show a dynamic scenario. It features 2 clusters of 50 vehicles in file, runing at 50 m/s in two opposite directions, and passing along at 10 m from each other. Only a temporary and slight loss in efficiency can be seen just when both lines are just coming in range.

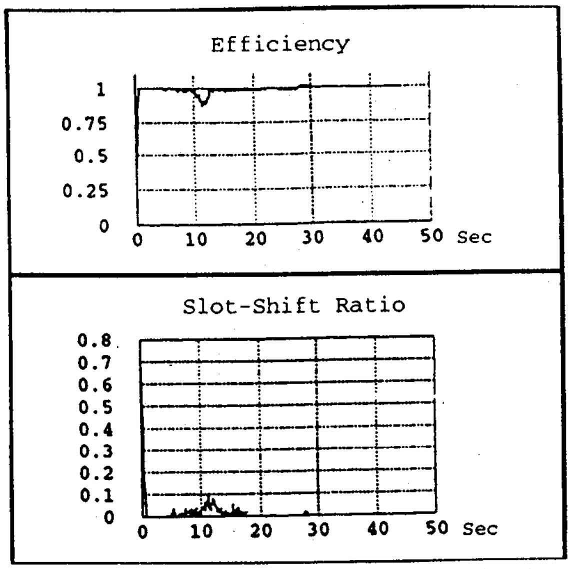

Figure 10. 2 opposite clusters of vehicles in file passing along (Efficiency/ Slot-Shift Ratio)

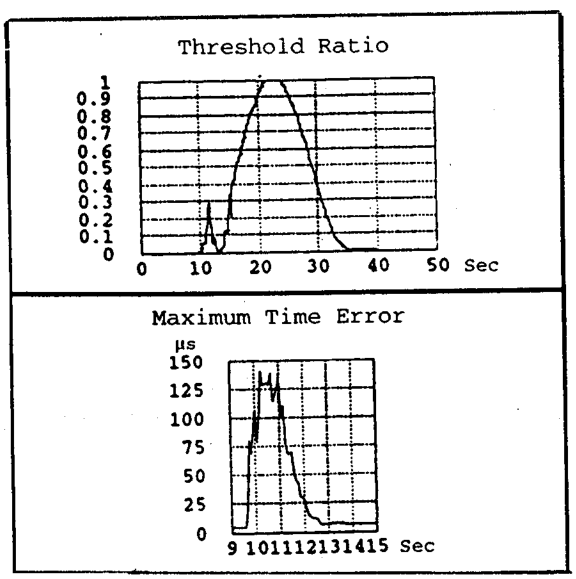

Figure 11. 2 opposite clusters of vehicles in file passing along (Threshold ratio/ Maximum Time Error)

Experimental results

Results have been obtained in both lab and field tests.

Laboratory tests

The laboratory tests were mainly dedicated to functional checking. They featured up to 4 prototypes and a jammer representing the rest of a dense network. Hence, this was transmitting noise for all but a few slots of the 100 ms TDMA cycle. Furthermore, the part of the cycle subject to jamming was moving along time.

Thus, it was shown that the stations under test tried and found different free slots to transmit, and swiftly changed them when jammed.

In one scenario jamming was applied to a single station and invisible to others. Nevertheless, all stations manage to choose slots in order to be received by the jammed one.

In another scenario, 2 stations were not in range. They still choose different slots so that they could be received by a third one in range of both.

Field tests

Extensive field tests have not yet been carried out. Nevertheless some preliminary results are available. They were carried out on a special car test track and on a highway in real traffic.The vehicle were fitted with stations fixed on top of cars.

On the test track, during a day when the weather was drizzle and mist, the results were message-lost ratios lower than 0.1% and 0.3% when the cars were in line of sight at respectively 250 and 400m from each other without running. At 250m, the ratio went up to 0.2% when a car was inserted as a mask between the vehicles. At last dynamic tests were run on the 8-shaped road, with one car lagging 100m behind the other. The overall message-lost ratio was 9%, mainly resulting from the curves when the cars were side by side with an occasional vegetation screen. In fact, further tests showed that range was about 20m between parallel cars and 50m between perpendicular cars. However the message-lost ratio is nearly zero when cars are side by side and close together as for overtaking.

On highway, the test featured 2 cars running at 50 to 300 m apart depending on the traffic. Different vehicles including trucks inserted between the 2 vehicles under test. The mean message-loss ratio was less than 2%.A static test showed that 100% efficiency is achievable at a 400 m range in a urban environment with vehicles in line-of-sight.

Figure 12 shows a statistical calculation of bit error ratio from received messages recorded on a short urban drive.

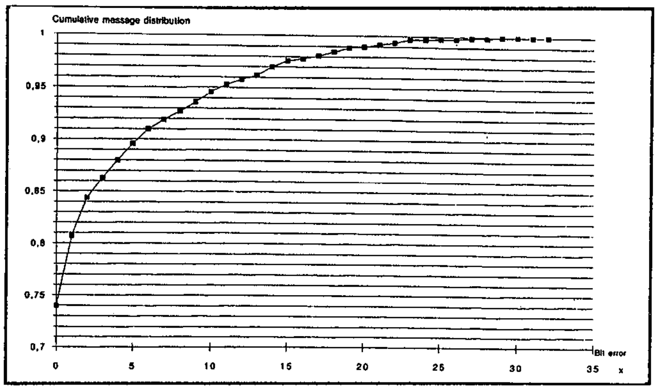

Figure 12. Field tests Percentage of messages spoilt by less than x bit errors

Only correctly decoded messages were taken into account. It shows that more than 25% of messages include at least one bit error and that less than 1% include more than 20 bit errors. This result confirms that some error correction coding had to be used, despite the previous hasty analysis related to multipath effect.

CONCLUSIONS

Extensive simulations and preliminary field tests have made us confident that a vehicle to vehicle communication system is possible. Such systems working without any central management station, with response time and probability of message loss low enough to meet the requirements for traffic security applications, can be achieved.

More tests are to be carried out to investigate greater in depth the performances and the limitations of such transmission system with the 4 prototypes already existing. It is a part of the work program of the current year which moreover includes the implementation in on-board computer of the 4 Copdrive applications mentionned above, in order to demonstrate potential benefit of such system in the field of safety improvement. According to the results, desirable adaptations to signal processing, coding scheme and link protocol, including time and spatial diversity, will be designed.

To complete system assessment, and in particular behavior in heavy traffic, it will be necessary to check the system with at least 10 to 20 equipped vehicles. These tests will be performed later, with less expensive radio sets which are already under consideration with MMIC currently under development.

There are still many problems to solve before considering that all vehicules will be fitted with such communication system. But in the long term, information exchange between driving vehicles seems to be a key point to improve traffic safety and traffic density by better knowledge of traffic conditions, and it is now that system definition and technologies development have to be undertaken.

Intelligent Occupant Protection Systems

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94-S3-O-11

ABSTRACT

Technology developments in sensors and smart signal processing/intelligent systems have increased our capabilities for developing advanced safety systems for occupant protection in crashes. The many developments in sensor technology for primary safety such as proper vehicle control and collision avoidance provide an underlying technology base that can be exploited for enhancing secondary safety systems that can mitigate the frequency and severity of injuries when a crash occurs.

Work at Loughborough University of Technology has been investigating a range of technologies for:

- Predicting the likelihood, force and direction of an impact and responding appropriately
- Enhancing secondary safety system performance by, for example, tailoring protection to the characteristics of the occupants, the vehicle and the crash.

This paper presents some ideas for the enhancement of the performance of secondary safety systems and reports on the progress made at Loughborough University in the design and assessment of technological requirements and injury mitigation potential of intelligent secondary safety systems.

BACKGROUND

Early progress in vehicle safety technology was primarily concerned with the structural integrity of the passenger compartment to protect the occupants in frontal crashes. In the 1960s the concept of energy management through crushable front-end structures was added. This approach aimed to preserve the occupant's survival space, while the vehicle's crushing structures absorbed energy, lengthened stopping time and distance of the passenger compartment, and reduced impact accelerations on the occupant. This is an important part of the total occupant protection system in current vehicles and further protection is achieved by the use of energy absorbing interior components. Enhancement of occupant protection in recent years has been chiefly through restraint systems such as seat belts. Seat belts link the occupant directly to the passenger compartment and allow the occupant to ride down the crash as the vehicle's front end crushes. Seat belts add significantly to the effectiveness of the total occupant protection system. The current safety thinking is to use airbags as a supplement to seat belts. Seat belts provide the primary coupling to the vehicle and control kinematics, while the airbag provides the additional protection of load distribution and crash energy absorption in certain types of impact (Viano D.C. (1991)).

The major gains in occupant protection over the last 20-30 years have been in the development of advanced mechanical systems to protect the occupant's survival space and dissipate the forces involved in the crash (Thomas P.D. & Bradford M. (1992)). Unlike the area of primary safety there is almost no published research on the application of intelligent systems technology to secondary safety although Digges and Morris (1991) in their review of opportunities for frontal crash protection at speeds greater than 35 m.p.h. concluded that research into 'smart restraints' in the American Intelligent Vehicle Highway Systems (IVHS) programme could provide rich returns by protecting a larger segment of the population from crash injuries.

This paper presents some ideas for the potential enhancement of the performance of secondary safety systems utilising intelligent systems technology and reports on the progress made at Loughborough University of Technology in the design and assessment of technological requirements and injury mitigation potential of intelligent secondary safety systems.

INTELLIGENT SYSTEMS DEVELOPMENT

The increase in performance and reduction in cost of microelectronics technology has revolutionised the complexity of systems that can be cost-effectively realised for automotive applications. Concurrent with this technological development there have been steady advances in the design and application of intelligent systems. These range through knowledge-based techniques pioneered in the first half of the 1980s, to the phenomenal growth in connectionist systems in the last 5 years. As such in the early 1990s we are faced for the first time with a low-cost enabling technology and a set of design techniques for realising intelligent systems. The speed of response during accidents is quite lengthy by computer systems time frames, with frontal impacts occurring in approximately 60 msecs and side impacts in 20-30 msecs, thus permitting relatively complex computations to occur during the crash phase. The convergence of the technology and the design methods makes it pertinent to consider their applications to advanced methods for vehicle occupant protection.

Intelligent systems/smart sensors can be thought of as comprising a number of layers (Figure 1). As this figure shows, the initial elements of the systems are sensors and actuators. In themselves, these act as transducers between the intelligent systems and the real world. At the next level up, there is signal conditioning which translates the behaviour of the sensor into data and takes the desired output data and causes the actuators to work.

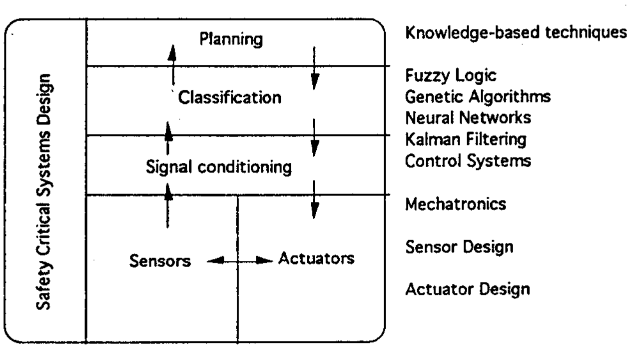

Figure 1. Intelligent system structure.

Traditional control systems design works at roughly these two first layers, mathematically transforming sensor input into actuator output, based on a known underlying model of the system, while monitoring actuator performance to assess the difference between actual and desired output. As such, these control systems have been widely exploited as means of manipulating systems within well-defined and known bounds.

When the demands on system behaviour are more complex and can vary on the basis of input from more than a few sensors and where the desired behaviour is complex and time varying, control systems design needs to be augmented by intelligent systems to fulfil the design requirements. As the figure shows, the control system adds, firstly, a further classification layer. This layer takes information from a number of sensors of different types, with possibly time and environment varying characteristics. Furthermore, some of these sensor inputs may be erroneous (indeed in complex systems like fighter aircraft it is very rare for all sensor/actuator combinations to work correctly). From this mass of information the classification layer must interpret what is actually happening to the system.

Above this layer is the planning layer which takes the classification information and determines which response should be chosen amongst many and then instructs the classification layer appropriately, this in turn sends commands to the actuator signal conditioning layer, which then modifies the behaviour of the system. The loop is closed by sensors detecting the actual response of the actuators and feeding this information back into the system.

To the right of the figure is a list of design strategies which can provide solutions to each of the layers in the system. Each of these strategies are either in the market place or are moving from strategic research laboratories such as Loughborough University of Technology into the market place.

To the left of the figure is the requirement for safety-critical systems. Traditionally, complex intelligent systems get it right 99%-99.9%. For the field of vehicle safety, this is an extremely poor figure (i.e. 1 in a 1000 crashes will not result in the safety feature operating as expected). Clearly 100% correct operation is needed for commercial application. In recognition of this, the left hand pillar extends across the design hierarchy. Substantial effort may be needed to increase the reliability of intelligent systems for this application area. It may be possible to address this issue in the short term, by causing the system only to prime, not activate the safety features if it suspects a crash is shortly to occur and then to require the kinetic energy from a crash to activate the safety features. A primed system may well reduce response time for a safety feature. However, if the intelligent system is designed to specify which of a range of safety features, for example, components of an airbag array, should be deployed, then the safety criticality requirements take on different characteristics and may demand different solutions.

The potential for intelligent systems applications for secondary safety lies in three main areas, namely providing an input that enables the system to better understand the characteristics of the environment in which it is operating, i.e. the characteristics of the vehicle, the occupant and the crash; in interpreting that input in order to provide an output in terms of appropriate occupant protection; and the initiation of that output via actuators. In effect, the intelligent system can gather relevant data, interpret it, tailor and initiate an appropriate response in order to maximise the protection of the occupant.

PRIMARY SAFETY APPLICATIONS

The advance in technological achievement applied to the primary safety aspects of vehicles has been immense. For example, anti-lock braking (ABS) systems are now commonly available to optimise the braking efficiency of the vehicle. Traction control can reduce the likelihood of spinning during acceleration on slippery surfaces and active suspension control systems can adjust the suspension to minimise vehicle roll during fast turns (Parviainen J.A. (1990)). In Europe, in the CEC DRIVE programme and the EUREKA Prometheus project, and in the Intelligent Vehicle Highway Systems (IVHS) initiatives in the USA there is much research concerned with the opportunities for introducing advanced electronics and communication systems into vehicles and the road infrastructure affecting primary safety. There are considerable advances in, for example, route guidance systems, collision avoidance systems, driver monitoring systems and so on (Galer M.D. (1992)). Currently no similar effort is being applied to advanced electronics technology for secondary safety. There is the potential to add value to the electronics implemented for primary safety by also using it for secondary safety applications where appropriate. An example of this might be to use the sensor technology currently applied to intelligent cruise control or collision avoidance devices as the source of a predictor technology for accident occurrence. Hence, further impetus for the work undertaken at Loughborough University of Technology has come from the realisation that the many developments in sensor technology for advanced vehicle monitoring and control, such as for collision avoidance, lane keeping support, driver condition monitoring; and other vehicle, traffic and driver related issues such as seating comfort optimisation, provide an underlying technology base which could be exploited for secondary safety systems.

OPPORTUNITIES AND POTENTIAL FOR ENHANCING SECONDARY SAFETY SYSTEM PERFORMANCE

The application of intelligent systems technology to occupant protection provides the opportunity to tailor the performance of the safety systems to certain features of the accident in order to provide a better level of protection for the occupant involved in the crash and hence a greater likelihood of injury reduction or avoidance. These features are the characteristics of the occupant(s), the characteristics of the crash and the vehicle in which the system is fitted.

The Characteristics of the Occupant

Vehicle occupants vary a great deal in terms of their physical characteristics. They comprise almost the whole spectrum of the population including babies, children and adults of all ages and both sexes as passengers, including the infirm and the elderly; with a subset of men and women over the age of 17 years (in the U.K.) as drivers but with no effective upper age limit. This wide range of physical characteristics is presently catered for by a limited number of secondary safety systems, principally seat belts and more recently airbags, and child restraints for the younger members of the passenger population. There is no doubt that seat belts are a major contributor to the decrease in occupant injuries and fatalities experienced since the introduction in the U.K. in 1983 of the regulations requiring compulsory wearing of seat belts by front seat passengers and latterly by rear seat passengers as well. However, at present a seat belt or airbag will perform in a crash almost independent of the size or age of the occupant or, in the case of drivers, their proximity to the steering wheel. The wide variation in occupant mass is difficult to deal with in the design of secondary safety systems because the acceleration of the occupant is a function of both the restraining force and the occupant mass. This means that, for seat belt systems in particular, the weight of the occupant will introduce a significant source of variance into the expected levels of deceleration. For the same restraint force a 100 pound occupant will be decelerated at a level twice that experienced by a 200 pound occupant. If a low weight occupant has a high relative velocity prior to the initiation of a restraint this could have significant injury implications because the force at which the belt begins to stretch may correspond to an unacceptably high deceleration. A heavy occupant runs the risk of stretching the belt beyond the maximum acceptable excursion. The reduction in slack in the seat belt by pre-tensioners addresses this problem by coupling the occupant into the crash pulse earlier and more closely. Seat belt fit is a significant factor. In order to position a seat belt system effectively to restrain all sizes of drivers and occupants, a considerable amount of adjustability is required, since the height and circumference of the occupant, seat position in relation to the vehicle facia or steering wheel, and seat belt mounting locations, interactively determine the angle at which the seat belt crosses the occupant's upper torso (Lehto & Foley (1993)). There is the potential, by obtaining input information from sensors in the vehicle seat about the occupant's weight, height, seating position, proximity to the steering wheel and so on to achieve a good fit for the seat belt thus also reducing the amount of slack in the belt. In addition the actual performance of the seat belt in a crash could be tailored to the physical characteristics of the occupant by, for example, controlling the way in which the seat belt is pre-tensioned and deployed via seatbelt load limiters to take account of factors such as weight and proximity to the steering wheel.

Both the mass of the driver and the proximity of the driver to the airbag are critical for the effective performance of an airbag. As the distance from the driver to the airbag decreases, for example for drivers with short legs who sit close to the steering wheel, it becomes more difficult to deploy the airbag without injury, given the amount of energy involved in airbag deployment and the short time between deployment and the driver contacting the airbag. There is a correlation between stature and weight and so shorter people who sit closer to the steering wheel also tend to be lighter. Taller people usually sit further from the steering wheel and also tend to be heavier. Hence as the distance from the steering wheel increases the driver reaches a greater relative velocity prior to contacting the airbag. This increases the required restraint force and the probability that the heavy occupant will go through the airbag without adequate reduction of their relative velocity (Lehto & Foley (1993)). There is the potential to tailor the airbag inflation to the needs of the occupant and the crash. The inflation time and volume could be controlled according to the relevant occupant parameters. Information on occupant weight could be made available from seat sensors and their proximity to the steering wheel from sensors in the seat mountings. In moderate energy crashes the airbag could be deployed in a 'soft' mode to reduce injury levels of an occupant hitting a 'hard' fully inflated airbag. The higher performance needed by larger occupants, or in more in severe crashes, could be triggered when needed to reduce serious injuries and where greater energy absorption is required. The airbag could also deploy more quickly if the occupant is short (positional information from sensors in the seat mountings), who will be sitting closer to the steering wheel and currently runs the risk of hitting a deploying airbag, or later for drivers positioned further away from the steering wheel.

Information about whether or not a seat belt is being worn at the time of the crash could also provide an input to the performance of the airbag, with, for example the phasing of the deployment of the airbag or it being deployed in one mode if no seat belt is being worn and in another mode if a seat belt is being worn. This would address the particular problem of serious injury and death in crashes occurring when the driver or passenger is not wearing a seat belt.

Information regarding the seating position of the occupant, their age and sex could provide a valuable input for the controlled deployment of seat belts. For example, at present elderly females are more likely to be front seat passengers than drivers and their higher injury risk and lower tolerance to injury makes it potentially advantageous to deploy the seat belt in a manner tailored to their tolerance levels. In addition, their seating position, as passengers, gives the time opportunity to more 'gently' operate the pre-tensioners and seat belt excursion Occupant height information together with seating position could also be used to tailor the seat belt pre-tensioning and controlled excursion for taller front seat passengers.

Many of the higher specification cars on the market today offer sophisticated tailoring of the seat parameters such as squab height and angle, seat back angle and lumbar support, to the physical characteristics of the occupant. There is considerable opportunity for using this data also for inputs into secondary safety system enhancement. If information about the occupant such as this could be made available via sensors in the seat and its mountings it would be possible to make the seat belt or airbag operate in a way that is tailored to the characteristics of that particular occupant. According to Digges & Morris (1991) smart airbags provide an opportunity to significantly extend crash protection.

A study of the potential for utilising seat and seat mounting sensor data for secondary safety is about to commence at Loughborough University.

The age of the occupant also makes a significant difference to injury outcome in crashes as the ageing process makes people more susceptible to injury and reduces their tolerance to the forces experienced by the occupant in a crash (Viano et al (1989), Verhaegen et al (1988)). Mackay (1988) reports that in a crash the probability of death or serious injury increases by about 70% for people over 60 years of age compared with a 20 year old group. Seat belts that are effective for younger people may not accommodate the reduced tolerance to restraint forces of older people. Increasing the maximum G-force exerted by a restraint system may increase effectiveness for younger occupants in high energy crashes but may also be more likely to injure older people unable to tolerate localised forces at similar levels. Air bags distribute the forces over a larger surface area than seat belts and so have an advantage over seat belts, particularly for older drivers, but are only effective for frontal crashes. However, the problem of bag slap (where the leading edge of the airbag hits the occupant during deployment) may be a greater problem, with older drivers being less able to tolerate the localised forces that occur. Tailoring the performance of seatbelts and airbags to accommodate the reduced tolerance of older people to the levels of forces experienced in a crash has the potential significantly to reduce the likelihood of older people being injured and the severity of any injuries sustained. This is particularly significant as the numbers of older drivers is increasing substantially and car use among this population is increasing even more rapidly among this age group as current car users grow into the range. It means that the 'average' occupant will be older and protection will need to be designed for older persons in the near future.

There is also evidence to show that women involved in crashes are likely to sustain more severe injuries than men. Unlike the other physical characteristics mentioned above, age and sex information is not readily available from sensor data. This may be a case for the development of a 'smart card' that could provide such information or the addition of such data to smart cards being developed for other applications such as electronic passports, identification and credit. If a smart card were to be developed then other data such as that discussed above from seat sensors could also be included.

Characteristics of the Crash

The enhancement of the performance of secondary safety features by the application of intelligent systems technology cannot address the problem of very high energy crashes often resulting in fatal injury. However, there is considerable potential to address the reduction of the occurrence and the severity of injury in less high energy crashes. The direction and force of the crash are critical elements in the performance of the secondary safety features and the injury outcome. The implementation of intelligent secondary safety systems could provide different levels of protection for different crash types and severity. For example, in lower energy impacts the performance of the safety systems could be focused on reducing the level of injury by constrained system deployment. In higher energy impacts additional safety features, such as an array of airbags or airbags that deploy in a phased manner, could be activated as required. Addressing the moderate and severe crashes has considerable potential as the numbers of crashes occurring below 30 m.p.h. are many times more frequent than those above 30 m.p.h...

The direction of the impact could be recognised, such as a side impact or an offset frontal impact, the closing speed and therefore the likely deceleration pulse, and appropriate secondary safety measures deployed accordingly. This could not only fire pre-tensioners and airbags at the optimum moment but could also shape the timing of the deployment sequence and the maximum loads to provide the best possible protection for the particular crash circumstances. For example, side airbags or an array including A-pillar airbags in an offset frontal impact could be selectively deployed. Airbags could be appropriately deployed inside the car from front and side roof rails, and elsewhere in the vehicle depending more precisely on the demands of the crash configuration. They could also be deployed on the outside of the car and over the A-pillars to protect pedestrians or cyclists involved in the crash.

Predicting that a crash is imminent (and beyond the point when avoiding action is feasible) has the potential to gain time for the activation or priming of appropriate secondary safety features. As mentioned earlier, it may not be advisable to fully activate the secondary safety feature on the basis of the prediction alone, given the current reliability of electronic systems, but it may well be advantageous to use the time gained to more closely couple the occupant into the vehicle. It is possible during the pre-impact phase to, for example, activate the seat belt pre-tensioners or adjust the position of head restraints for rear impacts.

Work carried out at Loughborough University (Bowdrey (1993)) has addressed the feasibility of predicting that a frontal crash is imminent. The original orientation of the project was towards the prediction of a frontal crash in order to gain time for the deployment of an airbag on a motorcycle. The rider of a motorcycle sits very close indeed to the point of airbag deployment and there is concern about the possibility of the rider hitting the deploying airbag and receiving injuries from this source (Finnis M.P. (1990), Zellner et al (1993)). One way of achieving this goal is to use a sensor to recognise that an object is close to the front of the motorcycle and likely to collide with it. The same concept applies equally well to other accident scenarios in which it would be advantageous to gain time for the activation of the secondary safety features, such as in car side impacts.

The project investigated practical sensing circuits that had to detect the conditions that made a collision inevitable and provide an actuation signal for the secondary safety feature (in this case an airbag but other forms of system could also be appropriate for cars). The signal had to be generated reliably and free of false alarms. Several means of deriving an anticipatory arming signal were considered and a practical circuit built in the laboratory. In particular Bowdrey investigated a look ahead collision prediction system based on existing in-vehicle technology, namely intelligent cruise control (ICC) and obstacle warning radar. A number of technologies are currently employed including 4-beam infra-red impulse laser, millimetre-wave (80 - 90 GHz) radar and Frequency Modulated Continuous Wave (FMCW) radar for forward scanning. FMCW was chosen for the initial exploration of the predictive sensor utilising modules developed for collision detection systems on earth moving equipment and industrial cranes.

FMCW radar transmits a continuous UHF signal which is modulated with a VHF frequency to give a swath sweep. The modulating frequency effectively gives the FMCW signal a discrete signature so that the probability of another transmission being able to harmonise with it is very slight. FMCW radar uses a combined microwave transmitter/receiver horn fitted with a twin tube wave guide. The radar Doppler module contains a local oscillator which produces the energy to be radiated and a mixer diode which combines the received (reflected) microwaves with a sample of the primary oscillating signal to produce a beat frequency. This is used to produce an output voltage proportional to the distance of the object reflecting the radar signal. A conditioning circuit was produced that took the output from the commercial radar unit and presented it to the signal processing unit developed in the project. When there is no change in the distance of the object (both travelling at the same speed or both stationary) the two signals are the same frequency but the phase may be different. With changing distance both phase and frequency differ. The positive going half of the signal from the radar Doppler module was amplified to a 5v signal whose frequency directly relates to a change in the distance between the motorcycle and an object in its path. The project then considered several approaches to initiating the deployment of the airbag but for the purposes of this paper it is sufficient to report here that we intend to continue further exploration of the potential for FMCW radar.

Simulation of outputs within its operating envelope have shown that it is capable of reliably detecting objects in its path of a size that could be a hazard to a fast moving motorcycle. The difference between the transmitted and the reflected signal being accomplished by a drilling between the wave guides gives the front end of the proposed system a high degree of inherent reliability. Microelectronics enable the detected conditions to be rapidly compared against imminent collision criteria. Such is the capacity of the electronics that repeated checks on the incoming data can be performed before triggering the airbag (or other secondary safety feature). Spurious signals from small objects passing across the line of travel would be ignored because of the high sampling rate employed by the system. Where the signal does not hold true, either rising or falling consistently, it would be ignored. Hence the danger of convoy driving activating the secondary safety system would be avoided. There is still the need for considerable further development and testing of the system and this will be reported at a later date.

IMPLEMENTATION ISSUES

Sensors

The overall aim is to add value to existing vehicle sensor technology where appropriate rather than develop additional sensors.

Actuators

The major actuator design issues are those of cost and speed of response. While the 20-60 msecs time scale of an accident allows plenty of time for information processing, it is an extremely short time for actuators to respond. Consequently, an important research topic is to identify actuator designs which can respond in sufficient time. One valuable role of intelligent systems here, is the application of predictive systems (i.e. those which anticipate that an accident is shortly to occur) to increase the time in which an actuator has to respond.

Processing

The time scales of an accident allow plenty of time for sophisticated information processing. Consequently, the challenges here are not in real-time information processing, but rather in identifying appropriate outputs to enhance secondary safety. One challenge is in terms of the availability of adequate data on human tolerance to injury and the way in which that data is applied in the tailoring of the performance of secondary safety systems. There appear to be two potential strategies for realising a controller. Firstly, a simple standard control algorithm, which monitors the sensors and makes a binary yes/no decision as to the nature of the event. In more sophisticated systems there may be a requirement to deal with multiple events simultaneously and the system will need to disambiguate the sensor information and prioritise its response appropriately. At each of the levels in the design hierarchy of an intelligent system there are well established techniques to realise the chosen system. A particularly interesting research topic is making use of the data available on crash behaviour as input to a connectionist (neural network) model in order to learn automatically the behaviour of a vehicle immediately prior to a crash and hence to provide extra time in which to respond to the accident.

But perhaps the most important issue in terms of processing is reliability and safety.

Reliability and Safety

Mechanical safety systems in vehicles rarely suffer false alarms since the energy of a crash is required to activate them. Electronic-based systems have no such in-built features. Consequently the correct operation under a wide range of conditions is an essential requirement if intelligent systems technology is to be used in this application area. The particular constraints of road user safety makes this topic somewhat problematical. This is caused by the difficulty of eliminating both false positives (the system behaves as if a crash is occurring, whereas in fact it is not) and false negatives (there is a crash, but the system does not detect it). Traditionally a low proportion of false events of one type can be achieved by accepting a large number of the alternative false events. Clearly while this might be acceptable to prevent unauthorised access to a building, for example, the effect of inadvertent operation of some secondary safety features could be unfortunate to say the least. Furthermore, the well-known unreliability of software poses substantial problems in guaranteeing correct response of the implementation even if the theoretical analysis behaves correctly. A partial response to this problem is to permit the intelligent system only to prime the safety features to respond, while still requiring the energy of an impact to activate the system.

The issue of the reliability of safety critical systems such as intelligent secondary safety systems is crucial to their effective implementation. The issues, however, are similar to those that apply in the implementation of advanced electronics for other vehicle applications such as ABS, four-wheel drive and engine management systems. They are all characterised by sophisticated internal and external monitoring circuitry. Much effort is going into this area and is well documented in the literature, for example, Hartl et al (1990), Hendrix et al (1990), White & Behr (1990).

CONCLUSIONS

- The enhancement of the performance of secondary safety features by the application of intelligent systems technology cannot address the problem of very high energy crashes resulting in fatal or serious injury. However, there is considerable potential to address the reduction of the occurrence and the severity of injury in less high energy crashes.

- This paper has looked at the potential for enhancing the performance of secondary safety systems by providing information to the system about the characteristics of the occupants and the characteristics of the crash on which appropriate, tailored system operation can be based. In particular the paper has addressed the sensor/input aspects of the system and has concluded that there is considerable potential to enhance secondary safety system performance.

- One of the next steps is to further investigate the processor and actuator/output aspects of the system. If we can tell the system about the environment in which it is operating what shall we then tell the system to do in order to deploy in an optimum manner in order to reduce the likelihood and severity of occupant injuries? This poses an exciting challenge for actuator/output technology.

- The reliability of these safety critical systems and the implications for product liability is also a topic for further investigation.

- A cost benefit analysis of the implications of the implementation of the systems and the predicted reduction in injuries is an essential next step.

- This initial exploration into the feasibility of FMCW radar indicates that further investigation in terms of predicting that a crash is about to occur (and unavoidable) is worthwhile, however, much more work is needed. Work will continue at Loughborough University of Technology.

- It is also likely that data from seat sensors could provide an input to intelligent secondary safety systems. Work is about to begin on this at Loughborough University of Technology.

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Methodologies for Evaluating the Impact on Safety of Intelligent Vehicle Highway Systems

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ABSTRACT

The IVHS program includes a wide variety of types of systems, all of which are intended to improve some aspect of highway travel. As these systems evolve, it is important to know if they are accomplishing their design goals; and it is also important to ensure that they are not introducing unwanted degradation of other aspects of travel. Safety is one of those aspects which should not be degraded; and if possible, should be improved. All operational tests which are supported by the United States Department of Transportation (USDOT) include safety as an element of the evaluation. The impact on safety of systems which are already being deployed is also being studied. This paper addresses the goals, methodologies, and preliminary results from safety evaluations and presents a summary of studies which are underway. Systems which are discussed include the TravTek route guidance and navigation demonstration, collision avoidance systems, and the TravelAid in-vehicle hazard warning demonstration.

INTRODUCTION

This paper discusses methods for evaluating the safety impact of intelligent vehicle highway systems (IVHS). The discussion is tailored to specific situations; however, the common focus throughout the paper is the following set of core questions:

- Do drivers drive more, or less, safely with the system than without it, in ways related to the system?

- Do vehicles equipped with the system have fewer, or more, collisions than vehicles without the system?

- If all vehicles in the fleet were equipped with the system, would there be a decrease, or increase, in the total number of collisions and collision-related injuries?

The third question is the fundamental question about performance of collision avoidance systems, and other systems, that have an impact on safety. However, frequently the data to directly answer this question are difficult or impossible to obtain. Also, the answer to this question does not provide a basis for understanding the reasons for the impact on safety. The first and second questions are important because they fill these gaps. The first question provides a basis for understanding the reasons for an impact and the second question provides preliminary collision data which complements the answer to the first question.

Two perspectives are used as the framework for the discussion. One point of view is the maturity of the technology. The most mature systems are those that have been reduced to commercial products and are available to the general public. The next level of maturity includes systems which have been reduced to producible systems, but which are not yet a marketed product. These systems are candidates for operational tests. The third level includes systems which are available as prototyes. These systems would be candidates for laboratory and test track evaluations. The fourth level includes systems for which design concepts exist, but which have not been produced as prototypes.

A second point of view for distinguishing types of system is in the context of the "intensity of action diagram" shown in Figure 1 [1]. This paper discusses three types of system which have a potential impact on the ability of drivers to avoid collisions. At one end of the spectrum are systems which help drivers reach their destinations in an efficient manner. These systems would be included in the "normal driving" region at the left end of the spectrum of systems in Figure 1. They are not designed to provide direct collision avoidance assistance and therefore require minimal level of effort. Systems which would be one step to the right are those which provide advance warning of roadway hazards. Examples of hazards are rockslides, snowplows, and closed lanes. These systems require the driver to take action, such as reducing speed or selecting an alternative route, in response to a hazardous situation. However, advice is provided sufficiently in advance of the situation that the driver has time, probably on the order of several minutes, in which to prepare for the needed action. Still further to the right of Figure 1 are systems which are typically classified as collision avoidance systems. These systems augment the driver's collision avoidance capability when hazardous situations or collisions are imminent.

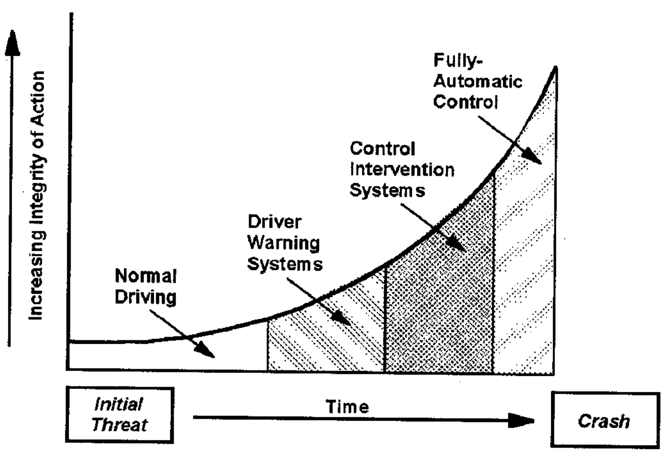

Figure 1. Time vs. Intensity Diagram

The remainder of this paper discusses methodologies for evaluating the safety impact of each of the three types of systems described above. The discussion for each type of system includes separate discussions for each of the three core questions.

ROUTE-GUIDANCE AND NAVIGATION SYSTEMS

This type of system has reached a state of maturity that prototype systems are available for use in operational tests. A key advantage of operational tests is that they provide an opportunity to not only assess driver perceptions and reactions to use of a system but also an opportunity to view operation of the system under a variety of controlled conditions.

Examples of route-guidance and navigation of systems are the TravTek system which was the subject of an operational test from April 1992 through March 1993 [2], the ADVANCE system which is the subject of a current operational test [3], and the FastTrac system which is also the subject of a current operational test [4]. Of these three systems, the operational test of TravTek is closest to completion. For this reason, the discussion in this paper is limited to the TravTek program. The TravTek program included a strong commitment to a comprehensive evaluation from the beginning of the project [5, 6]. The evaluation, which is being done by Science Applications International Corporation (SAIC) under contract to the Federal Highway Administration is not yet complete. Thus, the discussion in this paper is necessarily incomplete and focuses on methodologies; with only a preliminary review of results.

Two of the operational elements of the TravTek system are the in-vehicle subsystem and the traffic management center. These two subsystems were connected by radio links that allowed the vehicles to receive information on current traffic conditions and the traffic management center to receive information of travel delays from the vehicles. The in-vehicle subsystem provided navigation assistance plus autonomous on-board routing capabilities based on map-matching combined with signal from the satellite-based global positioning system (GPS) and dead-reckoning units for determining position. There were a total of 100 TravTek vehicles available for use during the operational test.

The system in each vehicle could be programmed by the vehicle-operations team to be in one of three system configurations. One configuration, known as the "Navigation" configuration, provided in-vehicle route-planning and navigation capability, but did not include the radio link to receive traffic information. A second configuration, known as "Navigation Plus", provided the in-vehicle capability plus the radio link that provided enhanced route planning capability based on current traffic conditions. The third configuration was a control condition which provided "yellow pages" information but did not provide any route-guidance and navigation capability .

The system in each vehicle also had six driver-selectable display configurations. The six consisted of three visual displays in combination with either an audio backup or no audio backup. One of the visual systems, known as the "Guidance Display", provided turn-by-turn instructions for reaching the designated destination. A second visual display, known as the "Route Map", provided routing instructions through a highlighted depiction of the route superimposed on a graphic of the surrounding traffic network grid. The third visual display did not provide any route guidance.

The evaluation of the safety impact, as well as the other elements of the evaluation, was organized to methodically move from stated objectives to analysis of relevant data for each sub element. This approach is shown in Table 1 [7].

Table 1
Study Definition [7]

Objectives	Hypothesis	Measures of Effectiveness (MOE)	Measures of Performance (MOP)	Data Sources	Methods of Analysis
Objectives are stated in terms of what to measure or what to evaluate	These include a statement of the primary hypothesis	MOEs are conceptual measures that convey "goodness" or ability to meet a set of criteria	These are data elements required to satisfy the MOEs (the variables needed to compute the MOEs)	This column refers to the TravTek data sources (e.g., in-vehicle logs, TMC logs, TISC logs) required to compute the MOPs	This column broadly defines the types of analytical procedures that will be used

The process includes establishment of meaningful measures of safe or unsafe driving (measures of effectiveness), determination of collectable data elements (measures of performance) that can be used to relate safe or unsafe driving situations to use of the TravTek equipment, and development of analytical methodologies which can be used to establish the relationship between use of TravTek equipment and instances of safe or unsafe driving. In this, as in all aspects of the evaluation, it is also important to establish control conditions so that comparative assessments can be done.

There were a total of five driving scenarios which provided data for use in the evaluation. Two of them allowed drivers to operate the vehicle in a naturalistic way with no direct oversight. These drivers were instructed to drive normally and there were no restrictions on destinations or other aspects of travel. One group of drivers was composed of visitors to the Orlando area who were from other states. This group was known as the "B1" drivers. A second group was composed of local residents in the Orlando area who were given use of a TravTek vehicle for a two-month period. This group was known as the "B2" drivers. The B1 drivers were assigned a vehicle with one of the three configurations and the B2 drivers were provided either a Navigation or a Navigation Plus configuration. The drivers were free to operate the vehicle with their choice of display configuration, including not using the TravTek system [8].

The other three driving scenarios, known as the C1, C2, and C3 studies, imposed controls on vehicle operation [9]. In all three studies, the conditions of operation included use of a limited number of pre-determined origin/destination pairs and presence of an observer during vehicle operation. These include the C1 study, a yoked-driving test in which sets of three drivers with the same destination simultaneously left a single origin. Each vehicle in the set was equipped with a one of the three system configurations described above. The C2 study was a second test which also included common origins and destinations. In this case each driver sequentially drove between a specified origin and a specified destination with each of the six display configurations described above. The third study, known as the C3 study, used a specially instrumented vehicle and also required drivers to drive between a specified origin and destination with a preselected display configuration. The Navigation system configuration was used for the C2 and C3 studies. In all three studies, the drivers were compensated for taking part in a controlled experiment.

QUESTION 1 (Do drivers drive more, or less, safely with the system than without it, in ways related to the system?)

This question, posed in the Introduction, has been subdivided into two component questions for purposes of the TravTek evaluation. These two subquestions are:

- What is the safety impact of the TravTek improvement in navigation and congestion avoidance?

- What is the impact of display type and driver experience on driver performance, behavior, and perceptions?

Among the sources of data for answering the first subquestion is a questionnaire which all participants in the B1 and B2 studies were invited to complete. Responses to the questions provide perceived safety benefits as well as perceived useability of the system. Preliminary analyses of the questionnaires have been reported in other papers [10,11]. Two questions which provide insight into the drivers' perception of savings in time and avoidance of congestion are:

- Do you think TravTek helped you save time in reaching your destinations?

- Do you think TravTek helped you avoid congestion?

Based on the preliminary analysis, the average value of the response to these two questions for B1 drivers with the Navigation Plus configuration was 4.6 and 2.9 respectively, compared to responses from drivers of the control configuration which on the average were 2.6 and 1.9, respectively. For each question, a "1" corresponded to the most negative response and a "6" corresponded to the most positive response.

It is clear from these answers that the rental drivers believed that the system helped them have quick and efficient trips. This perception of the B1 drivers was confirmed in the C2 study where, on the average, drivers with the TravTek system covered the assigned trips in significantly less time [9] than it took when they used a paper map.

Partial answers to the second subquestion can also be found in the questionnaire data. A sampling of entries from the questionnaire and preliminary responses is shown below. A complete analysis of all of the data will be included in the final report of the evaluation contract.

- The TravTek system helped me pay more attention to my driving. The average response of B1 drivers with the Navigation configuration was 4.5

- The TravTek system interferred with my driving. The average response of B1 drivers with the Navigation configuration was 2.1

- Do you think TravTek helped you drive more safely in Orlando? The average response of B1 drivers with the Navigation configuration was 4.1

The following cluster of questions on "close calls" was also included in the questionnaire.

- How frequently did you experience "close calls" (or near-accidents) while driving the vehicle?

- How many times did you experience "close calls" (or near-accidents) while driving the vehicle?.

- What were you actions immediately prior to the close call?

- Who or what caused the "close call" to occur?

- How does the number of "close calls" you experienced in Orlando compare with the number you usually experience in your hometown?

The data from this cluster have not yet been completely analyzed. However, a preliminary review indicates that drivers believed they had almost no close calls. For example, the average response by B1 drivers to the first question of the cluster was 1.3, on a scale 1-6, where 1 = "never" and 6 = "frequently". The preliminary analysis of data from questionnaires also suggests that drivers believed they had fewer close-calls with the TravTek system than with their own vehicle. However, these data also suggest that some of the close-calls may have been related to use of the TravTek system. Further analysis of these data will include comparison of data from the in-vehicle log to questionnaire responses.

Additional data to help answer the safety part of the question will come from analysis which will include the in-vehicle data logs and records of close calls and other safety related information that was collected during the C1, C2; and C3 studies. This analysis has not yet been completed.

The most detailed data for answering the second subquestion will come from the C3 study. In this study, a specially equipped vehicle was used to collect detailed information about driver actions. The additional instrumentation included accelerometers; monitors of motion of steering wheel, accelerator pedal and brake pedal; and four cameras which simultaneously monitored the driver's face, the road ahead of the vehicle, the lateral position of the vehicle relative to lane markings, and the TravTek display. In addition to the instrumentation, the onboard observer noted each event and activity which might be related to the safety of a driver's performance. The preliminary analysis indicates that visual turn-by-turn instructions with voice backup appears to provide the highest level of safety; and that the level of safety was not the same for all display configurations. The results also suggest that the level of safety improves as drivers gained experience in use the TravTek system [12].

The analyses which will be performed as part of answering the first basic question will involve several sources and types of data. They will also address the subquestions and contributing factors from a number of perspectives. The final step in the analysis will be to consolidate all of the findings into functional relationships which describe the safety impact.

Some of these functional relationships will be:

- Accident risk as a function of congestion

- Accident risk as a function of navigational waste (a measure of trip efficiency)

- Driver performance as a function of display type and experience

- Driver behavior as a function of display type and experience

- Driver perceptions as a function of display type and experience

The complete analysis will be published in the final report from SAIC.

QUESTION 2 (Do vehicles equipped with the system have fewer, or more, collisions than vehicles without the system?)

A key advantage of operational tests is that they provide an opportunity to observe drivers in normal driving situations. This includes the opportunity to determine the number of collisions experienced by drivers. It also provides an opportunity to do detailed analysis of the conditions associated with each collision. Thus, the analysis of collision data from an operational test can provide two forms of insight. One is the size of the collision experience compared to appropriate reference or control groups. The second is an assessment of the strong points and weak points in the system design based on details such as pre-crash activity by the drivers, types of collision, and extenuating circumstances associated with the collisions.

In the TravTek program, the vehicles were rented to participants by Avis Car Rental Company. Thus, a logical comparison group would be one drawn from other Avis renters. However, it was learned late in the program that data on the collision history of Avis renters is not kept in a retrievable manner within the company records. Thus, it was not possible to make a direct comparison with a control group of other Avis customers. Another comparison which can be made is to the total national population of collisions. The General Estimates System (GES) which is maintained by the National Highway Traffic Safety Administration provides such a national perspective based on police-reported collisions which occurred on public roads [13].

During the operationat test participants in the B1 study drove appoximately 0.8 kilometers and experienced 3 collisions on public roads. This relatively small exposure of the TravTek fleet makes it difficult to reach definitive conclusions on relative collision rate for the TravTek fleet. However, based on the summary above, it is seen that the collision rate during the operational test was about four collisions per million vehicle-kilometers (MVK) of travel. As a comparison, the national rate is two police-reported collisions per MVK [14]. A detailed analysis, which takes into account the fact that there are about three additional collisions which are not reported to police for every two collisions that are reported to police, was done as part of the overall evaluation and shows that there is no statistically significant difference between the national collision rate and the rate for the TravTek fleet [15]. Ideally it would be possible to determine the impact on the relative collision rates of relevant factors such as driver age, driver familiarity with the road network, driver familiarity with the vehicle, type of collision, and contributing circumstances. However, there was insufficient data to do such an analysis. One consideration which may have an impact is the fact that most of the drivers were members of the American Automobile Association (AAA). Members of AAA are predominantly in the age range that has a lower collision rate that the national average. Another consideration is that most of the TravTek participants were visitors to the area and were renting vehicles with which they were not familiar. This consideration may lead to a higher collision rate than the national average [16].

QUESTION 3 (If all vehicles in the fleet were equipped with the system, would there be a decrease, or increase, in the total number of collisions and collision-related injuries?)

An important step in the analysis of data from any operational test is the extrapolation of results to a population that includes a large percentage of vehicles with enhanced capability. In the case of TravTek, there were no more than 75 TravTek vehicles being driven at any one time. Thus, the impact of having TravTek vehicles in the system was negligible. However, if a large percentage of the vehicle fleet had TravTek capability, there may be impacts on several aspects of the overall traffic network. Among these impacts, are emissions, number of collisions, and total travel time for all users of the traffic network.

To estimate these impacts, a specialized version of the INTEGRATION computer model of traffic flow was developed for the Orlando area [17]. This computer program models each individual vehicle as it travels from origin to destination in the simulated Orlando traffic network. The model has the capability of including vehicles with and without TravTek capability. By combining this basic model with algorithms for estimating emissions, fuel consumption, and number of collisions, the results from the operation of TravTek vehicles can be extrapolated to populations with higher percentages of TravTek-like vehicle.

To address the safety impact, an algorithm is being developed which can predict the collision experience of a vehicle based on circumstances along the route between origin and destination. The concept, in simple terms, of the algorithm is that the instantaneous collision rate (e.g. collisions per kilometer) for a vehicle as it travels through a traffic network can be described by two components; one which describes the vehicle-related factors, and a second which describes the roadway-related factors. For purposes of this analysis, only one vehicle-related factor is considered; absence of TravTek capability (the baseline or control group) and presence of TravTek capability. The roadway-related factors are condensed into a single relationship between collision rate and level of congestion. Input for this relationship will be based on published results from other studies as well as the results from the TravTek program. Data from the Orlando traffic network will also be used to estimate the goodness-of-fit of the model. Use of this relationship also simplifies the interaction with the traffic flow model. Based on this concept, the likelihood of a vehicle having a collision while traversing the traffic network along route "a" from origin to destination ($L_{c/a}$) can be expressed by:

$$L_{c/a} = \int K \cdot W(x)dx$$

where:

$L_{c/a}$ is the likelihood of having a collision if route "a" is used

K is a constant that quantifies the effects of vehicle-related factors

W(x) is the level of congestion along the route

Based on this terminology, the total number of collisions during a specified period of time (N) will be expressed by:

$$N = \sum_{i=1}^{M} \int K\ W(x)dx$$

where M is the total number of trips taken by all users of the traffic network during the designated period of time

This algorithm relies on the results from controlled experiments and other sources of data from the TravTek program as the basis for parameter values and other boundary conditions. The value(s) for K will be derived from the analysis described in the discussion about answering Question 1 and from additional literature on driving performance. For basic analyses, two values of K will be needed; one for baseline vehicles and a second for vehicles with TravTek capability. If the data can support further subdivision, it may be possible to have values of K which vary according to such variables as driver age, driver experience with the local traffic network and level of congestion along the route.

The function W(x) will be derived from an analysis of collision and congestion patterns in the Orlando area. One source of these data will be records from the Freeway Management Center which show levels of congestion prior to collisions which occurred on the portion of Interstate 4 that was in the TravTek traffic network. To the extent possible, the function W(x) will include variations due to facility type (freeway, arterial, etc.), level of congestion (whether free flowing or queued), and intensity of traffic flow [18].

Once the values for K and W(x) have been established, the model will be exercised for a number of driving situations; for example, mid-day, rush-hour, weekend. It will also be exercised for different levels of penetration of vehicles with TravTek capability. The results of these simulations will be combined to estimate the impact on the total number of collisions of having an increasing percentage of vehicles with TravTek capability.

COLLISION AVOIDANCE SYSTEMS

At the opposite end of the spectrum of intensity-of-action shown in Figure 1 are collision avoidance systems. These systems are purposely designed to augment a driver's ability to avoid collisions.

Before discussing the methodologies for evaluating collsion avoidance systems, it is helpful to discuss several characteristics of systems which are related to theevaluation process.

The first characteristic is the category of the system. There are three basic categories for collision avoidance systems. The categories are determined by the function of the driver interface. Systems which advise the driver of a situation which has the potential for producing a collision but for which no immediate collision avoidance action is necessary belong to the first category (denoted as Category 1). Examples of this category are systems which advise of current headway, systems which indicate that another vehicle is present in an adjoining lane, and systems which advise the driver of reduced friction coefficient.

Systems which advise the driver of an imminent collision and elicit collision avoidance action belong to the second category (denoted as Category 2). Some examples of this category are systems which advise the driver to apply the brakes when the system has determined that a collision will occur otherwise, systems which advise the driver to reverse steering inputs to avoid a collision with another vehicle in the driver's blind spot, and systems which advise the driver of the need for braking and/or steering to avoid an unintended road departure. The form of the advice may be specific (e.g. a direct statement to "brake") or unspecific (e.g. a light or tone, in which case the driver will need to determine the meaning of the signal).

The third category of system (Category 3) encompasses those systems which direct the vehicle to take collision avoidance action automatically when a collision is imminent and the driver has not taken appropriate collision avoidance action. Examples of this category are systems which automatically apply the brakes when a rearend collision is imminent and systems which automatically apply the brakes when a pedestrian is behind a backing vehicle. Some systems may be hybrids which combine features from more than one of these stereotypes. Some features of these three system categories are summarized in Table 2.

The second characteristic is the set of three functional elements which form the building blocks for collision avoidance systems (and also systems which provide most of the other IVHS services). These functional elements are the sensing portion of the system, the processing part of the system, and the mechanism for interacting with the driver. Typical sensing elements which are found in collision avoidance systems include microwave radar, infrared radar, passive infrared, and ultrasonic transducers. The processing element takes signals from the sensors and converts them to useable messages that can be transmitted to the driver or vehicle control system. This element contains the algorithms for establishing the level of threat associated with any situation and for making a judgement about the imminence of a collision. The driver interaction element includes a broad range of presentations to the driver, including visual, audible and tactile. This element also may be a control system which automatically takes action.

Table 2
Description of System Categories

	Feature	
	Significance of Vehicle Posture	**Action Needed**
Category 1	Potential for collision exists - vehicle(s) <u>not</u> on a collision course	Caution needed but no immediate collision avoidance action is necessary
Category 2	Collision is imminent - vehicle(s) on a collision course	Immediate collision avoidance action by the driver is needed
Category 3	Collision is imminent - vehicle(s) on a collision course	Immediate collision avoidance action will provided by an automatic control system

The third characteristic is the set of dynamic situations which a system is designed to address. A dynamic situation is a set of conditions that can be described by time and space relationship and the interaction of drivers. The qualitative basis for establishing dynamic situations is contained in the cluster of precrash variables that was added to NHTSA collision data bases starting in 1992 . The five variables are Movement Prior to Critical Event, Critical Event, Corrective Action Attempted. Vehicle Control After Corrective Action, and Vehicle Path After Corrective Action. This sequence of events is then followed by the First Harmful Event. The goal of collision avoidance systems is to intervene at one of the initial five pre-crash stages so that the first harmful event does not occur. The processing functional element will include quantitative descriptions of these circumstances and the logic for providing the needed intervention. Descriptions of dynamic situations will be derived from a combination of dynamics analysis and analysis of collision data.

The NHTSA has put in place four contracts to develop performance specifications for collision avoidance systems. Each contract addresses one of the following four specific types of collision: rearend, lane change and other "blindspot", intersection, and off-road. As part of these contracts, each contractor will acquire available systems. These may be prototypes or they may be commercially available units. Data from the evaluation tests will be used to answer the first and third of the three basic questions noted in the Introduction. However, it will not be possible to answer the second question because these tests will not include driving for extended periods under normal driving conditions as is possible in operational tests.

The evaluation of available systems will consist of three steps. The first step will be to determine which of the three categories each system represents. This will be followed by a determination of which dynamic situations each system was designed to address. The third step will be to develop a series of appropriate tests which will provide a basis for assessing the performance of each of the functional elements of the system. It is important to note that a thorough evaluation of a system needs to address each functional element and assess the performance of each. This then forms the basis for an assessment of the performance of the entire system. The evaluation also needs to address the four possible outcomes of traditional experiments shown in Table 3.

Table 3
Conceptual Experimental Results

System Response	**Situations Requiring a Signal**	**Situations in Which a Signal is <u>not</u> Required**
Signal	True Positive	False Positive
No Signal	False Negative	True Negative

Based on Table 3, the performance of the individual elements, or the entire system, can be described by several measures. One would be the ratio of times that the element, or system, gives a true positive to the number of times it gives a false positive. (The inverse of this ratio is sometimes referred to as the false alarm rate) Another would be the ratio of number of times it gives a true negative to the number of times it gives a false negative.

As an example of collision avoidance systems, consider the following two systems which address the problem of collisions that occur during a lane change. The systems address the problem in two different ways, one continuously provides information while the other provides information only when a collision is imminent. As will be seen in the following discussion, the details of the systems are different and the procedures for evaluating the systems are also different. Each of these systems would address the problem of collisions that occur during a lane change. This type of collision accounts for approximately 250,000 police-reported collisions per year, of which approximately 200 involved a fatality [19].

The first system is one which is designed to provide a driver with an indication of the presence of another vehicle in a potentially hazardous position in an adjacent lane. This system would be in the first category of systems; that is, those which advise the driver of a situation which has the potential for producing a collision. For this system, the vehicle which might change lanes is denoted vehicle 1 and the vehicle in the adjacent lane is denoted vehicle 2. The system is designed to provide the indication when an adjacent vehicle is in a position that which would result in a conflict if the driver of vehicle 1 chose to change lanes.

The second system is one which interacts with the driver only when a collision is imminent. Thus, this would be in the second category, or a Category 2, system. For lane-changing situations such a system would monitor the relative motion between the vehicle with the system, which will be denoted as vehicle 1, and other vehicles in the vicinity, vehicle 2. When the system determines that the trajectories of the two vehicles put them on a collision course and that they are reaching the point of no return on that course, it will issue a message to the driver that control action is necessary. A key distinction between this system and the first one is that this one interacts with the driver only when action is needed whereas the first system interacts with the driver in a continuous manner when the potential for a collision exists but before a collision course has been established.

QUESTION 1 (Do drivers drive more, or less, safely with the system than without it, in ways related to the system?)

Reducing this situation to a quantitative description is an important step in the evaluation process. For example, the time-history of vehicle motion must be described. Two features of this time history are the rate at which the driver would normally change lanes and the lateral distance that the driver would move in a normal lane change. For purposes of this example, it is assumed that the driver would take five seconds to change lanes and that the lateral distance is one lane width.

Actions by the other driver also need to be considered. For example, if vehicle 2 is traveling at a higher speed and the lane change would bring vehicle 1 in front of it, the driver of vehicle 2 will need to decelerate. For purposes of this example, it is presumed that the driver will not decelerate until vehicle 1 has completed the lane change and then the deceleration will be at 0.1 the acceleration of gravity. For the case where vehicle 1 pulls in behind vehicle 2, no deceleration is necessary. This dynamic situation can be reduced to a set of conditions when the driver of vehicle 1 should be advised of the presence of the other vehicle. These conditions are shown in Figure 2.

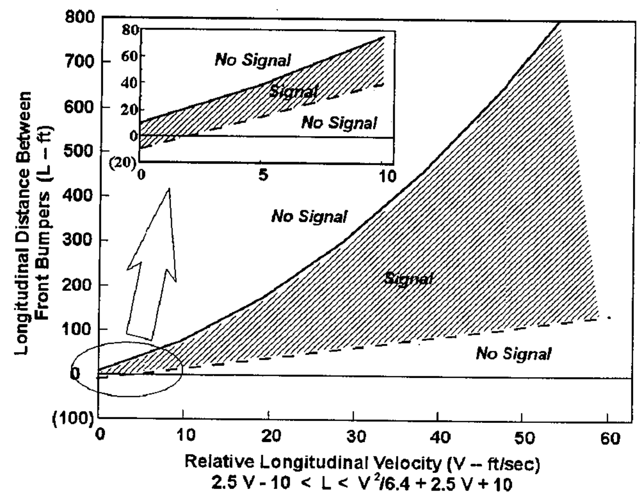

Figure 2. Envelope for Providing a Signal to Inform the Driver of a Potential Threat Situation

From Figure 2, it is seen that the sensing functional element must have the capability of reliably and accurately detecting the presence of a vehicle when the relative velocity and distance are within the shaded area of the figure. This means that the sensing element must provide data on the relative velocity, the length of vehicle 2, the relative longitudinal distance, and lateral distance to vehicle 2. Thus, a test of the sensing element for this system would include a matrix of test-track conditions that would exercise these features. The primary variables would be relative speed and relative longitudinal position between vehicles in adjacent lanes. Secondary variables would the be absolute speed of vehicle 1, background clutter (Jersey barriers, third lane of vehicles, street signs, parked vehicles, buildings, etc.), weather conditions, and road geometry (hills and curves).

Similarly, the functional element for converting sensor data to meaningful driver information should reliably give a signal to the driver if and only if a vehicle is present in the adjacent lane with the conditions of velocity and distance shown in the shaded area of Figure 2. The test for this functional element would seek to determine if the processing element can extract the necessary information from the sensor and accurately make a determination of whether vehicle 2 is in an adjacent lane or further away from vehicle 1 and whether the dynamic conditions are within the shaded area or outside of it. Testing of the sensing element and the processing element might need to be combined into a single test if the system does not include a port that can provide direct access to the sensor output. The functional element for interfacing with the driver should effectively, and in an unambiguous way, communicate this information to the driver.

The tests for the driver interface might include a means of determining how long it takes a driver to realize that a signal is present, the driver's interpretation of the meaning of the signal, and the driver's perception of the usefulness and distraction of the system. The tests for the driver interface functional element might be based on highway travel, probably with an observer. During this travel, data would be gathered to determine the length of time needed for the driver to recognize that a signal was present (with careful attention to the conditions that existed at the time of the signal) and the interpretation of the meaning of the signal by both naive and trained drivers. The combination of results from these tests would be used to estimate the effectiveness and the error rate, as summarized in Table 3, of the system.

A thorough evaluation of the second type of system would include a description of the various dynamic situations which produce collisions as a result of one vehicle changing lanes coupled with a determination of a quantitative description of the details of relative motion. This analysis would then be followed by an assessment of the features of the situation which must be sensed by the sensing functional element, the control law that needs to be applied to the data to be able to make a determination that a collision is imminent, and the control action message which should be transmitted to the driver. The evaluation of a candidate system would then consist of determining the capability of each of the three functional elements. This would include a determination of the capability of the sensing functional element to accurately gather all of the necessary data in a timely manner. It would also include a determination of the capability of the processing functional element to convert the sensed information into a cogent and timely message to the driver. Thirdly, the evaluation would determine if the driver interface effectively elicits the proper control action from the driver.

For the example described above, it is seen that the sensing functional element must include the capability of sensing the variables needed in the Category 1 case, plus at least the relative lateral velocity between the two vehicles. It will also need the capability for higher resolution of the relative lateral distance. (In the Category 1 system it is only necessary to know that vehicle 2 is in the adjacent lane.) Tests to determine the performance of the sensing functional element would need to include situations where the vehicles are placed on a collision course. This can be accomplished safely by having constant communications between a test director and the drivers of both vehicles with both vehicle 1 and vehicle 2 directed to follow preplanned trajectories. The performance of the processing functional element may be determined from this same test protocol. However, this protocol is not appropriate for determining the effectiveness of the driver interface in eliciting proper action from an unprepared driver. The tests for determining effectiveness of the driver interface may require actuation of the control action message by an observer during a lane change when there is no other vehicle present. The details of this test need to be carefully developed to ensure that the results are scientifically valid and that the test does not expose the subject driver to abnormal risks.

QUESTION 2 (Do vehicles equipped with the system have fewer, or more, collisions than vehicles without the system?)

There are currently no operational tests being performed with collision avoidance systems. Thus, there currently is no opportunity for collecting data on collisions, and near misses, for collision avoidance systems. However, the work done in answering Question 1 will provide a basis for understanding the details of performance that will be involved in evaluation of operational tests. It will also provide a basis for determining data collection needs for support of operational test evaluation.

QUESTION 3 (If all vehicles in the fleet were equipped with the system, would there be a decrease, or increase, in the total number of collisions and collision-related injuries?)

The process that is currently used to estimate the national impact of potential collision avoidance systems has two steps. The first is to estimate the effectiveness of the system in eliminating or ameliorating the severity of specific types of collision. This estimated effectiveness is then applied to data from national files of collision data to estimate the number and severity of collisions that would have been eliminated had the system been in place when the collision data was collected.

The basic expression for this process is:

$$E = (N_{wo} - N_w)/N_{wo}$$

where:

E is the estimated effectiveness of a countermeasure

N_{wo} is the number of collisions that occurred when no vehicles were equipped with the countermeasure

Table 4.
Effect of Rear-Axle Antilock (RWAL) Brakes on Single-Vehicle Pickup Trucks Crashes [20]

Type of Crash Involvement	Last 2 Model Years without RWAL		First 2 Model Years with RWAL	
	N	%	N	%
Primary Rollover	1095	14.5	737	9.6
Side Impact with Fixed Object	759	10.1	633	8.2
Frontal Impact with Fixed Object	2044	27.1	2095	27.3
Control Group (Multivehicle)	3634	48.3	4215	54.9
	7532	100.00	7680	100.00

N_W is the number of collisions that would occur if all vehicles were equipped.

An estimate of the number of collisions that would have occurred if all vehicles had been equipped with a countermeasure can be obtained by rearranging the equation.

$$N_W = N_{WO}(1 - E)$$

Estimates of effectiveness can be obtained from laboratory tests or from collisions records. One of the purposes for testing the performance of IVHS collision avoidance systems is to obtain estimates of effectiveness. A recent study of antilock brakes (ABS) provides an example of the latter approach [20]. In this study, records of single-vehicle collisions involving pickup trucks from the state of Michigan were used. These data are summarized in Table 4. Based on these data and a modification of the above equation which uses multivehicle collisions as a control group, an estimate of effectiveness for installation of ABS on the rear axle of pickup trucks would be 42 percent.

Another approach to estimating effectiveness utilizes the Monte Carlo method of statistical analysis. In this method, assumptions are made about the statistical distribution of critical parameters in the equations that represent performance of a specific system. A series of simulated encounters is then run with a determination made for each encounter of whether a collision would have been avoided or not. In an example of this type of analysis, a rearend collision avoidance system was modeled using a simple single-degree-of-freedom model of the system dynamics [21]. In this example, drivers were assumed to have perfect detection and driver compliance and to have a reaction time which fit a lognormal distribution with a mean value of 1.21 seconds, the level of deceleration was assumed to have a uniform distribution between 0.5g and 0.85g, and the acquisition range of the system sensor was assumed to be approximately 100 meters. The simulated encounters were of a vehicle approaching a stationary vehicle with a variety of initial speeds. A total of 40,000 combinations of reaction time and level of deceleration were randomly generated according to the specified distributions for each initial speed. The results of this simulation are shown in Figure 3.

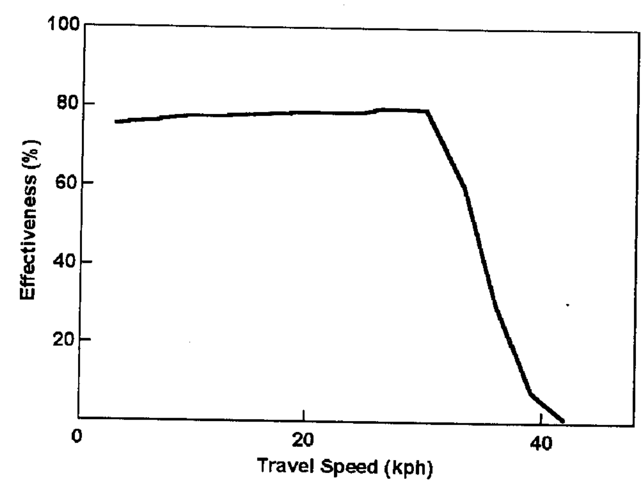

Figure 3. Examples of Estimates of Rearend Collision Avoidance system Based on Monte Carlo Methodology [21]

From this figure it can be seen that the estimate of effectiveness for this system is a function of the initial speed. Thus, to be able to calculate an estimate of overall effectiveness, it is necessary to combine this functional relationship with an estimate of the distribution of initial speeds. For this example, the speed distribution was obtained from an analysis of collision data. Using this distribution, the estimated overall effectiveness is 77 percent.

In the four contracts discussed previously, an estimate of effectiveness for each system will be developed for each relevant dynamic situation. The basis for these estimates will be the tests described in the discussion of Question 1. The collision files will be subdivided by the causal factors. For example, the five precrash variables discussed previously which were initiated in 1992 files provide a basis for more detailed description of causal factors associated with each dynamic situation. The estimates of effectiveness for each dynamic situation will then be combined with the fraction of total collisions for each dynamic situation. The total effect of the system will be obtained by combining the effect for each of the relevant dynamic situations.

In the future, the process described above will be augmented by a process that uses data on near-misses and other non-collision driving actions. The data to support this process will be collected using tools that are currently being developed. One of these tools will be capable of observing vehicles motions and converting this information to a quantitative description of the motion of individual vehicles as well as the relative motion between adjacent vehicles. A second tool which is being developed will provide a means of observing the detailed actions of drivers (e.g. eye point of regard, and time that eyes are off the road) and relating the actions to circumstances around the vehicle (e.g. close proximity of another vehicle). These tools for developing a more in-depth understanding of pre-crash circumstances are discussed in more detail in the companion paper by Leasure and Burgett [22].

IN-VEHICLE DRIVER ADVISORY SYSTEMS

The last type of system to be considered is an in-vehicle hazard warning system. These systems collect information about road conditions and hazards, convert it to meaningful messages to drivers and present these messages to drivers through in-vehicle displays.

Conceptually, these systems are similar to the Category 1 collision avoidance systems discussed in the preceding section because they both advise drivers of situations which have the potential for producing a collision. However, the systems are different in at least two major ways. One difference is in the location of the sensing functional element. In Category 1 collision avoidance systems, the sensors will in all likelihood be in the vehicle. By contrast, the sensors for hazard warning systems will probably be part of the highway infrastructure. The second way these systems are different is in the imminence of the potential collision. In medical terminology, hazard warning systems can be thought of as advising about situations that are *distal*, in both time and space, from the driver and vehicle. Similarly, Category 1 collision avoidance systems can be thought of as advising about situations that are *proximal* to the driver and vehicle. (*Proximal* describes biological features which are near the central body while *distal* describes biological features which are distant from the central body. For example, the shoulder is proximal while the hand is distal.) These differences lead to different evaluation procedures for the two types of system.

The system to be discussed is called TravelAid, the subject of an operational test on a section of Interstate 90 (I-90) east of Seattle, Washington [23]. This section of interstate experiences extensive snow and ice during winter months and carries a heavy load of both recreational and commuter traffic due to its proximity to Seattle and several winter recreation areas. The collision rate on this section is significantly higher during winter months than during the remainder of the year as can be seen in Figure 4 [24]. The TravelAid system will provide timely information on traffic, road, and weather conditions as well as information on specific situations such as presence of snowplows. The purpose of the TravelAid system is to reduce he number and rate of collisions by convincing drivers to reduce their speed to one which is consistent with prevailing conditions, by minimizing speed differentials within the traffic stream and by facilitating installation of snow chains and other overt actions. The TravelAid system will gather data from stationary roadside sensors as well as mobile observers such as road crews and police. These data will be transmitted by radio to a central control center. The control center contains the capability of converting sensor data into messages which can be sent to motorists. TravelAid will use three different driver interfaces for presenting messages to drivers; in-vehicle displays, variable message signs, and variable speed limit signs.

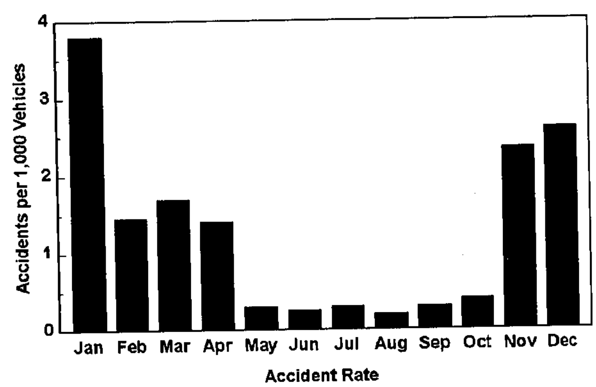

Figure 4. Accident rate by Month (Composite Data from 1988, 1989, and 1991)

This project provides a unique opportunity for evaluation because it includes both an in-vehicle display and variable message signs. The in-vehicle display will be installed in approximately 200 vehicles and the variable message signs will provide information to all highway users. It is expected that the infrastructure support, such as sensors and communications, for the in-vehicle units will be available about one year before support for the variable message signs will be available. This will help make it possible to separate the effects of the two types of driver interface. The evaluation of the performance of the in-vehicle unit is the focus of the discussion in this paper.

QUESTION 1 (Do drivers drive more, or less, safely with the system than without it, in ways related to the system?)

In this project, three methods will be used to answer this question. Details of driver interaction with the in-vehicle unit will be obtained from a driving simulator. The simulator will be used to realistically reproduce conditions where a message would be transmitted to the driver. The simulator will be used to observe driver behavior while driving with the TravelAid in-vehicle unit and without it. Time-to-recognition of the presence of the signal as well as interpretation of the meaning of the signal will be determined. Distraction caused by the in-vehicle unit will also be determined, as will any unsafe driving actions as the result of the distraction. Use of a driving simulator is an element of this evaluation which has not been used in the evaluation of other operational tests. A second method for addressing this question will be to request each user to complete a questionnaire about their experience. They will be requested to record in a post-crossing travel diary all instances when and where they received a signal from the in-vehicle unit as well as their response to the signal. The simulator will also be used as a means of checking and calibrating the answers to these questionnaires. A third method for addressing this question will be the inclusion of instrumentation in the subject vehicles. This instrumentation will be capable of recording time and location of messages as well as keeping a record of changes in speed. There are several challenges associated with acquisition of in-vehicle data. One is to find sufficiently inexpensive instrumentation that can be readily installed in the participants' vehicles. A second challenge will be to separate normal driving activities from those that are precipitated by a message from the in-vehicle unit. The results from the simulator studies may provide a basis for meeting this second challenge.

QUESTION 2 (Do vehicles equipped with the system have fewer, or more, collisions than vehicles without the system?)

The analysis of collision data will consist of three parts. The first part establishes the baseline. This will be done by reviewing collision data for this section of road from previous years. Additional analysis of state and national files will also be done to provide a quantitative description of collision conditions before availability of the TravelAid system. The second part of the analysis will consist of additional statistical analysis of state files after TravelAid is in use. The third part of the analysis will be a detailed investigation of each collision involving a vehicle with an in-vehicle unit. This detailed study of each collision will help establish the impact of the in-vehicle unit on occurrence of collisions.

QUESTION 3 (If all vehicles in the fleet were equipped with the system, would there be a decrease, or increase, in the total number of collisions and collision-related injuries?)

The TravelAid project consists of both an in-vehicle display and variable message sign display of information about hazards. Additionally, the in-vehicle units will be available during the winter of 1993-94 while the variable message signs will not be available until the winter of 1994-95. This provides an interesting possibility for extrapolating the results from the limited number of vehicles with the in-vehicle units to an estimate of effectiveness if all vehicles were equipped. During the first year, data will be gathered on driver reactions to the in-vehicle messages. During the second year, it will be possible to gather the same data, but in this case the driver actions will also be influenced by the information from variable message signs. During the second year, it will also be possible to gather data on the reaction of the general public to the information from variable message signs. These three sets of data can then be combined to provide an estimate of impact on collisions if all vehicles were equipped with an in-vehicle unit and there were no variable message signs. A key element of this analysis will be the opportunity to gather data on the reductions in speed that are produced by the variable message signs and the number of collisions which occur during inclement conditions. Thus, it will be possible to directly test the hypothesis that the number of collisions will be reduced if speed is reduced during snowy and icy conditions and when there are hazards in the road. A number of methodological approaches are being considered for this analysis. A detailed analysis approach will be formalized as the project progresses.

CONCLUSIONS

This paper has developed concepts and reported on results for obtaining answers to three fundamental questions about systems which can have an impact on the safety of driving. The three questions are:

- Do drivers drive more, or less, safely with the system than without it, in ways related to the system?
- Do vehicles equipped with the system have fewer, or more, collisions than vehicles without the system?
- If all vehicles in the fleet were equipped with the system, would there be a decrease, or increase, in the total number of collisions and collision-related injuries?

The paper discusses three systems and the methodologies for obtaining answers to these questions. The systems are discussed in the context of the criticality of the information they provide relative to the need for immediate action to avoid a collision.

The three systems discussed in detail are a route-guidance and navigation system, TravTek, which has been the subject of an operational test; two hypothetical collision avoidance systems; and an in-vehicle hazard warning system, TravelAid, which will be the subject of an upcoming operational test. These systems span part of the spectrum of systems which impact the collision avoidance capability of drivers.

This review of methodologies shows that there is no single approach to achieving answers to the above questions. For the first question, the methodologies include extended highway use of the TravTek route-guidance and navigation system by participants, coupled with in-vehicle data logging and post-driving questionnaires. The TravTek project also included controlled experiments that documented details of the driver interaction with the TravTek system, including relationships between use of TravTek and near misses.

The discussion of collision avoidance systems focused on the need to use test track and laboratory experiments to address the three common functional elements; the sensing element, the processing element and the driver/vehicle interface. It was also pointed out that these tests need to be related to quantitatively described dynamic situations which represent pre-crash circumstances associated with each type of crash. This is especially true of systems which have not reached the point of being available to the public. The methodologies which will be used to evaluate the hazard warning system include the same basic elements as the TravTek evaluation. However, in this case, the controlled experiments will be performed on a driving simulator instead of on the traffic network.

The discussion of methodologies for answering the second question point out the importance of establishing a representative control group which can provide a baseline for comparison of collision rates. This discussion also pointed out the insight on causes and interactions that can be obtained from detailed analysis of each collision that occurs during an operational test.

The paper discusses three different approaches which are being used to estimate the national impact of systems. In the evaluation of TravTek, a computer model which relates collision rates to roadway characteristics and conditions is used to extrapolateresults from the experience of the 100 vehicle fleet that operated for a year. In the evaluation of collision avoidance systems, a statistical approach which combines results from laboratory and test track results with data from crash data files is used. The third approach, which will be used in the evaluation of TravelAid, is to compare results from in-vehicle display of hazard information to a imited subset of drivers with results from the presentation of hazard information to all drivers through variable message signs.

Perhaps the most significant conclusion which can be drawn from this paper is that there is a variety of methodologies that can be used to answer the common set of questions about safety impact. As new projects are started the results from current projects can be used as guideposts for selection of the most appropriate methodologies.

The TravTek project is the only project discussed in this paper which is sufficiently complete to see the results from these methodologies. Even in this project, the evaluation is not complete and the results presented here are based on preliminary analysis. The preliminary analysis suggests that the collision rate during the test was about the same as the national average. The preliminary analysis also indicates that visual turn-by-turn instructions with voice backup appears to provide the highest level of safety; and that the level of safety was not the same for all display configurations. The results also suggest that the level of safety improves as drivers gained experience in use the TravTek system. Finally, the preliminary analysis of data from questionnaires suggests that drivers believed they had fewer close-calls with the TravTek system than with their own vehicle. However, these data also suggest that some of the close-calls may have been related to use of the TravTek system.

CLOSURE

The views expressed in this paper are those of the author, and not necessarily those of the National Highway Traffic Safety Administration. The author is greatful to the members of the TravTek Evaluation Working Group, and especially Dr. Rebecca Fleischman who chaired the group, Frank Mammano who is the FHWA Technical manager for the TravTek evaluation, and members of the SAIC evaluation team for the work which provides a basis for a large part of this paper. The careful review and comment by members of the staff of the NHTSA Office of Crash Avoidance Research and the Volpe National Transportation System Center is greatly appreciated. The work during preparation for publication by Denise Johnson and Wael Mahmoud was indispensable, and their help is greatly appreciated.

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Countermeasure Assessment on Real Crash Sites Part 1 - Description

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94-S3-W-15

ABSTRACT

We present briefly the purpose of the counter-measures, based on longitudinal and lateral control, developed at PSA Peugeot Citroën. Then we describe the hardware framework. This includes the short range communication and video systems involved in the environment detection. The implementation on the vehicle is discussed. Hence we detail the control strategies and we illustrate these procedures on academic examples.

INTRODUCTION

The converging conclusions of all the accidentology studies carried out in recent years have brought into focus the roles of intersections and bends as principal accident sites ; this has motivated PSA Peugeot Citroën to prioritize the scenarios met in these types of event as a counter-measures development theme. As a preambule we must indicate that our approach is designed to offer an assistance to his vehicule, such as for ABS at present, and our approach does not intend any form of automatic driving. We make a distinction between the counter-measures of the longitudinal control type, such as action on the accelerator and/ or brakes, and the lateral control type, such as action on the steering.

LONGITUDINAL CONTROL

For this type of counter-measure, the system must manage the situation with which it is confronted by an action either on the accelerator or on the accelerator and the brakes. We can schematize the problem as shown in figure 1. The system called COPILOT is designed to learn the environment and the dynamic state of the vehicle, as well as the driver's behaviour, in order to deduce a strategy appropriate for action on the accelerator and/or on the brakes, with information supplied to the driver.

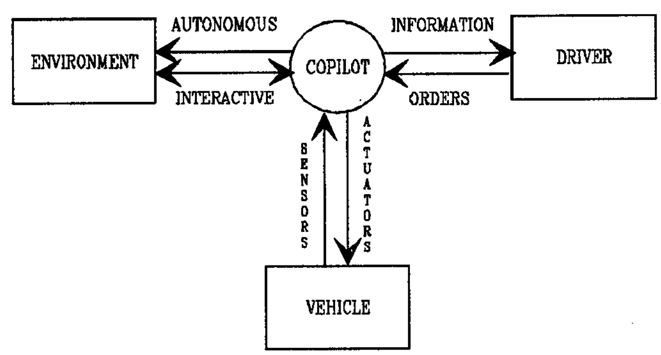

Figure1. Synoptique of the system

The Environment

The environment may be learned by means of autonomous or cooperative acquisition systems. So the vehicle is equipped with an infrared telemetry system (fig.2) which detects all objects situated in front of the longitudinal axis, and measures this distance and speed relative to the vehicle. On a cooperative level, we have an infrastructure-to-vehicle ISIS communication system (fig.2) developped by PSA Peugeot Citroën (1) which supplies information on the road topology (table 1).

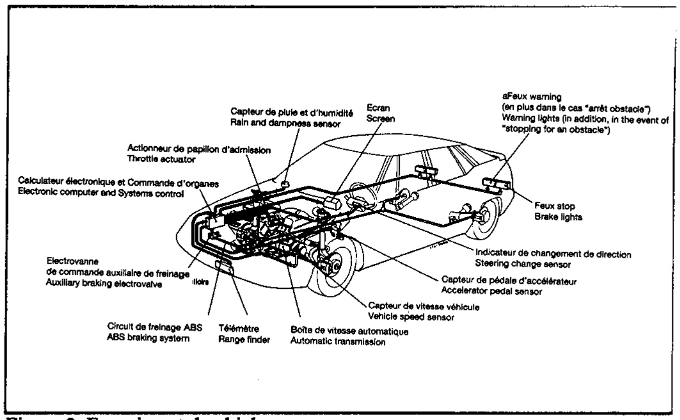

Figure 2. Experimental vehicle

The vehicle

The estimation on the dynamic evolution of the vehicle is obtained by measuring its speed and acceleration. Futhermore, the vehicle is equipped with a VDO motorised throttle and an auxiliary braking system of PSA Peugeot Citroën origin (fig.2 and fig.3), which we describe below.

In the standard car, the driver actuates, through the brakes pedal 3, the braking valve 2. It regulates the pressure sent to front end rear brakes 4a and 4b, through tubes 1a and 1b. It is a "full power" braking device.

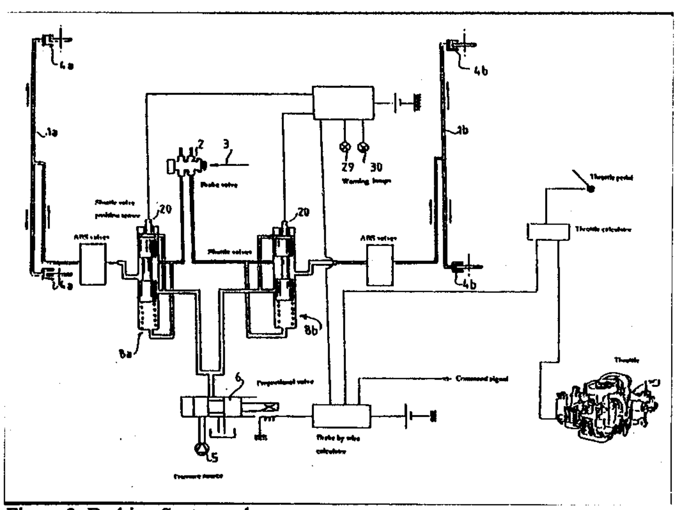
Figure 3. Braking System scheme

The brake-by-wire command incorporates, between the braking valve 2 and the brakes 4a, b a shuttle valve 8a and 8b on each circuit. Each shuttle valve is maintained by a small spring in a preferential position, connecting directly the standard brake circuit, from braking valve 2 to brake 4. The drive-by-wire circuit incorporates a proportional valve 6 arrives to the shuttle source of the car. When the pressure, delivered by the proportional valve 6 arrives to the shuttle valve 8, it is sent at the top end of the valve, which then moves while compressing the spring. The communication between the proportional valve 6 and the brakes 4 is established.

For control and safety, an electronic valve position sensor 20 checks the valve position. Its signal is sent to the calculator for action in case of false operation. At any time, even during the brake-by-wire action, the driver is able to apply the brakes himself : if through pedal 3, an effort is applied to brake valve 2, the pressure generated is sent to shuttle valves 8, and arrives at the bottom end of these valves. When this pressure is higher than the pressure generated by the proportional valve 6, the shuttle valves 8 move, and the direct circuits, between valve 2 and brakes 4 are reestablished. The ABS valves are located between shuttle valves 8 and brakes 4. The ABS works exactly in the same way in both standard and drive-by-wire configurations.

The copilot

This consists of a calculator developped by PSA Peugeot Citroën, arranged around a Motorola 68 HC 11 microprocessor. The programme recurrence cycle is 20 cm (the speedmeter serves as a "spatial clock" in the control process). On each cycle, the calculator

- verifies the eventual arrival of a new beacon
- updates the information relating to the beacon (resulting the actual distance),
- updates the telemetry data (resulting relative speed and distance),
- updates the dynamic state of the vehicle (speed, accelerator).

TYPE OF EVENT	ASSOCIATED PARAMETERS
STOP	•Distance to the stop •Coefficient of friction of the road surface.
BEND	•Distance to the entry •Speed advised for bend entry •Type of bend (left, right, multiple) •Coefficient of friction of the roadway.
SPEED LIMITATION	•Distance to the speed limit zone •Value of the speed limit •Coefficient of friction of the roadway.

Table 1 : ISIS messages

- generates the new commands controlling the actuations,
- informes the driver.

Two types of strategy are put into operation and are related to the type of situation envisaged (beacon or obstacle).

Beacon Strategy

The table 1 groups the types of event represented by this generic term. Generally, the message transmitted to the vehicle informs it of the objective to be achieved (the speed of the order signal Vc) and the distance available to achieve it (distance d_c before the application of the order signal). Knowing the vehicule speed Vv at every instant, the problem may be expressed as : "what is the acceleration Γ_n to be applied to the vehicule in order to achieve the speed Vc after having covered the distance d" or mathematically :

$$\Gamma_n = \frac{Vc^2 - Vv^2}{2d} \qquad (1) \qquad d \in [o, d_c]$$

d_c distance given by the beacon

This expression shows that the acceleration can be positive or negative. As the system developped is a safety system, we are only interested in negative values (decelerations). Futhermore, so as not to take away the driver's responsability, the system must be transparent to the user in the normal driving mode.

Consequently, the automatic braking action will only intervine if the necessary deceleration Γ_n exceeds a certain threshold. This threshold is function of the conditions of adherence of the road surface, of the imperative need to guarantee the safety of the driver and to not upset him in normal conditions.

Obstacle strategy

In this case the distance to the target and the relative speed are both available. A suitable distance dconv may be defined, a function of the speed Vv which must not be approached. The problem may be formulated as : "what is the acceleration Γ_n to be applied to the vehicle to reach the suitable distance dconv with a zero relative speed Vr and a zero relative acceleration " or mathematically :

$$\Gamma_n = \frac{Vr^2}{2(d - dconv)} \qquad (2) : \text{sign of Vr}$$

This expression may be seen to diverge when $d = d_c$. This is not of importance if it concerns a stop at an obstacle. Besides, it is not conceivable to accelerate the vehicle in this type of application ; consequently, only the negative values of Γ_n are interesting. As the two strategies may cohabit, the most penalising is chosen to develop the control commands of the actuators. Also, the command takes the vehicule acceleration into account.

The Driver

The concept assures the driver of permanent control of his vehicle and a total transparence in normal driving situations (analagous to ABS).

It supplies an information service by means of symbols displayed in the instrument unit and by messages transmitted by vocal synthesis concerning the vehicle's environment (road topography, presence of obstacles). In the case of normal driver behaviour, no automatic accelerator or brake activity is undertaken (trigger threshold superior to the normal driving operating threshold). In the contrary case, in the absence of driver reaction, an automatic action occurs. Nevertheless, the driver may at any moment take back control of the vehicle, either by an action on the direction indicator, or by a full-stroke action on the accelerator pedal.

Example : STOP sign with waiting line.

Hypothesis :
Beacon : type STOP
distance : 150 m
adherence : dry road
Vehicle : speed when passing beacon : 100 kph
Telemetry : range : 100 m : minimum distance to stop : 5m.
Waiting line : 10m
Driver : distracted, does not take any action.

Passing before the beacon, the vehicle receives the information : "stop-sign at 150 m, road dry". It immediately informs the driver by signalling a STOP sign symbol on the instrument panel and by emitting a synthetic vocal message "stop at STOP sign". Finally it calculates the necessary deceleration to apply (according to 1) :

$$\Gamma_n = \frac{28^2}{2 \times 150} = 2.6 ms^{-2}$$

This value being inferior to the assistance threshold on a dry road (3 ms^{-2}), the copilot does not intervene. This process is repeated every 20 cm up to the distance of 130,6 m (corresponding to Γ_n = 3 ms^{-2}) where the deceleration is applied to the vehicle. Arriving at 110 m from the stop the telemetry detects the presence of stopped vehicles and calculates the suitable distance to be observed.

dcon = $k \times V$ veh with k = 1.5 s (3)

At this distance from the STOP sign, the speed of the vehicule is 25.69 m/s (braking intensity is $3ms^{-2}$ from the 130,6 m point). The corresponding suitable distance is 38 m, according to 3. The application of the obstacle strategy indicates the necessary deceleration (according to 2)

$$\Gamma_n = \frac{25.69^2}{2 \times (110-38)} = 4.6\ ms^{-2}$$

As the deceleration Γ_n is superior to that required for beacon strategy $3ms^{-2}$, the braking instruction is increased. The process is repeated every 20 cm until the vehicle stops, which will be 5m behind the last vehicle in waiting line or at the mark symbolising the halt at the STOP sign if the waiting line of cars has disappeared.

LATERAL CONTROL

For this type of counter-measure, the system must maintain the vehicle in its traffic lane.

In order to do this, the vehicle uses the white lines painted on the road surface as references. A camera films the roadway. A calculator identifies the position of the white lines on the road and calculates the lateral position of the vehicle as well as its angle of direction. With these data we calculates an instruction sent to the electric motor which controls the direction of the car.

Environment

The system was designed to work on the motorway. However, we are developing our algorithm so that it can be used on trunk or on secondary roads. The counter-measures presented here were developed off-motorway. A standard painted white line on the road surface is the only necessity for the operation of such system, as well as the weather conditions which permit an adequat visibility of these white lines.

The Vehicle

The vehicle is fitted with a small CCD camera, a calculator for the treatment of images and an electric motor which guides the steering of the vehicle (see fig. 4).

When the system is in operation, the steering wheel is disconnected from the wheels of the vehicle, the vehicle then follows the road while the steering wheel remains stationary. At any moment the driver can retake control of his vehicle. By pressing a switch or by giving a small movement to the steering wheel.

The detection of white lines

The method does not require a specially adapted computer architecture. It should enable real time band following to be done on motorways at car speeds up to 130km/h.

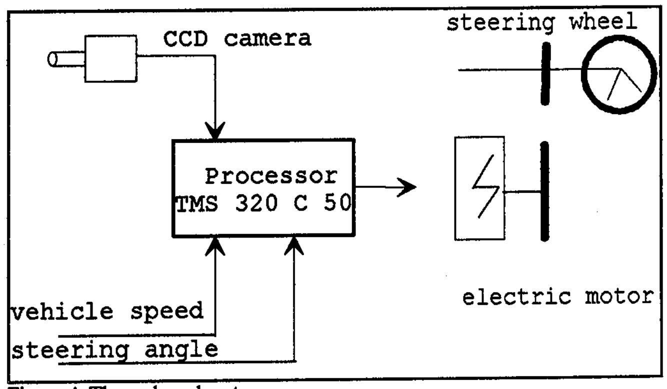

Figure 4. The on board system

The method uses a "prediction-verification-dating" principle.

A camera takes a picture of the road in front of the car. The originality lies in the image processing only along 12 analysis line whose position is fixed, versus the camera, for a given calibration type.

The prediction enables the estimation of the road bands position on each analysis line, and its comparaison to the actual road bands position detected on the next image of the camera. This operation is carried out using a road model integrating the following parameters :

- lateral curve of the road : C
- vehicle abscissa relative to the road center band : X_0
- vehicle horizontal deviation angle relative to road direction : θ

The modelisation selected has the advantage of being linear in regards to the vector parameters. Updating is handled by a quadratic minimization method, integrating a temporal smoothing constraint. The algorithm realises the real time modelling of both roadway and car position in the driving lane (computation of X_0, C and θ).

The small amount of data to be treated has allowed the algorithm to be installed on a standard equipement with a D.S.P. processor from Texas Instrument TMSC 50.

The general algorithm tests on the processing of the image 12 analysis lines. These lines are set and selected in order to get the maximum efficiency from the horizontal marking informations. As previosly remarked, the modelisation uses three dynamic parameters :
C, X_0 and θ.

Initialization must be realised on a straight lane approximately 30 meters long. For this phase, C and θ=0. It is assumed that the car is located in the center of its lane, then X_0 value is known. Subsequently the model predicts a band position. After this prediction phase, each road band is positioned on each analysis line. Then, the detection phase is initiated, which compares the predicted and actual road band position. The model updating procedure is then made in order to have better adaptation to the actual road configuration. The updated model will then allow the prediction of the road band position in the next image, and authorize the new detection phase. The process is then repeated. The model assumes that :

- the road is flat,
- the curve is locally constant,
- intrinsic camera parameters are constant,
- camera pitch angle of inclination, versus horizontal axis is fixed and small (< 10°),
- camera axial axis nearly located on vehicle axis,
- camera height over the ground is constant.

The reader can find more accurate information on this subject in (1) and (2).

The lateral control

With the data extracts X_0 ,θ and C we then calculate a steering wheel angle needed to keep the vehicle in its traffic lane.

We use a simplified model of the vehicle ; the bicycle el (see fig. 5).

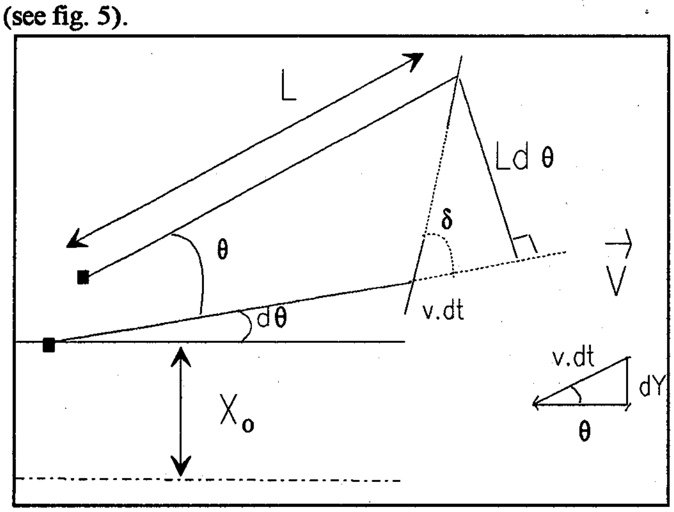

Figure 5. "Bicycle without tyres" model
The "bicycle without tyres " model is used, where the front axe follows the direction of the wheels, the near axe follows the direction of the chassis.
The following dimensions are introduced :
L : lenght of the vehicle from one axe to another.
θ : angle between the angle of the vehicle and the direction of the road.
δ : steering angle of the front axe.
X : lateral position of the vehicle.
v : speed of the vehicle.
θ and Y will be supplied by the system of on-board treatment of images.

With this cinematic model, an instruction angle is calculated to maintain the vehicle in its traffic lane.
This instruction is a function of the angle θ of the lateral offset X_0 and of the vehicle speed.

This very simple approach has allowed us to develop the counter-measures described today.

Experimental Results

Some tests have been done a test track at several speeds. We give here some reference points on typical situation :

- 130 km/h on straight road,
- 90 km/h in a curve with a radius of 600 m,
- 45 km/h in a curve with a radius of 60 m.

All these situations are achieved with good weather, and good quality of white lines.

On the fig.6 we show an example of experimentation. It corresponds to straight line of about 150 m (point 0 to 750), followed by an "s" curve (750-1200) another straight line (1200-1500) and the beginning of an other "s" curve (1500-2000).

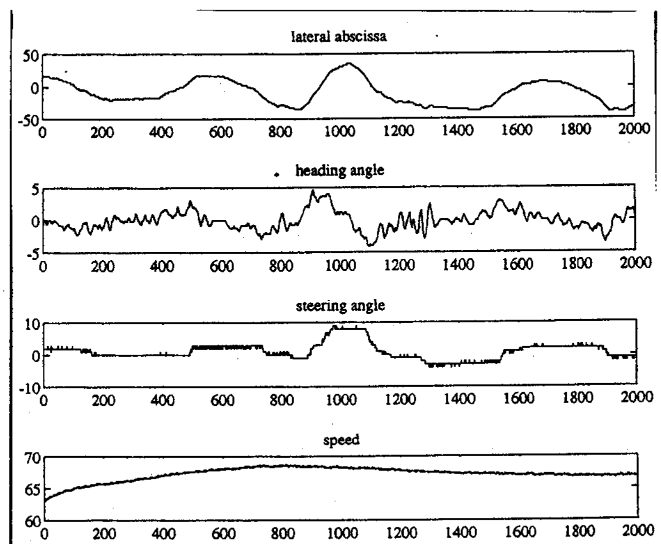

Figure 6. Experimental results

CONCLUSION

The counter-measures presented have demonstrated their efficiency and their robustness both in experimental site conditions and at real accident sites. They are by nature complementary ; it is not intended to install inframed signals on sites which do not have conventional signals, nor will the lateral counter-measures ever being the vehicule to a halt at a stop or allow it to take a corner at a speed higher than that authorised by the physics of the problem. The sale and general use of such equipment poses many questions, both legal (who is responsible in the case of an accident ?) financial (finance for the infrastructure, additional vehicle cost) and political (standardisation of the communication protocal and mode of communication).

The answer to these questions may not be provided by a single automobile manufacturer such as PSA Peugeot Citroën, it implies the cooperation of all actors in the field of road safety (governements, manufacturers), both French and European.

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Technical Session 4

Advanced Frontal Crash Protection: Intrusion and Interior Impact Crash Protection

Chairperson: Ralph Hitchcock, United States

A STUDY OF IMPACT TEST PROCEDURE FOR STEERING WHEEL TO REDUCE FACIAL INJURIES

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ABSTRACT

To study a steering wheel impact test procedure that reflects the actual conditions of automobile accidents in Japan, an analysis of those type of accidents was carried out to determine in which way injuries were inflicted by a steering wheel to a driver's head and face in a head-on collision; i.e., the regions of injury, the types of injuries and the parts of the steering wheel responsible for injuries. As a result, we found that in addition to head injuries, it was necessary to study facial injuries. These include soft tissue injuries which account for more than 70% of the injuries sustained by occupants in the driver's seat in Japan.

Second, in regard to soft tissue damage (the most frequently inflicted case of head and facial injuries), we arranged data concerning the structure and mechanical properties of the skin to develop a new impactor with skin-simulated material. The test conditions were established by taking into account the findings of the analysis of automobile accidents and the behavior of the head of a dummy in a crash.

Finally, we conducted a series of impact tests to determine issues of consideration for an impactor necessary to study soft tissue injuries.

INTRODUCTION

The types of injuries inflicted on the driver by the steering wheel in a frontal crash vary as the ratio of drivers wearing three-point seat belts increases. Specifically, the chest and abdomen of the driver came into contact with the steering wheel the most when the driver was not wearing a seat belt, but the ratio of sustained injuries to the head and face increased when the driver had a seat belt on. In Europe, a headform test was adopted to an impact test procedure for the steering wheel. In addition, the new testing procedures were also proposed for the purpose of protecting the driver's face.

In the present study from the viewpoint of studying a testing procedure, we conducted an analysis of data on automobile accidents in Japan, identifying injuries and the regions of injuries that should be considered for study. This was followed by the establishment of testing requirements and the development of an impactor that is suitable for a study of injuries. We then conducted a series of impact tests for evaluation of the impactor to define issues for consideration in the future as presented below.

ANALYSIS OF ACCIDENT DATA

In an effort to get the real status of injuries attributable to the steering wheel in Japan, we made an analysis of data on automobile accidents arranged by the Ministry of Transport from 1973 to 1992. The Ministry survey vehicle accident data with a view to expand and strengthen vehicle safety standards and to verify the effect of safety regulations. Therefore, the data consists mostly of cases of deaths and serious injuries.

The retrieval and gathering of accident data for the present study were made on the following conditions:

- Vehicles were passenger type.
- Assuming that an automobile crashed in the 11:00 to 01:00 o'clock direction (when the vehicle involved is supposedly heading in the 12:00 o'clock direction), the damage occurred to the front of the vehicle.
- The driver's head or face was injured by the steering wheel.

As a result of data gathered, 119 cases of vehicle accidents and 125 drivers (the number of automobiles) were found to coincide with the above-mentioned conditions. In terms of the use of a seat belt, however, it was disclosed that 37 drivers wore three-point seat belts, one driver wore a seat belt improperly, four wore four-point seat belts, and 85 drivers wore no seat belt. Therefore, the data on the 37 drivers, who were found to have properly worn three-point seat belts, was taken up for study.

At this point, we traced back to the case files of each accident to investigate what part of the steering wheel was responsible for the injuries, the exact region and details of the head and face injuries (some of which were impossible to retrieve from the Ministry's accident investigation data). From these case files, we made a detailed examination of the injured regions and the parts of the steering wheel responsible for those injuries. As a result, the number of injured regions or the number of parts of the steering wheel responsible for those injuries totaled 53, respectively.

<u>**The regions of injuries on the head and face**</u> - Distribution of the regions of injuries on the head and face was divided into regions as presented in Figure 1. The component ratio of each region of injury is shown in Figure 2. The accident data (16 cases), in which injured regions could not be identified, was excluded.

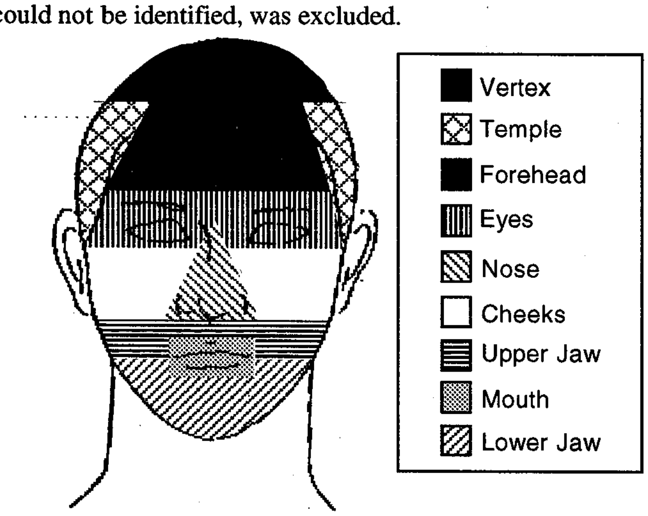


Figure 1. The injury regions on the head and face

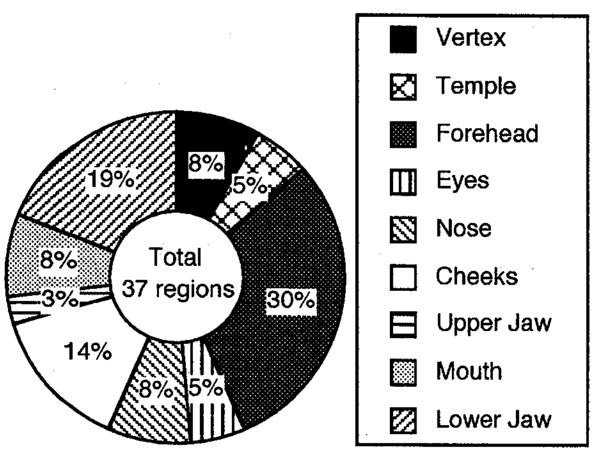


Figure 2. Distribution of the injury regions

In the component ratio of injured regions, the forehead accounted for the largest percentage, followed by the lower jaw. The face was found to have accounted for more than half of all the injuries, when the head and face injuries were compared.

<u>**Injury types**</u> - Figure 3 shows the component ratio of the injury types in all head and facial injuries (53 regions). As for the number of injuries, the most serious cases were counted in each region of injury, for example, brain contusion coupled with a skull fracture was counted as a higher degree of injury.

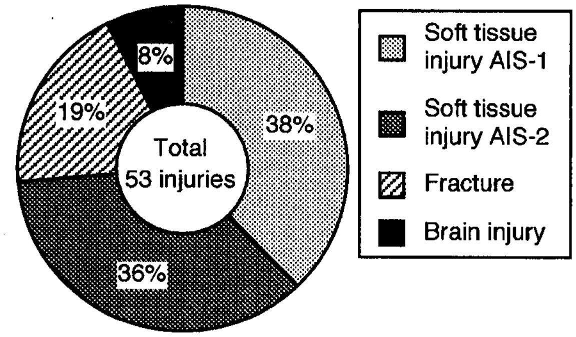


Figure 3. Distribution of injury types

As for the type of head and facial injuries, both minor soft tissue injuries of the AIS1 level and serious ones of the AIS2 level accounted for nearly 40%, respectively. More than 70% of all injuries were found to have been inflicted on the soft tissue when these two were combined. Also, fractures accounted for approximately 20% and brain injury for about 10%.

Shown in Figure 4 are the cumulative injuries relative to an automobile collision speed of equivalent barrier speed for each injury type. A curve of the cumulative injuries varies according to injury types. In terms of 50%ile, soft tissue injuries of the AIS1 level occurred at about 30km/h, those of the AIS2 level at about 40km/h and fractures at between 45 and 50km/h.

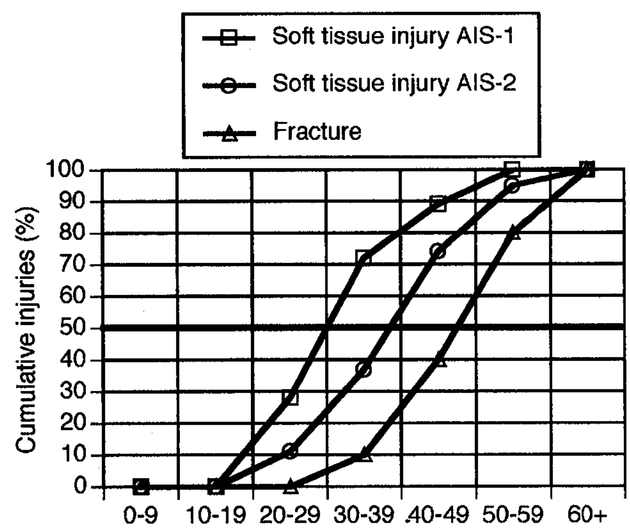


Figure 4. Cumulative injuries relative to the automobile collision speed for each injury type

<u>**Steering wheel contact locations**</u> - Steering wheel contact locations were classified, as shown in Figure 5, for the purpose of totalization. Presented in Figure 6 are the

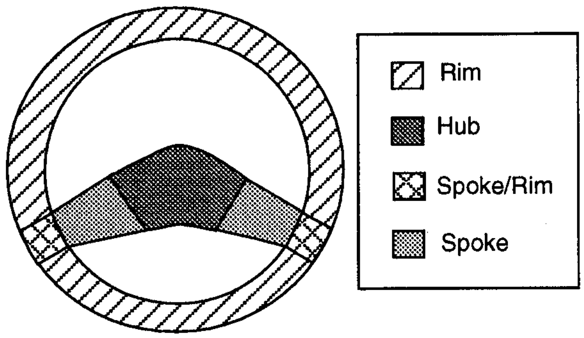


Figure 5. Steering wheel contact location

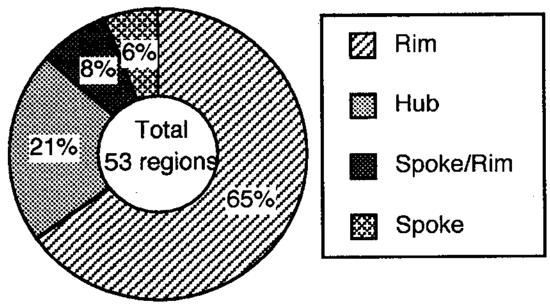


Figure 6. Distribution of the steering wheel contact location

results of totalization. In the component ratio of the contact locations, the rim accounted for the largest percentage (approximately 70%), followed by the hub (about 20%). The rim, and the junction of the spokes and the rim, accounted for more than 70%, indicating that many injuries were attributable to the rim.

Figure 7 shows what parts of the steering wheel are responsible for soft tissue injuries. In all degrees of soft

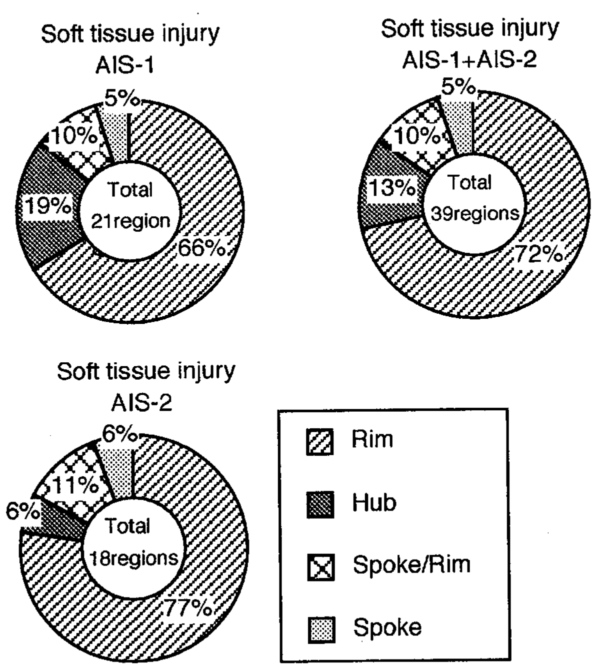


Figure 7. Distribution of the steering wheel contact location causing soft tissue injuries

tissue injuries, the steering wheel rim rates higher in the component ratio of the steering wheel parts which inflicted a soft tissue injuries, accounting for nearly 70% of the responsible parts. In soft tissue injuries of lower degrees, the distribution of the responsible parts of the steering wheel shows little difference from those in the soft tissue injuries of all degrees. In soft tissue injuries of higher degrees, however, the ratio of the hub declines, but the ratio of the rim increases.

As discussed above, it is clear that the face is more likely to sustain an injury than the head, as far as regions of injury are concerned, while the soft tissue is found more liable to be damaged. In the present study, accordingly, we decided to follow a testing procedure primarily designed for a study of facial soft tissue injuries.

IMPACTOR DEVELOPMENT

For the next phase of examination of a testing procedure, we developed new impactors with skin-simulated material.

For this, it is necessary to have a better understanding of the structure and mechanical properties of the skin in producing an impactor tailored for a study of soft tissue injuries. The skin is comprised of the dermis and the epidermis, with the subcutaneous tissue located below the skin. In medical terms, the subcutaneous tissue is known to be relatively weaker than the skin. As a skin-adhering tissue, there is also the retinaculum cutis linking the fascia and the periosteum with the dermis. In addition, the face has facial muscles connecting the bone and the dermis. Shown in Figure 8 is the skin structure ranging from the skin to the bone.

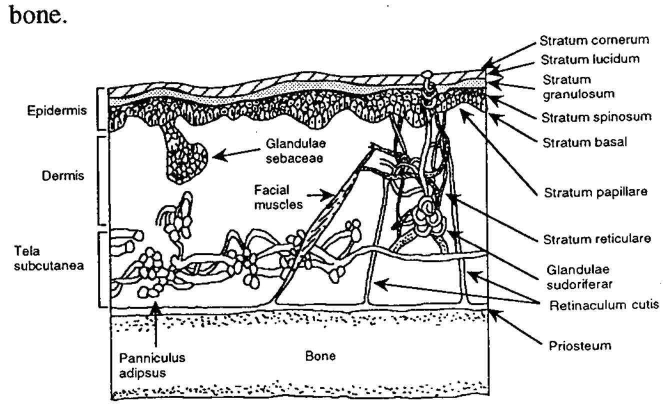


Figure 8. The structure of facial skin

As for the mechanical properties of the skin, the statistics cited in the present study were quoted from published documents. The document (3) shows the strength and strain of each of the human organs and tissues at the point of harm. However, testing conditions and procedure are unknown because these were not mentioned in the documents when this data was gathered.

Shown in Figure 9 is the laceration load of a unit skin width at the typical regions of head and face, with the corresponding laceration stress presented in Figure 10. The

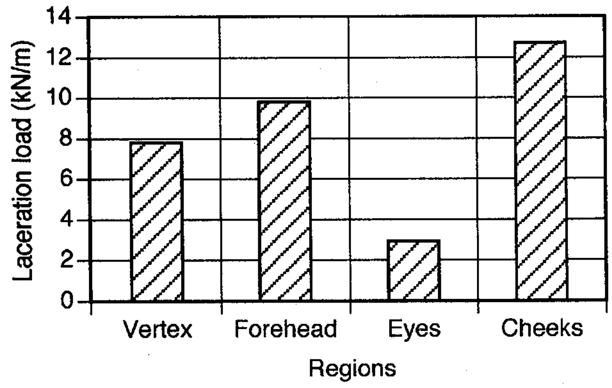


Figure 9. The laceration loads for typical regions

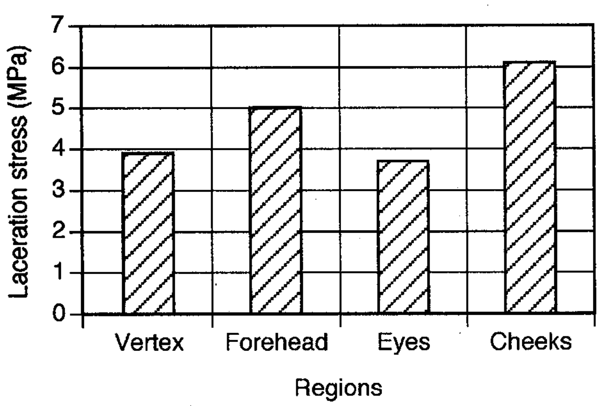


Figure 10. Typical regions of laceration stress

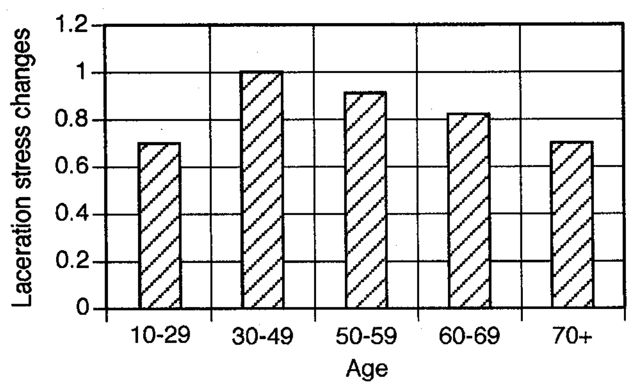


Figure 11. The laceration stress changes according to age

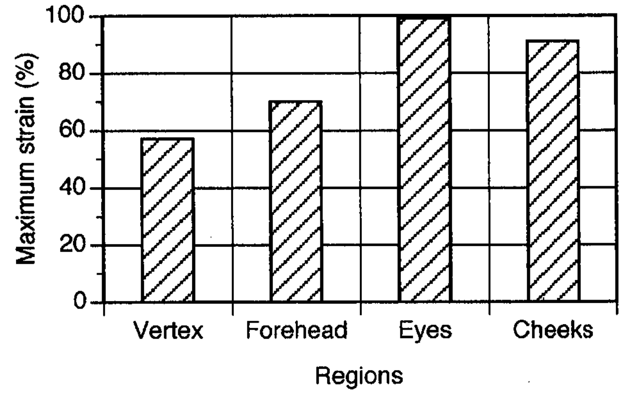


Figure 12. The maximum strain of the skin

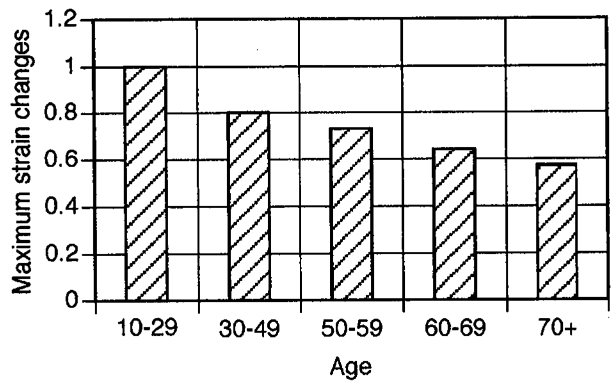


Figure 13. The maximum strain changes according to age

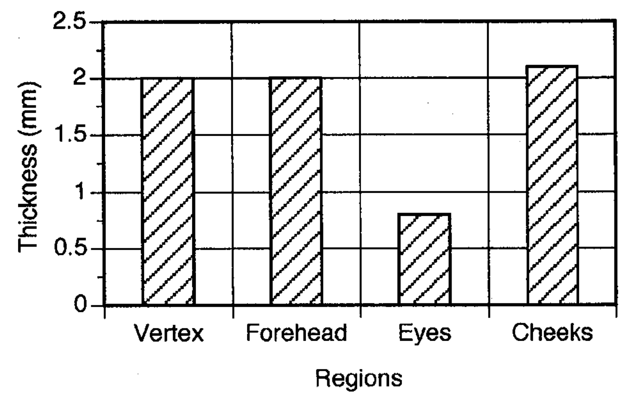


Figure 14. The thickness of the skin

laceration load varies according to regions of the head and face, with the lowest load on the eyes being at about a quarter of the highest load on the cheeks. However, no major differences were observed in the laceration stress of each region of injury. Figure 11 shows changes in the skin laceration stress according to age. The skin laceration stress is highest for people in their 30s and 40s and lower for younger and older age groups.

Figure 12 shows the maximum strain of the skin in the head region. The maximum strain of this skin varies depending on the region of the head and face, the highest strain being for the eyelid skin and the lowest for other areas of the head. Figure 13 represents changes in the maximum skin strain according to age, with the maximum skin strain in the 10 through 20s age group, and strain declining from age 70 to nearly half of the younger age group figure.

The thickness of the human skin was computed on the basis of the relation between the load and the stress presented in Figures 9 to 13, with the results of the computation shown in Figure 14. The thickness of the skin measured approximately 2 mm in all areas, with the exception of the eyes.

Taking into consideration the proposed impact test procedure in Europe, the newly-produced skin-simulated material such as silicon rubber was pasted on the impactor that was developed on the basis of the conventional head-form impactor and the U.K.-recommended honeycomb impactor. A single-layer silicon rubber was made to simulate the epidermis and the dermis of human skin, with the laceration stress and the maximum strain being nearly the same as that of the human skin. Figure 15 shows the appearance of these impactors. Shown in Table 1 is a comparison between the dynamic properties of the human skin and the newly-produced skin-simulated material.

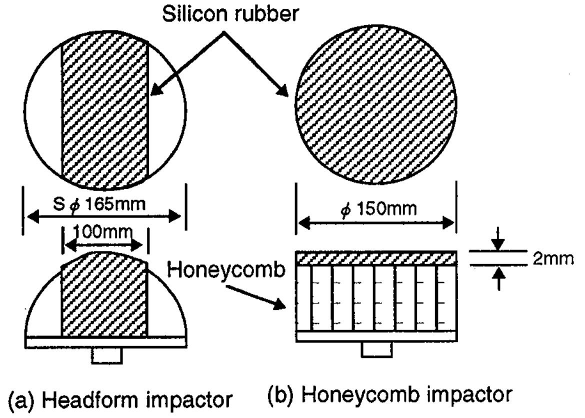


Figure 15. The apperance of the impactors with skin-simulated material

Table 1. The mechanical properties of facial skin and silicon rubber

	Facial skin	Silicon rubber
Laceration stress (MPa)	3.7-6.1	3.6
Maximum strain (%)	57-91	86
Thickness (mm)	0.8-2.1	2.0

ESTABLISHMENT OF TESTING CONDITIONS

__Impact speed__ - The impact speed of an impactor is set at 24.1 to 25.3 km/h, according to the European impact test procedure for the steering wheel. This impact speed was obtained from an impact speed at the center of gravity point of the head of an occupant in the driver's seat relative to the steering wheel at a vehicle collision speed of 40 to 50 km/h. In studying soft tissue injuries, however, it is necessary to obtain a speed at a point where the driver's head and face contact with the steering wheel.

Figure 16 shows a comparison between the speed at the center of gravity of the dummy head and the speed at a contact point on the head surface in sled tests conducted at an impact speed of 50 km/h. The contact point speed is higher than the speed at the center of gravity, specifically, about 1.7 times higher in terms of the timing when the head impacts against the steering wheel. Figure 17 shows the distribution of contact point speeds with respect to the speeds at the center of gravity of the head by adding data from full scale tests to the sled test data. These are presented in terms of the impact speed ratio in Figure 18. The impact speed ratio declines as the speed at the center of gravity increases, possibly influenced by the relative location relation between the head and the steering wheel and the restraining power of the seat belt. More specifically, where the locations of the head and steering wheel are relatively near and the restraining power of the seat belt does not function satisfactorily, the contact point speed and the speed at the center of gravity are believed to show little difference. This is because the impact speed at the center of gravity of the head relative to the steering wheel does not decline and the head does not rotate with the neck as the axis. Where the locations of the head and steering wheel are relatively far and the restraining power of the seat belt on the shoulders works effectively, it is believed the contact point speed is higher than the speed at the center of gravity of the head, causing the impact speed ratio to increase as a result. This is because the impact speed at the center of gravity of the head relative to the steering wheel decreases and the head rotates with the neck as the axis.

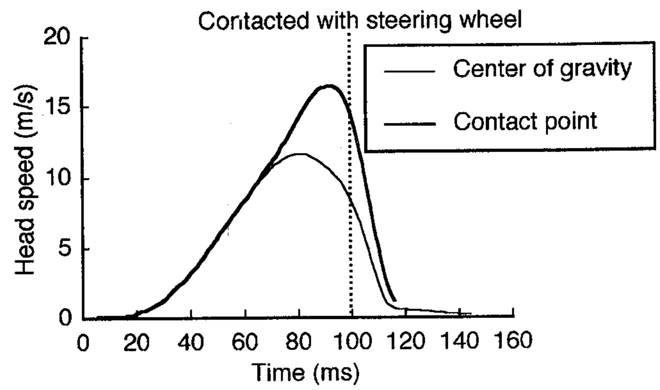


Figure 16. Comparison between the speed at the center of gravity and at the contact point of the head (sled test, impact velocity of 50km/h)

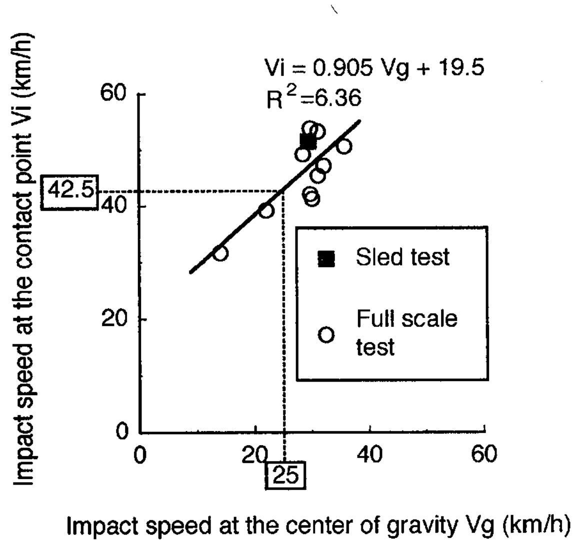


Figure 17. The impact speed at the contact point on the head surface

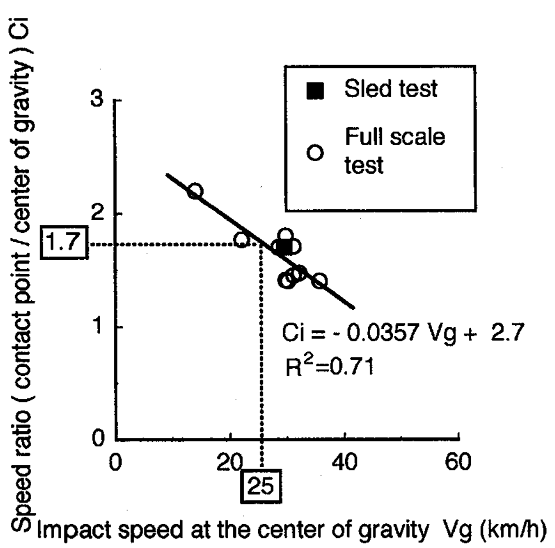


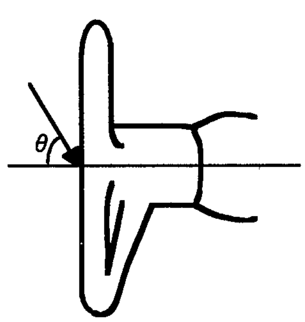
Figure 18. The ratio of impact speed (contact point / center of gravity)

When computed according to a regression formula that was obtained from Figure 18, the contact point speed at about 25 km/h of the impact speed of the impactor (as set in the European impact test procedure) is about 1.7 times the velocity ratio, or approximately 40 km/h.

Impact angle - To study the impact direction of the impactor, an angle of impact at the center of gravity and contact point of the head relative to the steering wheel were analyzed based on the results of sled tests. Shown in Table 2 are the results of a study of the direction of a velocity vector at the center of gravity and contact points of the head on the basis of velocity components of the horizontal and vertical axes of the plane of the steering wheel. The velocity vector at the center of gravity of the head is nearly horizontal with respect to the plane of the steering wheel, but the velocity vector at a contact point is inclined downward relative to the steering wheel. Accordingly, it is necessary to study testing conditions, such as a change of the installation angle of the steering wheel, when tests are conducted to study soft tissue injuries.

Table 2. Direction of the velocity vector of the head

	Sled impact speed	
	40km/h	50km/h
Impact angle at the center of gravity (deg.)	21.6	2.8
Impact angle at the contact point (deg.)	26.6	14.2



Impact point of the steering wheel - The impact position of the steering wheel is set at several points on the hub and rim of the steering wheel, according to the European impact test procedure. The component ratio of the parts of the steering wheel responsible for injuries in the vehicle accident data (Figure 6), shows that the rim accounts for the largest percentage. In the case of soft tissue injuries (Figure 7), the percentage of the rim increases as the degree of injury advances. It is necessary, therefore, to take into consideration a form of impact relative to the rim, when soft tissue injuries are studied.

IMPACT TESTS FOR THE STEERING WHEEL

To study the performance of the developed impactor, impact tests of the steering wheel were conducted in accordance with the aforementioned conditions.

By using a pneumatic cylinder impact machine, the impactor was ejected in free flight in a horizontal direction relative to the ground. The impact speed of the impactor was set at 40 ± 10 km/h with relation to the speeds at the center of gravity and the collision point of the head, specifically, at three speeds of 30 km/h, 40 km/h and 50 km/h. The steering wheel was installed 30° degrees downward, taking into account the behavior of the head at a contact point. The test conditions are presented in Figure 19.

As for the impactor, the skin-simulated silicon rubber was adhered on the impactor based on two models of impactors, specifically, a headform impactor and a

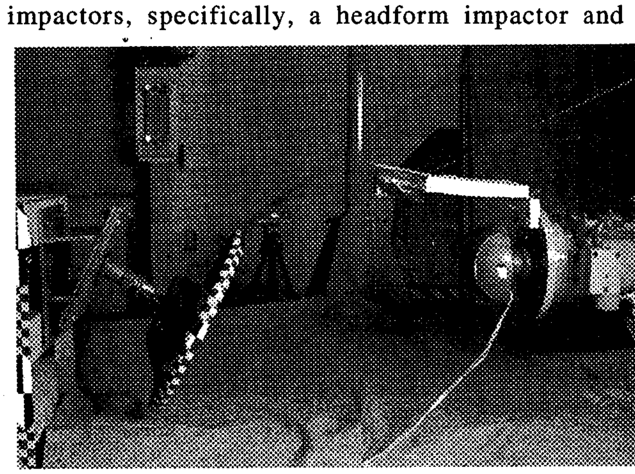
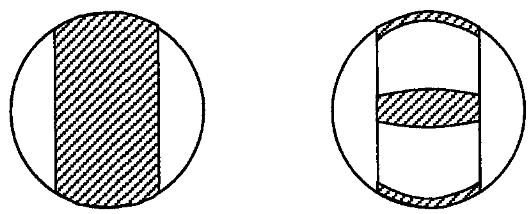


Figure 19. Test conditions



(a) Complete adhering (b) Partial adhering

Figure 20. Adhering area for the silicon rubber to the headform impactor

honeycomb impactor. For adhering the silicon rubber to the impactor, two methods were used. The silicon rubber was completely adhered to one model and partially adhered to the other. The reason for this is that the properties of joining between the skin and bones are unknown (Figure 20).

The contact point on the impactor is shifted from the center of the impactor, as a load is developed in the tensile direction on the silicon rubber at the contact point of the impactor, in the case where the headform impactor is used (Figure 21).

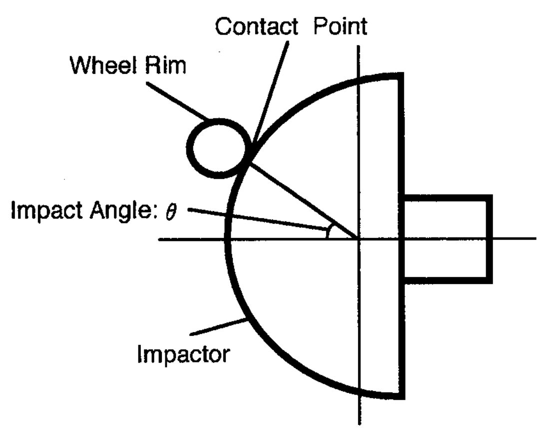


Figure 21. Impact angle of the headform impactor

Nine tests were carried out. In two cases, the silicon rubber broke because of impact with the rim of the steering wheel; in three cases, traces of scratches occured on the surface of the silicon rubber. The condition of the impactor following the tests is presented in Figure 22 and test results in Table 3.

The findings of these tests are as follows:

Comparison of results from the tests using the headform impactor and those using the honeycomb impactor showed that neither a break nor traces of scratches developed on the silicon rubber with the honeycomb impactor. This is apparently because strength in the tensile direction hardly affects the silicon rubber at a contact point because the honeycomb impactor is flat in configuration.

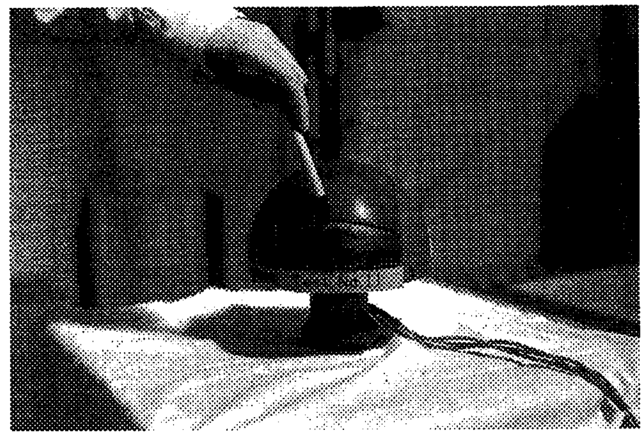


Figure 22. The laceration of skin-simulated silicon rubber

Table 3. Impact test results for steering wheel

Impactor	Adhering	Impact angle on the Impactor (deg.)	Impact speed (km/h)		
			30	40	50
Headform	Complete	-20	—	—	**
		20+	—	—	*
	Partial	-20	○	△△	○
		20+	—	—	△
Honeycomb	Partial	—	—	—	*

○: Laceration, △: Scratch, *: Unhurt

When compared in terms of adhering methods, it was observed that the completely-adhered silicon rubber developed no damage, but the partially-adhered silicon rubber broke or developed traces of scratches. The reason for this is that the strain of the silicon rubber in the tangent direction is prevented when the silicon rubber was adhered completely on the impactor, while strain is anticipated to a certain extent in the case using the partially-adhered silicon rubber. It is necessary, however, to study restraint on the skin in the future, since the method of partial adhering in the present tests did not fully simulate such restraint on the facial skin.

CONCLUSIONS

As a result of the study of an impact test procedure meeting the actual condition of automobile accidents in Japan, the following conclusions and issues for consideration were obtained:

(1) Japanese accident data proves that injuries resulting from contact with a steering wheel in the event of a

head-on vehicle collision are inflicted on the face more frequently than on the head. Accordingly, for driver's wearing three-point seat belts, it is necessary to study not only head injuries, but also facial injuries. In terms of the injury type, the driver frequently sustained soft tissue injuries.

(2) The speed at a contact point of the head and face of the dummy with respect to the steering wheel in a head-on collision was found to be higher than the speed at the center of gravity. Also, the direction of impact was found to have a tendency to incline from the vertical direction relative to the plane of the steering wheel. It is necessary, therefore, to make a review of the speed and direction of impact, when tests are conducted to study soft tissue injuries.

(3) In developing a impactor with skin-simulated material, it is necessary to know the mechanical properties of the skin, such as the maximum laceration stress, the maximum strain, etc., while taking into consideration the joining of the skin and subcutaneous tissue to the bone. It is also necessary to study an impactor, including the shape of the face, since laceration occures due to tangential force with respect to a contact point.

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Foot Loads and Footwell Intrusion in an Offset Frontal Crash

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ABSTRACT

Among all injury causing internal structures of the occupant compartment the footwell area deals with a percentage of more than 8 %. In three of four cases with accidental caused foot fractures a more or less destinct footwell instrusion/deformation must be stated. A high degree of physical disablement, mostly combined with a long lasting recovery period, is the characteristic consequence of even moderate foot injuries (AIS 2 +).

To evaluate the structural crashworthiness of passenger cars the offset crash test has developed to a commonly accepted test procedure. By this crash method the footwell compartment is extensively subjected to stress.

From a series of comparative offset crash tests with five different passenger cars of the subcompact mass class the measurement data of foot loads and objectives of the footwell intrusion are reported. Loads in terms of resultant acceleration range in a wide spread on 200 - 1000 g (1 g = 9.81 m · s -2). The extent of footwell reduction is fairly correlated to the loads. The inner foot position is mostly subjected to generally higher loads. From the loading mechanisms some injury preventional proposals of an advanced design in the footwell area can be derived.

As a contribution to different existing measurement procedures for the footwell reduction a more sophisticated volumetric evaluation method will be proposed. Footwell intrusion, foot loads and foot injuries with relatively severe consequences are highly correlated. Progress of internal safety can be established by means of an advanced deformation measuring method as a tool for a developed and more injury preventive design in this sensible compartment area which is a part of the unabandonable residual room.

RELEVANCE OF FOOT INJURIES

According to the mutual indemnity associations, injuries to ankles and feet consitute one of the highest quotas for stationary treatment; they have the highest complication rate and require most rehabilitation measures. A fracture of the calcaneum or heel-bone, for instance, can lead to permanent damage with a degree of incapacitation of approximately 25%. From a traumatological point of view, injuries to bones in the foot are quite relevant. This also applies unconditionally to accident-incurred foot injuries, the phenomenology and occurrence of which are presented and analysed in an accident study by OTTE [1]. Even if the percentage of foot fractures, distortions and dislocations amounts to only 8.3% of all accident-incurred injuries, more attention than that reflected in the published literature should be given to this type of injury in future, not least because of the magnitude of the accident consequences.

The accident analysis shows that fractures of the foot are directly linked with footwell deformations which are considered to be of a specific nature for the individual vehicle models. Injuries are caused by the fact that the feet are more or less fixed in position on the footrest area and are directly loaded by the shocklike penetration or deformation movement. According to OTTE, the risk of injury to driver or passenger is equally distributed. The accident analysis does not point to a higher risk of injury on account of the pedals protruding into the driver's footwell. The footrest area is that structural surface which is in constant direct body contact with the car occupant and can transfer collision-induced loads directly to the occupant - practically the only other example of this is the steering wheel. In this respect, there is basically no difference between the footwell on the driver's side and that on the passenger's side as long as the position of the driver's feet on the pedals is disregarded. In contrast to the steering wheel which can transmit a direct impact to the hands, the feet are exposed to a rather higher risk of injury with far more serious consequences.

An Australian study [2] comes to quite similar conclusions with regard to the mechanics and severity of accident-incurred foot injuries sustained by both drivers and passengers. In frontal collisions involving belted occupants, the lower limbs were injured in approximately 40% of the cases, about 30% of which were in fact foot injuries (AIS 2+). In 3 out of 4 cases, it was possible to prove that the injuries were basically due to larger intrusions into the footwell.

From the rather limited amount of literature available on the subject "foot injuries" it is apparent that crash-incurred footwell intrusion cannot be defined phenomenologically and, furthermore, cannot be compared objectively. The statements "smaller" or "larger" intrusions in the footwell, which are basically of a qualitative nature, will have to be presented more objectively if design measures are to be taken to combat the danger of severe foot injuries. This study is a first step in this direction.

COMPARATIVE CRASH TESTS

A series of tests involving 5 different subcompact cars which was selected from crash tests performed at TÜV Rheinland is described in the following. The cars were all subjected to a 50 km/h frontal crash with 40% overlap onto a right-angled rigid barrier under the same test conditions. The test weight of the cars, each fitted with two instrumented dummies, was in the range of 719 to 1112 kg. This study disregards many of the results obtained in the course of the test, for instance dummy loads and objective features of the structural deformation behaviour, and concentrates solely on foot loads and structural changes in the driver's footwell.

Foot Load Mechanics

As an example, Figure 1 shows the resultant measured accelerations acting on the feet as a function of time for one exemplary car model. The 3-axial acceleration sensor is based on the body-related system of coordinates and mounted on the metal dummy's foot near the pedal contact zone.

In three of the five tests, the driver's right foot was exposed to higher loads than the left or outside foot, as shown in Figure 2. When acceleration is considered as a function of time, it is apparent that the foot exposed to the lower load is loaded earlier. This slight but, nevertheless, typical time displacement of fairly 10 milliseconds can be explained if one considers the only vertical components of the measured acceleration.

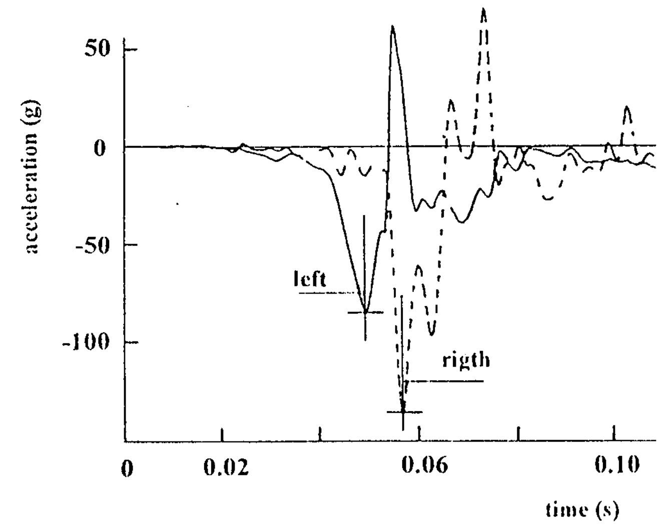

Figure 1: Foot loads on the driver's side, 50 km/h, 50 % offset crash test

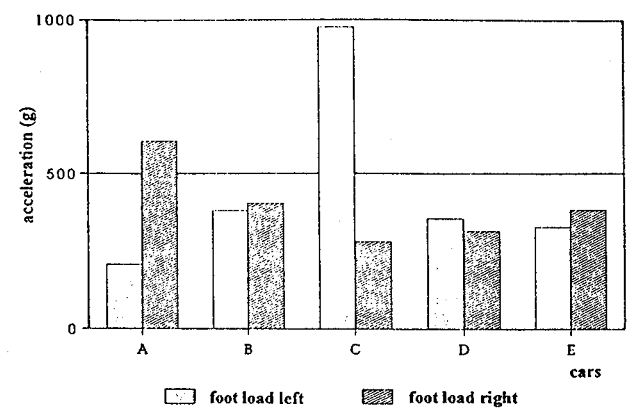

Figure 2: Foot loads on the driver's side, 50 km/h, 40 % offset, 5 cars A - E

First of all, the starting positions of the two feet are different. The accelerating foot is positioned on the accelerator at idling speed and only the heel is in contact with the floor. In longitudinal direction there is a V-shaped gap between the foot and the fire wall. The left foot, in contrast, is in closer, direct contact with the fire wall in the vicinity of the clutch - some cars are even fitted with a special footrest. As a result, the frontal, collision-incurred "shock wave" reaches the left foot earlier.

The specifically higher loading of the inside, accelerating foot is due to two load-mechanical influencing factors. The fire wall in the footwell can essentially be described as a sloping or curved membrane element which is laterally supported on the rigid longitudinal structures of the tunnel or on the sills/A-pillars and partitions off the aggregates in the engine compartment from the footwell. The fire wall is directly stressed and deformed by the backward displacement or compression of the aggregates in the engine compartment. This is clearly shown by the imprints on that side of the fire wall facing the engine compartment. On penetrating into the front section of the footwell, the fire wall has the same momentum and energy potential as the rearward shifting, compressed drive block.

Under the influence of its own forces of gravity, the accelerating foot, which is in an almost upright, unchecked position, is catapulted against the incoming fire wall. The momentum of the foot and that of the fire wall are acting in opposite directions and impinge on each other without any damping, Figure 3.

This assumed load mechanism with specifically higher loading of the right foot has proved to be correct in vehicles with a comparatively large free space between the position of the accelerating foot and the sloping or curved surface of the fire wall in front.

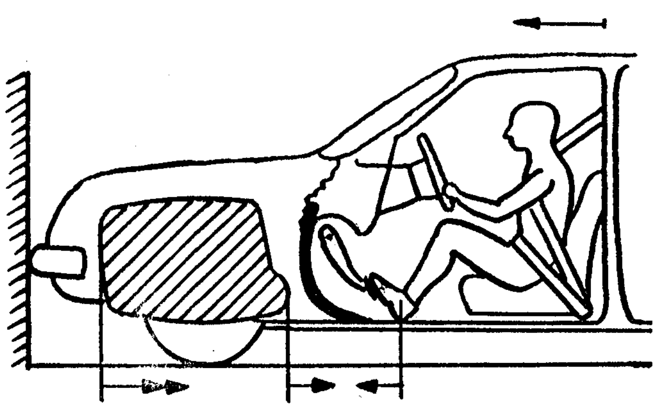

Figure 3: Schematic diagram of foot load mechanics

At the joint of the A-pillar and the sill, the left foot is loaded by frame sections which basically are designed to absorb energy. This load is not amplified by aggregate ingress or by unchecked impact of the foot. The left foot has the advantage of participating in the relatively low deceleration of the vehicle compartment. In the two test cases with higher loading of the outside foot (clutch foot, left), it was possible to verify that the position of the left footrest was unfavourable or that there was definite, local intrusion of hard aggregate contours.

The load mechanism described above can be transferred to the passenger position or to the frontal crash with full overlap with some restrictions. Since the passenger is not forced to keep his feet in a specific position required to drive the vehicle, both feet may be exposed to higher loads if they are not placed in contact with the fire wall but rather are near the seat. The momentum of longitudinal, aggregate-incurred fire wall intrusions is generally lower for a frontal crash with full rather than a partial overlap.

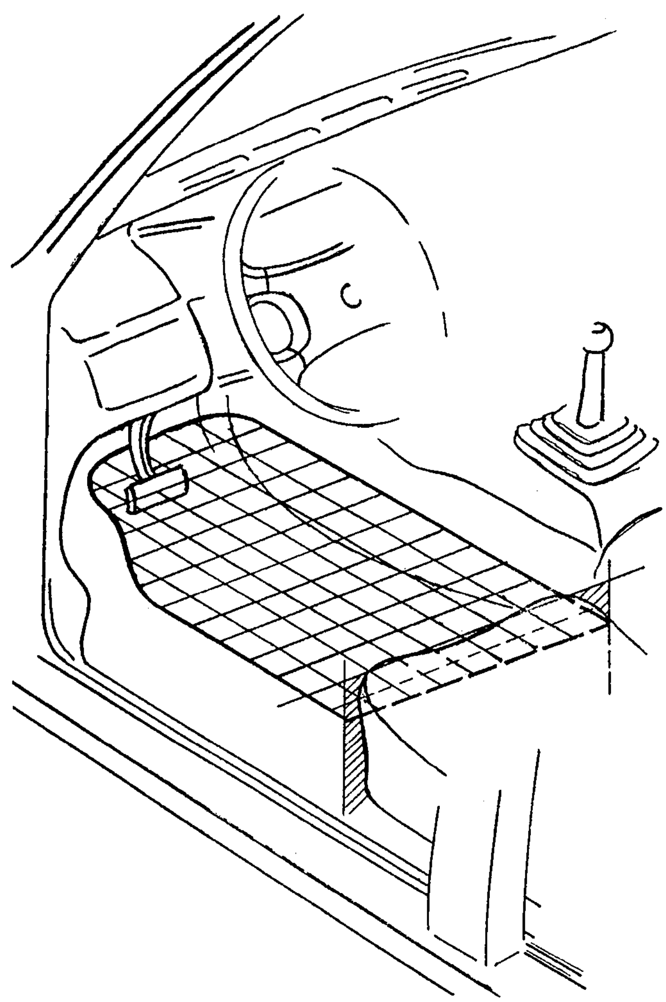

Figure 4: Method to measure footwell area reduction

Method to Measure Footwell Area Reduction

In addition to other deformation characteristics, the static footwell intrusion was determined in the course of the comparative crash tests. The measuring method used for this purpose is briefly described in the following.
Footwell deformation has been established using a reference plane, the area of which is measured before and after the test and subsequently compared. The reference plane is a vehicle-related horizontal plane passing through the middle of the brake pedal in the "pre-test" condition. The shape and size of the reference plane is defined in longitudinal direction by the front of the seat in the respective test position and by its intersection with the fire wall at the front. On the inside, the shape of the reference plane is determined by the normally curved intersection of the tunnel contour and the floor, and on the outside by the sill. In general, the reference plane is shaped like an oversized mat. The difference between the areas measured before and after the test represents footwell reduction, see Figure 4.

Method to Measure Footwell Volume reduction

The footwell area reduction method has been used in several former series of tests. We propose using the knowledge and experience gained in the course of these tests and during evaluation of the results to improve the method.

In individual test cases, which are characterized by folds in the floor, the dummy's feet are trapped or captured by the pedals and the dummy can only be released with considerable mechanical effort. A "hanging" pedal configuration amplifies intrusion of the upper part of the fire wall and, in the worst case, can trap the lower limbs.

Furthermore, dents, bumps and folds can occur in the floor, i.e. below the defined reference plane. Although these can also cause considerable foot loads, the method used to measure footwell area reduction cannot describe this load condition properly.

A more sophisticated but nonetheless simple technique has therefore been developed to measure footwell reduction. It is more suitable for the existing three-dimensional problem and provides comparable test results, fairly independent of the impact direction, and even better correlated with foot loads.

The enhanced concept for measuring and assessing footwell reduction is outlined in the following:

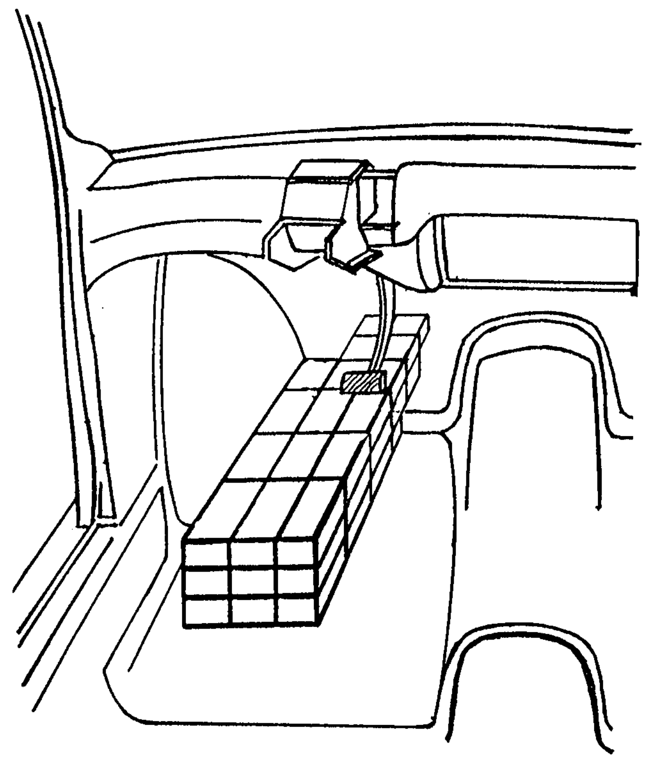

Figure 5: Method to measure footwell volume reduction

The shape and volume of the safety-related footwell is modelled using a modular block. This block consists of small, stackable modules with a very simple shape, e.g. cubes, rectangular or triangular elements. The dimensions of these uniform modules are selected and defined in such a way that they can be used as a criterion to assess the danger of lower limbs being crushed in accordance with DIN 31001 (safety-related design standard) or Military Standard 1472 D (Human Engineering Design Criteria for Military Systems, Equipment and Facilities, US Department of Defence). Consequently pedal movements caused by deformation and local dents and folds in the floor can be measured and assessed more easily.

The modules are stacked in such a way that the contour of the module block corresponds to the contour of the fire wall. The back boundary is the front of the seat or a displaced parallel plane. The width of the module block is a multiple of the width selected for the individual modules and should be defined uniformly for all vehicles as a tolerance criterion for acceptable footwell intrusion. A uniform dimension of [24] cm is proposed for the width of the module block to take account of a tolerable risk of trapping and crushing one or both feet. The total height of the module block is also a multiple of the height of the individual modules. The modules are stacked on top of each other until the block is on a level with or slightly higher than the middle of the brake pedal. Modules should be removed to leave space for the protruding pedals. This means that several horizontal reference planes are still available, see Fig. 5.

Methodically speaking, the proposed, enhanced method for measuring footwell reduction is quite similar to the standardized procedure for measuring the volume of car boots. The main problem is to shape and dimension the modules which are used as templates in this method. Modules with the smallest possible volume (e.g. pellets) could be suitable for the depiction of irregular deformations. However, in order to take account of the risk of trapping and crushing, the modules should represent a foot element as closely as possible. A module with a length of [12] cm and a cross-section of [8x6] cm seems to be most suitable. With reference to the volumetric depiction of folded or dented surfaces which are smaller than the modules, pellets can additionally be used to fill the dents before stacking the modules over them. This can improve measuring accuracy.

The area measuring method is normally retained as well and provides supplementary results for several parallel planes. In addition, this volumetric method provides comparable characteristics for evaluation of the risk of trapping and crushing the lower limbs, even in the case of lateral shock impact and corresponding deformations.

The type and extent of footwell intrusion, as discussed in accident analyses can be made more objective with the measuring method developed here which is similar to the index of outer vehicle deformation. Differently weighted evaluation factors for the risk of trapping either foot, the area-related intrusion values and the volume reduction of the modular block are available to achieve a comparative overall assessment of this local intrusion phenomenon.

Foot Loads and Volumetric Footwell Reduction

Figure 6 presents a simplified block diagram of the foot loads measured for the driver in the 5 cars. Although the accelerating foot was basically in the same position in all cases, different designs of the fire wall between drive block and accelerator led to a wide range of load and instrusion values. This is another difficulty that has to be overcome in the attempt to define objective foot load criterions.

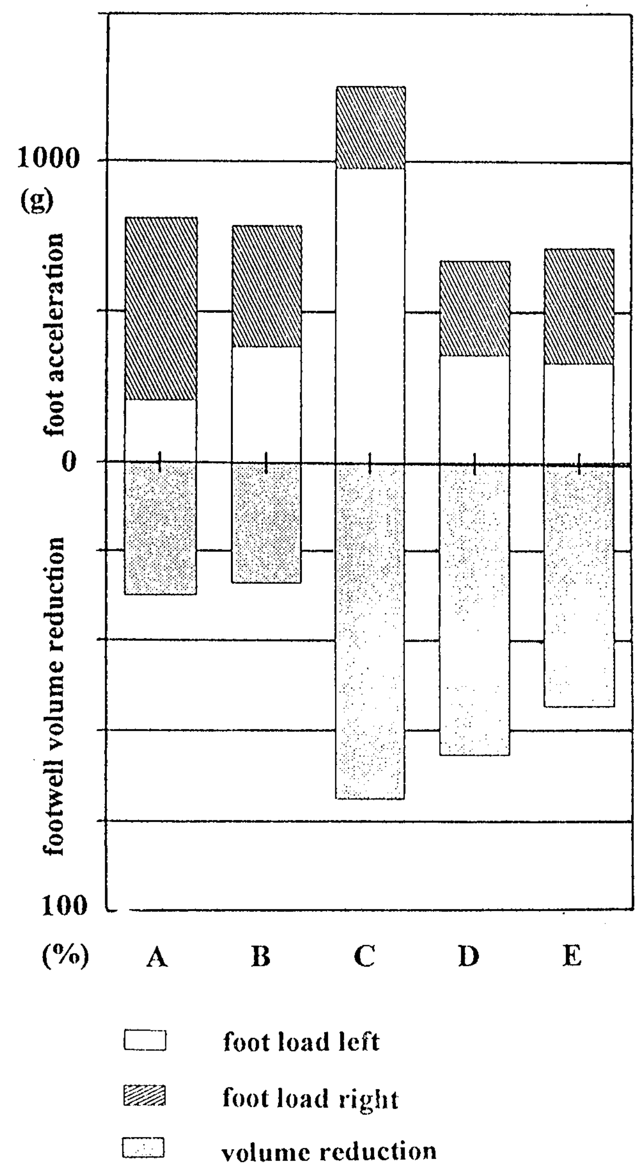

Figure 6: Foot loads and footwell volume reduction in 5 cars A - E, 50 km/h, 40 % offset crash test

The lower diagram part of Figure 6 presents a survey of footwell volume reductions calculated in this way and the corresponding foot loads for vehicles A to E. The fairly good correlation between footwell reduction and foot loads can be seen as a confirmation of the load mechanic model discussed above. Crash-incurred reduction of the reference volume can be subdivided into two zones. At the front, the fire wall is locally or partially pushed inwards, thus shifting its intersection with the reference plane. At the back, the driver's seat can be propelled forwards as a result of the crash, thus contributing to footwell reduction. It is sensible to include possible seat displacement in an assessment of footwell intrusion since this is frequently linked with a drastic change in leg position and with the risk of knee impact and additional loading of the lower limbs [3]. According to [1], a significant percentage of the loads causing injury to the lower limbs is due to the occupant's body being pushed forwards and hitting the lower dashboard, initialized by footwell intrusion.

More Sophisticated Method for Measuring Foot Loads

The methods normally used to measure foot loads today still do not take adequate account of the wide range of injuries. According to OTTE [1], the most important load cases dorsal and plantar flexion as well as pronation and supination can only be depicted in crash tests with dummies with the aid of sophisticated measurement systems. In principle, a system similar to the six axis neck load sensor seems to be necessary to measure the dominant loads of the feet and the lower limbs.

CONSTRUCTIVE IMPROVEMENTS

In three out of four cases, foot fractures are due to footwell deformation [1]. This justifies the demand for protective structural changes in the vicinity of the footwell:

- The fire wall should not be exposed to energy dissipation due to calculated displacement of the drive block. In our opinion, downward displacement of the compressed, almost rigid drive block has not been adequately considered to date.

- The theoretical energy-absorbing capacity of wheels on the impact side is still practically untouched. A tyre may depressurize or the rim may be deformed but these are normally sporadic cases. Indeed, the non-collapsing wheel would in fact seem to have a structural reinforcing effect. Here, the key question is whether approximately one or the other decimeter of available energy absorbing deformation space should be left unused.

- The potential foot loading area at the lower section of the fire wall must be designed to absorb energy. The foot loads could be reduced drastically with layer thicknesses no larger than those of the acoustic covers without any additional structural volume. Furthermore, the danger of the feet being trapped could be combatted with rounded pedals. As a development target, the struck side feet in offset frontal crashes should be exposed to a load of less than 60 - 80 g.

CONCLUSIONS

The footwell is responsible for 8.3% of all injuries caused by internal car structures. In three out of four cases, foot fractures are linked with footwell deformations. Footwell intrusions are to be expected from Δ v = 20 km/h. When compared to other injuries, foot fractures normally have rather serious and economically significant consequences.

A frontal crash against an offset rigid barrier leads to particularly high structural loading of the footwell. From comparative crash tests with 5 different subcompact cars it is apparent that the inside foot is normally exposed to a higher load. The peak acceleration values in this mass class cover a wide range from approx. 200 up to 1000 g.

As an approximation, the type and extent of permanent footwell deformation can be determined with the aid of a method to measure area reduction in a defined reference plane. There is a rather good correlation between footwell reduction and the measured foot loads.

The proposed and practicized supplementary volumetric measuring method can determine three-dimensional footwell reduction more accurately and higly correlating to the measured foot loads.

However, not only sophisticated methods to measure complex foot loads, but also structural, energy-absorbing improvements are urgently required in the footwell area. The risk of trapping must be countered by changing the design of the pedals.

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Development of Measuring System for External Forces Applied to Dummy and for Energy Absorption

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ABSTRACT

During the frontal crash testings, the Anthropomorphic Test Device, the dummy, is subjected to external forces caused by interacting with a restraint system and vehicle interior. The dummy's kinetic energy is dissipated by negative work done by these external forces. In addition, the dummy's injury indexes are caused by them. As measuring the external forces and their energy absorption lead to understanding the physics of dummy's injury, it is important to measure them for the development of restraint systems.

For the purpose of measuring external forces and their energy absorption, 10 newly developed force transducers and 18 linear accelerometers were added to the dummy and the software to analyze measured data was developed. By using newly developed system, the external forces applied to head, chest, pelvis, femurs, and tibias and how it affects each injury indexes could be obtained.

The hyge sled test with passenger side airbag using the developed system has revealed that the peak waveform of chest acceleration is caused because the right hip joint is locked as a result of the femur crashing into the pelvis. It has also clarified the energy absorption process and has revealed that the energy on the lower body is efficiently absorbed through the feet.

INTRODUCTION

Necessity to Measure External Forces and Energy Absorption

During the frontal crash testings, various external forces are applied to the dummy. On the other hand, injury indexes such as head injury criterion (HIC), chest acceleration, femur axial forces are either acceleration or force and are determined by the sum of external forces applied to each part. Consequently, these external forces cause the dummy's injury.

External forces applied to the respective part of the dummy are classified into two: external forces caused by interacting with the restraint system and vehicle interior, and external forces transfered through the other part of the dummy. Takeda[1] presented that the dummy's injurys are affected not only former but also the latter.

Measuring external forces is important for understanding the mechanism to cause the dummy's injury. Ten years, for instance, have passed without the analysis of pelvic interference physically since was first presented[1]. This is because current measuring method can not sufficiently explain this phenomenon.

The dummy's kinetic energy is absorbed by the negative work done by external forces applied to each part of the dummy to cause it to stop. The way how the dummy's kinetic energy is absorbed, therefore, is important for the development of a restraint system.

On the other hand, the work done by external forces is given by scalar product of each external force and the displacement of its point of action. This means that even if the external force is large, energy absorption is not large, if the displacement of point of action is small. On the contrary, even if the external force is small, energy absorption is large, if the displacement of point of action is large. Generally, the amount of external forces applied to the dummy is proportionate to the dummy's injury indexes. Although the external forces of the former causes larger injury indexes, the energy absorption efficiency is low. On the other hand, the external forces of the latter causes smaller injury indexes, and the energy absorption efficiency is high. Therefore, it is important for the development of a highly efficient restraint system to reduce the external forces with low rate of energy absorption.

In addition, as the displacement of the point of action of external forces relates to inertial coordinate system, the work done by external forces is not only affected by the relative displacement of the point of action to a vehicle, but also by the displacement of a vehicle in the inertial coordinate system. This energy is absorbed by a vehicle and this absorption is referred to as the ridedown effect, which is considered harmless way to absorb the dummy's kinetic energy. It is important to increase the amount of ridedown energy for the development of the restraint system.

Bonello[2] presented that the kinetic energy of a segment is not only directly transferred through the restraint system and dissipated, but also from one segment of the dummy to other segments and the energy transfer between the segments is important for reviewing the balance of the restraint system.

For the above reason, it is important to measure the external forces applied to each part of the dummy, and its internal forces and energy absorption for the development of the restraint system.

Problem in Measuring External Forces

For the measurement of external forces caused by interacting with the restraint system and the vehicle interior, force transducers may used to measure all the forces, but this is not practical as measuring is extremely difficult. A simple method is to estimate the contact force of the dummy with restraint system and vehicle interior using Newton's motion equation[3] [4], assuming that the head is a rigid body, and measuring the neck reaction force applied to head by the neck transducer. Authors [5] presented that this method was used for the chest and pelvis. But this method has not been used for other part of the dummy.

On the other hand, for applying the method [3], namely the external forces transfered between the segments, internal force, and the acceleration of the center of gravity of segment, must be measured.

To measure the internal force applied to the end of segment, force transducers [6] are existed. The values measured by them represent the forces applied to the sensitive center of force transducer and are different from the internal forces applied to the end of a segment due to the inertial force caused between the sensitive center and the end of a segment. Consequently, if the mass and inertial moment between the end of segment and sensitive center isn't negligible, the effect of the inertial force must be corrected.

To measure the acceleration of the center of gravity of segment, accelerometers are required to be mounted on the center. Mounting accelerometers on the center, however, is not always possible except for the head. On the other hand, the acceleration measured by accelerometer at other than the center of gravity represents different value from that measured at the center of gravity due to the effect of angular motion of segment. Measuring the angular motion of a segment, therefore, is required.

As is well known, angular motion of the segment can be measured by the accelerometers[7] and by the angular velocity sensors[8]. But 3 dimensional analysis of either one of these is extremely difficult.

Problem in Measuring Energy Absorption

Measuring energy absorption done by the external forces applied to the dummy are known two ways : (1)

measuring negative work done by external forces, and (2) determining the amount of energy absorption from the changes of kinetic energy of a segment.

The negative work done is given by the scalar product of external force and the displacement of its point of action. Consequently, to obtain the negative work done by the external force, it is required to get external force and the displacement of its point of action. Although the internal forces measured by the force transducer can be defined the point of action, the residual external forces applied to the segment, however, can not be generally defined.

On the other hand, Evans [8] presented to obtaine energy absorption of external forces from the changes of kinetic energy of a segment, but as it neglects the angular motion, it yields an error when the angular motion of a segment is large in the latter half of the crash event. Furthermore the method [8] can not provide how many external forces are applied to what parts of the dummy and how much energy is absorbed by each external force.

Also known is the method to integrate the acceleration obtained with the displacement of the point of action of external forces. However, the acceleration measured by a linear accelerometer fixed to a segment changes its direction with the angular motion of a segment. Consequently, as simple integration of the measured values will not yield the correct velocity and displacement, the acceleration must be converted to values in the inertial coordinate system reference prior to integration of the measured values, with due consideration to the angular motion of the segment.

The portion of dummy's kinetic energy that is absorbed by a vehicle is referred to as the ridedown energy. The conventional method which calculate the ridedown energy may not obtain the energy absorption done by a vehicle because of assuming no mass of the restraint system. It is extremely difficult to calculate the ridedown energy with considering the mass of restraint systems.

METHODOLOGY

Each segment of the dummy is measured and analyzed as follows, assuming that the segment motion during a frontal crash can be approximated as planar motion.

Measuring Angular Motion

Linear acceleration of a rigid body changes by the effect of the angular motion at its position on the body. Method [7] is known to measure angular motion based on this principle by measuring linear acceleration at different locations. This method, however, requires nine accelerometers to measure 3 dimensional angular motion, and complex calculations.

A simplified method was used on the assumption that the motion of the dummy is 2-dimensional in the XZ plane. This method uses two linear accelerometers at respective segment of dummy to measure angular motions. The accelerometers are fixed in the same XZ plane, and their sensitive axis is oriented perpendicular to the line connecting the two accelerometers.

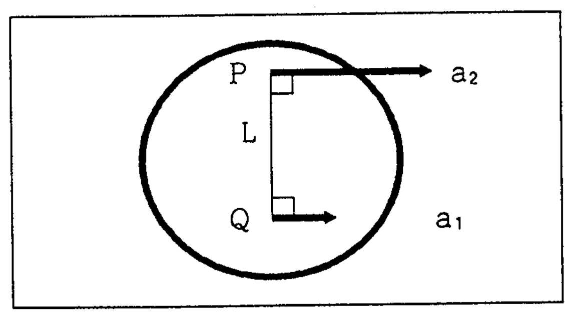

Figure 1. Method for measuring angular acceleration

The angular acceleration of a segment for Fig. 1 is given by EQ(1), and the angular velocity by EQ(2) and angle by EQ(3).

$$\dot{\omega}_y = (a_1 - a_2)/L \qquad (1)$$

$$\omega_y = \int_0^t \dot{\omega}_y dt \qquad (2)$$

$$\theta_y = \theta_{y0} + \int_0^t \omega_y dt \qquad (3)$$

$\dot{\omega}_y$:angular acceleration about Y axis

L :distance between point P and Q

a_1 :acceleration of point P

a_2 :acceleration of point Q
ω_Y :angular velocity about Y axis
θ_Y :angle about Y axis
θ_{Y0}:initial angle about Y axis

Acceleration at the Center of Gravity

In order to estimate external forces using Newton's motion equation, the acceleration of the center of gravity of the segment must be obtained. Mounting the accelerometer on the center of gravity, however, is not always possible. On the other hand, accelerations measured off the center of gravity and on the center differ as an effect of angular motion. The linear acceleration measured off the center of gravity, point P, is converted by EQ(4) to obtain the acceleration at the center of gravity.

$$a_{cg} = a+\omega\times(\omega\times r)+\dot{\omega}\times r \qquad (4)$$

a_{cg} :acceleration of the center of gravity
a :acceleration of point P
r :position vector of the center of gravity relative to point P
ω :angular velocity of segment
$\dot{\omega}$:angular acceleration of segment

Measuring Displacement

Linear acceleration measured at the center of gravity of a segment using the accelerometer fixed in the segment changes its direction with the angular motion of the segment, and direct integration will not provide the correct velocity and displacement. Consequently, the measured acceleration requires to convert the component of acceleration as measured in the local coordinate system fixed in the segment to its component in the inertial coordinate system reference. The conversion matrix of these two coordinate systems are obtained by the direction cosine matrix, EQ(5).

$$D = \begin{pmatrix} \cos\theta_Y & 0 & -\sin\theta_Y \\ 0 & 1 & 0 \\ \sin\theta_Y & 0 & \cos\theta_Y \end{pmatrix} \qquad (5)$$

θ_Y :angle of segment about Y axis
D :direction cosine matrix

Here, the acceleration of the center of gravity in inertial coordinate system reference is obtained by EQ(6).

$$a_{cgi} = D^{-1} a_{cgl} \qquad (6)$$

a_{cgi} :acceleration vector of the center of gravity in inertial reference
a_{cgl} :acceleration vector of the center of gravity in local coordinate system reference

The velocity at the center of gravity and its position are obtained by EQ(7) and EQ(8).

$$v_{cgi} = v_0 + \int_0^t a_{cgi}\, dt \qquad (7)$$

$$p_{cgi} = p_0 + \int_0^t v_{cgi}\, dt \qquad (8)$$

v_{cgi} :velocity vector of the center of gravity in inertial reference
v_0 :initial velocity vector of the center of gravity
p_{cgi} :position vector of the center of gravity in inertial reference
p_0 :initial position vector of the center of gravity

Measuring Dummy Internal Forces

Forces applied to each segment consist of the ones applied between segments, and of those that are caused by direct contact of the dummy with the restraint system and the vehicle interior. Out of these, a dummy mountable force transducer was developed and installed for measuring these forces. These measured forces and moment, however, are the forces obtained at the sensing center of force transducers. In addition, the transducers may not necessarily be installable at the end of a segment. On the other hand, the forces measured within the segment and the external forces applied to the end of the segment differ due to the effect of inertial forces, and the measured forces must be converted to derive the one at the end of the segment.

For this, a rigid body shown in Fig. 2 is introduced. Fig. 2 shows a segment with force transducer mounted on it to measure forces, and the sensitive center is point T.

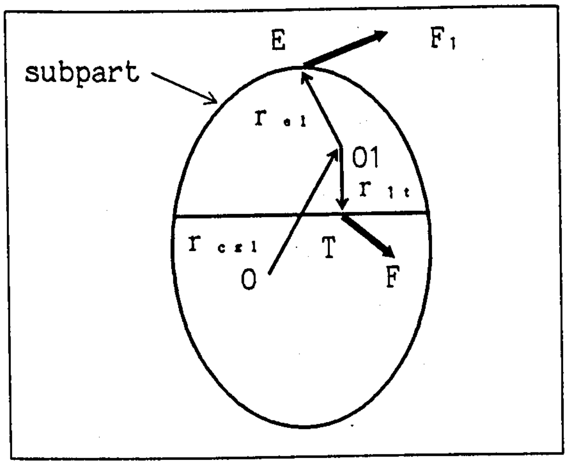

Figure 2. Geometry of rigid body

The part above the mounted transducer is a sub part. External force and moment, F_1 and M_{y1} respectively are applied to the end of the sub part, point E, and no other external force is assumed to be applied to the sub part. The acceleration at the point 01, the center of gravity of the sub part of segment, relates to EQ(9) in respect to the acceleration at the center of gravity of segment, point O. As F_1 and reaction of F is applied to the sub part, the sub part yields motion equation, EQ(10). By solving EQ(10) with F_1, EQ(11) is derived. Next, using angular motion equation about y axis, EQ(12) is derived. By solving the EQ(12) with respect to M_{y1}, the EQ(13) is derived.

$$a_1 = a + \omega_y \times (\omega_y \times r_{cz1}) + \omega_y \times r_{cz1} \qquad (9)$$

$$m_1 a_1 = F_1 + (-F) \qquad (10)$$

$$F_1 = m_1 a_1 - (-F) \qquad (11)$$

$$I_{yy}\dot{\omega}_y = (-M_y) + M_{y1} + (-F) \times r_{1t} + F_1 \times r_{1e} \qquad (12)$$

$$M_{y1} = I_{yy1}\omega_y - (-M_y) - (-F) \times r_{1t} - F_1 \times r_{1e} \qquad (13)$$

a : acceleration vector of the center of gravity of segment
a_1 : acceleration vector of the center of gravity of subpart
ω_y : angular velocity of segment about Y axis
$\dot{\omega}_y$: angular acceleration of segment about Y axis
m_1 : mass of subpart
I_{yy1} : inertial moment of subpart
F : force vector applied to point T.
M_y : moment applied to point T
F_1 : force vector applied to point E
M_{y1} : moment applied to point E
r_{cz1} : position vector of point 01 relative to point O
r_{1t} : position vector of point T relative to point 01
r_{1e} : position vector of point E relative to point 01

Method for Estimating Residual External Forces

As the force caused by direct contact of the dummy with a restraint system and the vehicle interior can not be directly measured by a force transducer, it is obtained by expanding the estimation method [3].

Fig. 3 shows a model whose segment has several applied external forces.

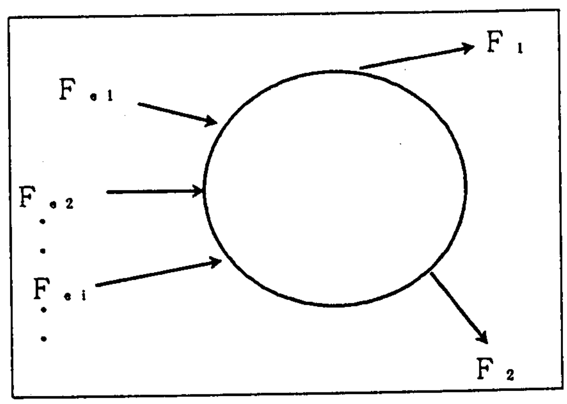

Figure 3. Model of external forces applied to a rigid body

The segment yields the motion equation EQ(14).

$$ma = \Sigma F_i + \Sigma F_{ei} \qquad (14)$$

m : mass of segment
a : acceleration vector of the center of gravity of segment
F_i : ith internal force vector acting on segment
F_{ei} : ith external force vector except F_i acting on segment

EQ(14) is solved to obtain ΣF_{ei} by EQ(15). By measuring each of the right side terms in EQ(15), the sum of residual forces applied to a segment, ΣF_{ei} is obtained.

$$\Sigma F_{ei} = ma - \Sigma F_i \qquad (15)$$

Next, from the angular motion equation of a segment, EQ(16) is derived. Also, by solving EQ(16) with the sum of residual moment applied to a segment, EQ(17) is obtained.

$$I_{yy}\dot{\omega}_y = \Sigma F_i \times r_i + \Sigma F_{ei} \times r_{ei} + \Sigma M_{yi} + \Sigma M_{yei} \qquad (16)$$

$$\Sigma M_{yei} + \Sigma F_{ei} \times r_{ei} = I_{yy}\dot{\omega}_y - \Sigma F_i \times r_i - \Sigma M_{yi} \qquad (17)$$

Measuring Energy Absorption

To measure energy absorption, there are two ways as described above: (1) to measure directly negative work done by external forces, (2) to measure the changes in kinetic energy.

As points of action can be defined, the work done by external forces is directly measurable to find the energy absorption of external forces delivered at the end of a segment. First, as energy absorption is the reduction of kinetic energy, EQ(18) is written.

$$dEA = -dKE \qquad (18)$$

As the work done by external forces equals the changes in kinetic energy, EQ(19) is written.

$$dKE = d(\Sigma W_i) \qquad (19)$$

By substituting EQ(19) into EQ(18), EQ (20) is given.

$$dEA = -\Sigma dW_i \qquad (20)$$

The energy absorption and the negative work done are related as expressed by this equation. In other words, the energy absorption done by an external force is obtained by finding the negative work done by it. Next, as the work done by an external force is obtained from the scalar product of the external force and the displacement of its point of action, EQ (21) is given.

$$dW_i = F_i \cdot ds_i + M_i \cdot d\theta_i \qquad (21)$$

ds_i, $d\theta_i$ of EQ (21) are given by EQ(22), EQ (23) and EQ (24) respectively.

$$ds_i = \left(\frac{ds_i}{dt}\right)dt = v_i\,dt \qquad (22)$$

$$v_i = v_{cz} + \omega_y \times r_{czi} \qquad (23)$$

$$d\theta_i = \left(\frac{d\theta_i}{dt}\right)dt = \omega_y\,dt \qquad (24)$$

Consequently, by substituting EQ(22),EQ (23), and EQ(24) into EQ(20), EQ(25) is derived.

$$\left(\frac{dEA_i}{dt}\right) = -F_i \cdot (v_{cz} + \omega_y \times r_{czi}) + M_i \cdot \omega_y \qquad (25)$$

With this equation, the energy absorption done by an external force applied to the end of a segment can be calculated.

The energy absorption of external forces caused by contacting the dummy with a restraint system and the vehicle interior is obtained by the following procedure, as the point of action of such external forces can not be defined. The work done can be divided into (1) the work done by the internal forces and (2) the work done by the residual external forces. EQ(26) can be obtained by dividing the right side of EQ(20) into each term.

$$dEA = -\Sigma dW_i = -(\Sigma dW_i + \Sigma dW_{ej}) = d\Sigma EA_i + d\Sigma EA_{ej} \qquad (26)$$

By solving EQ(26) with d Σ EAej, and substituting EQ(18), EQ(27) is derived.

$$d\Sigma EA_{ej} = dEA - \Sigma dEA_i = -dKE - d\Sigma EA_i \qquad (27)$$

On the other hand, kinetic energy of a segment can be obtained from EQ(28) with considering the linear and angular motions.

$$KE = mv^2/2 + I_{yy}\omega_y^2/2 \qquad (28)$$

By substituting EQ(28) into EQ(27), EQ(29) is derived, and the energy absorption done by the external forces caused by contacting the dummy with the restraint systems and the vehicle interior can be obtained.

$$\frac{d}{dt}(\Sigma EA_{\bullet i}) = -\frac{d}{dt}(mv^2/2 + I_{yy}\omega_y{}^2/2) - \Sigma\left(\frac{dEA_i}{dt}\right) \quad (29)$$

KE :kinetic energy of segment
EA :absorbed energy of segment
W_i :work done by external force and moment acting on ith point
F_i :external force acting on ith point
M_i :external moment acting on ith point
s_i :displacement of ith point
θ_i :angular displacement of ith point
I_{yy} :inertial moment of segment about Y axis
ω_y :angular velocity of segment about Y axis
m :mass of segment
v :velocity vector of the center of gravity of segment

Calculation of Ridedown Energy

New definition of the ridedown energy, which is the energy transfer caused by the displacement of vehicle, was introduced by expanding and generalizing the conventional method.

The work done by an external force is given by the scalar products of the force and the displacement of its point of action, which can be divided into two: (1) displacement of a vehicle, and (2) relative displacement of point of action to the vehicle, shown in EQ(30) and EQ(31). As the ridedown energy is the energy absorption that is caused by the displacement of the vehicle, EQ(21) is rewritten as EQ(32) by substituting EQ(30) and EQ(31).

$$ds_i = ds_{vi} + (ds_i - ds_{vi}) \quad (30)$$

$$d\theta = d\theta_v + (d\theta - d\theta_v) \quad (31)$$

$$\begin{aligned} dW_i &= F_i \cdot ds_i + M_i \cdot d\theta \\ &= \{F_i \cdot ds_{vi} + M_i \cdot d\theta_v\} \\ &+ \{F_i \cdot (ds_i - ds_{vi}) + M_i \cdot (d\theta_i - d\theta_v)\} \end{aligned} \quad (32)$$

$$dW_{ri} = F_i \cdot ds_{vi} + M_i \cdot d\theta_v \quad (33)$$

$$ds_{vi} = ds_v + d\theta_v \times r_i \quad (34)$$

The first term on the right side of EQ(32) is the work done by the displacement of the vehicle, and EQ(33) is attained. The displacement of point of action of ith internal force can be expressed by using the linear and angular displacement of vehicle. By substituting EQ(34) into EQ(33), the ridedown energy is obtained by EQ(35).

$$\begin{aligned} dEA_{ri} &= -\{F_i \cdot (ds_v + d\theta_v \times r_i) + M_i \cdot d\theta_v\} \\ &= -\{F_i \cdot (v_v + \omega_v \times r_i)dt + M_i \cdot \omega_v dt\} \end{aligned} \quad (35)$$

$$\omega_v = 0 \quad (36)$$

Also, as the angular motion of the vehicle is extremely small, it is ignored to derive the ridedown energy of each external force which can be written as in EQ(37) and EQ(38).

The ridedown energy caused by the dummy's internal forces applied to the end of a segment can be obtained as following equation:

$$\frac{dEA_{ri}}{dt} = -F_i \cdot v_v \quad (37)$$

The ridedown energy caused by the sum of residual external forces can be obtained as following equation:

$$\frac{dEA_{re}}{dt} = -(\Sigma F_{ei}) \cdot v_v \quad (38)$$

W_{ri} : ridedown work done by ith force
EA_{ri} : ridedown energy absorption done by ith internal force
EA_{re} : ridedown energy absorption done by residual forces
s_{vi} : displacement vector of vehicle of point of action of ith internal force
s_v : displacement vector of vehicle
θ_v : angular displacement vector of vehicle
r_i : position vector of point of action of ith internal force

SYSTEM DEVELOPMENT

For analysis based on the measuring and calculation methods described in the preceding section, system development was made.

Development of Dummies

HybridⅢ Dummy and Hybrid Ⅱ Dummy were developed for the head, chest and pelvis. For the upper and lower leg, Hybrid III Dummy was developed.

To measure angular and linear motions of each segment, additional linear accelerometers were added, as shown in Fig. 4.

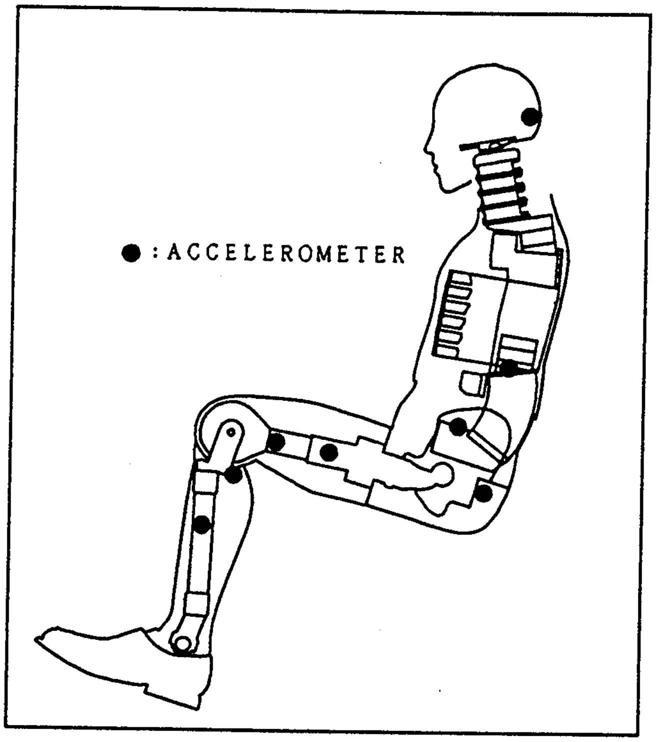

Figure 4. Added accelerometers for HybridⅢ dummy

The number of accelerometers was one for the head, 2 for the chest, and 3 for other segments.

To measure internal forces acting on segments, force transducers were added as shown in Fig. 5.
Of the transducers added, neck transducers for Hybrid Ⅲ Dummy and transducers for the lower tibia were existing ones, and others were newly designed and made. The directions of the forces measured by all the force transducer were those needed for analysis:(1) shearing forces in longitudinal axis, (2) vertical force, and (3) the moment about lateral axis.

Development of Analytic Program

For analysis of the data measured by linear accelerometers and force transducers, an analytic program was developed. This program analyzes data per segment and the analyzed results are output. Also, for hip and knee joints, segments are connected to each other with joints, and the results of analysis of the reaction force in each joint is reflected. The results obtained are as follows:
(1) time history of angular and linear motions of a segment
(2) time history of internal forces transferred among segments
(3) time history of external forces applied to segments
(4) time history of effects of internal and external forces on linear acceleration of segments
(5) time history of effects of internal and external forces on angular acceleration of segments
(6) time history of energy absorption done by each external force and their ridedown effect

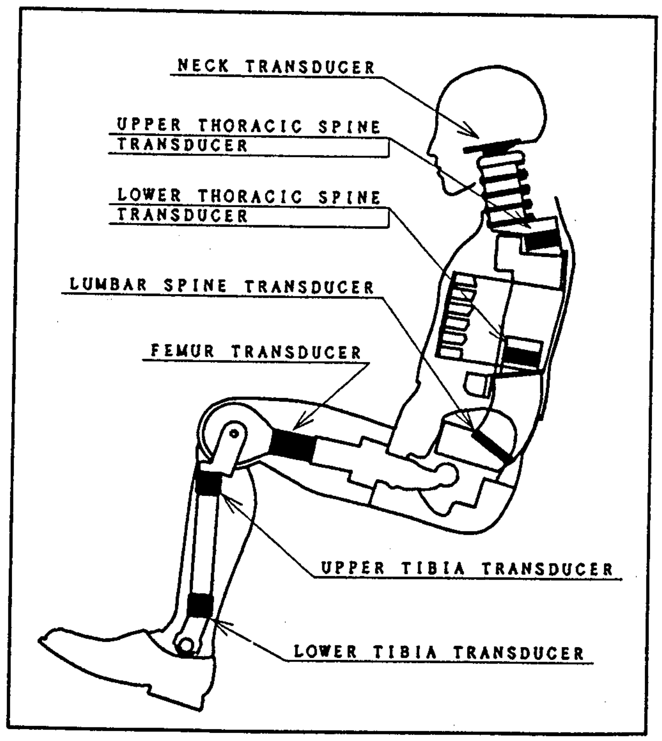

Figure 5. Added force transducers for Hybrid Ⅲ dummy

APPLICATION

The sled test with passenger side airbag was conducted to use the developed system. The sled test was simulating the 30mph frontal crash test.

Cause of Peak on Chest Acceleration Waveform

The chest acceleration obtained by the test is, as shown in Fig. 6, indicating that peaks are generated at 86ms for both horizontal, and vertical accelerations.

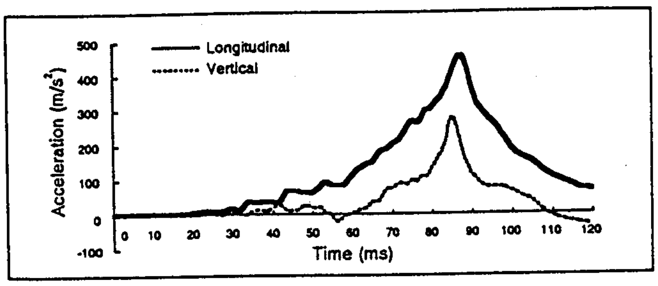

Figure 6. Chest acceleration

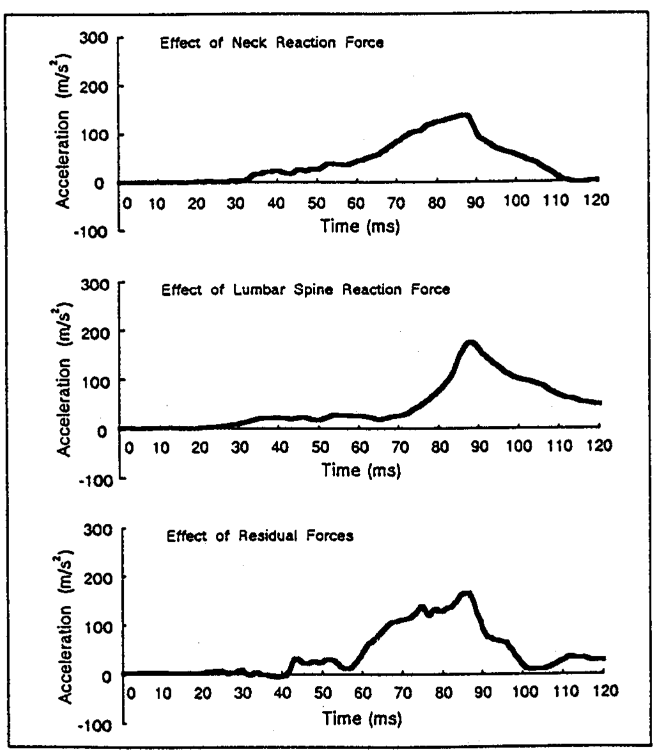

Figure 7. Effect of each force on chest longitudinal acceleration.

As the conventional method provides chest acceleration only, the cause of peaks can not be identified. For this reason, many parametric experiments are required to search for the cause. The developed system can be used to find the effect of each external force on the chest acceleration.

Fig. 7 and Fig. 8 show the effect of neck reaction force, lumbar spine reaction force and the sum of residual external forces applied to the chest on the chest linear acceleration. As shown in Fig. 7 and Fig. 8, the cause for the wave peak on the chest linear acceleration is known because the lumbar spine reaction force applied to the chest increases rapidly between 75ms and 86ms.

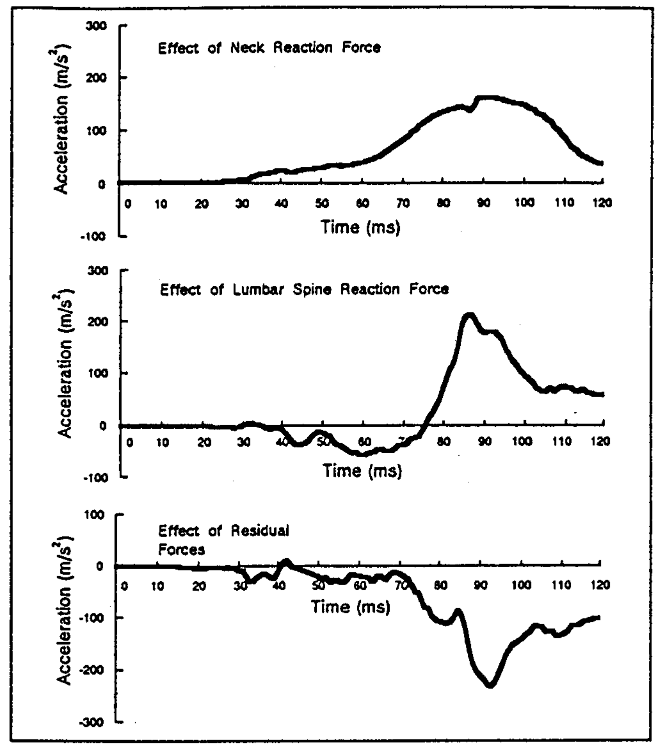

Figure 8. Effect of each force on chest vertical acceleration.

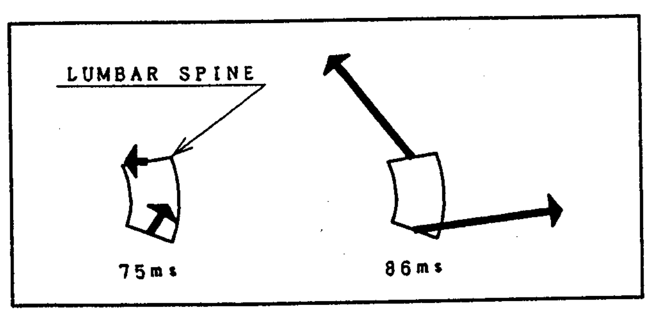

Figure 9. Change of external forces applied to lumbar spine

Fig. 9 shows the changes of external forces applied to the lumbar spine between 75ms and 86ms. The increase of the lumbar spine reaction force applied to the chest is caused by the increase of the horizontal component of pelvis reaction force applied to the lower end of lumbar spine.

For investigating the cause of the horizontal component of pelvis reaction force, angular and linear acceleration of the pelvis are analyzed.

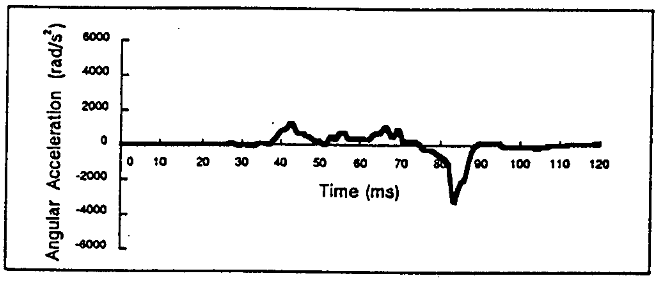

Figure 10. Pelvis angular acceleration about lateral axis

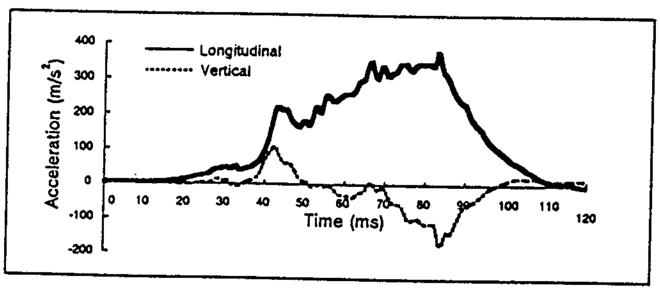

Figure 11. Pelvis linear acceleration

The angular acceleration of the pelvis, shown in Fig. 10, rises abruptly at 84ms immediately prior to the chest acceleration wave reaching its peak, and then the angular motion of the pelvis rapidly decreases. On the other hand, Fig.11 shows the linear acceleration of the pelvis, with no rapid horizontal and vertical changes. Consequently, the peak of the chest acceleration is caused by the angular motion of the pelvis.

The cause of angular acceleration of pelvis is analyzed. Fig.12 shows the effect of the lumbar spine reaction force, the right and left femur reaction force, and the sum of residual force applied to the pelvis on the angular acceleration of pelvis. The increase on the angular acceleration of pelvis, as shown in Fig.12 shows, is caused by the femur reaction forces and moments applied to hip joints. In addition, the amount of these forces and moments is such that it will causes much larger angular acceleration of pelvis, but it is canceled by increasing the lumbar spine reaction force and moment. As a result, the angular acceleration of pelvis represents much smaller changes.

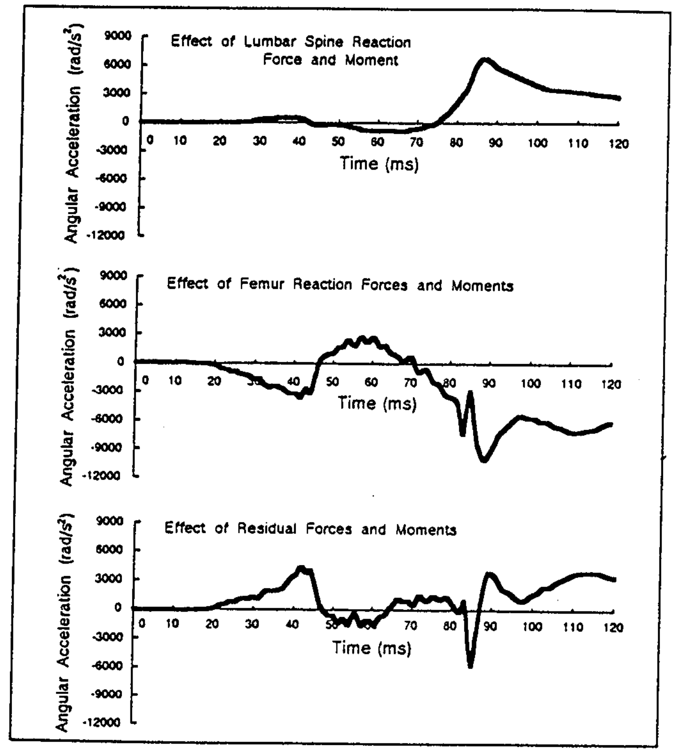

Figure 12. Effect of each force and moment on pelvis angular acceleration

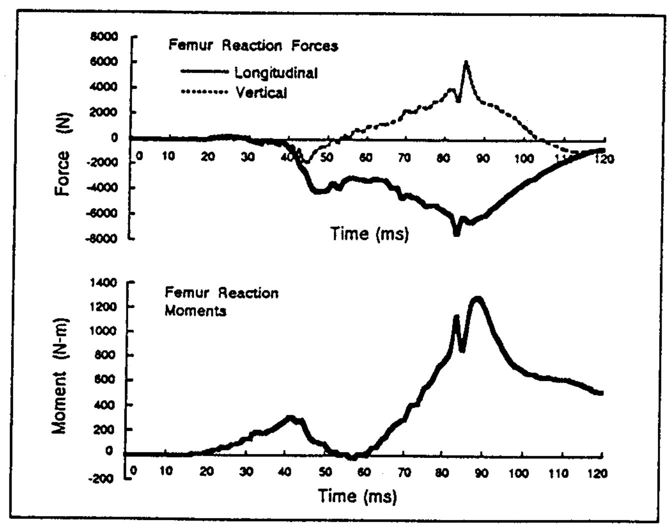

Figure 13. Force and moment applied to hip joints

Next, the cause of external forces

and moments applied to the hip joints is analyzed. Fig. 13 shows that the moment sharply increases between 75ms and 85ms, and this rapid increase of external moments causes a sharp increase in angular acceleration of the pelvis.

For this reason, the external moment applied to the right and left hip joint to the pelvis is analyzed. However, no sharp external moment is applied to the left femur, as shown in Fig. 14, and it reveals that sharp external moment is applied to the right femur. Consequently, the sharp increase in angular acceleration of the pelvis is known to have been caused by the sharp increase of the moment on the right hip joint.

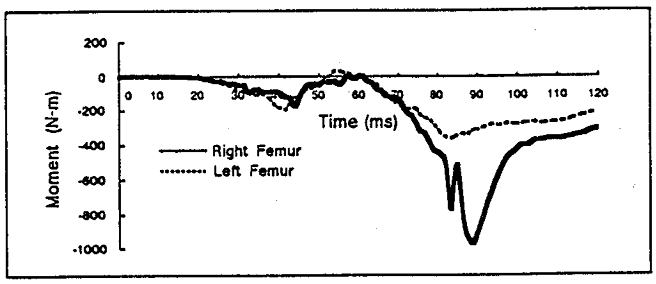

Figure 14. Hip joint reaction moment applied to each femur

In order to investigate the cause of the sharp increase in the external moment applied to the right femur, the effect of the right femur axial force is analyzed. Fig.15 shows the effect of the external forces on the femur axial force. The external force acting on the knee, tibia, and foot does not vary substantially between 75ms and 86ms. This reveals that the external force is not the cause for the sharp increase in the external moment applied to the right hip joint.

Consequently, it is concluded that the cause of the moment occurs on the hip joint only. However, as the hip joints are ball joints, an excessive moment will not be generated unless the hip joints to come to a stop angle, and the joint is considered to be locked when the hip joint is at the stop angle.

It is concluded that the cause of the peak of the waveform on the chest acceleration is because of an extremely large moment generated by the locking of the right femur joint, causing the angular motion of the pelvis to suddenly stop. As a result, a large horizontal force is generated at the lower end of the lumbar spine, and the force is transmitted to the chest through the

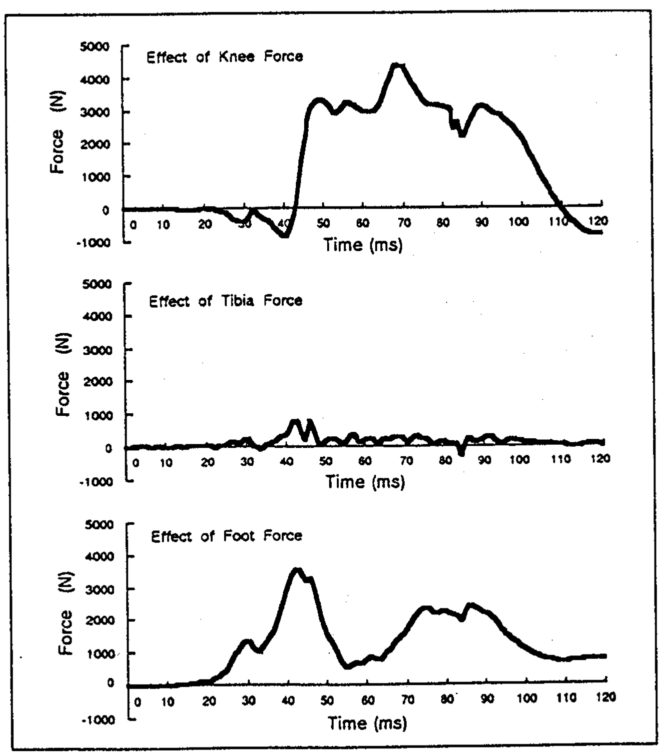

Figure 15. Effect of each force on right femur axial force

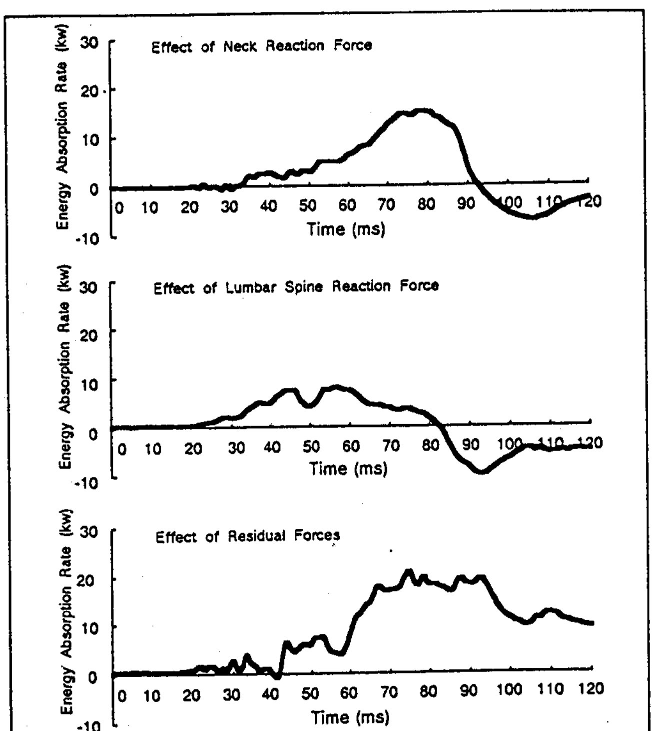

Figure 16. Energy absorption rate done by external forces applied to chest

lumbar spine to cause the peak on the chest acceleration waveform.

External Forces with Low Rate of Energy Absorption

Energy absorption on the chest is analyzed. Fig. 16 shows the energy absorption done by each external force applied to chest. As shown in Fig. 16, the amount of enrgy absorption done by the lumbar spine reaction force is apparently small as compared with that of the sum of residual forces and neck reaction force.The increase of lumber spine reaction force at 86ms causes a peak on the chest acceleration waveform but this force absorbs the chest energy hardly. Consequently, it is known that reducing this external force will be most efficient way to reduce the peak on the chest acceleration.

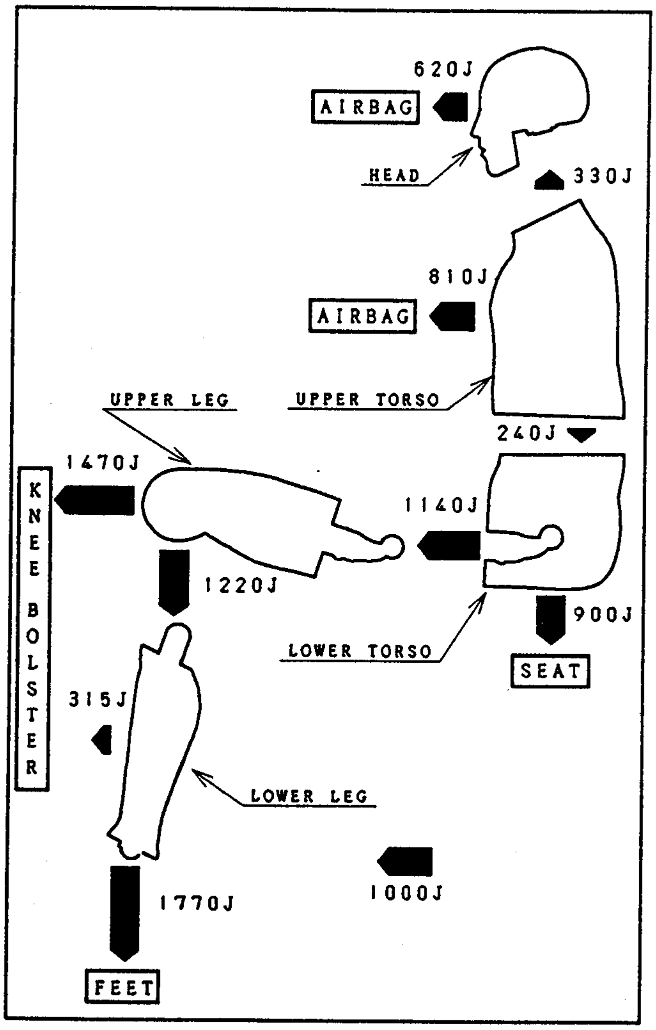

Figure 17. Energy transfer at 100ms

Energy Transfer of Whole the Dummy and Absorption

Fig.17 illustrates the amount of energy transfer at 100ms after the crash obtained by the results of each segment.

The energy absorption process on the chest reveals that 810J of kinetic energy of chest is absorbed by the external forces directly applied to the chest, 330J is transferred to the head through the neck, and 240J to the lower torso through the lumbar spine, as shown in Fig. 17.

The energy absorption process in the lower body reveals that 240J is transferred to lower torso through the lumbar spine and the energy of the lower torso is externally applied, 900J is transfered and absorbed by the external forces between the seat and the lower torso, and 1140J is transferred from lower torso to upper legs through the hip joints.

The energy of the upper legs, transferred from the lower torso, increases and 1470J is transferred to the knee bolster through the knee and absorbed, and 1220J is transferred to the lower legs through the knee joints. The energy of the lower legs, transferred from the upper legs, increases and 315 J is transferred to the knee bolster by contacting the lower legs and knee bolster, and 1770J is transferred to the feet through the ankle joints.

The results of this experiment reveal that a large amount of energy is transferred from one segment to another and absorbed by the internal forces applied to each other segment. All in all, energy transfer in the lower body is done on a large scale.

Ridedown Effect

The rate of ridedown energy on the dummy is analyzed. Fig. 18 shows the energy absorption of each external force and its ridedown effect. It reveals that the ridedown effect at the leg part is extremely large, while the ridedown effect of the head and chest part is small.

The energy absorption of the right upper leg, of which the ridedown effect is large, is analyzed. As shown in Fig.19, a large amount of energy is transferred from the lower torso to the upper leg between 30ms and 50ms after the crash. At the same time, still larger energy is transferred to the lower leg from the upper leg through the knee joint. Approximately 70% of the transferred energy, as shown in Fig.20, is the ridedown energy. Although the axial force applied to the femur is not large, as shown in Fig. 15, the energy absorption is efficiently made not only for the upper leg but also the lower torso because of the displacement of a vehicle is so great in this phase.

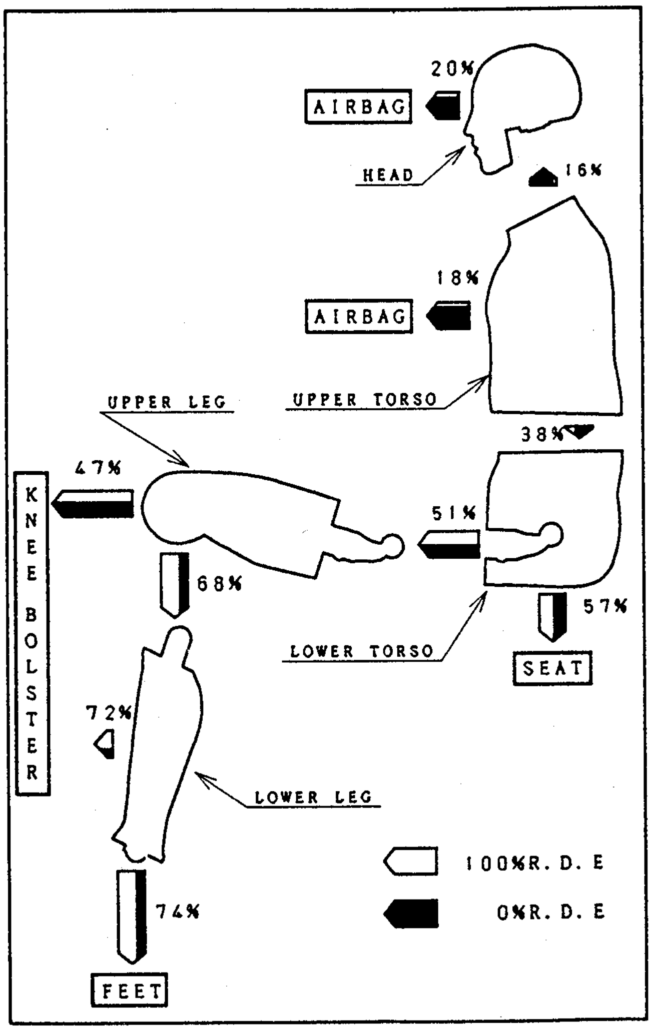

Figure 18. Ridedown effect on each energy transfer

CONCLUSIONS

The new system has been developed, which obtains external forces applied to head, chest, pelvis, femurs, and tibias and their energy absorption.

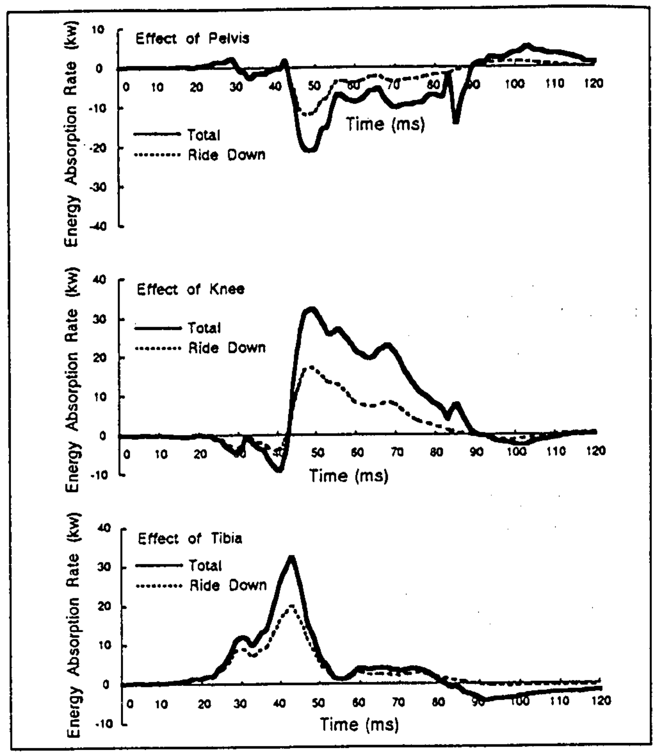

Figure 19. Effect of each force on right upper leg energy absorption rate

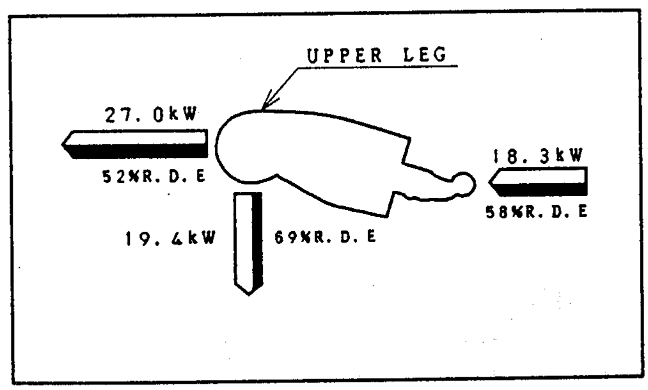

Figure 20. Energy absorption rate and its ridedown effect on right upper leg at 46ms after the crash

The developed system can rationally explain that the peak on the chest acceleration is caused by the locking of the right hip joint, the pelvic interference which the conventional method can not explain. For this reason, the developed system can make the development of restraint systems more efficient to reduce the parametric experiments for researching into the cause of injury indexes.

Increase of one external force

applied to a segment causes other forces to resist and to cancel it, as shown in the external moment applied to pelvis. As this result of the interaction among the external forces applied to a segment, linear acceleration and angular acceleration of a segment represent far smaller variations than an external force actually acting on. The conventional method to measure linear accelerations and axial forces on the femur can be difficult to explain these phenomenon. Consequently, the developed system, which can measure each external force applied to a segment, is quite useful for finding out the cause of the injury indexes.

The external forces with low rate of energy absorption, which absorb small energy and cause high injury indexes, are existed in the external forces applied to the dummy. Reducing these external forces will lead to the development of more efficient restraint systems. Consequently, the development system that can measure absorption of each external force applied to the dummy is useful to find out them and to make restraint systems more efficient.

Energy transfer analysis reveals that large scale of energy transfer among segments occurred within the dummy. However, the conventional analysis method of energy absorption provides changes in kinetic energy, but it does not explain through what route the energy is transferred. The conventional method may leads the development of restraint systems to the wrong direction if energy absorption of a restraint system is made assuming that kinetic energy of segment is absorbed by external forces directly applied to segment. The developed system that permits to measure energy transfer among segments, therefore, is useful to estimate the energy absorption of a restraint system.

Increasing the amount of the ridedown energy, which is harmless way to absorb the dummy's kinetic energy, lead to development of more efficient restraint systems. However, the conventional method could not provide what external force provides a higher ridedown effect. Therefore, the developed system which provides the ridedown effect of each external force will be useful for developing more efficient restraint systems.

The developed system will be useful for making future restraint systems more effective and the development of the restraint system more efficient.

ACKNOWLEDGEMENTS

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Opportunities and Limits of an Airbag Optimization Based on the Passive Requirements of Standard 208

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ABSTRACT

Airbag systems that must satisfy FMVSS 208 can only be optimized within narrow limits due to the passive restraint requirements.

An airbag system developed according to Standard 208 brings with it, with reference to aggressivity among other things, such serious disadvantages that, considering the very high belt usage rates, one cannot speak of such a system as optimized for the majority of vehicle occupants.

This presentation points out which problems originate from system development to meet passive requirements, as well as how an airbag can be optimized when it is designed as a restraint system supplemental to safety belts.

INTRODUCTION

Belt Usage Rates and Laws

In Europe and especially in Germany, the acceptance for usage of safety belts is at an extremely high level.

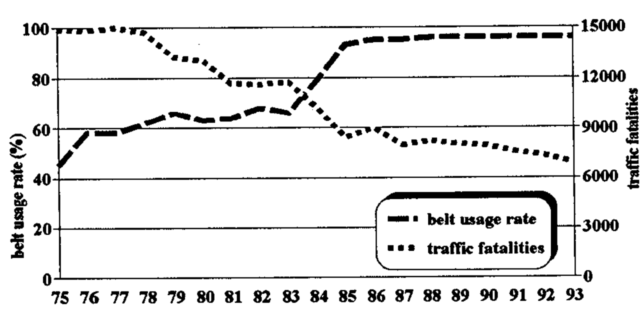

Figure 1
Belt usage rate and traffic fatalities in Germany, 1975 - 1993 (Source: Statistisches Bundesamt)

The implementation of the belt usage law in 1976 and its continuation with financial penalties caused the usage rate to climb to over 93 % in 1991. Accompanying with other suitable actions this had a traceable effect in the statistics for severe- and fatally-injured occupants of motor vehicle accidents.

In the United States of America, the belt usage rate was at a low 15 % in 1968, the first year of implementation of Federal Motor Vehicle Safety Standard 208. Based on this situation, the requirement for restraint systems to provide a minimum level of protection by means that require no action by the unbelted front seat occupants was established. In the 1980's, FMVSS 208 was amended to encourage the passage of belt usage laws, which now apply to more than 95 % of the U.S. population. The implementation of these laws with fines and safety campaigns such as the "Click it or ticket" campaign in North Carolina demonstrates their effect: The usage rate there increased to 80 %, a value comparable to the European situation. One can extrapolate the belt usage curve for the entire U.S., so that in a few years an asymptotic approach to a maximum value similar to that of Europe could result.

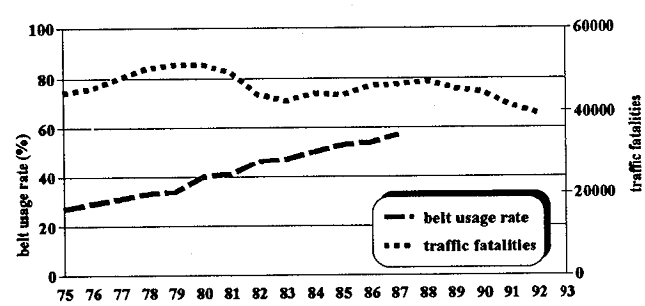

Figure 2
Belt usage rate (driver) and traffic fatalities in USA 1975 - 1992 (Source: SAE)

Regulatory Situation and Requirements of FMVSS 208

The American Federal Motor Vehicle Safety Standard 208 requires that all vehicle manufacturers equip their vehicles with passive restraint systems that, without action by the occupants, do not allow certain biomechanical limiting values to be exceeded in specific crash situations. Since 1986, all passenger cars must be equipped with either automatic belts or driver airbags.

This passive requirement is, up to this point, the only one of its kind in the world. Indeed, several countries have implemented requirements for crash conditions, occupant protection criteria and extent of testing, but except for the U.S., no other country requires compliance with the regulations exclusively with airbag without the help of safety belts.

FMVSS 208 prescribes adherence to the requirements in crash tests at angles between 0° and 30° against a fixed, rigid barrier. However, in addition crash tests are more frequently being conducted against a barrier with only 40 - 50 % overlap, since this produces more realistic vehicle deformation.

VEHICLE CONSTRUCTION BASED ON 0°-BARRIER IMPACT OR OFFSET-CRASH?

In a 0°-barrier-impact with full overlap, all elements of the vehicle's front structure are utilized for deformation. From this comes the shortest stopping distance and therefore the highest deceleration of the vehicle.

Figure 3
Vehicle deformation in offset (left) and full overlap (right) crashes

The impact against a barrier with a partial overlap, such as is seen in many real-world crash situations, involves considerably higher vehicle deformation, since only a portion of the available front structure deformation elements are utilized for energy absorption. With a comparable impact speed, a lower deceleration results. This situation places lesser demands on restraint systems, but instead a higher demand on the specific energy-absorbing capacity of the front structure. The front structure must necessarily have greater stiffness.

In order to give consideration to both crash situations, BMW Engineering utilizes the following sequence in the development of new vehicles: this is primarily accomplished by the more realistic offset-crash. After determination of the resulting body stiffness, the tuning and verification of the restraint systems in a 0°-crash with full overlap takes place. Vehicles developed in this way naturally place considerably higher demands on their restraint systems than do those vehicles that are developed solely according to the full overlap impact of FMVSS 208.

KINEMATIC DIFFERENCE IN RESTRAINT PERFORMANCE WITH AND WITHOUT SAFETY BELT

In a frontal impact involving a safety belt and airbag, the occupant is restrained primarily by the belt, the initiation of upper body rotation takes place relatively early due to the lap belt and the airbag restrains the upper body and head. The energy is distributed over both restraint systems. In angled-impact situations, the safety belt likewise guarantees good restraint and the deflection of the occupant's movement from the longitudinal axis is relatively small.

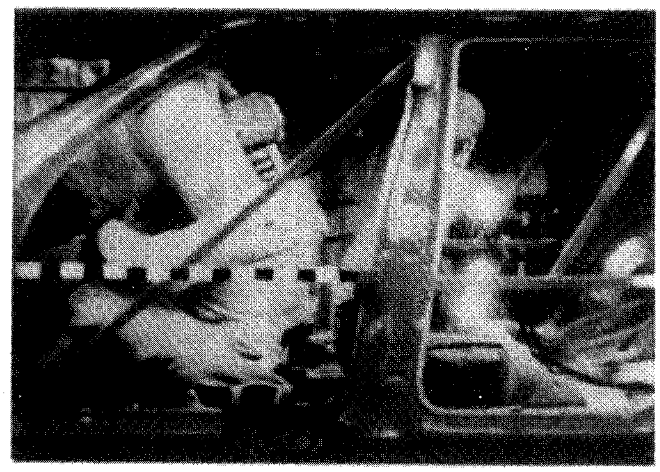

Figure 4
Kinematic in an airbag-plus-belt-situation

In a passive restraint situation with airbag, the occupant slides forward nearly in a straight line into the airbag and knee bolster. Initiation of rotation takes place relatively late due to the knee bolster. The energy absorption of nearly the entire kinetic energy of the upper body must be solely accomplished by the airbag. In an angled impact, the occupant moves relatively early to the side.

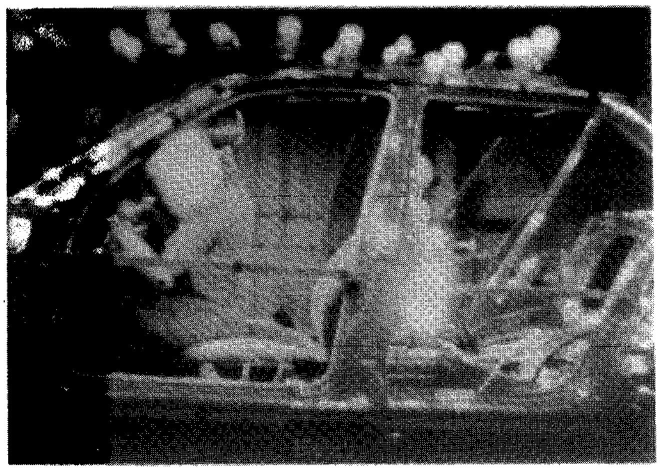

Figure 5
Kinematic in a passive restraint situation

SPECIFIC DESIGN FEATURES THAT RESULT FROM THE PASSIVE REQUIREMENT

Due to the special kinematics and the higher energy to be converted based on the requirement for passive restraint, constructive necessities in the development of airbags result and are described in detail in the following:

Airbag Module

Size (Volume) - In order to be able to restrain the complete upper body during a passive restraint event, the diameter of the airbag must be very large. The occupant slides forward pushing the airbag forward and upward due to the relative angle between upper body and steering column. With insufficient airbag diameter, the lower steering wheel rim could be exposed, which would necessarily lead to increased chest loading.

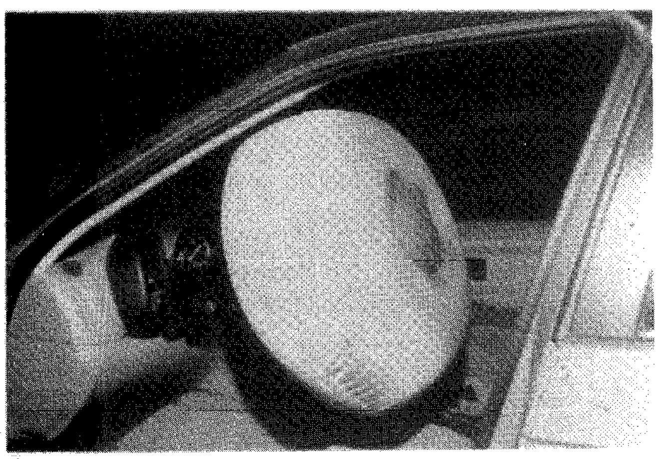

Figure 6
Typical form of a passive airbag

Vehicles that are not constructed according to offset crash conditions, manage with smaller airbag diameters and volumes, due to the weaker vehicle structure and the associated lower specific deceleration characteristic.

Form - The form of the driver airbag should be as much like that of a lens as possible; the greatest thickness is not needed in the centre of the airbag, but rather on its rim. The occupant should, specifically in the chest area, have contact as early as possible with the airbag.

Tether Straps - Since the airbag, during deployment, tries to take on a form as spherical as possible, a volume increase by about a factor of 3 would be necessary for an increase in the diameter of about 50 % without an additional device for controlling the shape of the bag. Since this is not realizable nor desired, tether straps are installed to give the airbag a lens-like form. The straps also assume the function of holding the airbag, during the restraint of an unbelted occupant, in the desired position.

Sealing - The tether straps are on one end securely attached in the area of the mouth of the airbag. On the occupant-side, on the other hand, they must also be sewn. These seams represent a problem since hot gases can escape through the stitch perforations, presenting the risk of occupant injury. As a solution, airbags are in general sealed with a coating at least in this area. For ventilation of the bag, vent holes are provided.

Material - Passive airbags must necessarily exhibit higher material strengths on the basis of the higher propagation speeds, the greater energy to be absorbed and the higher-powered gas generators.

Gas Generator - Since a high gas volume within a certain time must be achieved, the requirement for a larger, higher-performance gas generator necessarily follows. Moreover, in some cases certain propellant types are prohibited, since the concentration of toxic materials with such high gas quantities can be problematic.

Sensor - In the consideration of unbelted occupants, the airbag system must already be activated at low speeds. With belted occupants, the safety belt is completely sufficient as the exclusive restraint system in the lower speed range. In order not to deploy the airbag in these situations, to remain ready for possible secondary impacts and at the same time to be able to guarantee the exclusive airbag restraining function for unbelted occupants at low speed, an expensive sensor system is required, such that the belt latch can detect belt usage and according to the known situation reduce or raise the deployment threshold.

DISADVANTAGES OF THESE SYSTEMS

Aggressivity

Maximum Airbag Elongation - Due to the higher airbag volume and the necessity to absorb almost the entire kinetic energy of the occupant, a relatively larger maximum distance between the steering wheel plane and the farthest point of occupant contact on the airbag results during deployment. The airbag will, therefore, certainly be projected further toward the occupant than would be necessary in an airbag system developed solely for belt-restrained occupants. Values up to 500 mm (20 inch) are realistic. For occupants seated near the steering wheel, the possibility of an airbag-induced injury cannot be eliminated.

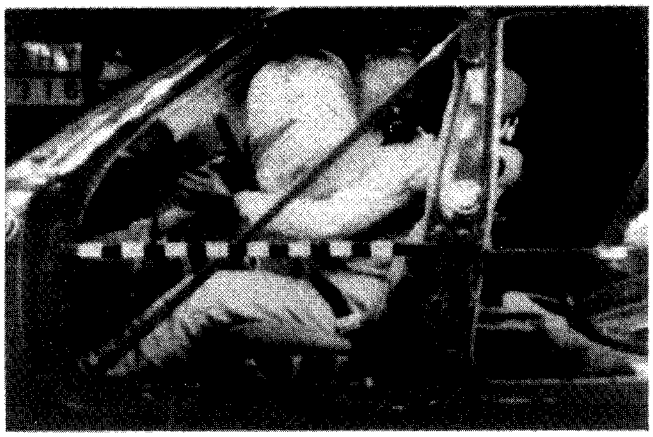

Figure 7
Airbag impacting the occupant

Propagation Speed - In order to bring the airbag into position at the right time, it must be deployed at a high rate of speed. Depending on the system, 80 m/s (180 mph) and more can be measured. The propagation does not proceed uniformly in one direction. The airbag folds also move diagonally to the deployment direction while the airbag is moving towards the occupant. Under these conditions, it is no surprise that abrasions are among the most frequent airbag-induced injuries. These wounds are especially critical, when it is a question of abrasions of the eyeball, since the occupant is not able to close the eyes fast enough because the airbag deployment proceeds faster than the motion of the eyelid.

Kinetic Energy of the Airbag - The airbag has a large mass and its high volume must be filled in less or the same time as a smaller bag developed as supplemental to a safety belt. The kinetic energy impacting the occupant necessarily increases to a level such that, in some cases (the press has reported on them), unnecessary injuries have been inflicted on drivers seated near the steering wheel.

Size of the "Risk Zone" of Deployment - Due to the high airbag maximum elongation, one finds that not only are small persons in the formost seating position located in the deployment area of the airbag, but also drivers that choose a seating position with bent arms for better vehicle control. In certain cases, these situations can be dangerous.

Out-of-Position Unbelted Occupant due to Pre-Crash Maximum Braking - In a situation involving maximum braking of the vehicle, the unbelted occupants, especially on the passenger-side, run the risk of sliding into a dangerous position near the airbag module before the actual crash. Occupants should be belted for this reason, especially on vehicles with airbags.

Costs

Puchase Price - For airbag systems that must fulfill the passive requirements of FMVSS 208, fewer cost reduction possibilities are available, as compared to systems developed as purely supplemental to belt restraints. These costs must ultimately be paid by the customer in the vehicle's purchase price.

Proportionate Airbag-Related Repair costs after a Crash with Minimal Severity - Due to the necessity of airbag deployment at a low level of Crash severity when the occupants are unbelted, airbag-related repair costs take a certainly higher proportional share of the total repair cost as compared to an airbag system for belted occupants. The economy is inappropriately burdened by the unnecessarily high insurance premiums that result.

Design

Large steering wheels are not in style, don't appeal to consumers as much as sporty, small 3-spoke wheels, hinder the ergonomic efforts of designers, reduce the visibility of instruments and allow less design freedom. Airbags that are supplemental to belts permit, due to the smaller required space, the use of attractive, sporty steering wheels as well as the use of ergonomically-positioned control switches on the wheel.

POSSIBILITIES FOR OPTIMIZATION

Situation-Appropriate Airbag Deployment

Double-Threshold Deployment - in order to satisfy the passive requirements on one hand and the justifiable wishes of customers for appropriate deployment threshold on the other, BMW has brought into use an airbag control unit with two deployment thresholds.

Depending on the usage of safety belts, the threshold will be raised or lowered. The unbelted occupant is already protected at low impact speeds by the airbag, while the belt-restrained occupant experiences, due to the avoidance of inappropriate deployments, the additional airbag protection only at higher crash speeds.

Seat Occupancy Detection - Likewise, the goal of situation-appropriate airbag deployment is served by the occupancy detection feature on the passenger seat, which intentionally deactivates the airbag on this side if the seat is unoccupied, in order to avoid unnecessary repair costs and sound pressure loads. Furthermore, only with this occupancy detection feature can a very difficult-to-explain situation for the customer be avoided, that would otherwise result from the application of double-threshold detection: When the belted driver sits alone in the vehicle and experiences a crash in a frequently-occurring speed range between the lower and upper thresholds, the driver airbag logically does not deploy. However, without seat occupancy detection on the passenger side, the passenger airbag deploys due to the unbuckled belt.

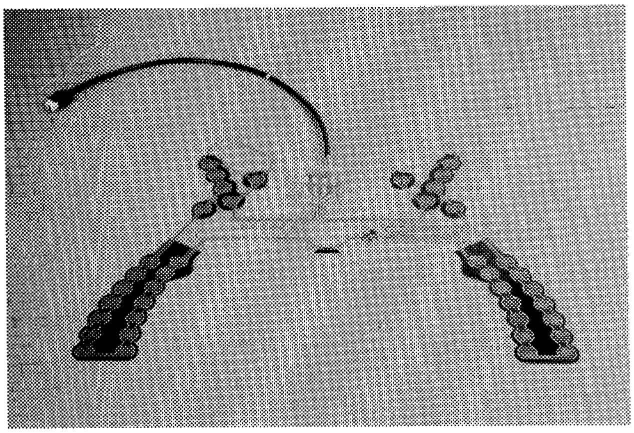

Figure 8
Resistance foil for occupancy detection

Adaptive Airbag Deployment

The newest developments in gas generators strive for a variable fill rate of the airbag as a function of crash severity. In this way, the airbag can, in high speed impacts, be quickly positioned in front of the occupant without regard for the deployment aggressivity. On the other hand, if a lower impact severity is detected, the deployment intensity, in order to reduce aggressivity, can be reduced.

LIMITS OF OPTIMIZATION

Protective Effect

Maximum protective effect is currently achieved with the combination of safety belt and airbag. Only the safety belt offers protection in rollovers, side collisions and rear impact situations. The belt also holds the occupant in position in an actual crash preceded by maximum braking. The use of safety belts, Restraint System Number One, is to be recommended in every case.

A passive restraint system can be so constructed that specific biomechanical limits in defined, controlled laboratory crash simulations are not exceeded. However, the comprehensive protective effect in all real-world crash situations cannot be represented by this solution.

Vehicle Stiffness

Vehicles that are not developed according to offset crash conditions are provided with much softer deceleration characteristics. Since, under this assumption, lower demands can be placed on the quality of the restraint systems, it cannot be obscured that for real-world crash events the disadvantages predominate. In no case can it be said that there is optimization in terms of an improvement in the chance of survivability.

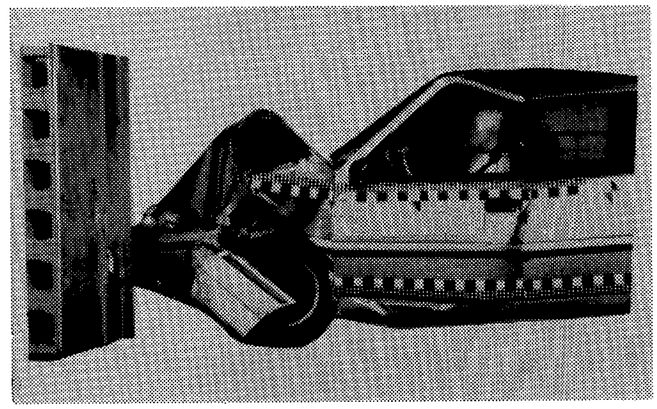

Figure 9
Higher risk of injuries in vehicles not developed according to offset crash conditions

Constant Airbag Form and Volume

All optimizations cannot change the airbag form depending on the type of crash and its severity. An airbag that is intended to function as the sole restraint system must have another form and a larger volume than an airbag provided as supplemental to a safety belt with the least possible aggressivity.

Absence of Information regarding Occupant Position

For passive restraint situations the principle to bring the airbag as early as possible in contact with the occupant applies. Only in this way can the relative speed between occupant and vehicle be held to a desired low level. Here, the optimum can only be achieved for a specific seating position of the occupant. If the occupant sits further rearward, the restraint function occurs later. If the occupant sits further forward, the danger of injury from the unfolding airbag is encountered.

OPTIMIZATION WITHOUT THE LIMITATION OF THE PASSIVE RESTRAINT REQUIREMENT

Airbag

With belt-supplemental restraint systems, the airbag takes on the function of a soft and large-faced cushion that is effective in instances of potential head impact on hard interior parts as well as a large pre-displacement of the occupant. This impact cushion must necessarily not be positioned close to the occupant.

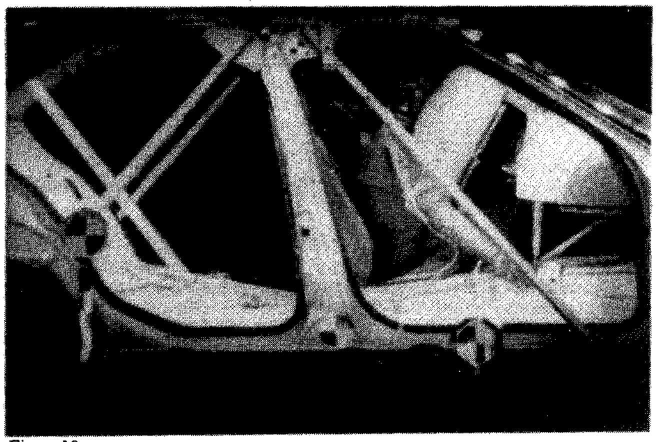

Figure 10
Optimum restraint with belt-supplemental airbag

Certainly, a small volume is sufficient to fulfill this function. Tether straps can be eliminated and airbag deployment can be conducted in a sufficiently gentle manner either via the folds or ripping seams. Propagation speeds under 30 m/s (65 mph) are entirely realistic. Maximum elongation of about 300 mm (12 inches) drastically reduces the injury potential.

Due to the much lower propagation speed, the airbag material will be stressed less and a lighter fabric can be utilized. This lighter fabric, the smaller maximum elongation and the lower propagation speed mean a lower kinetic energy during the deployment event. The occupant will be contacted with very little or no aggressivity by a smaller airbag.

Table 1
Comparison of deployment violences with two different bag volumes

type of airbag	volume	maximum elongation	maximum propagation speed
passive restraining airbag	74 l	20 inch	180 mph
belt-supplemental airbag	45 l	12 inch	65 mph

Gas Generator

The fact that a lesser bag volume must be filled permits the application of gas generators with smaller capacities. This also results in lower expenditures for cooling and filtering of the gases. On the basis of the smaller gas volume, propellants can be utilized that, for passive systems, must be rejected on the basis of excessive harmful emissions.

Sensor

An increase in the sensor deployment threshold brings the advantage of having more time available for detection than with a system for unbelted occupants. There are stronger deceleration signals up to the time of ignition decision, the deployment decision gains in safety and the "Must Fire" signal discriminates itself more distinctly from the "No Fire" signal.

Module

On the basis of the smaller gas generator, the smaller airbag volume and the possible elimination of coating and tether straps, the package volume of the airbag can be made considerably smaller. An airbag in a sport steering wheel appeals more to customers, the acceptance for this restraint system increases, the visibility of the instruments is improved and there is the possibility for the application of buttons and switches in the steering wheel for control of important vehicle functions.

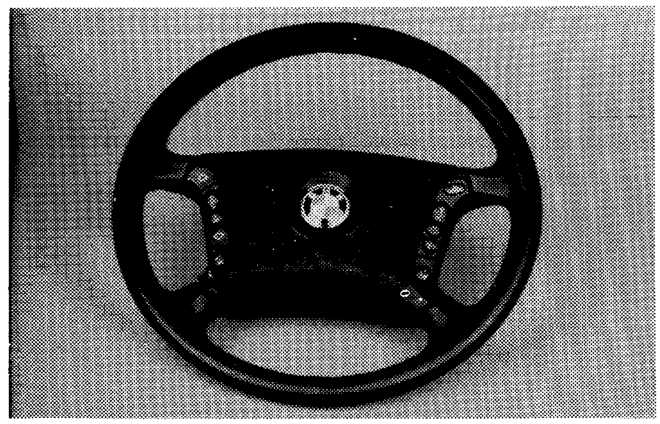

Figure 11
Airbag steering wheel with control switches

The outer cover of the module can also be smaller, the lower opening resistance reduces the required energy of the deploying airbag. This, in turn, produces a reduction in aggressivity.

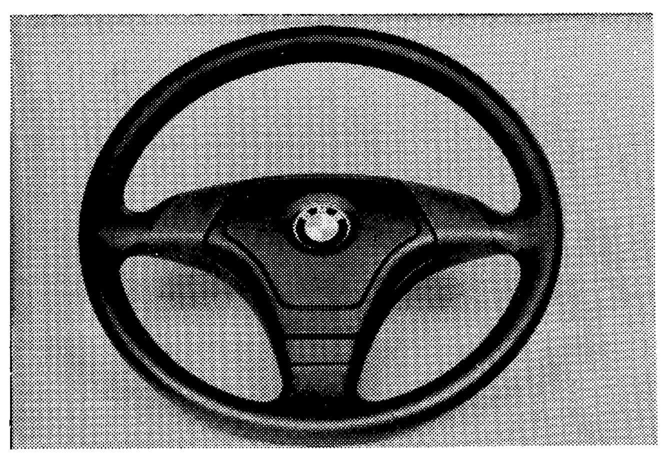

Figure 12
Sporty 3-spoke airbag steering wheel

SUMMARY

No one today would question the effectiveness of an airbag, especially on the driver's side. The additional restraint system has demonstrated beyond a doubt that it is effective in the reduction of severe or fatal injuries. More frequently the airbag is expected by consumers to be standard equipment an a new automobile. Most vehicle manufactures have equipped at least a few of their models with airbag as standard equipment. With this high penetration rate however, the customer is less ready to accept the disadvantageous aspects of such systems. Injuries in minor collisions that are demonstrated to be caused by the airbag, reduced comfort, a worsening of the ergonomics due to larger steering wheels and unnecessarily high repair costs due to deployment at lower speed ranges will no longer be accepted.

Standard 208, with its passive requirements in a 0° frontal impact with full overlap, produces airbag systems that resist a reduction of the known disadvantages.

The number of safety-conscious vehicle occupants who, in their own interest, use safety belts is increasing. From this comes a situation where, with an improving belt usage rate, an increasing number of rational people will be subjected to higher loads by the airbag than is necessary, in order to ensure a minimum level of safety for a decreasing number of less safety conscious (i.e. "unreasonable") people.

The elimination of the passive requirements can produce a remedy: Through the possibility to apply the airbag as a restraint system supplemental to safety belts, considerable advantages result that are beneficial to all vehicle users.

An Effectiveness Analysis of Chrysler Driver Airbags after Five Years Exposure

W. Randall Edwards
Chrysler Corporation
United States
Paper No. 94-S4-0-09

ABSTRACT

This paper is a continuation of one presented at the Thirteenth International Technical Conference on Experimental Safety Vehicles*, assessing the effectiveness of Chrysler driver airbags. That study and this one compare the driver fatality rates of Chrysler passenger cars before and after the introduction of the driver airbag. Because of wide variation in fatality rate changes from carline to carline and the small sample sizes in the initial study, it was believed that a couple more years of exposure would lead to convergence among the carlines. The earlier study included 1986 through 1990 Fatal Accidents Reporting System (FARS) data while this one includes 1986 through 1992 data. While the fatality and exposure data increased substantially between studies, the carline to carline variance largely remains unchanged, indicating that carline driver demographic differences and other factors contribute to the system effectiveness. In the aggregate, the driver fatality rates are 29% lower in frontal crashes and 22% lower overall in Chrysler vehicles equipped with driver airbags.

INTRODUCTION

In 1988 Chrysler Corporation began installing driver airbags as standard equipment in some of its United States market passenger cars, in response to automatic crash protection phase-in requirements and consumer preference versus automatic seat belt alternatives. By 1990 all of Chrysler's United States built passenger cars were driver airbag equipped. In every case, each of these vehicles had the driver airbag system adapted to an existing model.

This changeover of restraint systems provides a made to order opportunity to determine the effectiveness of the driver airbag at reducing driver fatalities. By comparing the driver fatality rates before and after their introduction, one can hold constant many contributing factors to fatal accidents to concentrate on the benefit of the driver airbag. That is, demographic patterns and target markets remain the same. For example, comparisons are not made between a Dodge Daytona (a two door hatchback sports coupe) with a Chrysler New Yorker Fifth Avenue (a four door luxury sedan). By comparing individual carlines with themselves, before and after the driver airbag seasonal driving conditions, road conditions, time frame, seat belt use and impaired driving patterns will remain the same for both or change very gradually. Table 1 shows Chrysler's passenger car line up from 1987 to 1993 (the Premier and Monaco were built in Canada). Shaded vehicles are driver airbag equipped. Boxed in vehicles are included in this study.

METHODOLOGY

First, the NHTSA's 1986-1992 Fatal Accident Reporting System data for all Chrysler products (cars, trucks, imports and joint venture vehicles) were gathered. The initial sort of the FARS data resulted in 9,300 occupant records (some fatally injured, but most not). To concentrate on the vehicles boxed in Table 1, the vehicle identification number

*"A Preliminary Field Analysis of Chrysler Driver Airbag Effectiveness", W. Randall Edwards, Paper No. 91-S9-O-11, Thirteenth International Technical Conference on Experimental Safety Vehicles.

Table 1.
Chrysler Corporation Passenger Carlines By Model Year

Body Code	1987	1988	1989	1990	1991	1992	1993
AA			Dodge Spirit Plymouth Acclaim	Dodge Spirit Plymouth Acclaim Chrysler LeBaron	Dodge Spirit Plymouth Acclaim Chrysler LeBaron	Dodge Spirit Plymouth Acclaim Chrysler LeBaron	Dodge Spirit Plymouth Acclaim Chrysler LeBaron
AC/AY		Chrysler New Yorker Dodge Dynasty	Chrysler New Yorker Dodge Dynasty	Chrysler New Yorker Dodge Dynasty Chrysler N.Y. Fifth Ave Chrysler Imperial	Chrysler New Yorker Dodge Dynasty Chrysler N.Y. Fifth Ave. Chrysler Imperial	Chrysler New Yorker Dodge Dynasty Chrysler N.Y. Fifth Ave. Chrysler Imperial	Chrysler New Yorker Dodge Dynasty Chrysler N.Y. Fifth Ave Chrysler Imperial
AE	Chrysler New Yorker Dodge 600 Plymouth Caravelle	Chrysler New Yorker Dodge 600 Plymouth Caravelle					
AG	Dodge Daytona	Dodge Daytona (1)	Dodge Daytona	Dodge Daytona	Dodge Daytona	Dodge Daytona	Dodge Daytona
AH	Chrysler LeBaron GTS Dodge Lancer	Chrysler LeBaron GTS Dodge Lancer	Chrysler LeBaron GTS Dodge Lancer				
AJ	Chrysler LeBaron	Chysler LeBaron (1)	Chysler LeBaron	Chysler LeBaron	Chysler LeBaron	Chysler LeBaron	Chysler LeBaron
AK	Chysler LeBaron Chysler Town & Country Dodge Aries Plymouth Reliant	Chysler LeBaron Chysler Town & Country Dodge Aries Plymouth Reliant	Dodge Aries Plymouth Reliant				
AL	Dodge Omni Plymouth Horizon Dodge Charger Plymouth Turismo	Dodge Omni Plymouth Horizon	Dodge Omni Plymouth Horizon	Dodge Omni Plymouth Horizon			
AM	Chysler Fifth Ave. Dodge Diplomat Plymouth Gran Fury	Chysler Fifth Ave. (1) Dodge Diplomat (1) Plymouth Gran Fury (1)	Chysler Fifth Ave. Dodge Diplomat Plymouth Gran Fury				
AP	Dodge Shadow Plymouth Sundance	Dodge Shadow Plymouth Sundance	Dodge Shadow Plymouth Sundance	Dodge Shadow Plymouth Sundance	Dodge Shadow Plymouth Sundance	Dodge Shadow Plymouth Sundance	Dodge Shadow Plymouth Sundance
BB		Eagle Premier	Eagle Premier	Eagle Premier Dodge Monaco	Eagle Premier Dodge Monaco	Eagle Premier Dodge Monaco	
LH							Chrysler Concorde Dodge Intrepid Eagle Vision
SR						Dodge Viper	Dodge Viper

(1) Mid-Year Driver Airbag

100% Driver Airbag

FARS Study Vehicles

Table 2.

Chrysler Corporation U.S. Market Passenger Car Production

Body Code	Driver Airbag	Model Year 1987	1988	1989	1990	1991	1992	1993 (1)	Total Vehicles	Vehicle Exposure (2) (Veh*Years)	~Curb Weight (Kg.) (#)	Relative Vehicle Size: Length (MM) (In.)	Width (MM) (In.)
AA	Without	-	-	131384	0	0	0	0	131384	455654	1282	4602	1730
	With	-	-	0	206328	231187	183696	51951	673162		2827	181.2	68.1
AC/AY	Without	-	127153	208893	0	0	0	0	336046	1334038	1392-1550	4877-5156	1750
	With	-	0	0	190777	178749	146399	40765	556690	908925	3066-3416	192-203	68.9
AG	Without	33197	43944	0	0	0	0	0	77141	388679	1280	4552	1760
	With	0	22869	70388	38752	17645	11719	7514	168887	505949	2822	179.2	69.3
AJ	Without	83531	63682	0	0	0	0	0	147213	753488	1300	4696	1740
	With	0	24769	91163	59236	40047	46766	3795	265776	693550	2875	184.9	68.5
AL	Without	-	-	84943	0	0	0	0	84943	304654	1042	4146	1682
	With	-	-	0	32579	0	0	0	32579	92230	2296	163.2	66.8
AM	Without	145802	66987	0	0	0	0	0	212789	1176393	1700	5250	1840
	With	0	7608	27233	0	0	0	0	34841	138093	3750	206.7	72.4
AP	Without	-	-	166767	0	0	0	0	166767	604110	1200	4361	1710
	With	-	-	0	134508	140263	146073	51152	471996	693374	2645	171.7	67.3

(1) Production Through 10/31/92

(2) Exposure Through 12/31/92

Table 3.

1986-1992 FARS Data-All Occupant Fatalities by Seating Position

	Seat Belts Only							Driver Airbag + Seat Belts							
	Front			Rear				Front			Rear				
Body Code	Driver	Center	Passenger	Left	Center	Right	Unknown	Driver	Center	Passenger	Left	Center	Right	Unknown	Totals
AA	46	0	22	2	0	1	0	93	0	47	7	5	5	3	231
AC/AY	109	1	47	4	1	10	1	63	1	36	10	1	6	1	291
AG	73	0	34	2	1	1	1	74	1	29	0	0	5	2	223
AJ	130	1	42	3	3	9	3	44	1	19	2	0	2	0	259
AL	46	0	9	1	0	1	0	16	0	4	0	0	0	1	78
AM	130	0	52	4	1	11	4	6	0	1	0	0	0	0	209
AP	80	1	31	5	1	4	0	94	1	34	8	1	4	0	264
Totals	614	3	237	21	7	37	9	390	4	170	27	7	22	7	1555

was used to further differentiate them. Table 3 shows all occupant fatalities for the study vehicles by seating position.

For the vehicles in the study, month by month United States market production shipments were obtained from production control records. Vehicle exposure was calculated from the monthly production and assuming a two month dealer inventory prior to entry into customer service (Table 2).

Since airbags are designed to offer head and torso protection in frontal and near frontal collisions, but not side, rear and rollover impacts, only most harmful event (FARS vernacular) principle impacts between 11 o'clock and 1 o'clock were retained. That is, all rollovers (first and most harmful events as described in FARS) were deleted, as well as, 2 o'clock to 10 o'clock principle impacts, top impacts, submersions and fires.

Driver fatalities and fatality rates shown in Table 4 were then computed by dividing the number of fatalities by the vehicle exposure, shown in Table 2.

DATA ANALYSIS

With the addition of 1991 and 1992 Fatal Accident Reporting System data, the total number of fatalities increased to 1,555 (Table 3) from 628. Similarly driver fatalities with and without airbags increased from 39 and 139 to 152 and 263 respectively for 11 o'clock to 1 o'clock frontal impacts.

As one can see in Table 4, overall driver fatality rates and frontal driver fatality rates still vary considerably between carlines, as well as, the percent change with airbags from without. For all crashes, driver fatality rate changes range from a 14% increase for AL body to a 63% decrease for AJ body, but the total exposure weighted fatality rate reduction is 22%.

When only frontal crashes are considered the driver fatality rate reduction increases to 29%, but similar rate change differences exist between carlines.

Because of small population sizes and demographic changes between airbag and non-airbag vehicles, one further data transformation was made to normalize the data. Since the risk of fatality of the typical eighteen year old male is lower than that of someone older, male or female, each frontal fatality for this reason was converted to that of a twenty year old male [*,**]. For example, the likelihood of a 20 year old male dying in a frontal crash that killed and 80 year old woman is 0.32. The equivalent fatality probability for each case is then summed. In Table 4 one can see this reduces the equivalent fatalities and fatality rates substantially. In this analysis, frontal fatality rates range from an increase of 12% to a decrease of 62% with an exposure weighted reduction of 22%.

[*] "The Effectiveness of Automatic Seat Belts in Reducing Fatality Rates in Toyota Cressidas", Carl E. Nash, NHTSA, June 1989.

[**] Traffic Safety and the Driver, Leonard Evans, 1991, Van Nostrand Reinhold, pp. 241-245.

DISCUSSION OF RESULTS

Demographic comparisons for the frontal fatalities (shown in Table 4) offer some explanations for the carline to carline difference. While demographics were not expected to change or only change slightly, significant differences exist. For example, the fatality ratio of male to female drivers in AA bodies with driver airbag is much higher than without. The introduction of the Chrysler LeBaron Sedan in 1990 (a luxury version of the mid size Dodge Spirit - Plymouth Acclaim) may have shifted these male-female demographics. Since male collision and fatality rates are much higher than female's, this shift would mask the fatality rate reduction expected with constant demographics. A similar shift in the AC/AY body male-female demographics may understate the fatality rate reduction benefits for these vehicles. In 1990 the AY body was introduced as a stretched wheelbase, luxury AC body with additional rear seat legroom.

Two areas where demographics did not explain the fatality rate changes are the AJ body (Chrysler LeBaron Coupe and Convertible) and the AL body (Dodge Omni - Plymouth Horizon).

The AJ body male-female fatality ratio increased with the driver airbag and yet the fatality rate reduction is one of the greatest. In the case of the Omni-Horizon (AL) the demographics are remarkably consistent, but the airbag fatality population is so small that convergence of the fatality rate has not yet been achieved, and similarly for the AM body with an airbag with still only two frontal airbag fatalities.

Subjectively, if any one set of data looks right, it would be for the AG body (Dodge Daytona). Here one sees a fatality rate reduction in the middle of the pack, near the overall average, with nearly identical demographics before and after the airbag and the 32% fatality rate reduction in frontal impacts can be trusted.

Although seat belt usage (as reported in FARS) is included in Table 4, its reliability has been challenged many times and any comparisons based on those differences would be similarly challenged and so are not presented.

Table 4.

1986-1992 FARS Data Analysis for Chrysler Cars

Without Driver Airbag			All Crashes			11 O'clock-1 O'clock Frontal Collisions Only						Driver Fatality Demographics			
Body Code	U.S. Vehicles	Vehicle Exposure (Veh*Yr)	Driver Fatalities	Driver Fatality Rate (/Million Veh*Yr)		Frontal Driver Fatalities	Driver Frontal Fatality Rate (/Million Veh*Yr)		20 Year Old Male Equiv. Fatalities	Normalized Driver Frontal Fatality Rate (/Million Veh*Yr)		Average Age (Yr)	Age Range (Yr)	Male-Female	Seat Belt Use Yes-No-Unknown
AA	131384	455654	46	100.95		20	43.89		9.94	21.81		51.7	28-87	11-9	10-9-1
AC/AY	336046	1334038	109	81.71		58	43.48		24.68	18.50		57.8	16-86	39-19	22-33-3
AG	77141	388679	73	187.82		25	64.32		19.45	50.04		30.1	16-78	17-8	4-19-2
AJ	147213	753488	130	172.53		34	45.12		21.36	28.35		38.8	16-87	18-16	14-16-4
AL	84943	304654	46	150.99		30	98.47		16.90	55.47		47.0	19-92	20-10	12-15-3
AM	212789	1176393	130	110.51		55	46.75		21.24	18.06		63.7	29-93	35-20	16-38-1
AP	166767	604110	80	132.43		41	67.87		29.57	48.95		32.8	16-74	27-14	14-21-6
Total	1156283	5017016	614	122.38		263	52.42		143.14	28.53					

With Driver Airbag			All Crashes			11 O'clock-1 O'clock Frontal Collisions Only						Driver Fatality Demographics			
Body Code	U.S. Vehicles	Vehicle Exposure (Veh*Yr)	Driver Fatalities	Driver Fatality Rate (/Million Veh*Yr)	Driver Fatality Rate Percent Change	Frontal Driver Fatalities	Driver Frontal Fatality Rate (/Million Veh*Yr)	Driver Frontal Fatality Rate Percent Change	20 Year Old Male Equiv. Fatalities	Normalized Driver Frontal Fatality Rate (/Million Veh*Yr)	Normalized Driver Frontal Fatality Rate Percent Change	Average Age (Yr)	Age Range (Yr)	Male-Female	Seat Belt Use Yes/No/Unknown
AA	673162	1070009	93	86.92	-13.91	46	42.99	-2.06	23.57	22.03	1.0	52.1	18-86	31-15	22-16-8
AC/AY	556690	908925	63	69.31	-15.17	26	28.61	-34.21	13.83	15.22	-17.8	50.3	15-90	19-7	9-15-2
AG	168887	505949	74	146.26	-22.13	22	43.48	-32.40	17.03	33.66	-32.7	29.4	17-69	15-7	8-13-1
AJ	265776	693550	44	63.44	-63.23	11	15.86	-64.85	7.20	10.38	-43.9	36.8	19-56	10-1	3-5-3
AL	32579	92230	16	173.48	14.89	10	108.42	10.11	5.71	61.91	11.6	45.9	16-82	7-3	6-4-0
AM	34841	138093	6	43.45	-60.68	2	14.48	-69.02	1.16	8.40	-53.5	41.0	38-44	2-0	1-1-0
AP	471996	693374	94	135.57	2.37	35	50.48	-25.62	22.83	32.93	-32.7	38.9	14-78	20-15	15-16-4
Total	2203931	4102130	390	95.07	-22.32	152	37.05	-29.32	91.33	22.26	-22.0				

The data in this study in the aggregate is very consistent with other studies by the National Highway Traffic Safety Administration * ** and the Insurance Institute for Highway Safety*** **** which indicate 19-20% and 23-29% reductions in overall and frontal fatality rates respectively. None of those studies tries to segregate individual carlines for analysis, which would likely result in similarly wide differences between carlines.

Despite the good news that driver airbags are saving lives and reducing moderate to severe injuries, many more are still dying in frontal collisions than are being saved. A review of the Fatal Accident Reporting System data used in this study indicates that 93% of airbag and non-airbag vehicles with frontal crash driver fatalities were severely deformed (coded 6 in FARS). Chrysler's studies of driver fatalities in frontal crashes concur with this and indicate that a very high percentage of these be termed unsurvivable by conventional judgement. Driver airbags are meeting their design intent. To measurably expand the envelope of survival, much higher degrees of frontal crashworthiness will have to be achieved, which maybe beyond practicability, human tolerances, or other regulatory and market constraints (i.e. fuel economy, utility or consumer preference). While greater degrees of crashworthiness is one approach to reducing fatalities, the more expedient and cost effective approach is through the modification of driver behavior with respect to seat belt use, impaired driving habits and excessive speed.

CONCLUSION

The inclusion of two more years of Frontal Accident Reporting System data was beneficial. The population of driver fatalities with airbag quadrupled. Exposure of the contrasting restraint systems is balanced, but not identical. Individual carline analyses are not predictive of aggregate performance because of small populations and unidentified demographic factors. One can have confidence that the net effect of the driver airbag is significantly positive, but immortality is not guaranteed. Airbags are but a piece of the entire safety system and strategy to making motorways safer.

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*"Evaluation of the Effectiveness of Occupant Protection", NHTSA, June 1992.

**"Effectiveness of Occupant Protection Systems and Their Use", NHTSA Report to Congress, January 1993.

***"Driver Fatalities in Frontal Impacts: Comparisons with Airbags and Manual Belts", Insurance Institute For Highway Safety, October 1991.

****"Effectiveness of Airbags in Preventing Driver Fatalities in the U.S.", Insurance Institute for Highway Safety, October 1992.

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Mid-Atlantic Driver Air Bag

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ABSTRACT

Seat belt usage is not zero percent in the United States (one side of the Atlantic) nor is it one hundred percent in europe (the other side of the Atlantic). Yet, air bag systems have been and are still being designed in these areas as if this were the case. Furthermore, very few air bag deployments occur in the United States under impact conditions for which they were designed. In fact percentage wise this is less than 6% for speeds greater than 25 mph and for 30 mph or greater, less than 2%. In this paper the concern is the relatively large number of air bag deployment injuries, which are occurring. It is often inferred that these deployment injuries are more or less the price which must be paid in order to have high speed crash protection. These injuries are not however, believed to be necessary by this author.

INTRODUCTION

A Mid-Atlantic driver air bag is not so much a thing as it is a philosophy. This philosophy attempts to recognize and design for the conditions under which deployments of air bag systems are actually occurring in the real world.

Seat belt usage is not zero percent in the United States (one side of the Atlantic) nor is it one hundred percent in europe (the other side of the Atlantic). Yet, air bag systems have been and are still being designed in these areas as if this were the case.

Furthermore, very few air bag deployments occur in the United States (where we have good statistical data back to 1988), under impact conditions for which they were designed. In fact percentage wise this is less than 6% for speeds greater than 25 mph and for 30 mph or greater, less than 2%. In this paper the concern is not the expense of replacing these systems after deployment, 78% of which occur below a delta V or velocity change of 19 mph, but rather the relatively large number of air bag deployment injuries which are occurring. It is often inferred that these deployment injuries are more or less the price which must be paid in order to have high speed crash protection. These injuries are not however, believed to be necessary by this author. Air bag deployment injuries are not only a technical problem but also a problem due to; the way air bags are being sold (marketing), politics (government regulation), and consumer pressure (consumer advocate groups). We are all in part responsible for the problem and certainly can all be part of the solution.

This short paper therefore is an attempt to not only bring attention to this concern but further it is a plea that we all recognize that we are part of the problem and hopefully will take steps to bring about "kinder, gentler" "Mid-Atlantic" air bag systems.

DISCUSSION

Air Bag Deployments

Accident analysis has indicated that moderate injury may occur to unrestrained occupants at barrier equivalent velocity crashes (delta V's) down to 10 or 12 mph. Historically, therefore air bag crash sensors have been designed for threshold velocities equivalent to this threshold of injuries. Because of a large number of variables involved one could easily expect a ± 2-3 mph uncertainty in calibration of the crash sensors, see for example Reference 1. Therefore, it is not surprising that many deployments occur at delta V's even below 10-12 mph.

Besides this calibration uncertainly there also exists what this author calls the hyperbolic relationship of the crash velocity and the number of crashes which occur. Every time we have bumper contact during parking we essentially have a crash at near zero velocity. On the other hand crashes at a barrier equivalent velocity of say for example 60 mph are extremely rare. Thus it is believed that the frequency distribution of crashes as related to velocity is generally as depicted in Figure 1, or $n = c/V$ where n is the number of crashes, V is velocity and c is a constant.

Hence compared to the crashes which occur at FMVSS 208 (30 mph) or NCAP (35 mph) the number of crashes and hence air bag deployments which occur at threshold velocity is huge.

Figure 2, taken from 1988-1992 NASS Files for towed vehicles crashes, shows this hyperbolic distribution of crashes. Obviously since these data represent only damage cases sufficient to tow away the vehicle they under-represent the crashes which occur at low speed.

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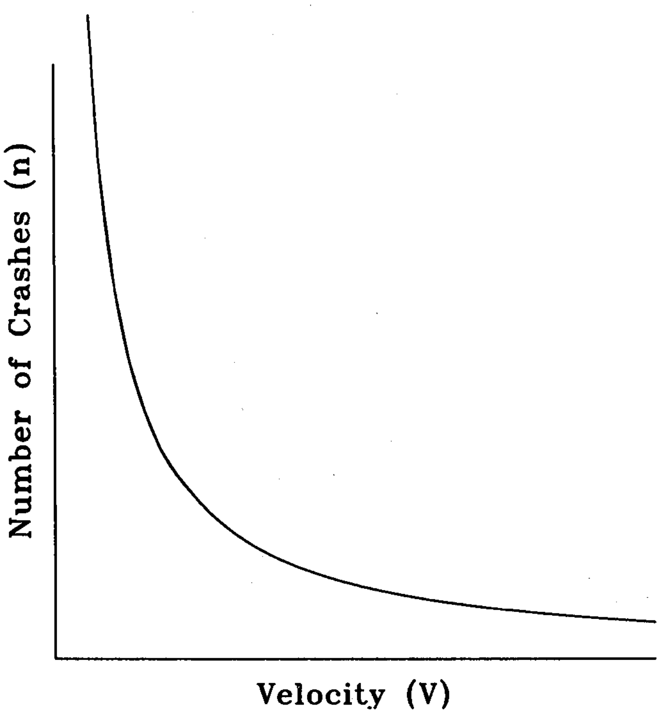

Figure 1. Hyperbolic nature of crashes.

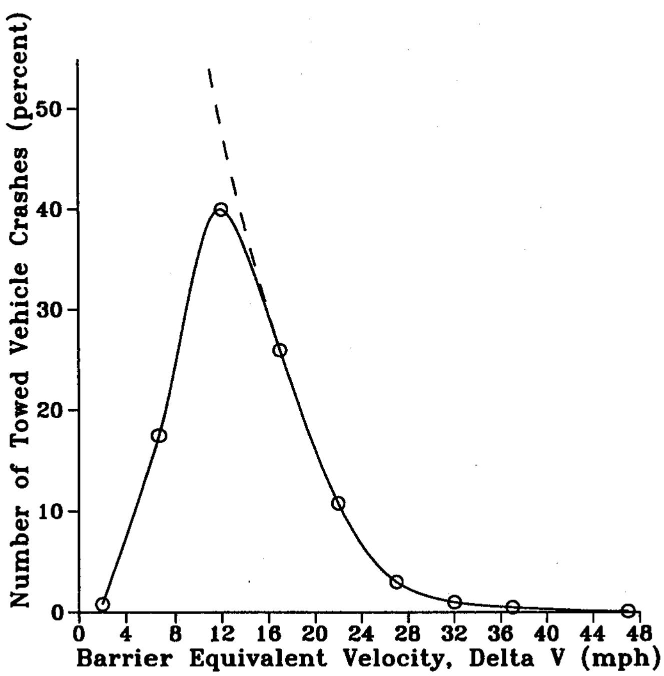

Figure 2. Percentage of towed vehicle crashes for given barrier equivalent velocity.

From this one could conclude that large numbers of air bag deployments will correspondingly occur near or just above sensor closure threshold. Indeed this is the case. Figure 3, also taken from 1988-1992 NASS Files, presents air bag deployment occurrence as a function of crash velocity, delta V. Note that 35% of deployments occur at or below 14 mph, and 78% occur below 19 mph. Only a little over 2% of all air bag deployments occur at conditions of FMVSS 208 or NCAP, i.e. 30 mph or above.

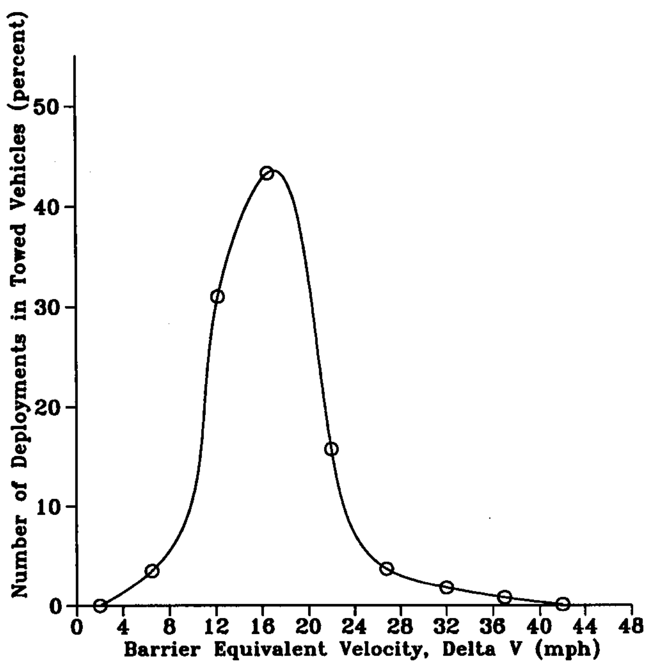

Figure 3. Percentage of air bag deployments in towed vehicle crashes for given barrier equivalent velocity.

This hyperbolic relationship explains why so many air bag deployments occur at such low speeds. It's just like when they asked Willie Sutton why he robbed banks. "Because," he answered, "that's where the money is." Why do so many air bag deployments occur at or near threshold, i.e. at low speeds? Because "that's where the crashes are." In conclusion we can say that nearly all of our air bag energies, i.e. technical, political, and marketing focus on 2 percent of the deployment occurrences. But that's not the only problem. The time of sensor closure is also, basically hyperbolic in character as shown in Figure 4. The data are for an actual representative sensor system. The dotted curve in Figure 4 is the hyperbolic function:

$$t = c/(V-V_t)$$

where c is a constant and V_t is the threshold velocity. Furthermore, as said earlier, we know that due to a number of sensing variables an actual threshold velocity, i.e. the point where 50% of crashes result in deployment and 50% do not,

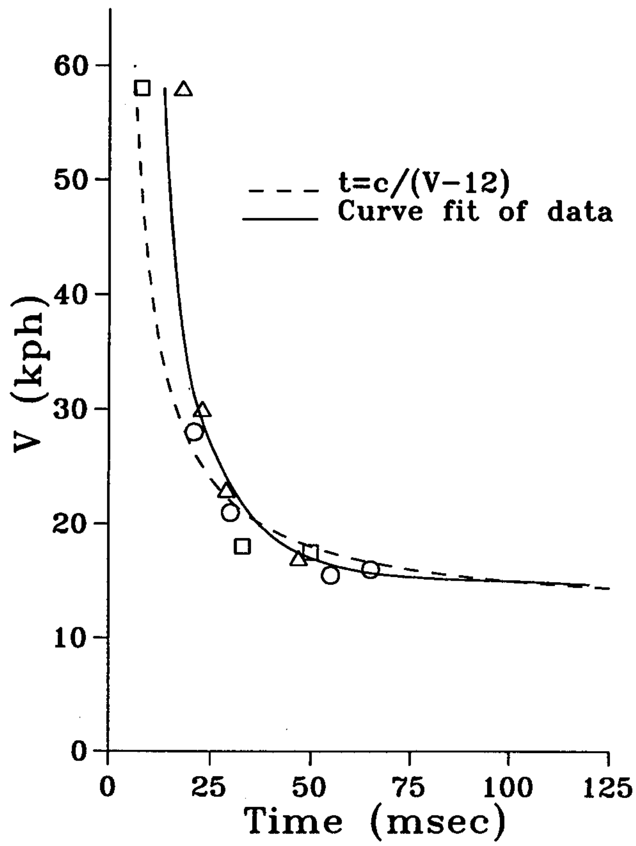

Figure 4. Typical production crash sensor closure characteristics.

has a dispersion of approximately $\pm$ 3 to 4 Kph. Thus the closest together we can set "must fire" and "must not fire" specifications is about 6 to 8 Kph, e.g. must fire, 20 Kph; must not fire, 12 Kph.

Because of the hyperbolic nature of the sensor closure behavior, and the known dispersion in closure threshold it follows that air bag deployments which occur at or near threshold velocity will occur at times which can vary between the FMVSS 208, 30 mph closure times, (typically around 20 msec) all the way out to the end of the crash pulse, including rebound. This could be as late as 100 or 120 msec.

It is not unreasonable to assume therefore that in many threshold or near threshold deployments the occupant may well be forward or "out of position."

An obvious solution is to increase the sensor threshold to reduce the deployments. This should be looked at carefully because the hyperbolic nature of crashes suggests that a small increase in threshold could significantly reduce the number of deployments and therefore deployment injuries. However, due to the wide dispersion of threshold conditions it will not be possible to obtain large increases in threshold settings lest non-deployments occur when the air bag is needed.

Air Bag Deployment Injury, Field Experience

This section will briefly review air bag deployment injuries which are occurring in the United States. First however, an attempt to categorize the types of injuries and their sources is given.

Air bag deployment injuries can be grouped, for further discussion as follows:

<u>Mechanical</u> - These are injuries associated with being physically struck by the air bag cover or deploying air bag. They are caused by the forces and pressures which result from the mass and velocity of the cover and bag. These forces and pressures occur because the cover, due to its stiffness, mass, and resistance to break open allows high pressure, as much as 5 bars, to build up in the module prior to cover rupture. Even without the cover the rapid production of gas in combination with the mass of the air bag can generate sufficient pressure to expel the bag at very high velocity.

The types of injuries which occur are: abrasions, bruises, fractures, and dislocations of limbs and hands; eye retina tears and detachments; and thorax compression and subsequent internal organ damage.

<u>Chemical</u> - Sodium Azide-Oxidizer compositions burn and produce gaseous nitrogen. However, over 50% of the products of combustion are particulates or solids which must be retained by the gas generator filter system. Since filter systems are of course not perfect some sodium oxide particulate is released into the air bag and flows out the air bag vents. This particulate (often misidentified simply as talcum powder) is released in quantities (allowable in some specifications), of up to 3 grams. The particulate combines with moisture on the skin, in the eyes or in the respiratory system to form sodium hydroxide, a caustic liquid. Results of this occurrence can range from simple skin irritation, to coughing, to serious eye injury.

<u>Thermal</u> - The gas and particulate which flow into the air bag and subsequently from vent holes can and do impinge on the body, particularly on the hands and arms. This can cause thermal burns. Anyone who has passed their hand through a candle flame can reason that the gas itself has insufficient mass to cause serious problems for the very short, millisecond exposure time to which the body part is exposed. It is believed that it is the particulates (solids) which have concentrated stream lines when they flow from the vent that are chiefly responsible for thermal burns.

Mechanical, chemical and thermal are the three types of air bag deployment injuries to which automobile occupants are being subjected. Following is a brief review of these injuries.

As of July 1, 1993 (see Reference 5), NHTSA had looked at 1,200 air bag crashes in which some injury occurred. The Insurance Institute for Highway Safety (IIHS) studied 273 of these since in these 273 cases it was determined that air bags were solely responsible for the injuries which had occurred. IIHS found 280 occupants with 436 injuries. Thus we can say that in the United States air bag induced injuries occur about 25% of the time. Nearly all of these injuries were classified as AIS 1. Of the remaining, they were classified AIS 2 or 3.

Of the 436 injuries 50% were abrasions, 26% bruises, 11% cuts, and 9% burns. Of the 436 injuries 28 involved the eye and of those 11% were moderate.

One could say that AIS-1 injuries are of no real consequence. However, it should be pointed out that the AIS scale of severity of injury is with respect to permanently caused disability and death. Hence, included as AIS minor injuries, were eye injuries including lacerated retina, detached retina, ruptured eyeball and cataract. I'm sure that recipients of these injuries did not think of them as minor.

Don Huelke of the University of Michigan has studied about 200 air bag crashes. He reports sprained and dislocated thumbs, forearm fractures and dislocation, burns, blisters, and reddening of the skin. The New England Journal of Medicine reports that a women suffered an atrial tear as an air bag induced injury.

To date, to my knowledge, no fatalities have been officially attributed solely to air bag deployment. Unofficially it is generally acknowledged however that this has, in fact, occurred in approximately a dozen cases or more.

Big, fast, hard, highly vented air bags generally produce the best FMVSS 208 and NCAP crash test HIC's. Is this all our air bag designs should be striving for? In view of air bag deployment injuries at low crash speeds; the very low incidence of severe, high-speed crashes with resulting air bag deployment; and the recent high usage rate of safety belts; our air bag design goals must be re-evaluated.

Air Bag Deployment Injury, Experimental Results

It is my opinion that the greatest single factor that could be changed to reduce bag deployment injury would be to increase the time allotted to inflate the air bag. An increase of 15-20 msec, for example from 25 msec to 40 or 45 msec, on the driver side, would be a very big improvement.

This position is based to a large part on personal experience over the years including studies of effects of staging on injury to animals with passenger side air bag systems. Production experience with deployment loads on air bags, covers, metal and plastic module components, instrument panels, etc. has also led to this position. To document this position three references are cited herein and will be briefly discussed. All three references deal with driver side systems and all three at least in part compare potential injury to occupants for varying gas generator output.

The first paper, Reference 2, by Horsch and Culver discusses driver air bag loads as measured by chest and sternum acceleration and chest compression using a Hybrid III dummy. Type A and Type B air bag modules are compared. The primary difference in these modules, to this author's best information, is that Type A used the gas generator in production in GM automobiles during 1974-1976, and Type B were gas generators to be used for the early 80's introduction. To GM's credit, bag fill and onset rates of present GM gas generators are believed to be the same or less than Type B. Type A bag fill and onset rate were considerably greater (as much as 50 to 75 percent) than Type B but not unlike some that may be in use by others today. The results, for the case of the dummy chest located up against the steering wheel, were as seen in Table 1.

For obvious reasons, little was said in this paper regarding the relative potential injury which could be caused by Type A versus Type B modules, but the data speak for themselves.

In the paper by Reed, et al, Reference 3, commercially available driver air bag modules were deployed such that the deploying bag stuck the shin (ouch!) of human volunteers. Regarding gas generator differences they also carefully spoke of "Lower" versus "Higher" inflator capacity.

Injury rating was based upon severity of skin abrasion and the results clearly showed that at a distance of 225 mm the "Higher" capacity inflators caused the most severe injury. In fact, even with tethers the injuries were greater than those of

Table 1
Air Bag Deployment Loads

Test	Module	Chest Compression (mm)	Sternum Accel (g's)	Compression Rate (m/sec)	Column Stroke (mm)
948	Type A	84	538	17	84
969	Type A	81	374	17	94
984	Type B	43	190	5	33
985	Type B	43	190	4	37

Table 2 Air Bag Deployment Characteristics			
Type	Velocity Peak (mph)	Velocity at face contact[1] (mph)	Inflation Time (msec)
B	157	95	30
C	116	98	28
D	98	46	46
E	112	39	47
I	211	184	21

1. If face would have been struck

the "Lower" output inflators without tethers. The injuries also correlated well with bag leading edge velocity. For untethered bags these velocities were 65 m/sec (145 mph) for the "Lower" inflators verses 100 m/sec (224 mph) for the "Higher" inflators.

Reference 4 does not cite gas generator output but this can be inferred from the measured leading edge velocity and bag fill times. Table 2 lists peak velocity and bag fill time for various systems tested. Only untethered results are shown. In these tests a 5th percentile dummy profile was drawn on a grid located to the side and fifteen inches rearward of the deploying air bag and not struck by it.

Bag fill time relates quite well to bag velocity and therefore gas generator onset rate and output. Table 3 is proposed as a means of relating bag deployment injury potential to bag deployment time.

Table 3 Air Bag Deployment Aggressivity	
Driver Bag Deployment or Inflation Time (msec)	Air Bag Design Aggressivity
20-25	high
25-40	medium
40-45	low

It would be very beneficial to have a means to encourage the use of gas generators with lower aggressivity as a way to help reduce air bag deployment injuries. To the degree that doing so may somewhat degrade FMVSS 208 or NCAP results, the NHTSA should not penalize but rather find means to praise and encourage automotive manufacturers that move in this direction.

Solutions

<u>**Marketing**</u> - Automobile advertising and marketing is apparently in love with the air bag. In most advertisements today it seems that you buy an air bag (driver and passenger of course) and an automobile comes with it. This would be good if it were not for the public perception that air bags are soft, pillowy things that slowly come out and gently protect. In fact people today are often disappointed in fender-bender accidents when the air bag doesn't deploy. Accidents where air bags must provide protection are very violent occurrences. Air bag deployment itself is rather violent, it's something to be taken seriously. The bigger, the faster, and the harder air bags are, the more violent they are, and the more they can and do cause injury.

Advertising needs to reflect this, to teach the consumer that the air bag system needs proper respect. NCAP advertising is in many ways counter productive. Often corporate zeal to come out with the lowest dummy injury scores possible, forces the air bag system design engineers to do things and go in directions they know are not beneficial to overall system performance. Some of my colleagues in the automobile industry have told me that they are personally outraged that they must produce optimized HIC number for FMVSS 208, 50th percentile male sized, stupid (i.e. unbelted) dummies at the expense of the small, belted, women that will actually sit with their seats forward in front of these systems. (When the feminists figure this one out they'll be marching on the DOT; with good cause).

Marketing people must be taught to understand that they are not in a HIC race, that bigger isn't necessarily better and that the overall performance of the air bag system under conditions where it is mostly deploying is important too.

<u>**Regulatory Solutions**</u> - Charles Gadd of G.M. Research Laboratories more or less invented HIC (or at least its predecessors) approximately 25 years ago. At that time he really just wanted people working in the field of biomechanics to agree that a person's ability to withstand rapid deceleration

was time duration dependent. He used a Gadd Severity Index (GSI), later called Head Severity Index (HSI), of 1,000 as a more or less threshold of serious injury.

In a related area, after petitioning the NHTSA, chest resultant acceleration C_R was raised at GM's request from 40 to 60 g's. Since a stuntman by the name of Ross Collins was routinely taking 40 to 50 g's in a stunt show in Las Vegas every night, 60 g's seemed to be a reasonable change.

Today these numbers, i.e. HIC = 1,000, C_R = 60 g's, appear to be cast in stone even though at the time Charles Gadd himself wrote that an HSI of even 1500 would be a reasonable tolerance limit when restrained by a load distributing device such as an air bag. He further wrote that whole chest accelerations of 70 to 80 g's also would be acceptable under similar load distributing restraint.

Today if we were to accept these recommendations for HIC and C_R for the case of air bag restraint it would result in a great reduction in air bag deployment injuries as well as an improvement in overall air bag system performance. This is explained as follows: Increasing acceptable tolerance limits for HIC and C_R would allow the design and implementation of smaller, slower, softer, and safer air bag systems. Air bag venting therefore would not be so critical or always necessary. Bags could be de-tuned and stay inflated longer for real world crash scenarios.

Often corporate goals for air bag system design require safety margins so that vehicles will never fail to pass FMVSS 208. Due to normal variability concerns these corporate goals can be as low as 600 or 700 on HIC and 48 or 50 g's on C_R. As noble as this may seem it actually results in the design of aggressive over-filled, over-vented air bag systems.

If the tolerance limits are raised, systems can be de-tuned and they can be designed more for the real world and less for the simulated 50th percentile male sized dummy crash test. This would seem to be a modest proposal. Completely eliminating FMVSS 208, would also work toward reducing deployment injuries and providing a better overall system for the real world but it is doubtful that this would be acceptable, at least for the near future.

Technical - If it is not possible to give up our obsession with HIC from either a marketing or regulatory perspective there are, at least potentially, technical solutions toward reducing air bag deployment concerns.

1. Increase the Threshold of Deployment - Because of the hyperbolic nature of the frequency of occurrence of crashes and the increased incidence of usage of seat belts a reasonable approach would be to increase the nominal threshold of air bag deployment. It should not be too difficult to perform an analysis which trades off deployment injuries versus low speed crash induced unrestrained injuries. It is believed that the threshold could be increased by 2-4 mph to produce an overall reduction in occupant injury. This would be especially true if we were to weigh in the present approximate 75% or greater seat belt usage in air bag equipped automobiles.

2. Anticipatory Radar Crash Sensor - If we could not significantly increase threshold level because analysis would indicate unacceptable non-deployment injuries we should concentrate on reducing the severity of the deployment exposure. Many factors can and have been considered to reduce the severity of deployment, including reducing air bag size and mass, using straps, folding methods, and other bag changes. However, it is believed that the greatest effect could be brought about be increasing the time allotted to filling the bag, i.e. bag inflation time. Since the time at which the inflated bag is needed can't change much we would need to reduce the crash detection time in order to be able to increase the bag inflation time.

If we could detect a crash and make a decision to deploy the bag within say 10 msec, we could add 10 to 15 msec to the available deployment time. It is believed that adding 15 msec to bag inflation time would significantly reduce deployment injuries (this feeling is based upon comparisons of fast versus slow, or high onset rate versus low onset rate gas generators as previously discussed).

Present crash sensors are more or less velocity change or delta V indicators. Hence sensing time is usually required to determine that threshold velocity change has occurred prior to sensor closure. This could be as little as 20 msec for a serious high speed crash or up to 100 msec for a threshold crash.

Suppose in all cases we could make a decision to fire or not fire within 10 msec. One way to do this would be to use closure velocity as measured by a pre-crash radar sensor, Reference 6, and delta V as measured by the crash sensor. The delta V measured by the crash sensor could be a value much smaller than the threshold velocity since the radar would have already indicated that the threshold velocity criteria had been met. Take as an example the hypothetical vehicle crash behavior shown in Table 4.

Table 4
Vehicle Crash Behavior

t (msec)	V (mph)	delta V (mph)
0	30	0
5	28	2
10	25	5
15	21	9
20	18	12
25	15	15

Without radar the closure velocity of 30 mph would not be known. Therefore, the crash sensor would require 20 to 25 msec before it knew the crash speed was above the threshold,

Table 5
Sensor Closure Logic

Radar V (mph)	Crash Sensor delta V (mph)	Deployment	Situation
5	5	no	bumper test
10	5	no	fender bender
15	5	yes	threshold
30	5	yes	serious crash
30	0	no	cardboard box
30	2	no	mailbox post
0	10	no	radar unsighted
0	12	yes	radar unsighted
30	0	no	target is missed

i.e. 10-12 mph and could therefore close and allow deployment. With radar the crash speed would be known at time zero and only a signal necessary to assure the crash was real, i.e. not a 30 mph crash into a cardboard box, would be necessary. This could be determined in 5 to 10 msec. The crash sensor closure logic would be such that a closure command would be given provided for example,

$V_{radar} \geq 12$ mph and

delta $V_{crash\ sensor} \geq 5$ mph

or delta $V_{crash\ sensor} \geq 12$ mph.

Illustrative crash examples using this logic are given in Table 5.

With this system we could add 15 msec to the normal air bag deployment time and thus reduce the occurrence of bag deployment injury. If the radar failed to pick up the target, the crash sensing system would still operate as normal.

This approach, i.e. to use an anticipatory radar crash sensor in combination with a more or less conventional crash sensor is introduced here as only one example of technical solutions which might be used to reduce air bag deployment injury.

CONCLUSIONS

1. By far the majority of air bag deployments occur at threshold to moderate crash speeds.

2. When air bags deploy they can and often do cause some injury. There is always an attempt to place these injuries in perspective to more serious injuries which can be abated in more serious crashes. It is inferred that this is more or less the price that must be paid, but this is not the case.

3. Due to requirements for protection of unbelted occupants at 30 mph in the U.S., air bag designs are not properly weighted for the real world.

4. Belt usage in the U.S. has seen an enormous increase since requirements for passive restraint were first introduced nearly twenty five years ago. Therefore particularly in view of air bag deployment injuries more realistic real world regulatory requirements are needed.

5. Bigger, faster, harder, highly vented, optimized HIC result air bag systems are not better. Deployment injuries and overall crash injury reduction can be improved by adapting a more moderate "Mid-Atlantic" approach to air bag system design.

6. Air bag systems can be made less aggressive but this requires cooperative efforts in marketing and regulations as well as in the technical arenas.

7. Eliminating FMVSS 208 would work toward reduced air bag deployment injuries and increased overall system benefit. A more modest proposal would be to increase HIC and chest resultant acceleration limits to 1500 and 75 g's when air bags provide the load distributing restraint means. Biomechanics data support these numbers for the case of air bag restraint.

One final note: Deployment injuries have occurred so far primarily on the driver side because relatively speaking, there are few passenger systems. Therefore, this paper is directed toward driver air bags. If these concerns are not addressed, we are merely seeing the "tip of the iceberg" as to when wide spread introduction of passenger side air bags has occurred.

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SMARTTM Airbag System

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ABSTRACT

The SMARTTM airbag system is an adaptive restraint system which utilizes inputs on crash situations, occupant status and the vehicle environment to optimize the airbag system performance to an actual crash. This system is designed to function with improved performance over a wider range of crash situations than is possible with conventional airbag systems which have no adjustment capabilities. Tailorability is achieved by sensing changes in conditions such as occupant and vehicle status and utilizing an electronic control unit (ECU) which identifies the crash situation and adjusts a variable gas generation source appropriately. The ECU thus adapts the system performance level for the actual situation present at the time of the crash.

INTRODUCTION

Conventional airbag restraint systems are typically designed and optimized based on nominal crash conditions. These "nominal" conditions are:

- Ambient temperature conditions
- Fiftieth percentile occupant
- Seat in the mid-track position
- Column tilt in the mid position
- A Crash at 0 degrees into a rigid barrier at approximately 50 KPH for the unbelted scenario and 56 KPH when using all available restraints.
- Off-axis accelerations (30 degree barrier)

Once the restraint system has been satisfactorily designed for these "nominal" conditions, "due care" testing is typically performed (although not required) to check for adequate protection in conditions at the extremes. Typical "due care" testing includes:

- Different occupant sizes
- Various seat track positions
- Various steering column tilt positions
- Out-of-position occupants
- Alternate crash scenarios (pole, threshold speeds, offset, etc.)

One drawback of the conventional system is that many airbag deployment crashes occur at velocity changes significantly less than 50 KPH. The restraint system is more aggressive than required for these conditions and thus increases the risk of inflation induced injuries. In addition, the threshold velocity changes needed to trigger deployments are typically based on the requirements for an unbelted occupant, and could potentially be set to a higher ΔV when the occupant is belted. This would reduce the number of low speed deployments and minimize repair costs.

Furthermore, occupant position and size as well as inflator temperature are seldom all at nominal conditions and all have significant effects on occupant protection. Additionally, much expense could be saved if the passenger airbag did not deploy when an occupant is not present. Out-of-position occupants (especially children and infants in rear facing child seats) are susceptible to increased risk of harm due to inflation induced injuries.

In order to reduce the effects of these problems, Morton International, Inc. and Robert Bosch, GmbH began developing the SMART™ airbag system working through our UNAS, GmbH teaming agreement.

SMART™ AIRBAG SYSTEM

The SMART™ airbag system can be described as the interaction of three separate functions which together form an adaptive airbag restraint system. The three functions are 1) sensory input, 2) evaluation of the input and determining the appropriate action, and 3) responding in a way which adjusts for the situation.

A crash "situation" can be identified by various sensors in the vehicle which monitor parameters which affect airbag system performance. These sensors monitor status of vehicle acceleration, seat belt usage, occupant presence and position, and inflator temperature. The ECU interrogates the input of each sensor at appropriate time intervals and sets deployment parameters accordingly. This crash situation can be divided into two aspects: environmental influences such as crash severity and inflator temperature, and occupant status such as belted/unbelted and/or out-of-position. Deployment parameters include which inflation level to produce and what time delay, if any, between inflation levels. By varying the inflation level and delay time between inflation levels it is possible to compensate for factors that potentially degrade the performance of the restraint system.

Functional Description

<u>Sensing the Environmental Situation</u>

The complete system is designed to function on the basis of a quasi "open loop" control system. Adaptation of the firing strategy is continuously updated according to "state" measurements of the environment. Required inflation level performances for these environmental "state" conditions have been predetermined by off-line investigations using HYGE Sled testing and MADYMO simulations.

Any changes in the environment must be determined using sensors mounted in the vehicle or electronic control unit. The information is then processed by the electronic control unit to determine the inflator performance required for the particular crash and environmental conditions. Finally, trigger commands start the firing process. Thus the inflator represents an actuator in our control system analogy. An overview of the system functionality is shown in Figure 1.

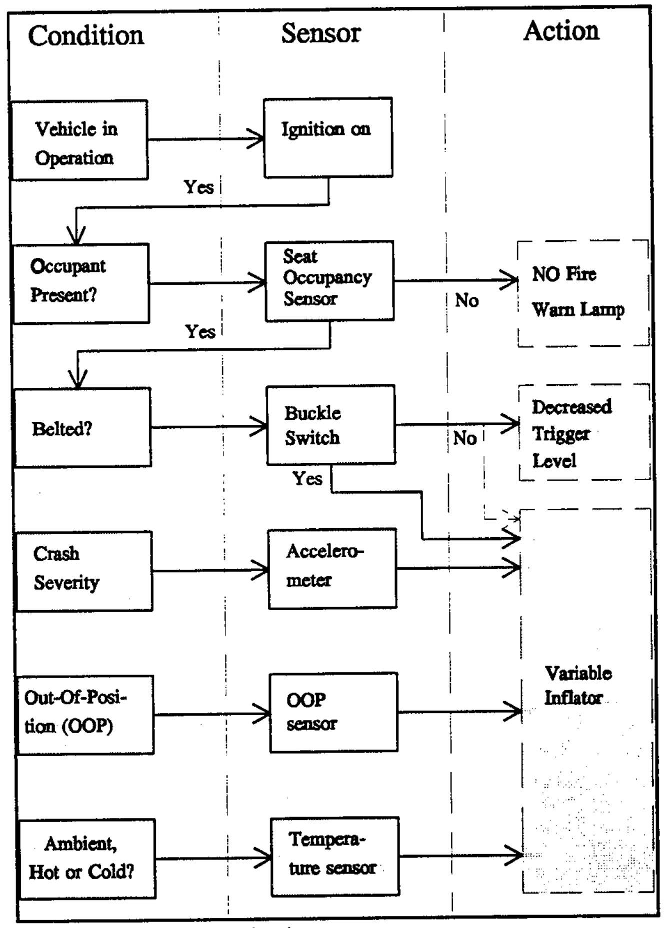

Figure 1. Functional Diagram

The condition represents the state of the environment which needs to be determined and accounted for by the system. The sensor group includes the means of ascertaining the current conditions and preparing the measurements for the decision making electronics. The action group includes both the decision making algorithms for inflator performance and thresholds, and the "actuators" that are used to tune the system performance.

The operation of the electronic control unit is activated when the vehicle's ignition is turned on. Airbag firing is then dependent on the presence of an occupant. The first decision to make the airbag operational is based on measurements taken from the seat occupancy sensor (passenger side only). Thus the SMART™ system decides whether an airbag is needed or not. If there is no occupant present, or a child seat has been mounted on the passenger seat, then the airbag should not be made operational. Sensing the presence of an occupant is carried out using a seat occupancy sensor. Capacitive changes due to the electrolytes in the human body can be used to discriminate between simple objects which do not require the protection of an airbag, and actual occupants who require the safety device during a crash.

Further information about the occupant's "status" contributes to improved operation of the airbag system. The belt status of the driver or passenger can be determined by a belt switch. A belted occupant requires less energy to be absorbed by the airbag, thus allowing a less agressive performance to be used. Out-of-position detection provides information concerning the location of the occupant with respect to the airbag. The chance of injury from the airbag itself can increase if the occupant is located closer to the module. Zones of increased danger can be determined based on the variable performance of the inflators. A high performance inflator would have a larger danger zone. If an out-of-position occupant is within this danger zone then only the inflation level 1 performance would be initiated given that all other parameters have not changed. A device such as microwave radar can be used to detect such out-of-position conditions.

Information about the type of crash or "crash severity" can be derived from accelerometer measurements that are currently used for basic crash detection. Classifying the type of crash adds indirect information about forces acting on the occupant, whereby the forward displacement of the occupant depends on the deceleration of the passenger compartment. It may be advantageous for a crash with a long delay to fire a two stage inflator in a predetermined sequence with a proportional time delay. This relies on the evaluation of the accelerometer signal and predictive properties of the algorithm. Table 1 summarizes possible classifications for various types of crashes.

Table 1
Severity for Various Types of Crashes

No.	Velocity	Type	Severity
1	50 KPH	Frontal	High
2	25 KPH	Frontal	Low
3	50 KPH	Vehicle/Vehicle	High
4	50 KPH	40% Offset	High
5	20 KPH	40% Offset	Low
6	40 KPH	Pole	High
7	30 KPH	Pole	Low
8	50 KPH	30 Deg Angled	High
9	30 KPH	30 Deg Angled	Low

The airbag inflator performance is currently dependent on the temperature of the generant inside the unit. Mass flow out of the inflator can vary between "hot" and "cold" inflators. In a cold inflator the mass flow peak is lower, but the inflator has a longer burn duration than with an ambient inflator. Correspondingly a hot inflator shows higher peaks with a shorter burn duration. This temperature dependency means that the inflation device also has variable characteristics that can be accounted for (or taken advantage of) by the electronic control unit.

ECU Trigger Algorithm

The SMART^{TM} airbag system is designed to provide the best performance possible in all operating ranges. Not only does the system have to assess the current situation in the environment (crash severity, occupant status), but it has to compensate for variations in inflation device performance (i.e.: temperature variations in the inflator). Deviations from the original "ambient" design performance can be classified in terms of slow and fast time constants. Temperature variations are generally much slower than the actual crash itself and thus the ECU would only have to update any temperature dependent commands at widely spaced time intervals. Crash severity, however, is directly related to the crash detection itself and thus must be determined within the shortest possible time (hence a fast time constant). It must therefore be evaluated with the highest frequency in the ECU. Occupant position can change within an order of magnitude slower than the crash and thus would only have to be evaluated and integrated into the firing commands with a priority lower than crash severity, but higher than the temperature change.

Table 2 is a matrix that shows the theoretical relationships between a given set of conditions and the best inflator performance for each scenario. The inflator performance differentiates only between Level 1 and 2, but would ideally include various levels within each classification. A completely variable inflator is proposed, but a two stage inflation source is used for initial testing and demonstration purposes. The matrix also shows what type of delay between two stage inflator firings could be expected for each scenario.

Table 2
Inflator levels for Various Deployment Scenarios

Scenario	Temperature			Crash Severity		Occupant status				Inflation Level		Inflation Level Delay
	Amb	Hot	Cold	Low	High	A	B	C	D	1	2	
1	X				X	X				no	no	
2	X				X		X			yes	yes	mod
3	X				X			X		yes	yes	short
4	X				X				X	yes	yes	mod
5	X			X		X				no	no	
6	X			X			X			yes	no	
7	X			X				X		yes	yes	mod
8	X			X					X	yes	yes	long
9		X			X	X				no	no	
10		X			X		X			yes	yes	long
11		X			X			X		yes	yes	mod
12		X			X				X	yes	yes	long
13		X		X		X				no	no	
14		X		X			X			yes	no	
15		X		X				X		yes	yes	long
16		X		X					X	yes	no	
17			X		X	X				no	no	
18			X		X		X			yes	yes	short
19			X		X			X		yes	yes	none
20			X		X				X	yes	yes	mod
21			X	X		X				no	no	
22			X	X			X			yes	no	
23			X	X				X		yes	yes	short
24			X	X					X	yes	yes	long

Occupant Status A: No occupant present
B: Belted occupant in-position
C: Unbelted occupant in-position
D: Out-of-position occupant

Implementation of the matrix in an electronic control unit is shown in Figure 2.

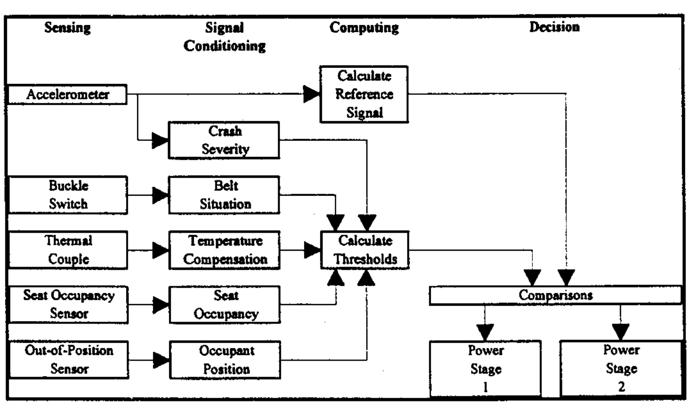

Figure 2. Firing Decision Methodology Used by the ECU Triggering Algorithm.

Figure 2 shows some of the details of the SMART™ airbag system deployment algorithm. A conventional airbag algorithm generally consists of a single signal processing path based on the acceleration. The additional, sensors in the SMART™ airbag system are used as shown here to influence the inflator performance. In this investigation the algorithm makes a decision on whether to fire one or both inflators if a trigger condition has been detected.

Crash detection itself is performed, as in conventional systems, using signals obtained from an accelerometer located in the ECU. In the SMART™ airbag system the ECU computes both a reference signal and an estimation of the crash severity level. Deployment decisions are then made by comparing the reference signal and the thresholds derived from each sensor. These thresholds are computed based on sensor measurements of the system "status" (i.e. crash severity, belted/unbelted, temperature, out-of-position, etc.) and parameters that have been determined "off-line". It is proposed here that fuzzy logic be used as one possible means of generating the thresholds. This not only allows more flexibility in the classification of the signals, but improves the algorithm transparency.

Inflator/Module Assembly

Once system conditions are known, the key is adapting to them. Actuation or action is achieved by using an adjustable performance inflator or a multiple level gas generation source. Firing a combination of inflators simultaneously results in an aggressive behavior of the airbag itself. The aggressiveness of the system is adjusted by varying the timing between actuation of the different levels or, in some scenarios, by actuating only the Level 1 gas generation source. Figure 3 demonstrates the effects of various delays on the ballistic performance of the gas generation source.

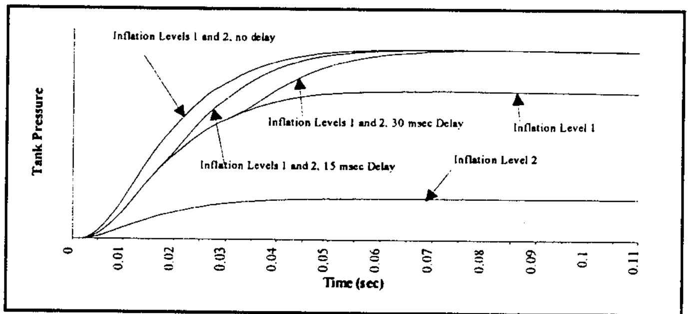

Figure 3. Combinations of Inflation Levels 1 and 2 Showing the Effects of Various Delays.

Although the best performance split between Level 1 and Level 2 gas generation sources will depend on vehicle crash characteristics, an approximate 75% Level 1 and 25% Level 2 split on performance is anticipated to work for most applications. It can be seen from Figure 3 that the most aggressive performance is achieved by deploying both sources simultaneously with no time delay. The least aggressive performance is achieved when only Level 1 is deployed.

A multitude of different performances can be achieved by using different timing between the Level 1 and Level 2 deployments. Presently all gas generation devices have temperature dependent performance which can be somewhat mitigated by varying the timing between levels as demonstrated in Figure 4. The hot, ambient, and cold, no inflation delay curves are representative of the typical temperature dependent performance of a pyrotechnic inflator. By including a delay between Levels 1 and 2, the range on rise rate from hot to cold can be narrowed considerably.

Therefore, a wide range of vehicle and occupant conditions can be accommodated by using this adjustment method. Table 2 summarizes the types of timing delays required between Level 1 and Level 2 to adjust for various scenarios including temperature.

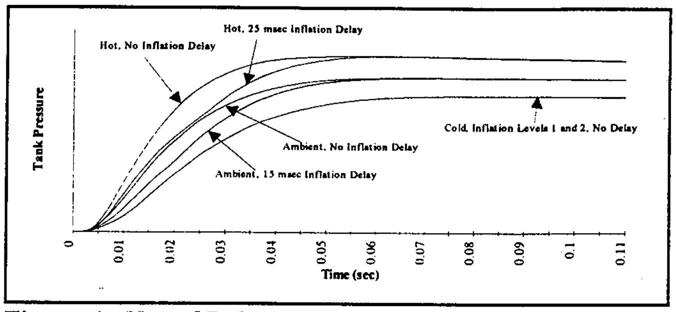

Figure 4. Use of Delay Between Inflation Levels 1 and 2 to Mitigate Temperature Effects.

Analytical Simulation

Numerical simulation of both components are employed to help reduce both development time and costs. The use of simulation plays a significant role in the case of the SMART™ airbag system. This tool can be used both to speed up the design process by providing design direction for various components and aid in the evaluation of the complete system performance.

A simulation of the crash signals using the crash detection algorithm will yield the minimum amount of time required to detect a crash and determine the ability to identify the type of crash.

The different crash types in combination with the environmental conditions result in a large number of test variations. Carrying out barrier or even sled testing for every possible variation would be virtually impossible. Such parameter studies combined with design studies carried out using simulation tools provide an important development environment for the SMART™ airbag system. The design methodology based on simulation is shown below in Figure 5.

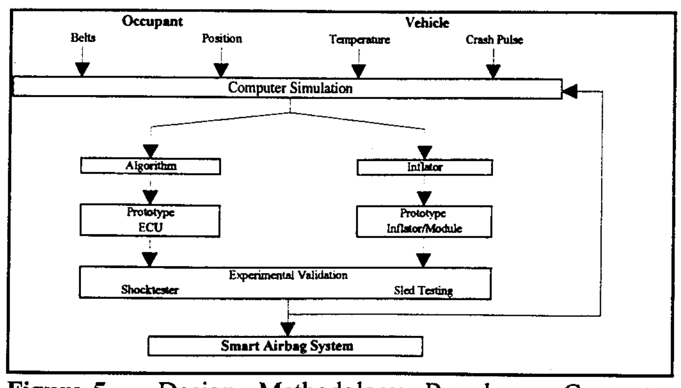

Figure 5. Design Methodology Based on Computer Simulation.

MADYMO 5.0 2D & 3D has been used as the primary simulation tool. A standard generic model has been developed and validated with sled tests. This model serves as the basis for the parameter studies that determine what inflator performance will give the best performance for the given input conditions. Inputs to MADYMO are based on values that will be sensed in the vehicle to determine the status at the time of the crash: temperature, crash pulse (from accelerometer), and the status of the occupant (belted/unbelted, out-of-position).

Crash pulses that are included in the Madymo input deck are the same acceleration signals that are used for the ECU simulation described earlier. These signals are combined along with the following parameters by a program that generates a MADYMO input deck:

- Vehicle geometry
- Occupant position
- Belt usage
- Inflator/module characteristics:
  - Mass flow
  - Temperature profile
  - Firing time
  - Vent size
  - etc.

Temperature inputs into Madymo are made in the form of variations in the inflator performance. Mass flow data has been derived from testing inflators at the various temperatures. Although airbag components are typically designed for 90°C (hot limit) and -40°C (cold limit), thresholds proposed for the SMART™ airbag system are based on expected frequency of deployment at various temperatures. This relationship varies for different vehicles but the principle proposed is shown in Figure 6. Thresholds used for experimental validation were 65°C and -10°C.

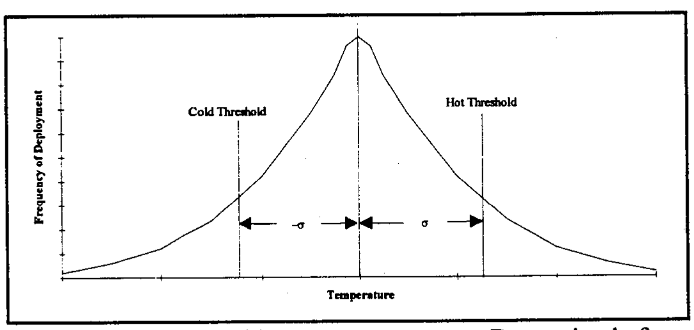

Figure 6. Threshold Temperatures as Determined from Vehicle Temperature Versus Deployment Frequency Data.

Parametric studies are conducted on Madymo to define system combinations that meet occupant protection guidelines. This system definition would then be verified using sled testing of the most critical situations. Correlation of these extreme cases leads to acceptance of the simulated less *critical* situations. Thus design time and cost stay in check, while system improvement expands.

A combination of injury criteria (i.e. HIC, chest loading (3ms), head accelerations, etc.) are currently used to evaluate and classify the MADYMO output. Desired inflation level performance is selected based on these injury values. The selection can be quantified into a single number by using an equation similar to that presented by Schaper (Autoliv) at "Haus der Technik" *Stadtfahrzeug im Zielkonflikt von Sicherheit, Ökonomie und Mobilität*. The only variable left here is the weight factor used for each injury value. Basically, inflation levels that give the lowest possible injury values are selected. Based upon the complete field of experiments, the ECU can distinguish between the various crash scenarios. A prototype ECU is now being constructed to meet these requirements. The desired mass flow curves are then taken as guidelines for the development of new inflators.

Results from a MADYMO simulation which analyzed crash severities for various types of crashes are summarized in Table 3. The results compare a SMART™ airbag system to a conventional airbag system. The results indicate that the SMART™ airbag system is a "friendlier" system, especially during low severity crashes.

Table 3

Computer Simulation Predicted Occupant Protection for SMART™ Airbag System as a Percentage of Occupant Protection for Conventional Airbag System

No.	Crash Type	Sev	HIC	3 ms Chest g's
1	Frontal	High	75%	87%
2	Frontal	Low	29	72
3	Vehicle/Vehicle	High	72	92
4	40% Offset	High	75	94
5	40% Offset	Low	28	71
6	Pole	High	26	72
7	Pole	Low	24	71
8	30 Deg Angled	High	28	77
9	30 Deg Angled	Low	26	74

Experimental Validation

Sled Test Setup

To demonstrate the feasibility of the SMART™ airbag system concept, dynamic testing was conducted using a HYGE sled. Goals of the testing were to directly compare the performance of a SMART™ airbag system to the performance of a conventional airbag system. This would establish the feasibility of the SMART™ airbag system concept and form a basis for future testing and development. Crash scenarios were selected which were expected to task the airbag system to a level which would provide discrimination between systems. Table 4 summarizes the matrix tested. Each scenario was tested with both the SMART™ airbag system and the conventional airbag system.

Table 4
Validation Sled Test Matrix

Severity	%ATD	Temp	Seat Pos	Belts	Occupant Position
high	50th	ambient	mid track	none	normal
high	50th	cold	mid track	none	normal
high	95th	cold	full rear	none	normal
high	5th	hot	full fwd	none	normal
low	5th	ambient	full fwd	none	against str wheel

A driver side set-up was used on a generic sled test buck representative of a typical mid-sized car. Hybrid III Anthropomorphic Test Devices (ATD) were used. A rigid steering wheel was used to minimize variables. An energy absorbing column was used, however, the stroke was limited to 50 mm. All other components were set up in a way to minimize variations in the testing and to isolate the airbag system. The crash pulse used for the high severity scenario had a 30 g peak acceleration at 52 milliseconds which integrated to 57 KPH at 100 milliseconds. The low severity crash pulse had a peak acceleration of 12 g at 50 milliseconds which integrated to 27.5 KPH at 138 milliseconds.

Sled Test Results

In general, the sled testing results indicated that the SMART™ airbag system performed superior to the conventional airbag system. While the improvements were not as large as predicted with computer simulation, the results followed similar trends. In almost all scenarios the SMART™ airbag system out performed the conventional airbag system. The largest improvement was observed for the out-of-position occupant scenario in which the 5th percentile ATD was positioned with the chest directly against the steering wheel and airbag module. For the test setup used, temperature effect did not appear to be a significant factor, although some improvement was realized with the SMART™ airbag system temperature adjustment capability. Figure 7 provides a comparison of the sled test results for Head Injury Criteria (HIC). Figure 8 provides a comparison of the sled test results for 3 millisecond chest acceleration clip. Figure 9 provides a comparison of the sled test result for resultant chest acceleration.

Summary/Conclusions

This paper has provided an overview of a new methodology for occupant protection systems. The SMART™ airbag system has demonstrated an improved performance capability over conventional airbag systems. Computer simulation and subsequent verification by sled testing has shown the ability of the SMART™ airbag system to adapt itself to numerous crash scenarios. The greatest improvements

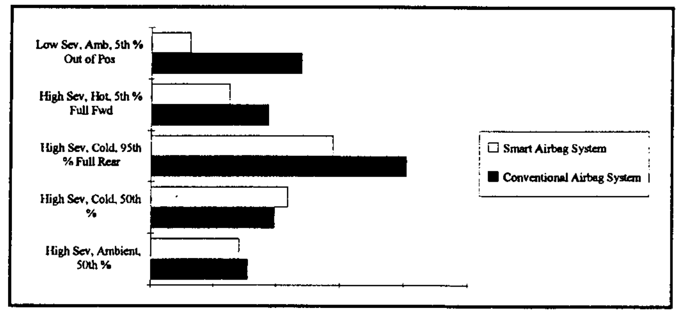

Figure 7. Sled Test Comparison - HIC.

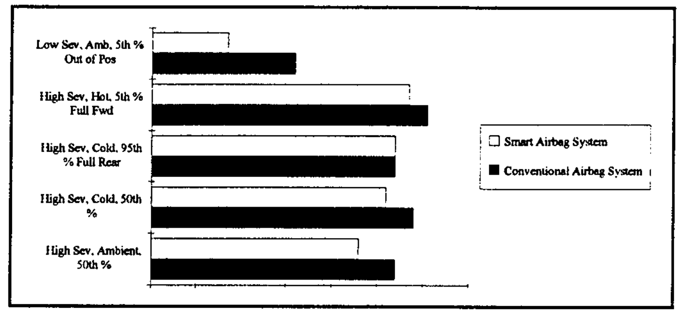

Figure 8. Sled Test Comparison - 3 Millisecond Chest Acceleration Clip.

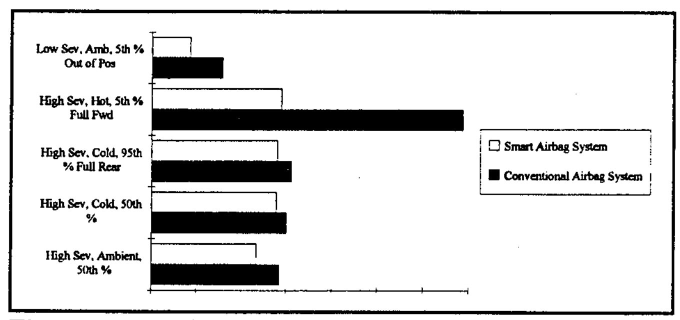

Figure 9. Sled Test Comparison - Chest Resultant Acceleration.

were observed for out-of-position occupant scenarios where the risk of inflation induced injuries is highest. Even greater improvements are likely on the passenger side of the vehicle. It is in this case that the possible presence of children and/or infant seats, and increased probability of out-of-position occupants make the risk of inflation induced injuries the greatest. While the technical feasibility of the SMART™ airbag system has been adequately demonstrated to justify further development, the cost effectiveness of the system will have to be demonstrated. The added complexity of the system will require greater use of computer simulation which should not be a problem with recent advances in these capabilities.

Future work will include:

- Expanded testing including passenger side and more out-of-position occupant scenarios
- Refinement of inflators with adjustable or multilevel capability
- Refinement of the ECU, algorithms, and sensing capabilities
- Detailed cost analyses

Systems Optimization of Vehicle Crashworthiness

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Paper No. 94-S4-O-12

ABSTRACT

Optimal crash countermeasure designs must successfully balance two potentially conflicting objectives: (1) maximizing passenger protection in the vehicle under design, and (2) minimizing aggressiveness toward other vehicles in the fleet mix. To meet these objectives, vehicle crashworthiness must be evaluated, not just on the basis of a single test configuration or test speed, but also on the safety performance of the vehicle when exposed to the entire traffic accident environment. Ideally, the goal of vehicle design should be to minimize injuries on a system-wide basis, i.e., across the full spectrum of expected collision partners, collision speeds, occupant heights, occupant ages, and occupant injury tolerance levels.

This paper presents a comprehensive methodology for global optimization of vehicle impact designs, and considers total injuries in both the subject vehicle and its collision partners. The paper presents a systems approach to vehicle crashworthiness design which combines computer simulations of vehicle/occupant dynamic crash responses with a stochastic representation of the U.S. accident environment and crash victim population. The results of the safety systems design optimization of a 3,000-lb production passenger car are discussed illustrating the potential for design modifications which simultaneously improve passenger protection while reducing aggressivity.

Are Optimal Designs Aggressive?

Pursuing an optimal crashworthy design for a vehicle without regards to its potential collision partners can lead to a very aggressive design. Figure 1 shows how design modifications which minimize injuries in one vehicle may actually accentuate injury levels in the collision partner. In this hypothetical example, the frontal stiffness of the subject car is increased as a means of reducing injuries in the subject vehicle. While this is effective in reducing frontal intrusion in the modified car, this design modification will likely also produce increased injury levels in the other car -- particularly if the other car is impacted in the side.

As can be seen in Figure 2, a design can be counterproductive. The total injuries in both vehicles actually can increase according to the initial value of the stiffness for the baseline vehicle and the level of stiffness increase selected for the modification. A better approach is to strike a balance between injuries in the subject vehicle and in the collision partner. The method discussed in this paper for achieving this balance is to seek designs which minimize total injuries considered in the collisions in which the design vehicle is involved.

This means for minimizing injury on a global basis was first used in the Safety Systems Optimization Model developed by Ford Motor Company [1] and enhanced by the University of Virginia [2]. The MOSS (Model for Optimization of Safety Systems) computer model presented here has evolved from these earlier efforts, and has benefited from the availability of recently developed injury criteria, and improved structural and occupant models.

The agency's current research program for improved frontal crash protection is exploring the development of test procedures that mimic crash responses in frontal offset collisions. These collisions impart significant intrusion into the occupant compartment. Increasing the stiffness of the frontal structures would be required to minimize this intrusion. Hence, it is appropriate to develop techniques to evaluate the global effects of such developments.

Methodology

The approach to crashworthiness optimization in this study may be stated formally as the following non-linear problem:

$$\min \text{Inj}(\underline{x},u) = \sum p_i\, s_i(\underline{x},u) \qquad [1]$$

subject to $Wgt(x) \le Wgt_{max}$
$Cost(x, w(x)) \le Cost_{max}$
$x_{min} \le x \le x_{max}$

where

x	- Vector of Design Variables
u	- Belt Usage Rate
Inj (x,u)	- Total Injuries
Wgt(x)	- Incremental weight associated with design 'x'
Cost	- Incremental cost associated with x and Wgt(x)
Wgt_{max}	- Upper Constraint on incremental weight
$Cost_{max}$	- Upper Constraint on incremental cost
p_i	- Probability of Event i
s_i	- Injuries resulting from occurrence of Event i

The objective expressed in Equation 1 is to determine that vector of design variables which minimizes total injuries or some measure of societal cost of total injuries [3]. Our simulations attempt to minimize normalized harm, defined as total harm in dollars normalized by the harm associated with an AIS 6 injury level. Total harm is computed by summing the harm incurred in each of accident encounters i weighted by p_i, the annual expected probability of event i.

The incremental weight penalty associated with any proposed design modifications w(x) is limited to the upper constraint Wgt_{max}. Similarly, the incremental cost of the proposed design modifications is limited to an upper constraint of $Cost_{max}$. The incremental cost in this context includes both the additional cost of design modifications and an estimate of the cost of material substitution to reduce weight. To ensure that design modifications lie within realistic ranges, the design variable vector is constrained by lower and upper limits on each design modification.

The annual expected probability of a crash event i, sometimes referred to in the literature as exposure, is computed based on historical accident data. The probability distributions applied in this study were abstracted from NASS Crashworthiness accident files for the years 1988 to 1991. Impact speed distributions were obtained from the earlier NCSS accident data system.

For the model, a crash event i is completely characterized by prescribing the crash speed, the impacting vehicle weight, the occupant seating location, the occupant height, the occupant gender, and the occupant restraint type. For the frontal impacts studied in this paper, p_i and Inj_i are defined as follows:

p_i = p_i (v, mode, impwgt, seat, height, gender, age, restraint)

= p(v) p(mode) p(impwgt) p(seat) p(height) p(gender) p(age) p(restraint)

where

p(y) -	Probability of condition y
mode -	Accident Mode (e.g. frontal-frontal offset, frontal-barrier, or others)
v -	Impact velocity
impwgt -	Impacting car weight
seat -	Seating location (Driver or Passenger)
height -	Occupant Height (as a function of occupant gender)
gender -	Occupant Gender
age -	Occupant Age
Restraint -	Restraint Type (Belted, Air bag, or none)

The injury severity for frontal impacts in this model considers only head and chest injuries. With the appropriate injury criterion, the model could be readily extended to include injuries to other body regions, e.g., lower extremities. For frontal impacts, the injury severity is formally defined as follows:

Inj_i = Inj (HIC, CSI | x, v, mode, impwgt, seat, height, gender, age, restraint)

Design Variables

The design variables x which describe the subject vehicle are divided into two categories. The structural variables describe the energy absorbing front structure of the vehicle. Occupant variables describe the occupant restraint system and the occupant-interior contact surfaces.

The model presented here uses the following four structural design variables:

(1) Foreframe Constant Collapse Force Level
(2) Aftframe Constant Collapse Force Level
(3) Sheetmetal Constant Collapse Force Level
(4) Total Available Crush

Figure 3 presents a one-dimensional lumped mass-spring model of a vehicle frontal structure showing the locations of these variables. The masses and all remaining nonlinear springs are fixed at their baseline values. Vehicle impact responses for the system are computed from either the CRUSH or SISAME code [4,5].

Figure 4 presents a two-dimensional lumped mass model of the occupant and the interior of the occupant compartment. The occupant model describes the occupant, the restraint system, and all occupant-interior contact surfaces. Occupant impact responses are computed separately from simulations using either Madymo, ATB-40, or MVMA-2D occupant simulators. The complete set of available occupant design variables are described below:

Restraint System
- (1) Belt Stiffness (lb/ft)
- (2) Air bag Stiffness (Driver)
- (3) Air bag Stiffness (Passenger)
- (4) Air bag Inflation Time (Driver)
- (5) Air bag Inflation Time (Passenger)

Contact Surfaces
- (1) Steering Column Collapse Force
- (2) Upper Dash Panel Force (Driver)
- (3) Lower Dash Panel Force (Driver)
- (4) Upper Dash Panel Force (Passenger)
- (5) Lower Dash Panel Force (Passenger)

Structural and Biomechanical Response

The response of a vehicle structure subjected to impact is characterized by the deceleration crash pulse. Vehicle deceleration crash pulses were determined from the vehicle crash simulations using either the CRUSH or SISAME code. Together with the impact speed, the crash pulse represents the impact forcing function which drives the occupant model.

The significant response of occupants subjected to impact is characterized by the acceleration signatures of the head and thorax of the occupant. The acceleration response of the head to impact is summarized by the Head Injury Criterion while the acceleration response of the chest is summarized by the Chest Severity Index [6].

For frontal collisions, the overall occupant response is determined by specifying the overall AIS level. For this study, the overall AIS level is defined to be the maximum AIS (Abbreviated Injury Scale) level derived from the two injury criteria.

The harm associated with an overall AIS level is obtained from Table 1 below. The model uses values which have been normalized to the injury cost associated with an AIS=6 (unsurvivable) injury. In this sense, each normalized harm unit is roughly equivalent to one fatality.

The total normalized harm is used as the figure of merit when evaluating the crashworthiness of a particular design. The system computes the amount of normalized harm resulting from each collision between the subject vehicle and another vehicle, and for single subject vehicle crashes. For each crash event, the associated harm is weighted by the expected probability of occurrence and summed to obtain the total normalized harm. Design modifications which lead to a lower total harm are preferred over designs which lead to a higher total harm.

Simulation Requirements

The system evaluates each design, as described by its design variable vector x, across all accident modes, impact speeds, and impacting vehicle weights. Vehicle response is described in terms of a vehicle deceleration crash pulse. For multi-car accident modes, the vehicle response of both the subject vehicle and the struck vehicle must be simulated. This study considers five accident configurations or modes: frontal-barrier collisions, frontal-frontal centerline crashes, frontal-frontal offset collisions, frontal-side, and side-frontal collisions. Frontal-rear, rollovers, and other collision modes were not modeled in this study.

For each selected accident, MOSS evaluates the occupant response to that crash pulse for each of all possible occupant types. Each occupant is described by the occupant seating location, the occupant gender, occupant height, and the restraint system used by that occupant (air bag, 3-point belt, or none). Note that this study considers only front seat occupants.

Simulation requirements for a complete evaluation of each design are listed below:

Vehicle Simulations
- Accident Modes 5
  - Frontal-barrier (single vehicle)
  - Frontal-frontal centerline (multi-vehicle)
  - Frontal-frontal offset (multi-vehicle)
  - Frontal-Side of other vehicle (multi-vehicle)
  - Front of other vehicle-Side (multi-vehicle)
- Impact Speeds 7
  - 10, 20, 30, ...70 mph
- Vehicle Weight Categories 4
  - 2,000, 3,000, 4,000, 5,000 lb
- Subject and Other Vehicle 2

Total ((2*4*4 + 1) *7) 231

Occupant Simulations (per crash pulse)
- Occupant Seat Location 2
  - Driver
  - Right Front Passenger
- Occupant Gender 2
- Occupant Heights 3
  - 5th, 50th, and 95th Percentile
- Restraint Types 3
  - Air bag, 3 point belt, none

Total 36

Total Occupant Simulations (231*36) 8,316

Vehicle Optimization Algorithm

Optimization of the vehicle design is performed by either a modified Box or Rosenbrock non-linear optimization algorithm [7]. The optimization strategy is to minimize the total harm objective function by exploring the design variable space, computing the associated value of the objective harm function, and pursuing design directions which lead to reduced injury levels. Convergence to an optimal design is typically achieved in under 100 iterations which corresponds to 831,600 occupant simulations.

Sample Problem

To illustrate the capabilities of the system, the model described in this paper was exercised to optimize all production 3,000-lb cars in the current U.S. traffic environment. The specific goal of this study was to optimize the frontal structure and frontal crash performance of the occupant interior and restraints. As discussed earlier, the traffic environment is described by accident statistics derived from 1988-1991 NASS. Because these accident statistics contain insufficient numbers of air bag deployments for model validation, the example problem will focus on unrestrained and 3-point belt restrained occupants. Under these conditions, each design evaluation requires approximately 5,500 vehicle and occupant simulations.

Belt usage rates for all occupants were set to 50 percent. Incremental weight was constrained to 180 pounds and incremental cost was constrained to $300. Separate evaluations were conducted for the baseline vehicle and for the optimized vehicle. As shown in Table 2, the effectiveness of crashworthiness optimization can be dramatic: the optimized design reduced overall harm by 21 percent.

The optimized design which results in these reduced occupant injury levels is contrasted with the baseline design in Table 3. As might have been predicted, the optimal structural design is characterized by a softer front frame and a stiffer rear frame. The softer front frame results in a subject vehicle which is less aggressive in collisions with other vehicles -- especially when striking other vehicles in the side. However, to protect the occupants in high speed multi-car impacts and in frontal-barrier impacts, the optimized design selects a greatly stiffened frontal aftframe structure and adds to the length of the front structure.

The optimal occupant compartment design reflects the fact that only half of the occupants were restrained in this study. Belt stiffness was significantly increased to limit restrained occupant contact with occupant compartment surfaces. At the same time, the occupant compartment contact surfaces (e.g, the instrument panel and steering column collapse forces) were softened to mitigate unrestrained occupant injury levels.

Figure 5a presents the distribution of the optimized design benefits by impact mode. The first point to note is that injury reductions were observed across all accident modes. One concern occasionally voiced about global optimization of vehicles is that the optimization simply trades injuries from one source for injuries from another source. Figure 5a shows that for this subject vehicle there are benefits in each of the accident modes.

The largest benefit is for side impacted occupants of the other car for which injuries decreased by over 50 percent. This substantiates the experimental findings of a side impactary research program conducted by NHTSA which conducted a series of full systems side impact tests with a modified Movable Deformable Barrier (MDB) and Volkswagen Rabbits [8]. In this program, side struck occupant thoracic injury levels were found to decrease as the frontal stiffness of the striking MDB was reduced and as the barrier face was lowered.

As shown in Figure 5b, benefits were almost evenly distributed between the other car and the subject car. Note that the subject car benefits in Figure 5b include single car collisions as well as collisions with a collision partner. Finally, Figure 5c shows the distribution of benefits as a function of the weight of the collision partner. Fully 46 percent of all benefits accrued to the subject vehicle when involved in a single car collision. Most of the benefits were distributed to the lower weight classes. Note that because the simulation effectively optimized all vehicles in the 3,000 lb weight class, any benefits to this weight class are attributed to the subject vehicle.

Future Work

The methodology presented in this paper has focused on the crashworthiness performance of cars - both as a subject vehicle and as the collision partner. Work is now underway to develop vehicle structural models of light trucks and minivans as potential collision partners. It should be noted however that the simulation presented in the sample case was based on a weight distribution of collision partners which included both cars as well as light trucks and vans. The advantage of explicitly modeling light trucks and vans is the expectation that this class of increasingly more prevalent vehicles exhibit significantly more aggressive structures than cars.

As discussed under biomechanical response models, occupant impact response in this model is characterized exclusively by head and chest injuries. Studies of accident statistics have shown that harm resulting from injuries to other body regions, particularly the lower extremities, account for a significant fraction of total harm. Future enhancements to the model will incorporate lower extremity and pelvic injury mechanisms as potential injury sources. Additionally, future enhancements will incorporate more recent information regarding the costs of preventing the injuries and fatalities.

Finally, the methodology presented here is restricted to investigating aggressiveness resulting from incompatibilities in striking-struck car weight and force-deflection characteristics. Not investigated are geometric incompatibilities, e.g. bumper height, hood profile, and side door sill height. Future modifications to the model will explore the feasibility of monitoring the relationship between geometric incompatibilities and injury. Also, lumped mass models were used in this study, whereas finite element models (FEMs) can more accurately define vehicle and occupant interactions. However, FEMs are extremely computer intensive and must be carefully utilized to allow global optimization scenarios, which are also computer intensive, to be used.

Summary

Crashworthiness design must balance the two potentially conflicting design objectives of maximizing passenger protection in the subject vehicle while minimizing aggressiveness toward other vehicles in the fleet mix. This paper has presented a comprehensive methodology for global optimization of vehicle impact designs which seeks to minimize total injuries in both the subject vehicle and its collision partners. To achieve a global optimization, each vehicle design is evaluated on a system-wide basis, i.e., across the full spectrum of expected collision partners, collision speeds, occupant heights, occupant ages, and occupant injury tolerance levels.

The methodology is founded on a systems approach to vehicle crashworthiness design which incorporates a stochastic representation of the U.S. accident environment and crash victim population with computer simulation of vehicle/occupant dynamic crash responses. The results of the safety systems design optimization of a 3,000 lb production passenger car demonstrate the potential for design modifications which simultaneously improve passenger protection while reducing aggressivity.

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Table 1. Normalized Harm

AIS Number	Injury Severity	Harm ($)	Normalized Harm
6	Unsurvivable	2,620,516	1.0000
5	Critical	2,122,648	0.8100
4	Severe	1,017,331	0.3882
3	Serious	400,310	0.1526
2	Moderate	107,638	0.04108
1	Minor	6,180	0.00236

Table 2. Overall Crashworthiness Enhancement

Design	Harm-Weighted Injuries	Percent Reduction
Baseline	99,134	—
Optimized	78,763	21

Table 3. Example Design Parameters

Parameter	Design Parameter	Units	Min Value	Max Value	Base Value	Optimal Value
Structural	Foreframe Force Level	Kip	13.6	25.5	17.0	13.6
	Aftframe Force Level	Kip	18.4	34.5	23.0	20.0
	Sheetmetal Force Level	Kip	2.5	7.5	2.5	2.6
	Total Available Crush	Inch	-2.5	10.0	0.0	9.4
	Side Structure Force Level	Kip	25.0	25.0	25.0	25.0
Restraints	Belt Stiffness	LB/Ft	3000	10000	6500	6952
	Steering Column Collapse Force	LB	500	4000	2250	521
	Upper Instr Panel Frc Lev (Dr)	LB	500	4000	2250	3809
	Upper Instr Panel Frc Lev (Pass)	LB	200	1600	900	416
	Lower Instr Panel Frc Lev (Dr)	LB	500	4000	2250	799
	Lower Instr Panel Frc Lev (Pass)	LB	500	4000	1350	812
	Knee Bolster Force Level	LB	4250	4250	4250	4250
	Knee Bolster Thickness	Inch	0	0	0	0

Figure 1. Are Optimal Designs Aggressive

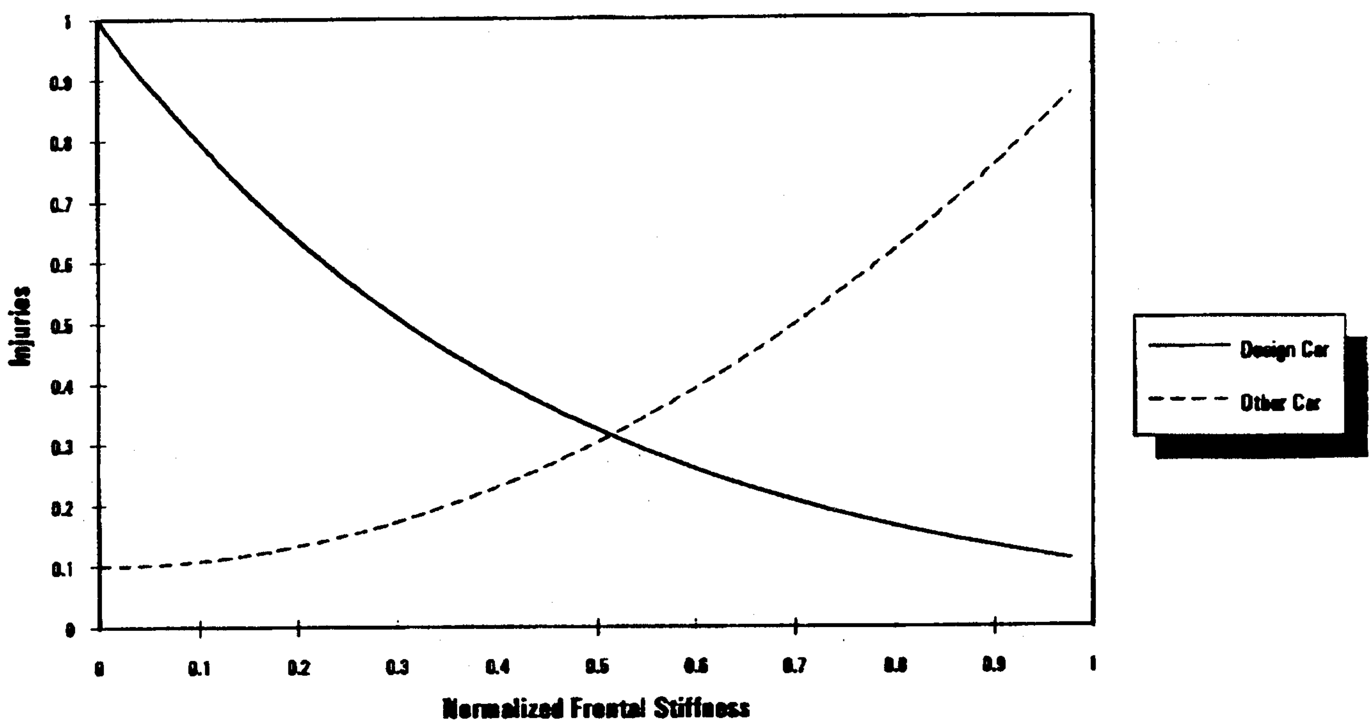


Figure 2. Optimal Designs Minimize Total Injuries

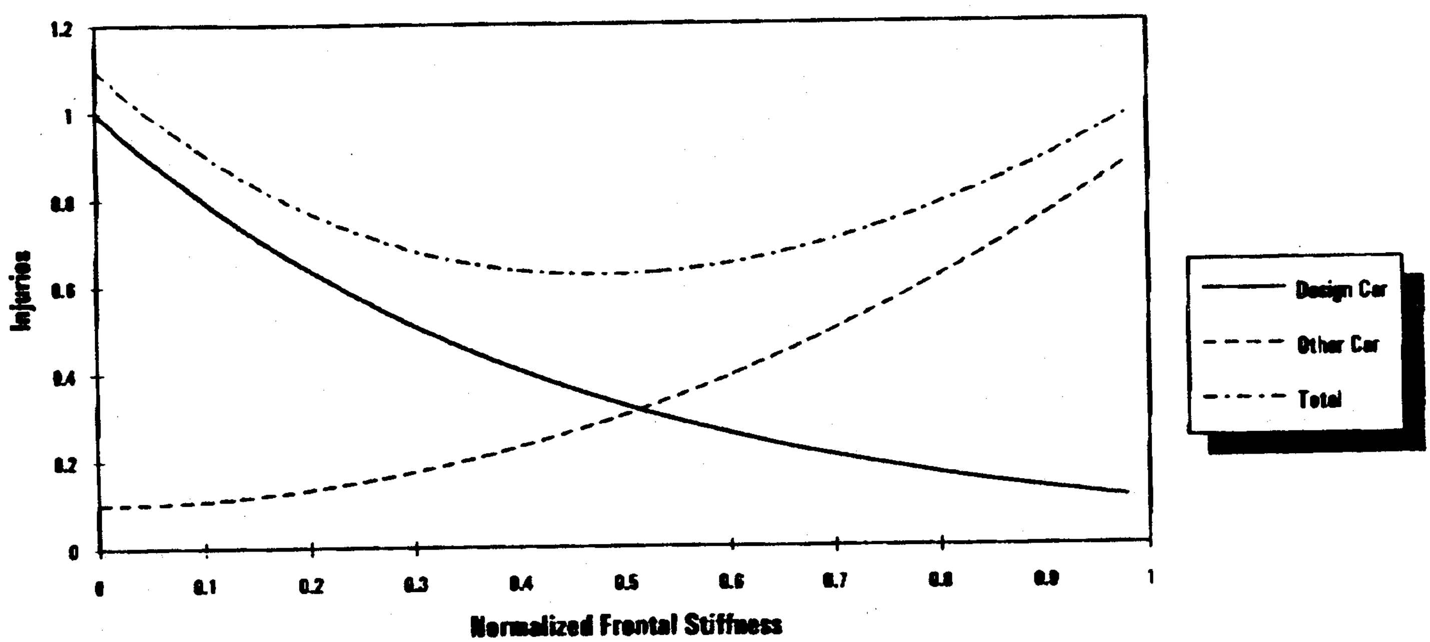
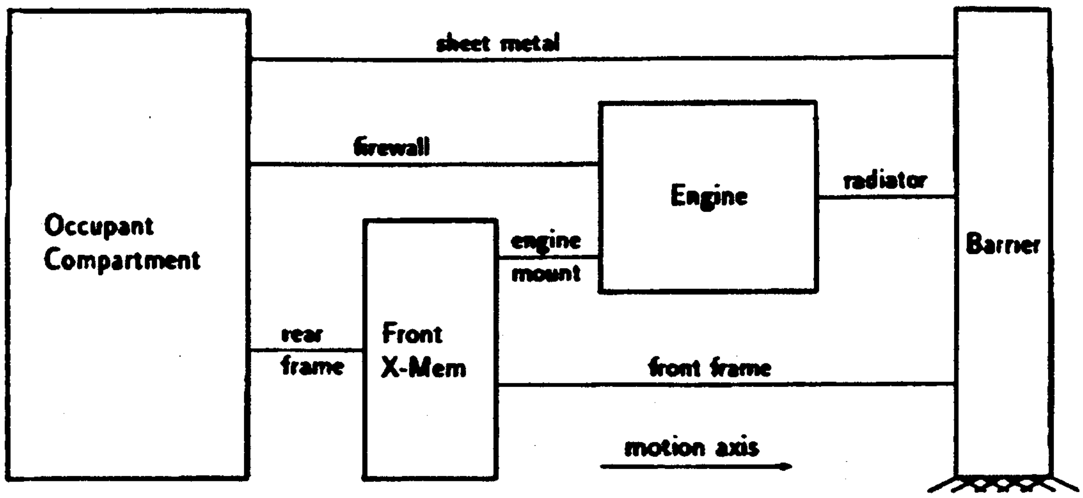


Figure 3. The Vehicle Model



SISAME Frontal-Barrier Impact Model

Figure 4. The Occupant Model

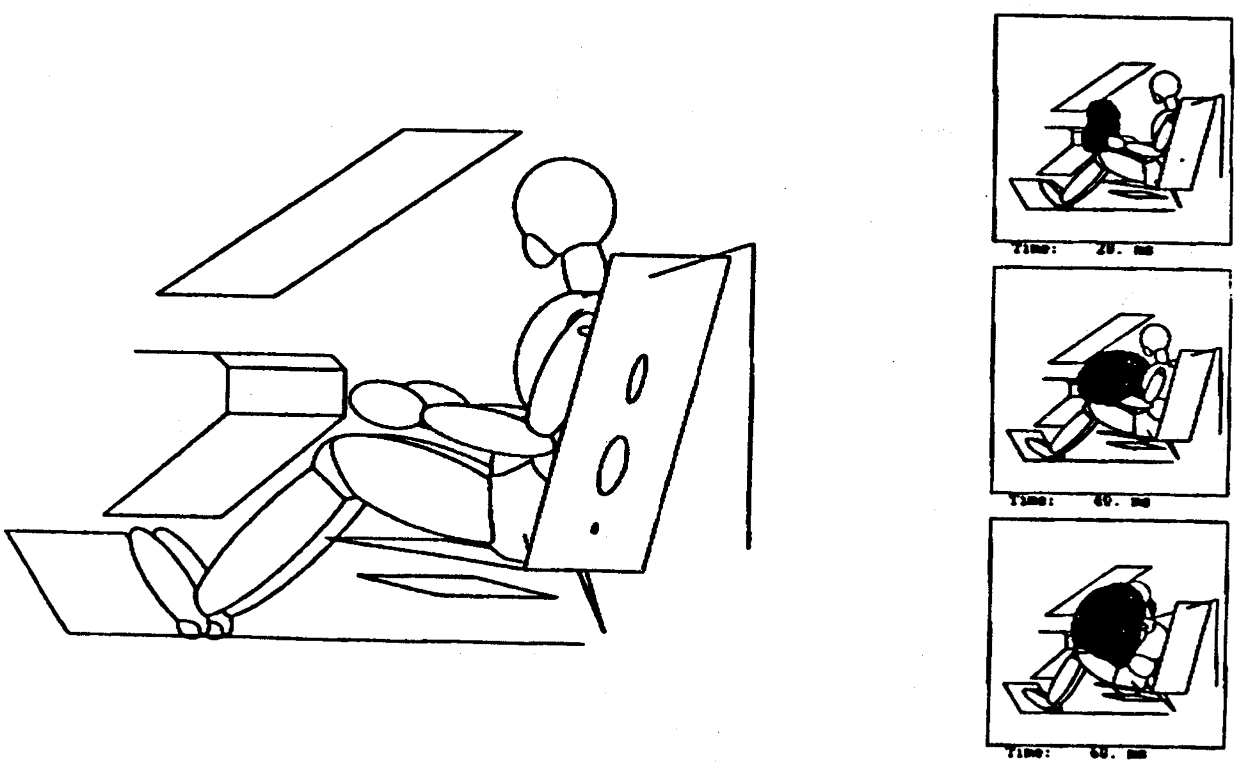
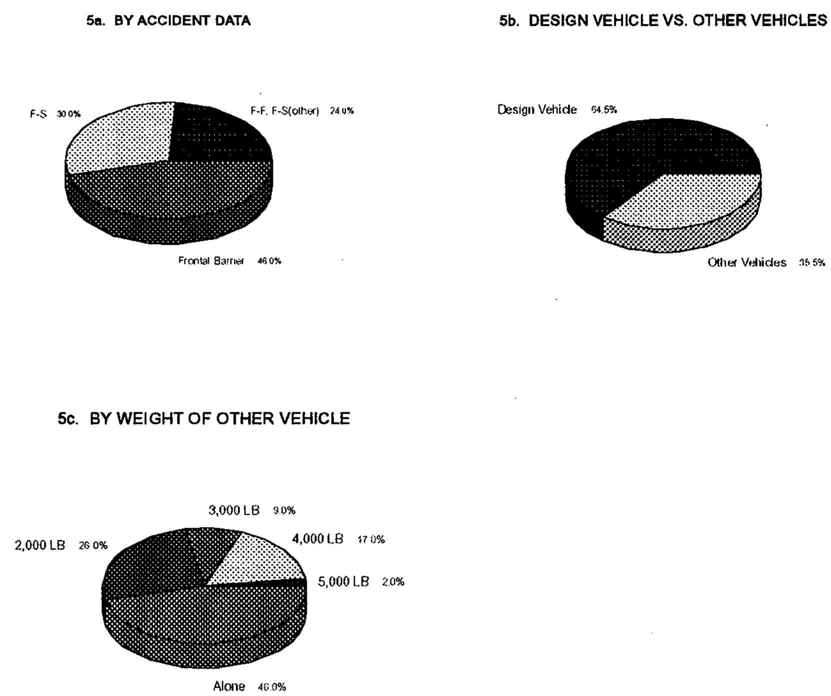


Figure 5. Distribution of Optimization Benefits



Improved Protection Through Greater Compatibility Between Road Vehicles

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ABSTRACT

This paper arises from the observations of several accident investigators that not many more fatalities in cars can be saved in present day traffic and speed conditions, because intrusion of damage is extending right back into the occupants in many cases. Even air bags cannot perform as intended in these circumstances. Therefore it is proposed that the fronts of all vehicles are matched in respect of their height above road level (350mm to 550mm and then to 700mm) as well as to their structural stiffnesses when impacted. The initial proposal is that this matching extends back 700mm from the front face, although the proposal would be improved if this could be increased. The frontal structure is based on the needs in impact of the small car and the implications are discussed in this paper.

INTRODUCTION

It is desirable to consider how the design of cars should develop, if the protection they are to offer is to be improved beyond the incorporation of features needed to meet regulations currently under discussion in Geneva and Brussels. Two long term factors are likely to affect car design. Firstly is the need for a reduction of atmospheric pollution from road traffic and the build up of carbon dioxide. Despite all the advances in engine efficiency, the prospect of more cars and increased travel by car is likely to lead to a general downsizing of cars in mass and size being required if pollution levels are to be improved. This would lead to some increase in fatalities and severe injuries to car occupants, but possibly by only about 15% for the conditions in Great Britain (1). The second factor is that the primary cause of many of the current fatalities in small cars is that of intrusion of the external damage reaching the occupants. The intrusion is often caused by striking another road vehicle, although frontal intrusion when cars strike roadside objects such as trees and embankments is also important. Accident investigators tend to write off many such impacts as being inevitably fatal because the damage extends into the passenger compartment. However there are two ways in which this situation may be improved. A general reduction in the speeds of cars, especially on rural roads could help greatly, but it is often the cars of reckless drivers that are involved! On the other hand an increase in the frontal crush depth of cars would help to reduce intrusion. A further gain would result from extending the front structures of all road vehicles so that the impacting structures of the small cars and the other vehicles match in height above road level and in their stiffnesses when impacted. These structural considerations for the frontal design of road vehicles are the basis for this paper.

POINTS OF IMPACT BETWEEN VEHICLES

Although there is a need for matching the parts of vehicle structures that impact each other in road accidents it is only when the small car is taken to be the norm that the need becomes insistent. Until now there have been a variety of underrunning and overrunning situations causing many fatalities, but only piecemeal measures have been introduced to alleviate them. The present proposal is to use the small car as the basic vehicle and to use its structural layout to define an impact height band at which not only the initial contacts occur in impacts but to arrange that this is the height at which the structures are designed to take almost all of the impact interaction. For the present a height band is suggested from 350mm to 550mm above ground for the fronts of all vehicles because it suits impacts into pedestrians and the sides of the passenger compartments of all cars. As the frontal impact crush increases in severe frontal impacts the maximum interaction height might be raised from 550mm to 700mm above ground when the crush is more than 300mm in depth. Further aft this height restriction is maintained until a depth of crush of 700mm is reached. This depth is just a preliminary compromise and could be altered. If it were to be as low as 200mm the whole proposal would have little or no effect beyond matching up with frontal design needs for pedestrian protection. However if it were to be as high as 1600mm the proposal would be very effective but it would pose great problems for vehicle designers. The implications are slightly different for each category of vehicle.

Cars

The front bumper and air dam can readily be designed to meet pedestrian leg protection requirements for small levels of impact.

The critical stiffness of the front of a small car should be the greatest that can be built into the lower sides of the passenger compartments of cars for the sake of car front to car side impacts. Assuming that cars are constructed to this strength at the sides, it is expected that this will be close to the yield stiffness of car front bumpers built to provide protection for the legs of pedestrians. Then in a car front to car side impact at the required impact test speed both the front structure and then the lower car side can be designed to collapse without subjecting the pelvis of any adjacent occupant to excessive loads. The middle and upper sections of the door would not be severely crushed and the interior structure and trim should be designed to protect the chests and heads of occupants.

Structural development would be needed at the side of the passenger compartment to resist impacts from car fronts at up to 550mm above ground without buckling doors inwards above this height by more than small amounts. This might be helped by extending the outer seat rails sideways and upwards towards the 550mm height so that the lower structure could be raised at its outer ends to resist lateral impacts at up to that height. The rear structures of cars should resist impacts from other car fronts without involving their fuel tanks and passenger compartments.

The design of the front compartment of small cars is not further specified by these proposals as this would in any case have to meet the offset frontal test procedure using the mobile deformable barrier which is currently under debate in Europe (2).

Small Commercial and Recreational Vehicles and Minibuses

These vehicles would be required to meet similar requirements at their fronts as those for cars. Their lower structures at the sides and rear would extend down to about 350mm and have to be sufficiently stiff that small cars could neither underrun them nor penetrate sufficiently for the car windscreens to reach any vehicle structure in severe impacts. The possibility that loaded vehicles might roll on to the tops of cars would need to be considered, but this is probably not critical.

Large Vehicles of All Types

Their fronts would also have to meet similar requirements to those for cars. This would not preclude some of the structural interaction in crashes between two large vehicles occurring at above 700mm above ground. However in order to alleviate the large vehicle front to car side impact situation it might be required that the fronts of the large vehicles should not extend above 550mm above ground for a depth of say 250mm.

Roadside Fences

The proposal should ensure that vehicles interact with roadside safety fences and rails in as satisfactory a manner as possible,but it would not prevent medium sized vehicles rolling over the fences in some circumstances or stop large vehicles overriding them in severe impacts.

THE DESIGN OF LARGER CARS AND OTHER VEHICLES IN RELATION TO SMALL CARS

Structural Stiffness of the Fronts of Larger Cars and Other Road Vehicles

Having matched points of impact, the second need is to match the structural collapse loadings of all vehicles to those for small cars. This is different from the currently accepted method of design which ensures that each vehicle performs satisfactorily when impacted into a rigid wall at the speed of impact at which protection is required. The rigid wall is very approximately equivalent to impacting the car into a similar one travelling at the same speed exactly head-on. The result is that generally, but not always, larger cars are built more stiffly than smaller cars at their front compartments. On the one hand the front compartments of small cars may be more tightly packaged than those of large cars. On the other hand a car of twice the mass of another car designed to crush at a similar deceleration level must have a frontal structure of twice the stiffness of the other car. The consequence of this is that when a large car hits a small one head-on it is often the front of the small car that crumples right back to the passenger compartment with the resulting intrusion and a high risk of severe injury for its occupants.

When a larger car impacts a smaller one, nothing can be done to alleviate the effect of their relative masses. However it would be possible to reduce the stiffness of the front of the front compartment of the larger car down to that of the smaller car (and consequently make it longer if its own protective features are to be maintained in other crash circumstances).The proposal is that the fronts of all cars should be of similar size and crush stiffness for the first say 700mm of crush. This would reduce the risk and amount of intrusion into the smaller car in head-on crashes until at least a crush of twice 700mm (i.e. 1400mm) had occurred. There would also be a small benefit to the occupants of some larger cars. An analysis of accident data by Tingvall and others suggests that this is the case(3). In a population of cars most of which were small, this would be a reasonable design penalty to impose on the relatively few cars which were large.

Further Design Implications

The implications of these suggestions are sketched in Figure 1 for the various categories of vehicle. There would be little change to most small cars; just a slightly longer and softer nose section for some to match up with their stiffened side structures. Those larger cars which are currently built with rather rigid fronts might need up to an extra 700mm of soft front section with a low profile. They would then look more like some luxury designs, which would be a small price to pay for existing among an environment of small cars. However other larger cars might require only small changes to their frontal profiles even if their frontal stiffnesses had to be reduced somewhat.

Vans would need to have up to an extra 700mm of low front as sketched in Figure 1. There is a conflict of interest for the frontal shape. When impacting a small car it is preferable to have no structure above 700mm for this area. However some light structure is needed above 700mm for the sake of absorbing the impact of the torso and head of a pedestrian unfortunate enough to be struck by the van. Such a lightweight structure could be useful in the styling of a van or cab front and would be acceptable if it folded backwards when impacted by the A posts and screen of a small car. Similar considerations apply to the design of the front sections of a bus or mini-bus.

The inclusion of a 700mm frontal structure low down at the front of a heavy goods vehicle would replace the need to have a front underrun guard or its equivalent which is proposed in the recent legislative discussions. Its advantage over the underrun guard would be that there would be an additional 700mm of crush before the windscreen of a small car would be struck.

Test Procedures

Apart from checking that the front profile was within the suggested dimensions the actual test would be no more than a slightly modified version of the partial overlap frontal impact test that is currently under discussion in legislative circles. The difference would be in the specifications of the dimensions and stiffness of the mobile deformable barrier. It would correspond to the front design for the small car that is now proposed for the first 700mm of crush. The barrier stiffness would be determined after an investigation of how strong passenger compartments could be built to resist lateral impacts when struck by this barrier. The first 150mm or so of crush would meet the pedestrian protection sub-system tests. From 150mm to 700mm of crush the barrier stiffness would match with the crush stiffness of a small car, while at over 700mm of crush the barrier might be very similar to the one currently under development.

In principle when the modified barrier face would be tested laterally against the passenger compartment of a car it would be the barrier that would crush rather than the door and its surrounding side structure. On the other hand when tested in a frontal partial overlap mode it would be expected that the car front and the barrier face would crush similarly for the first 700mm of crush of each.

Stiffness of Side Structures

The sides of large cars would be at least as stiff as those of small cars. The sides and rears of all larger vehicles would also be constructed to be at least of this standardised stiffness. This would ensure that small cars could not underrun any larger vehicles with the severe intrusion into their passenger compartments that often occurs at present.

FINAL DISCUSSIONS AND CONCLUSIONS

The need to further reduce the annual number of road accident fatalities and disabling injuries is likely to continue into the future, spurred on by public demand. Unless drivers are persuaded to drive increasingly slowly, this desire is unlikely to be achieved. However improvements in the structural layout of road vehicles could make a large contribution and this paper seeks to set out the way forward. The proposal is to match up the points of impact between vehicles in shape and crush stiffness so that resulting intrusion injuries can be minimised. This is achieved partly by extending vehicle structures at these points of impact so that crash pulses can be softened and intrusion into the occupants would then become more unlikely. Softening the crash pulses reduces loadings on occupants from seat belts and air bags and is very desirable in near to fatal impact conditions.

The proposal is that the structures needed to reduce intrusion and impact severity at the fronts of small cars are matched by similar structures on the fronts of all other vehicles. This means that the depth of crush available in a frontal crash is double what it would be if the smaller vehicle had hit a rigid front of another vehicle. Another important gain is that another vehicle could not strike the side of a car at the level of the chests or heads of its occupants; at least until the structure lower down had been fully crushed.

The need to further improve protection in severe accidents to cars could well be coped with by adopting these measures to achieve compatibility between vehicles at their points of impact. It may be asked whether there are any alternative proposals which could be so effective.

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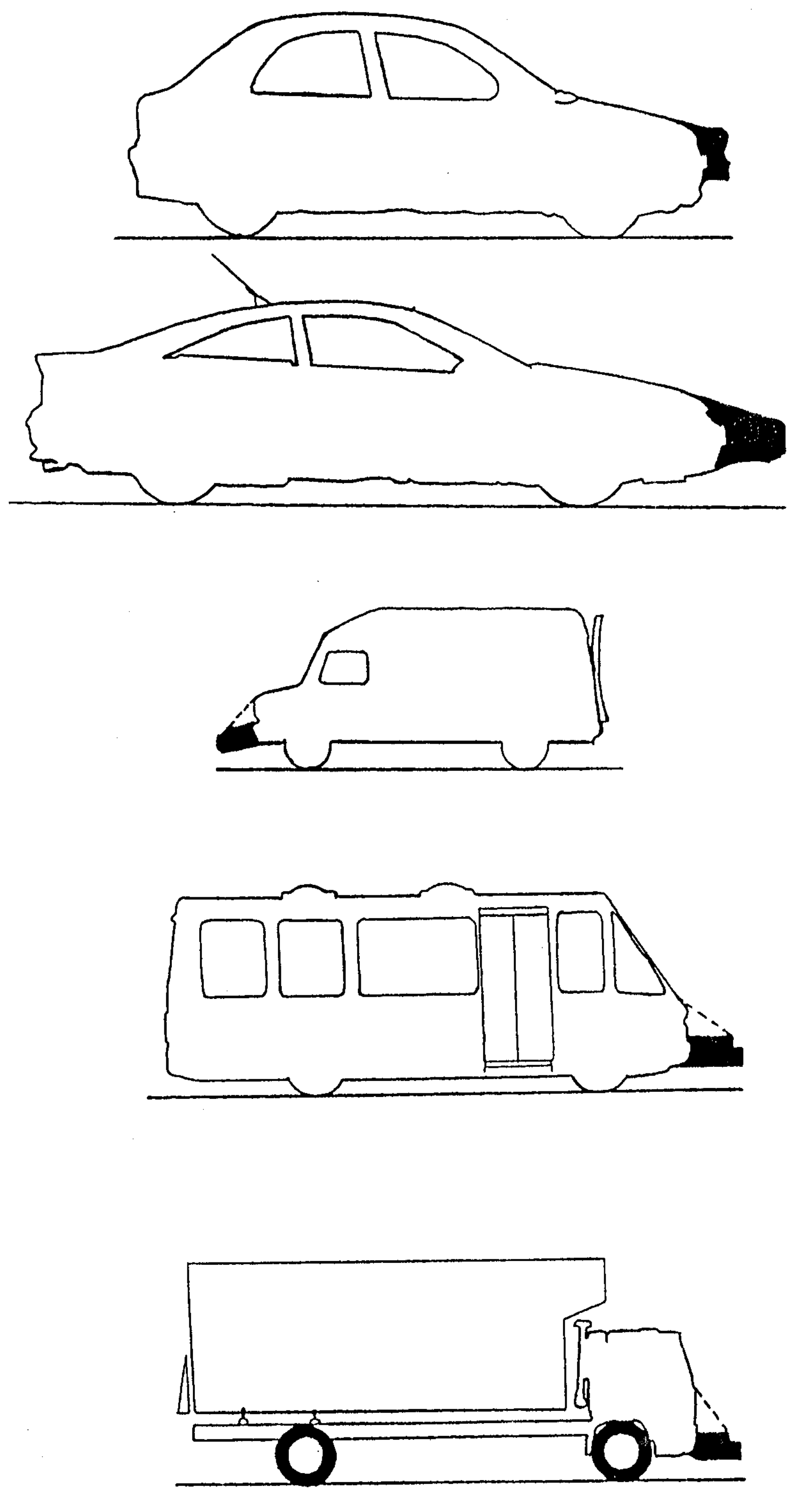

Figure 1. Positions of additional structures at the fronts of different types of vehicle.

Accident research and experimental data useful for an understanding of the influence of car structural incompatibility on the risk of accident injury

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ABSTRACT

Previous papers have already shown that a global assessment of the injury risk needs to take into account not only the victims inside a given vehicle but also the victims outside due to the vehicle's aggressiveness.

New analyses have described all the phenomena, in absolute figures and as percentages. It appears for example that the injury risk is higher in accidents occurring between heavy cars than for accidents between lighter cars.

An attempt is made to distinguish between the effects of car structural stiffness and the effects of car weight.

Consequences are drawn concerning present trends in car design on the one hand and conflicting environmental and safety requirements on the other hand.

INTRODUCTION

The early seventies were marked by intense activity concerning the topic of car compatibility (1 to 17). As of the first conference on experimental safety vehicles held in 1970, a new concept emerged: car aggressiveness. The concept, applied first to side collisions (1), was immediately extended to head-on collisions (2) (3) and, in 1972, Philippe Ventre presented very interesting experimental results showing that it was not unrealistic to search for structural compatibility between two cars within a weight ratio of 1 to 2 for a closing speed of 140 km/h (3).

Analysis of collisions between dissimilar cars enabled a distinction to be made between three types of aggressiveness:

. aggressiveness due to stiffness;
. aggressiveness due to weight;
. aggressiveness due to architecture.

The report given to the 3rd ESV Conference entitled "Homogeneous Safety Amid Heterogeneous Car Population?" deserves further examination. It presents and summarizes "the work carried out on these three types of aggressiveness and proposes solutions illustrating how vehicles of different weights and designs may coexist on the same roads" (3).

20 years have gone by. Compatibility has made no progress on the roads throughout the world. Some might even claim that it has deteriorated further, with a greater increase in weight for the large cars and with the appearance of leisure vehicles of exceptionally aggressive architecture.

We prefer to emphasize the most positive aspects, which show that this time has not been entirely lost if the international community wakes up:

- Structural engineers have worked hard and acquired greater control of structural behaviour in very diverse conditions of impact. In particular, they have increasingly efficient mathematical simulation tools.

- The performance of restraint systems has been greatly improved, and in the 1990s the following have become widespread:
  - the adoption of seat belt pretensioning and strap locking systems;
  - the use of airbags as a very useful complement to the seat belt.

The limit to compatibility which was visible in 1974 in small light cars (strong deceleration at the dummy head and thorax level) (3) would no longer be as critical at present with the restraint systems undergoing optimization.

The time has now come, therefore, to intervene so that the expected progress in restraint systems may be used to redistribute the chances of survival in collisions between cars of different categories rather than increase further - without taking precautions - the protection in very severe impacts at the cost of increased aggressiveness of the heaviest cars and hence an aggravation of incompatibility on the roads. This concern has been expressed by a few experts, although they are still too few to deal with this question. All the more reason to quote Prof. Ulrich Seiffert who, on 2 February 1994, concluded a speech devoted to the safety of the small light car with the following words: "To protect the other users, compatibility must be included in the criteria of the future legislation. Above all, it is important that the question of compatibility should be considered as a priority over increased speed in collisions against a fixed barrier, or else heavy vehicles would become less compatible" (18).

This paper has two main purposes:

- To describe exhaustively the harmful consequences of car-to-car incompatibility based on the characteristics of the cars of the 1980s.
- To reformulate the theoretical and experimental groundwork governing compatibility, and by so doing, to outline what could be the framework for extensive cooperation in an essential area for progress in road safety at the start of the 21st century.

ACCIDENT RESEARCH DATA ON THE CONSEQUENCES OF CAR STRUCTURAL INCOMPATIBILITY.

Only by analysing large samples covering tens of thousands of cars of all brands and types is it possible to draw up a realistic evaluation of the road situation based on known car characteristics.

One of the most appropriate data banks is that established in France, as in most other countries, by national police reports covering all accidents causing bodily harm.

This data bank of course contains approximations, especially with respect to the severity of injuries. However, by selecting only those cases in which the driver was killed, a highly acceptable analysis tool can be obtained. The inevitable biases relating to driver characteristics and wearing of the seat belt are largely neutralized by working on very large samples. In a second stage, being carried out at present, an endeavour will be made to perform exhaustive analysis to determine more precisely this complex reality, by establishing, for example, the influence of driver age and sex and the rate of overlap between the two cars. This involves compiling sub-samples in which "all else will be equal". An attempt to classify cars in terms of stiffness is in progress within the framework of this more general study.

We are not yet there. Before discussing the exclusive analysis of head-on collisions between two cars and two cars only, let us describe the general situation in which such collisions occur, without forgetting to highlight an essential parameter, the "power/weight" ratio.

Such analyses have already been carried out on smaller samples, in particular by Mr Thomas in 1990. His study shows a higher overall danger level (inside and outside the car) for heavier cars (19). These results are confirmed by analyses performed on the same database but using the power/weight ratio to characterize cars (20) more comprehensively on the basis of US data (21) and again on French data in 1990 using, as in (20), the weight and power/weight ratio (23) (24).

OVERALL ACCIDENT RESEARCH SITUATION IN FRANCE FROM 1988 TO 1992.

It is logical to distinguish between several major families of accidents in which the cars are broken down differently according to their weight, power, and power/weight ratio (Figure 1). For example:

Family 1: . Accidents involving a single car (32% of fatalities). These include impacts against fixed obstacles, especially due to loss of control of the vehicle in curves for example.

Family 2: . Collisions with heavy vehicles (6% of fatalities); most of these severe collisions are against the front of heavy vehicles.

Family 3: . Complex accidents involving three vehicles or more (less than 5%).

In family 1, the risk of decease does not vary with the weight of the car but with its power/weight ratio.

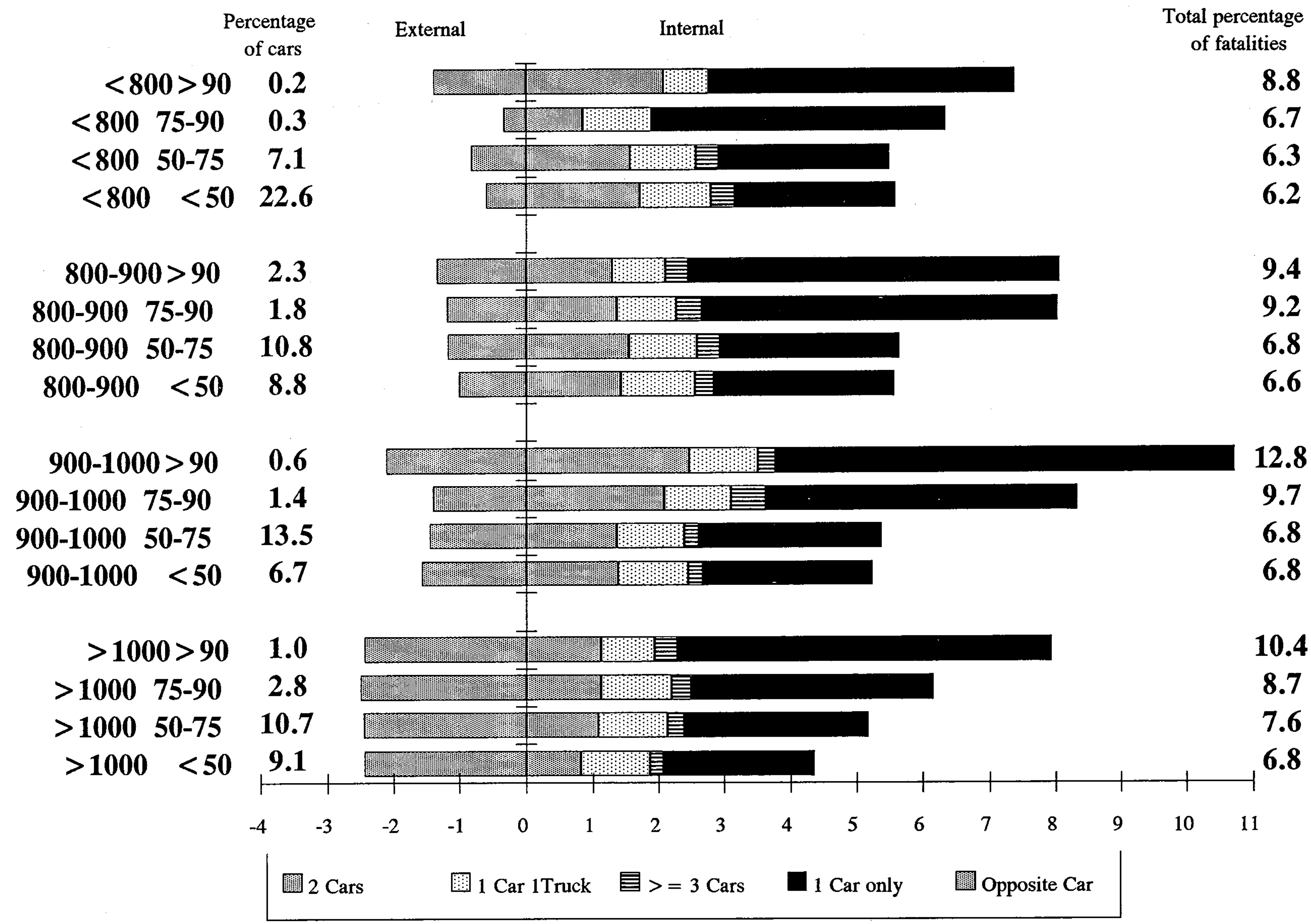


Figure 1. Repartition in percent of drivers fatalities , by weight and 'power/weight' ratios

Source : Gendarmerie Nationale Data File 1988-1992 (All collisions except 2 or more trucks.) 198106 cars, 13812 fatalities

The higher this ratio, the greater the risk for the driver of losing control of his vehicle and seeing it end up against a tree or a fixed rigid obstacle. It is in this family that the greatest number of fatalities is observed.

Families 2 and 3, even when taken together, represent the smallest number of fatalities; there is little difference between the risk for the various cars, irrespective of their weight or power per metric ton.

Family 4: Collisions between two vehicles and two only. This large family accounts by itself for one third of fatalities. This family is shown on the figure divided by a vertical line separating fatalities in the "car involved" (on the right) and fatalities in the opposing car (on the left).

The interpretation is as follows : light cars of weight < 800 kg and having a power/weight ratio < 50 kW/metric ton accounted for a total of 1.8 driver fatalities per 100 accidents causing bodily harm, and 0.4 driver fatalities in all cars with which a collision occurred.

Conversely, it can be observed that for the heavier car category (> 1000 kg) with powerful engines (more than 75 kW/ton), the results are reversed: 1.1% of fatalities in the vehicle involved, but 2.5% fatalities among the drivers of all the opposing cars encountered.

Finally, one observes from the figures in the right-hand column of this figure that the total number of fatalities for each weight and power/weight category is between 6.2 and 8.6 for the lightest cars and reaches values greater than 9 for the heaviest and most powerful cars.

However, an important comment should be made : only 0.2% of cars weighing less than 800 kg exceed an overall fatality rate of 6.7, compared with
14.9% for lower-medium cars
22.2% for upper-medium cars
and 23.6% for cars exceeding 1000 kg.
It can therefore be said that, overall, the heaviest cars are also responsible for a greater number of fatalities. The term "aggressive" therefore seems appropriate.

This family 4 really poses the problem of structural compatibility between cars of different weights; it is to this family that we shall devote the remainder of this paper : we shall consider only head-on car-to-car collisions involving only two vehicles. Such cases represent 35% of fatalities in frontal impacts and 49% of severe injuries and fatalities (M.AIS 3+).

Too often car safety comparisons take into account merely the fate of the occupants of one car involved and ignore what happens to those in the opposing car. In fact, whenever a collision involves two vehicles of different weights, it is clear that protection in the larger car is achieved at the expense of protection in the smaller car.

In a head-on collision between two cars, the velocity change (DV) for each restrained occupant is inversely proportional to the weight ratio of the two cars. Accordingly, whatever the speed of each car prior to the impact, if the closing speed is 120 km/h and the weight ratio is, for example, 1600/800, the DV will be respectively 40 km/h for the larger car and 80 km/h (or twice as much) for the lighter car.

Everyone knows that the forces exerted on the human body, which are the sole cause of occupant injuries, are proportional to the square of speed. In the preceding example, whatever the speed of each vehicle (and even if the lighter vehicle was not in motion), it will in fact be just as though the larger car were to impact a wall at 40 km/h and the smaller car at 80 km/h. This is not an extreme example, since the weight ratio (in this case two) can be up to three on European roads.

This illustrates clearly that the protection of large cars is indisputably achieved at the expense of protection for the smaller cars.

Let us say straight away that this is hardly acceptable. One of the most serious challenges for the future of the motor car is to determine how to change this state of affairs. This will undoubtedly not be achieved by regulating car weight, but rather by requiring that the heavier cars provide for deformability, even if it is not necessary for their occupants (although the result would in any case be beneficial), but designed to protect the occupants of opposing cars.

This amounts therefore to defining the conditions for lower aggressiveness in the heavier cars, knowing that the smaller cars are themselves likely to become stiffer.

This is not a new concept. Philippe Ventre, the present "product process" manager at Renault, in the publication already referred to (3), presented in the conclusions the following formula, shown in italics: Compatibility must consider *"the equality of passenger compartment deformation forces between all vehicles"*.

The feasibility of this was demonstrated for two cars weighing 660 and 1320 kg, involved in head-on collisions at closing speeds of 100 and 140 km/h.

Structural compatibility was ensured for both cars.

Before reformulating the theoretical and experimental foundations of the physics of compatibility, we should like first to describe the harmful consequences of the incompatibility resulting from the characteristics of the cars of the nineties.

ANALYSIS OF CONSEQUENCES FOR THE DRIVERS OF STRUCTURAL INCOMPATIBILITY IN HEAD-ON CAR-TO-CAR COLLISIONS

The same basic sample described above is used, i.e. 198,106 passenger vehicles involved in accidents causing bodily harm, resulting in 13,812 deaths in 5 years (1988-1992). This statistic covers the entire French road network except for those cities in which road accidents are taken in charge by the urban police force.

From this accident population is taken the sample of cars involved in head-on collisions (two cars only), i.e. 11,966 collisions which caused the death of 1,063 drivers.

Once again, to simplify the analysis, only the drivers will be considered here.

Comparison between a small and large car.

What precedes can be represented clearly in schematic form in answer to the question of the comparative fatality rate of a light, low-power car (< 50 kW/ton) (Renault 5) and a heavy, powerful car (in fact we take here the mean for vehicles of more than 1300 kg to obtain a representative sample). The fatality rate is 50% higher for the latter cars : 6 for the Renault 5 and 9 for the heavier models. But the breakdown of injuries "inside" and "outside" the car shows the opposite result (Figure 2).

This overall analysis is simplifying, because it does not take into account exposure characteristics (e.g., distance travelled) and representation within the fleet (Table 1).

The study by Hélène Fontaine (INRETS) published in 1990 (Table 2) concludes that "the risk of being involved in an accident causing bodily harm, relative to the number of kilometres travelled, is twice as great for vehicles of more than 75 kW/ton as for the overall fleet of light vehicles.

Analysis of the fleet based on rate of accident involvement

The representation within the fleet of weight and power classes per metric ton shows a very strong predominance of cars of upper-medium weights (750-900 vs 750-900; 750-900 vs 900-1050 and 750-900 vs > 1050).

These three combinations are strongly represented in collisions (about 50% of all collisions) and also result in a large number of fatalities, although slightly less than implied by their rate of accident involvement.

It is very clear that with cars weighing more than 1050 kg the fatality rate exceeds the rate of accident involvement (Figure 3).

Influence of weight on the total driver fatality rate.

An examination of Figure 4 shows that the fatality rate is lowest for impacts of light vehicles with one another (< 750 vs < 750 at 5.5%). This rate increases with increases in weight for an equal weight class (from 5.5% to 10%). The highest rate is obtained for impacts between large and small vehicles (10.5%), but it is noteworthy that the fatality rate for collisions between a light car and an increasingly heavy car rises rapidly (from 5.5% to 10.5%). This rate remains very high whenever a large car is involved (10 to 10.5%).

This figure shows clearly the aggressiveness of heavy cars, even when impacting one another.

Influence of parameters such as stiffness or architecture.

It is hard to characterize stiffness for vehicles which are not very well known or for foreign brands. However, the influence of these parameters can be analysed by observing how different vehicles of similar weight can behave.

Observing Figure 5, it can be seen that vehicle No. 3 (in the 700-800 kg class) accounts for the largest total number of fatalities out of the 27 cars studied, with the most inside victims and the smallest number of outside fatalities.

This provides a good characterization of a vehicle which is not very stiff or aggressive (unfortunately not stiff enough to protect its own occupants).

From this it can be concluded that:

when a heavy car is involved, the frequency of fatalities for both cars involved in the collision is greater than the frequency of collisions; in other words, fatalities are over-represented in such head-on collisions.

In addition to weight, other factors can contribute to this effect:

- higher speed (more violent impact);
- greater stiffness.

The situation is reversed when a light car is involved, except when it is opposed by a heavy car, due to incompatibility of weight.

When there is a difference of weight between two vehicles, the proportion of driver fatalities is always greater in the lighter car. There is no exception to this rule.

When the cars are of similar weights, the fatality rate increases with weight.

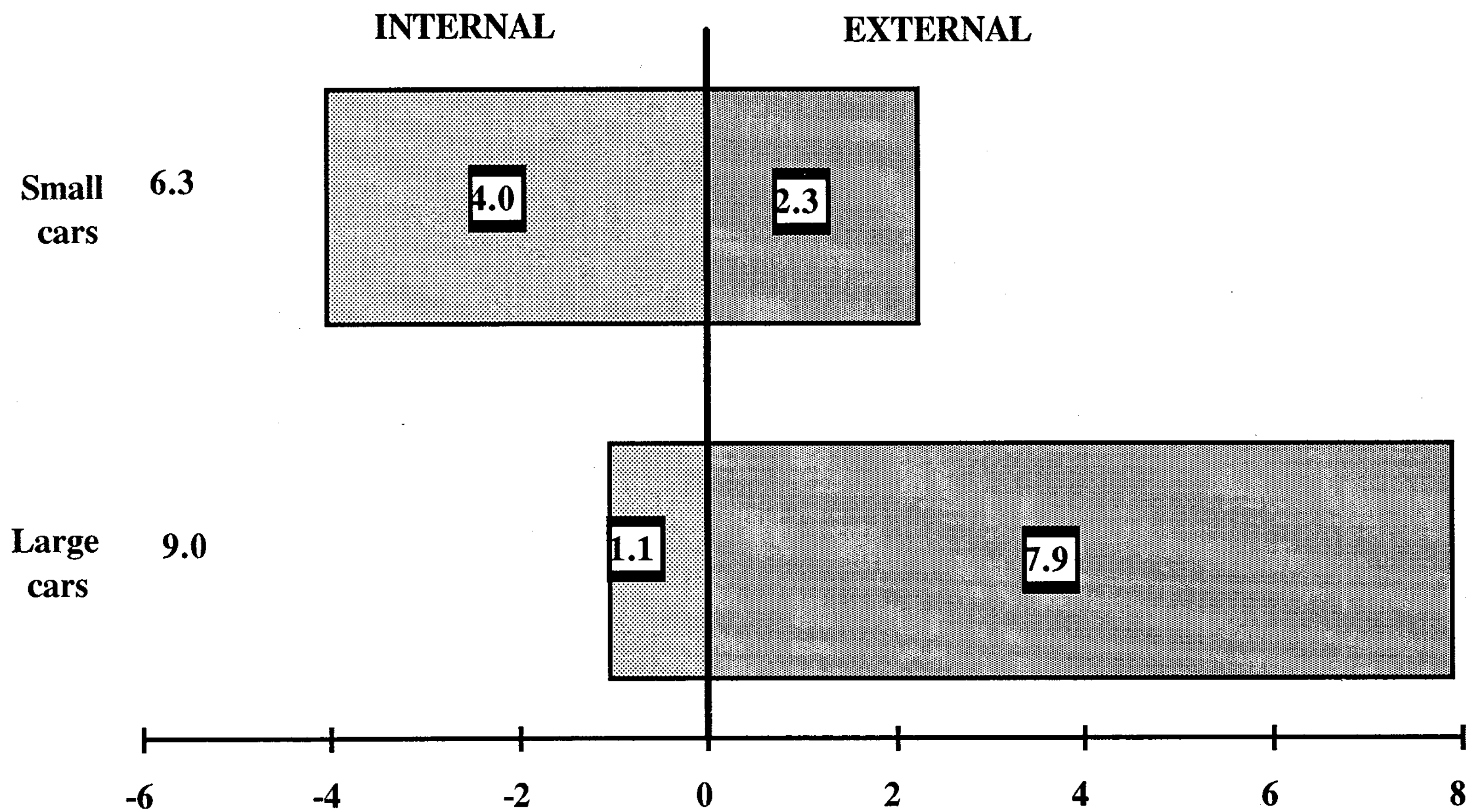


Figure 2. Fatality Rate
Source : Gendarmerie Nationale 1978-1992

Small car : Renault 5
Large Car : 3 european heavy cars

Table 1
Head-on Collisions involving 2 cars only
(Source : G.N. 1978-1992)

	Large cars			Small cars		
	948			5589		
Sample	Internal	External	Total	Internal	External	Total
Number of fatalities	10	75	85	226	131	357
Driver fatality rate	1	8	9	4	2,3	6,3

Large cars : Mercedes + BMW 5 and 7 Series
Small cars : R5 Ratio power/weight < 50 kw/tonne

Table 2
Definition of high-performance cars above 75 kW/ton

Performance class	Breakdown of vehicles	Annual mileage	Mileage breakdown	Breakdown of accidented vehicles
Less than 75 kW/ton	96.6%	12600 km	95.9%	91.8%
75 kW/ton and over	3.4%	15300 km	4.1%	8.2%
Total	**100%**	**12700 km**	**100%**	**100%**

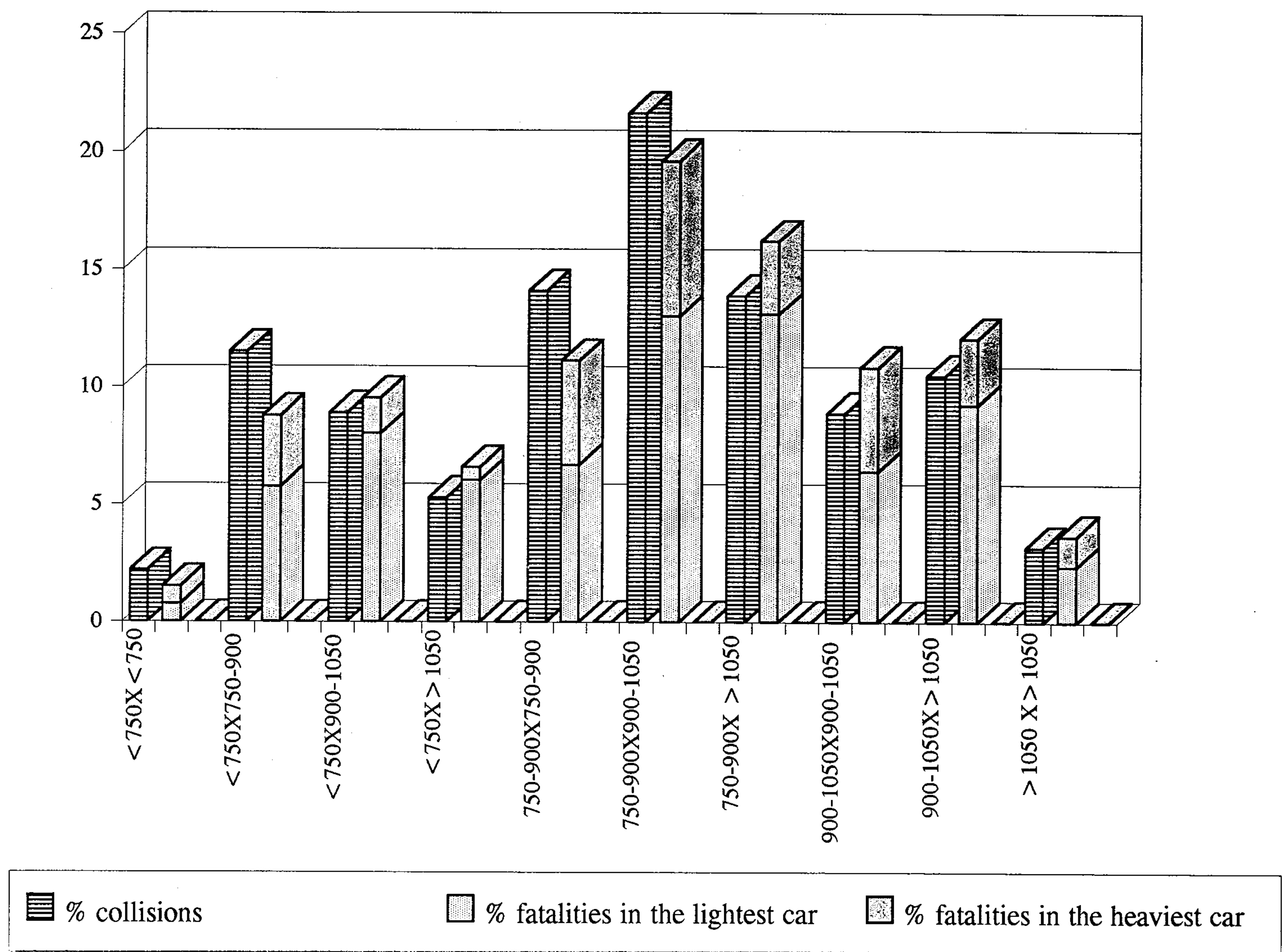


Figure 3. Repartition of 100 collisions and 100 fatalities.
Car to car head-on collisions according to weight class
Source : Gendarmerie Nationale Data File 1988 to 1992

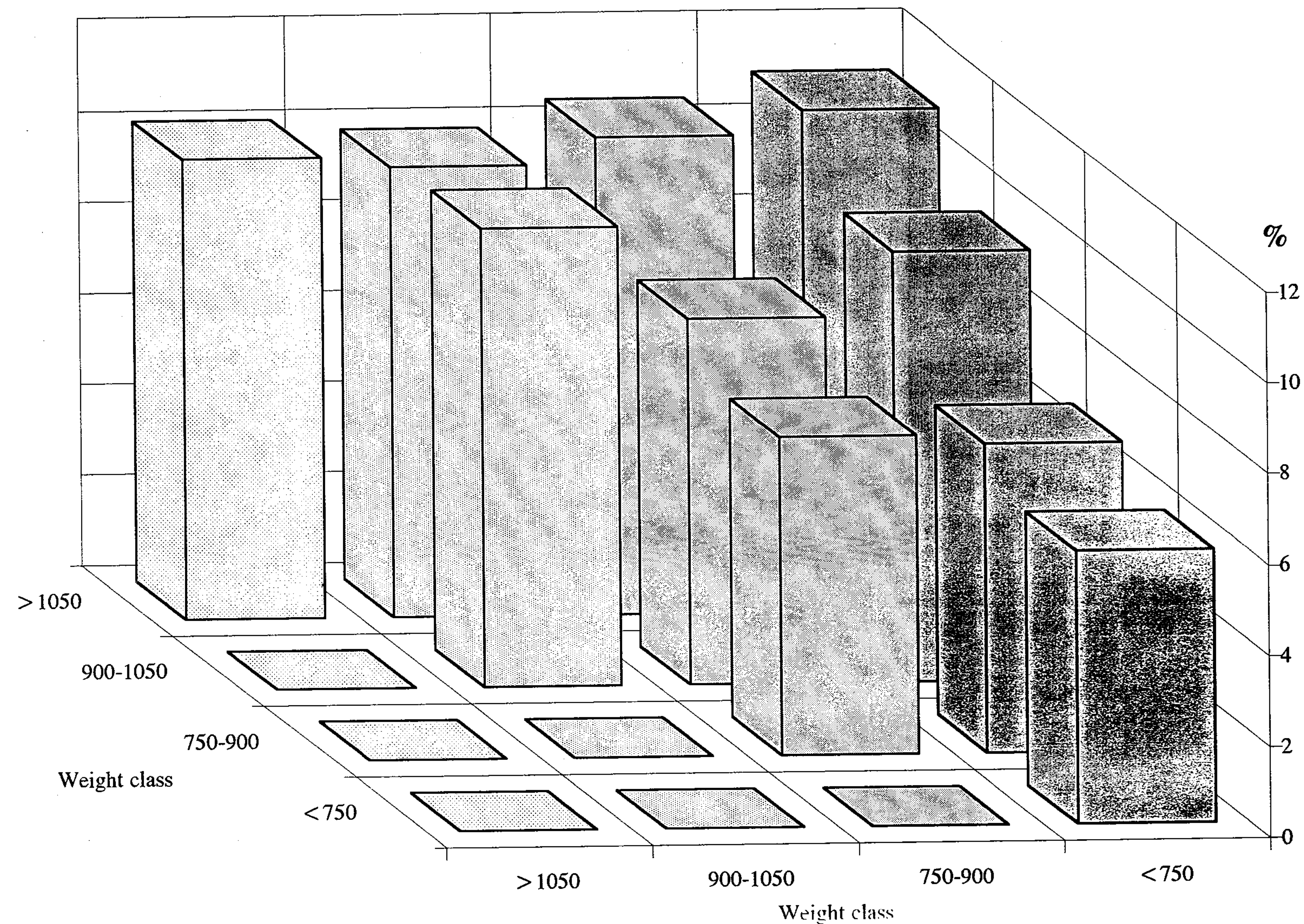


Figure 4. Percentage of drivers fatilities by accident .
Head-on collisions according to weight class.
Source : Gendarmerie Nationale Data File 1988 to 1992 (1063 Fatalities 11966 Collisions)

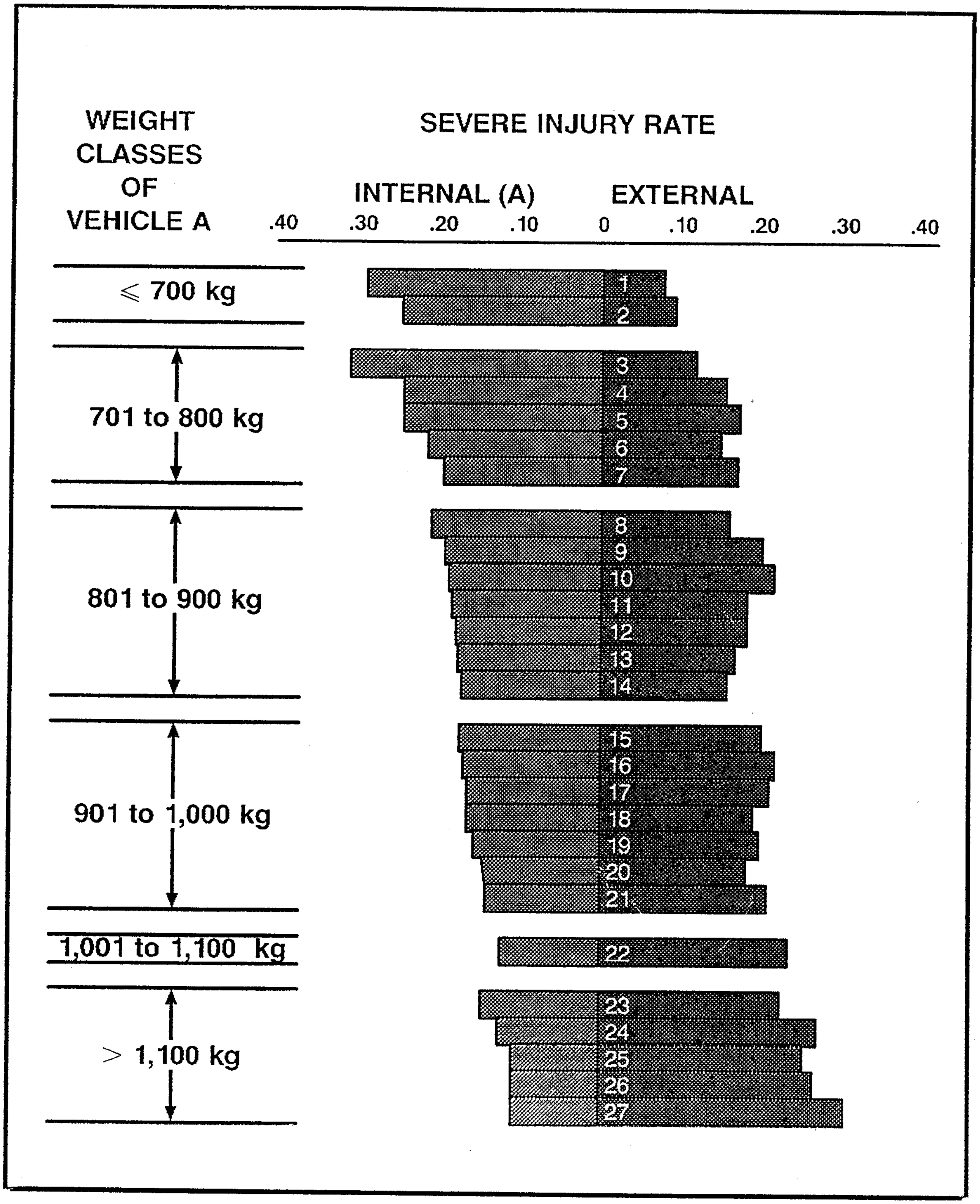


Figure 5. Internal and external severe injury rate for belted drivers of 27 cars involving at least 500 drivers by weight class (all car-to-car collisions)

EXPERIMENTAL AND ANALYTICAL APPROACH OF COMPATIBILITY

Introduction

A very great number of parameters is driving compatibility between vehicles. The best known is the mass effect which will induce necessarilly a more important change of speed on the lighter car in case of symetric impact. As we will see later, some measures on the car construction may limit those effects. The next important parameter is the stiffness of both vehicles. This problem is extremely complex. The stiffness is first the result of the compression of the longitudinal front structures. Those will behave quite differently on a crash against a rigid wall and on a car-to-car crash. In the latter case, too stiff structures will not find enough support to crush on the impacted vehicle and thus are going to aggress it. The apparent stiffness of the front of a car is also a result of the mass distribution in the front unit. This is what we can call architecture aggressivness and concerns mainly the engine.

Reproducing in a simple interaction model all those phenomenons do not seem very realistic. We tried anyhow to build a principle model that could take into account the most important parameters to be able to draw some partial conclusions.

The baselines of the proposed method are shown in figure 6.

First step : experimental crash on a rigid wall - To caracterize one car, we first use a test on a rigid wall with a given overlap. The first difficulty is that we cannot track the force on the rigid wall during the crash event on such an offset crash. So we have to re-build that reaction force from the available decelerations on various points of the crashed car. We first derive a main stiffness K1 between the wall interface and the rear mass of the body from the B-pillar decelerations. The engine decelerations lead us to an engine behaviour model. We limit the peak deceleration values to 80 g to be more representative of the later car-to-car crash. The remaining front mass is stopped on the wall step by step which leads to a mass distribution on the main stiffness K1.

Second step : car to car calculation - The calculation program is meant to estimate the deformation in both cars in a car-to-car crash with the same overlap as the single car tests. We had to simplify the interface between the two cars to a rigid surface. To calculate the crush of both cars, we make an iterative calculation : at each step of 50 mm we put the deformation in the car that has the smallest reaction force. We thus neglect the inertia effect of the mass bloqued at the interface between both cars.

The car to car simulations

Three car models have been chosen to run the simulations. We took a small car and two very different representatives of the European upper-middle class. Those three cases will enable use to draw general conclusions that will also apply for some other size or weight classes.

The equivalent stiffness model was built with crashes on a rigid wall with 50% overlap at 56 km/h . That overlap was chosen because we had a good number of tests available.

For each car, we defined a limit in the total crush distance for which the dashboard intrusion reaches 200 mm. This intrusion limit is lower than the usual threshold of increase of the intrusion injuries which is rather 300 to 350 mm. The tests we have were not conducted at a high enough speed to reach those limits for the two heavier cars,so we had already to extrapolate the tests to reach the 200 mm intrusion values.

The mass we took is the kerb weight with an addition of 200 kg representing the weight of the dummies and the test equipment.

Let us now review the main features of the three car-models.

The first car is a small car with a kerb weight of 840 kg. The rigid wall force vs crush law is shown in figure 7. The total crush leading to 200 mm dashboard intrusion is 800 mm. The corresponding energy is 126 kj with an impact speed of 56 km/h.

The second car is a first representative of the European upper middle class. We will call it " medium car A ". The kerb weigt of that car is 1250 kg. The rigid wall vs crush law is shown on figure 8. In that case, we need a total crush distance of 1.00 m to reach 200 mm of intrusion at the dashboard level. Those values were not obtained in the 56 km/h test on the rigid wall. To reach them, we extrapolated an equivalent speed of 59 km/h and an impact energy of 193 kj.

The third car is equivalent to the second one for its major features. We will call it " medium car B". The only diference is the force vs crush law of figure 9. The limit crush distance and associated speed and energy are the same as medium car A.

Simulation results - We run the simulation for the three possible combinations between those cars. Those simulations are valid for an impact speed close to the one used for the rigid wall tests.

We are computing the total energy that can be dissipated in the collision until one of the cars has reached its total crush limit with 200 mm intrusion.

First case : medium car A / small car - The theoritical energy limit leading to the intrusion limit on both cars is

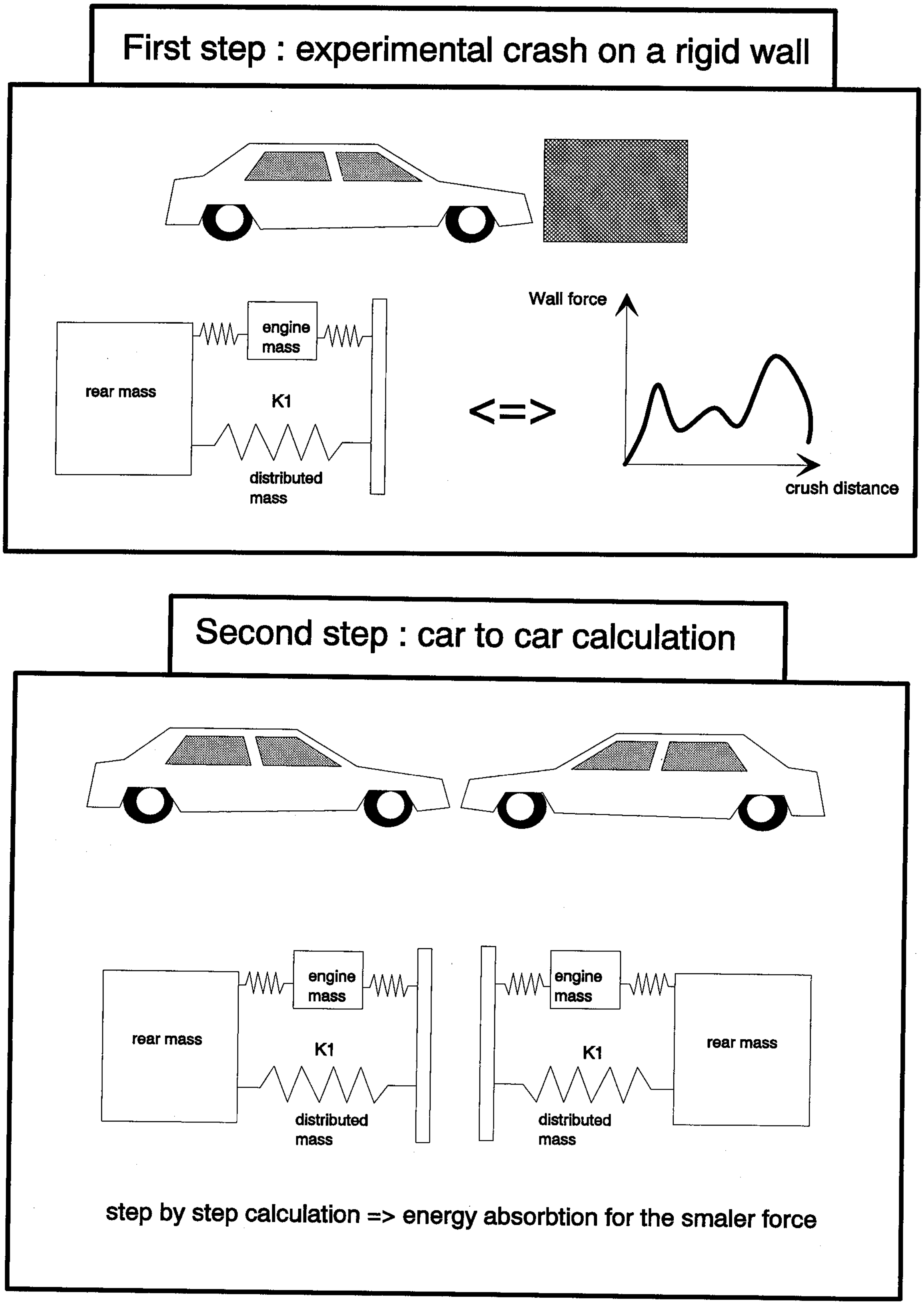


Figure 6. Principle of the calculation method

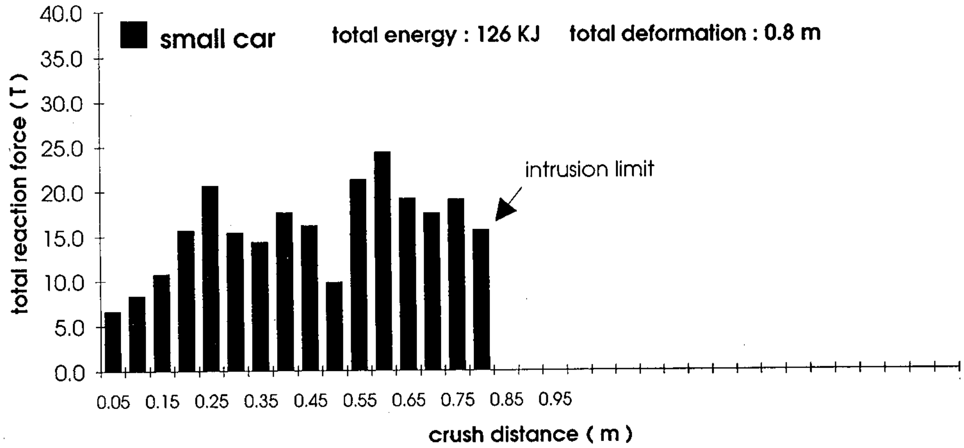


Figure 7. Force vs crush law for the small vehicle on rigid wall (impact speed 56 km/h)

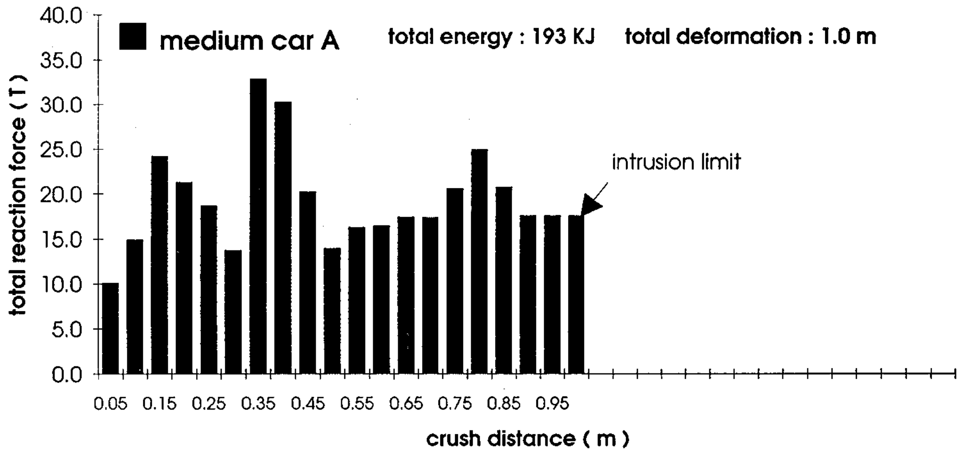


Figure 8. Force vs crush law for medium car A on rigid wall (impact speed 59 km/h)

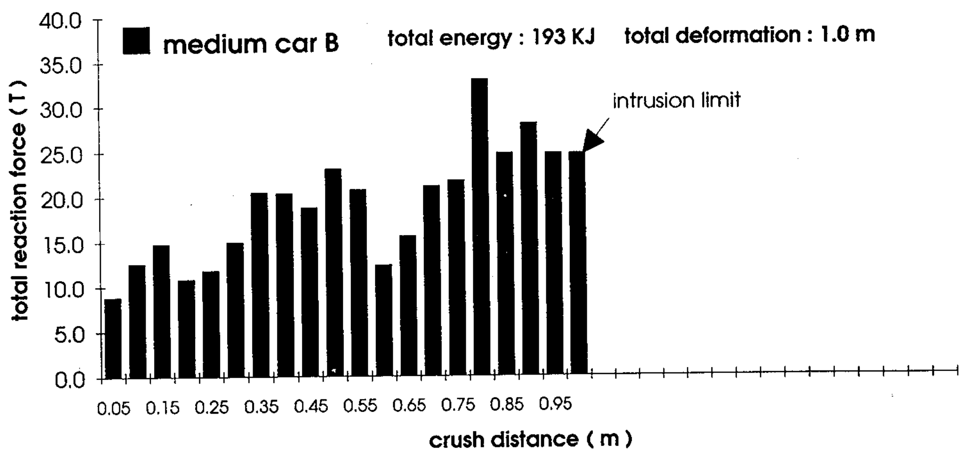


Figure 9. Force vs crush law for medium car B on rigid wall (impact speed 59 km/h)

the addition of both energies on the rigid wall reference crashes : 193 + 126 = 319 kj. The simulation result is presented in figure 10. For each calculation step, the color of the bar indicates which car deforms and the size of the bar the amount of energy involved in that step. The total energy until the intrusion limit on the small car is only 177 kj. The efficiency compared with the ideal is 55%. The resulting maximum closing speed in a real accident would be 87 km/h.
The small car reaches its intrusion limit as medium car B has only a crush distance of 300 mm. The current force on the small car is 16 T whereas the other car has a reaction force potential of 31 Tons. Even the approximations of the model as the neglected inertia effects would certainly not change that result.

<u>Second case : medium car B / small car</u> - The theoritical energy limit is the same as in the previous case : 319 kj. The calculation of figure 11 shows that medium car B deforms a lot more (750 mm) before the small car reaches its limit. The resulting total energy is of 250 kj with an efficiency of 78%. The maximum possible closing speed goes up to 103 km/h which is an improvement of 16 km/h compared with the first case. This means a far better protection for the occupants of the small car considering the speed distribution of crashes in real accidents. We should remind here that the self protection of the two medium cars on fixed obstacles is comparable with a potential speed of 59 km/h.

<u>Third case : medium car A / medium car B</u> - In that case the theoritical energy limit is : 193 + 193 = 386 kj. Figure 12 shows that the total absorbed energy is 317 kj with an efficiency of 82%. It is a paradox that medium car A, which is less compatible against the small car, is more crushed than medium car A. Nevertheless the difference between the force levels at the end at the crash is relatively small. The calculation model may be slightly wrong here. The maximum closing speed is 106.5 km/h which is very acceptable compared with the theoritical limit of 118 km/h.

Conclusions - If you consider two collisions at the same closing speed of 103 km/h with in one case the small car against medium car A, and in the other case the small car against medium car B, you can calculate by extrapolating the first simulation case that you would get an intrusion of 700 mm on the small car in the first case with only 200 mm in the second case. This shows very clearly the stake of the stiffness compatibility problem.

Influence of the car deceleration on the occupant risk

The question we would like to raise here is the influence of the crash pulse on the dummy responses regardless of intrusion effects. This is meant to cover the other very important family of injury risks induced by the occupant decelerations. We used a simple judgment on the base of delta V to compare, for each car, the car-to-car crashes with the crash against the rigid wall.

<u>First case : medium car A / small car</u> -
delta V for small car = 50.7 km/h
delta V for medium car A = 36.3 km/h
With the limit closing speed of 87 km/h the risks are lower than on rigid wall both for the small and medium car. For higher closing speeds, the intrusion risk will be dominant on the smaller car.

<u>Second case : medium car B / small car</u> -
delta V for small car = 60 km/h
delta V for medium car B = 43 km/h
With the limit closing speed of 103 km/h the deceleration risks on the smaller car are more important than on the rigid wall. If the restraint systems of the small car are already pushed at their limits on the crash against the rigid wall at 56 km/h, an improvement of the stiffness compatibility will require also an improvement of the restraint systems on the small car to be fully effective.

<u>Third case : medium car A / medium car B</u> - That case is very close to the car to rigid wall crash for the restraint systems : the delta V for each car is 53 km/h when the intrusion limit is reached on medium car A.

Proposal for a better compatibility

The major principle is to control the force vs crush laws of all the vehicles with a few design rules.

We propose first on the heavier cars a certain deformation area dedicated to car-to-car compatibility. If we want this area to deform in all situations, we have to specify a maximum force level during the deformation of that area. According to this study a value of 20 Tons seems acceptable.

The length of that area depends on the length of the car, but 700 mm seems an acceptable value for a car of the European upper medium class. This length should not be too important even on heavy cars to keep a good protection for crashes on a rigid wall or against another heavy car. It could be increased on bigger cars and reduced on smaller cars. The force limitation will induce also a deceleration limitation inversly proportional to the mass of the car during the crush of that deformation area. The heavier cars will have to absorb more energy in the end phase of the crash.

The medium car B of our presentation is very close to those specifications, and has also a good behaviour on a rigid wall so that kind of compromise is possible.

The smaller cars must be stiff enough to ensure a complete crush of that deformation area of the opposite car before his body collapses. A minimum resistance force of 25 Tons seems required to make sure that the deformation area tuned at 20 Tons will work in all cases. As we saw, a special effort will have to be put on the restraint systems of

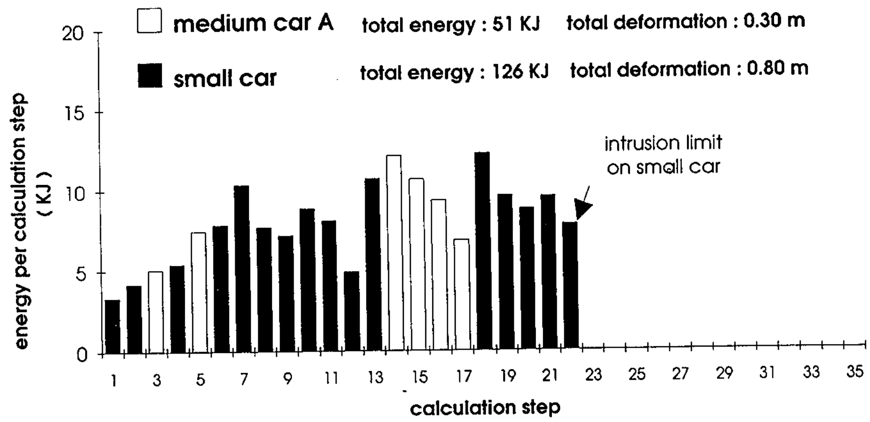


Figure 10. **Car-to-car simulation between medium car A and small car (total energy 177 KJ)**

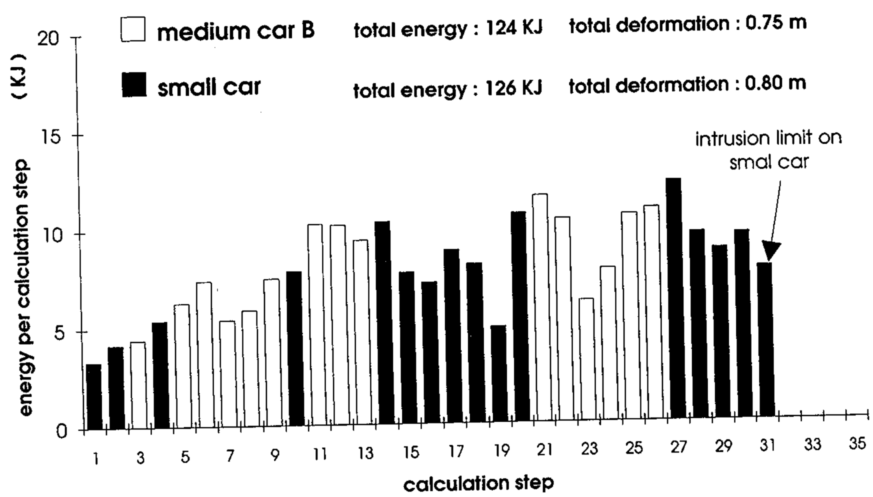


Figure 11. **Car-to-car simulation between medium car B and small car (total energy 250 KJ)**

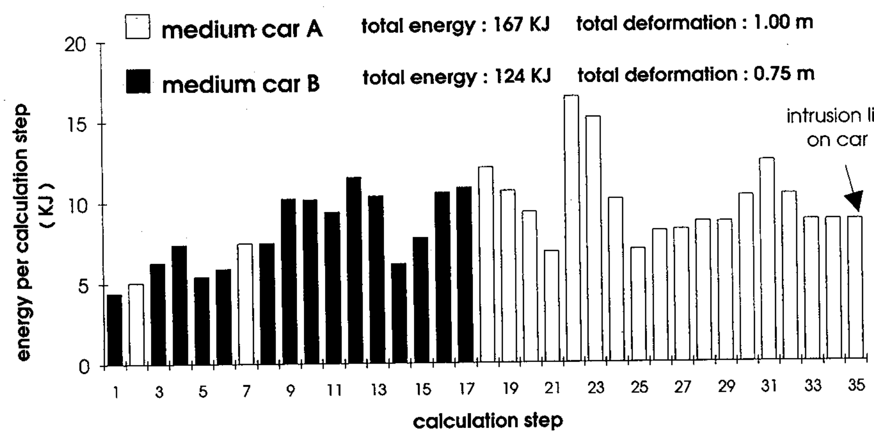


Figure 12. **Car-to-car simulation between medium car A and medium car B (total energy 317 KJ)**

those small cars to cope with the higher resulting delta V in car to car crashes.

CONCLUSIONS

1. Gloal accident research carried out on large representative samples clearly shows the issues at stake : apart from progress in passive safety, which will become widespread by the year 2000, no significant improvement can be achieved without reducing the aggressiveness of the heaviest cars.

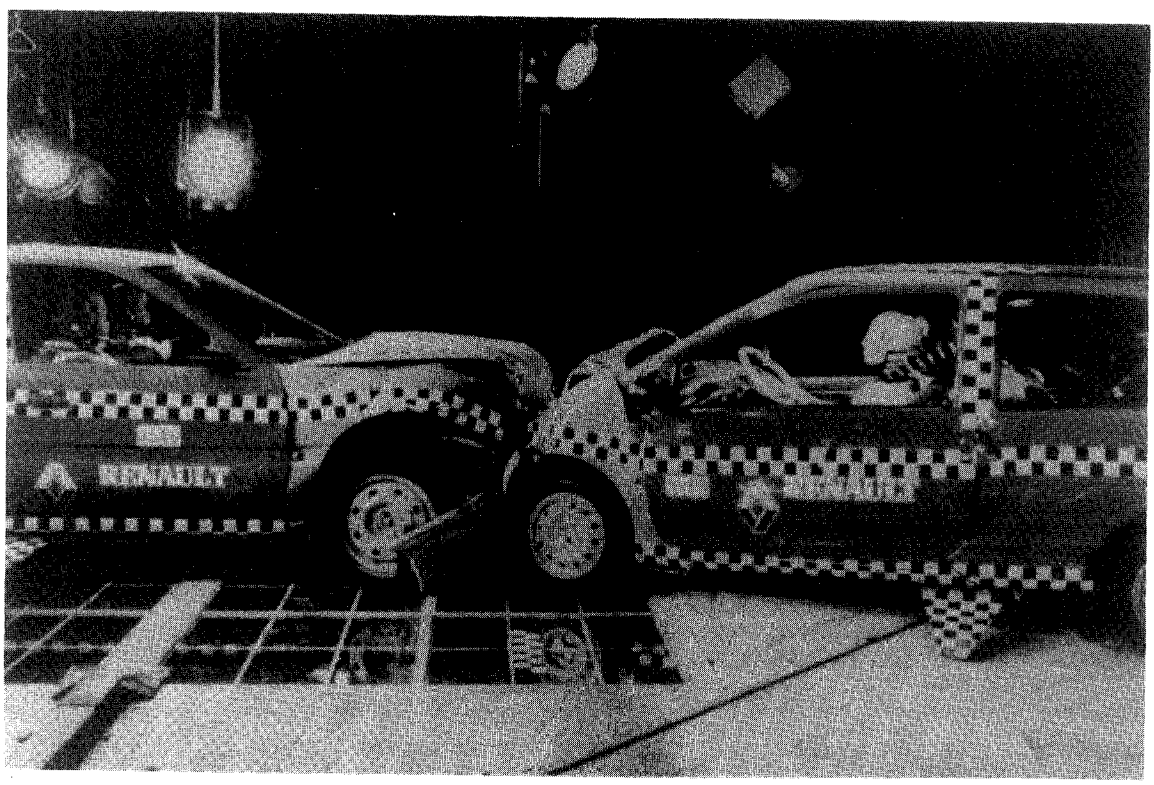
2. The experimental approach shows that there is potential for limiting the consequences of incompatibility due to the weight of cars.

3. The deformable barrier, which attracts great interest in Europe, is no doubt useful to eliminate local stiffness, but **ineffective for assessing the overall stiffness of a car.**

   A deformable barrier makes no distinction between a highly aggressive car which consumes the entire deformable section of the barrier and which comes to a stop against the rigid barrier itself, and a car of identical weight having a shock absorption area which crushes the deformable barrier in the same way at the end of the impact.

   Every car would have to have a minimum deformation area which can be observed in an impact against a rigid barrier at moderate speed. The proposed value of 700 mm for a European car of the upper-medium category would vary in inverse proportion to the cars' weight.
   In the present situation, progress could only be achieved by means of a dedicated additional test which remains to be worked out.

4. **It is of the utmost necessity that a regulatory proposal be prepared urgently to accompany any change in design rules**, because the trend to build stiffer cars to achieve good ratings under more stringent test conditions is resulting in further increases in incompatibility.
   Pending agreement on an effective regulation, **a tax incentive** could help halt this natural trend towards greater incompatibility on European roads. The tax could be made progressive to include a concept of social utility and would be stronger for an all-terrain leisure vehicle, with high ground clearance and front reinforcing bars.



Head-on collision between a RENAULT Safrane and a RENAULT Twingo
at closing speed of 80 km/h

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INTRODUCTION OF COMPATIBILITY IN THE DEVELOPMENT OF A FRONTAL TEST PROCEDURE

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Paper N° 94 S4 O 15

ABSTRACT

In frontal impacts involving two light vehicles, two injury mechanisms are jointly involved, namely, deceleration and intrusion. Generally speaking, the objective of research aimed at improving safety in case of an accident is primarily to improve the occupants internal protection by acting on these two mechanisms. In this paper we will pay particular attention to giving some research orientations with the aim of taking into account the occupants safety of the antagonistic vehicle. After trying to determine the main parameters to be taken into account (mass, power/weight ratio, geometry, stiffness...) as well as some indicators, we give a few research directions for study in the framework of the test procedures' definition, in order to take into consideration the notion of aggressiveness and more widely the compatibility between the frontal structures of the light vehicles. Among the paths worth exploring, we suggest working on the deformation of the obstacle which is defined in the regulatory test procedure projects. This work is supported by a literature study and our experience of impact testing against rigid or deformable fixed obstacles.

INTRODUCTION

For many years now, everyone involved in passive safety sector have been working at improving the protection offered by vehicles when subjected to frontal impacts. These studies, whether those of the manufacturers, consumers or public laboratories involve a behavioural evaluation of the frontal structures of vehicles, during impact tests. The need is therefore to come to an agreement on a test procedure definition which involves the most often observed mechanisms during real accidents. Studies already undertaken in this sense have primarily been aimed at protecting the occupants of the vehicle concerned, but it would seem equally important to be concerned about protecting the other users. These other users include the occupants of the other vehicles, which leads us to think that maximum account should be taken of the structures' compatibility.

We will also stress the importance which can be put on these compatibility questions in accidentology and we will indicate some paths we consider possible for taking this characteristic into account in the development of impact test procedures.

PARAMETERS TO BE CONSIDERED

It is well known that safety takes into account the combined characteristics of the environment, the driver and the vehicle. Even though we stress the combination of these three factors, we will pay particular attention here to defining the criteria linked to the vehicle which will enable us to define the quality compatibility indicators.

H. Fontaine (1994) shows that from amongst all the vehicles characteristics, the unloaded weight and the power/weight ratio seem to be the most pertinent criteria to analyse from the safety viewpoint. Indeed, a very powerful and very heavy vehicle, will not have the same technical possibilities as the same powered vehicle but lighter in weight. Figure 1 shows the weight and power/weight ratio characteristics for some models. It is also seen that the average top speed increases with the weight and power of the vehicles (table 1).

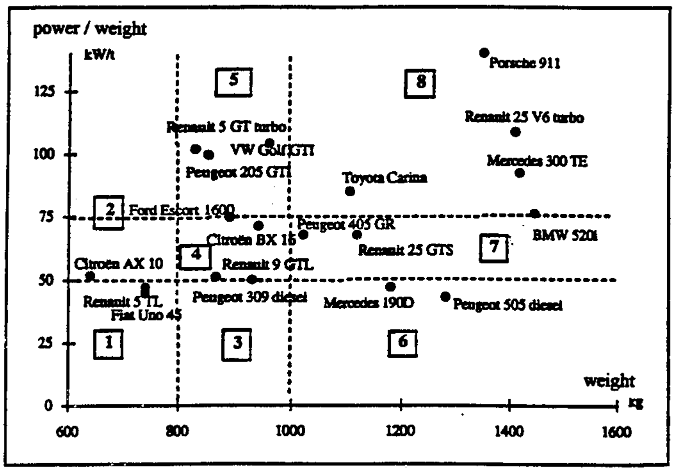

Figure 1. Tonnage weight and power of some vehicles

Table 1
Top Speed per Vehicle Category.

vehicle type		top speed (km/h)
< 800 kg	< 50 kW/t	131
< 800 kg	> 50 kW/t	153
800 to 1000 kg	< 50 kW/t	149
800 to 1000 kg	50 to 75 kW/t	163
800 to 1000 kg	> 75 kW/t	186
> 1000 kg	< 50 kW/t	156
> 1000 kg	50 to 75 kW/t	175
> 1000 kg	> 75 kW/t	196
all vehicles		157

As far as the effect of vehicle weight on the seriousness of the accident is concerned, the same author found that for all accidents between two cars, the percentage of external drivers killed increased with vehicle weight. It went from 7.5 killed per 1,000 vehicles under 800 kg up to 15.1 per 1,000 intermediate category cars, and can reach 23.5 killed per 1,000 vehicle in the over 1,000 kg category. These results confirm those of Thomas et al (1990). In internal mortality, the most protected group was that involving the heaviest vehicles (10.5 killed per 1,000 vehicles) whereas the drivers of the lighter vehicles were the least protected (16.4 killed per 1,000 vehicles). Figure 2 shows the number of seriously injured victims (killed or badly injured) in collisions between two cars as a function of their weight category.

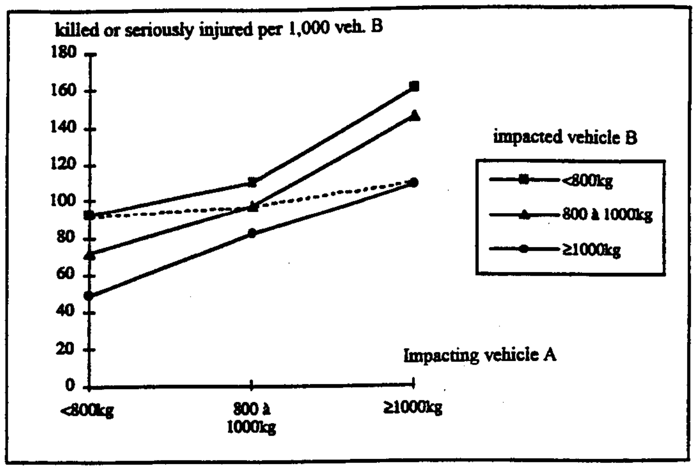

Figure 2. Drivers killed or seriously injured per 1,000 vehicles as a function of the weight of the impacting vehicles and that of the impacted vehicle.

Collision analysis between vehicles of the same weight category do not show significant differences in the percentage of drivers killed or badly injured (dotted line). Some analogous results were obtained by Thomas et al (1990) for drivers involved in frontal collisions in non urban areas. A German analysis (Ernst et al 1991), on the contrary, observed a decrease in the percentage of seriously injured drivers when the weight increases in frontal collisions between private cars of the same weight and revealed that the number killed and badly injured is much lower in a crash between heavy vehicles than between light vehicles.This can be due to the fact that heavy vehicles which are used more often and cost more to be repaired are over represented in accidents which caused considerable damages.

It has to be acknowledged however that the passenger space dimension of large vehicles is safer, because in a crash situation, the occupants have more freedom to move. Further, if the occupants of the vehicle are forced to come in contact with part of the compartment, in general, the thickness and type of materials used are better adapted to absorbing part of the energy.

The effect of the vehicles dimensions and especially its front part is also a significant parameter, since it enables the energy absorption to be managed during a shock. D.P. Wood et al (1992, 1993), analysed this energy absorption and introduced the notion of specific energy, that is to say the energy absorbed per unit of mass. They concluded that the specific energy absorption capacity is independent of the vehicles size but that the vehicles length had an effect on the mean deceleration level, with the two parameters being inversely proportional.

ACCOUNTING FOR AGGRESSIVITY IN A TEST PROCEDURE

A frontal impact test procedure aimed at evaluating the degree of protection given by a vehicle has to be able to take the main injury mechanisms into consideration. The most frequently known mechanisms are deceleration and passenger space deformation, or in other terms, intrusion. The evaluation of a vehicle is firstly aimed at analysing the protection of the vehicles occupants. It is here a question of directly analysing the impact test results. However in the global safety optic, we consider it is very important to be concerned about the consequences of the accident on the occupants of the antagonistic vehicle when it concerns a frontal impact between two vehicles. The evaluation test procedures carried out in laboratories generally involve a test against a fixed obstacle. The external aggressivity of the tested vehicle is in this case estimated as a function of what can be observed on the obstacle. It can be a matter of recording the forces, in the case where the fixed obstacle is rigid, or forces associated to deformation measurements in the case of a deformable obstacle.

The forces measured on a dynamometric wall perpendicular to the vehicles trajectory showed that an analyse was necessary. G. Vallet (1994) showed that the forces produced by vehicles on the obstacle were not always symmetrical. It is therefore clear that the engine compartment's architecture can have an influence on the compatibility.

Further, we know that numerous evaluation tests were carried out using an asymmetric procedure, and that it concerned a general trend. In particular, the test procedure developed by the EEVC (1994) which is for regulatory purposes, imposes that the partial overlap is on the steering column side. The protection offered to the occupants and the vehicles aggressivity will be different depending on whether the steering column is left or right.

However, in this type of test procedure, it seems to us that the deformation of the obstacle can be an evaluation element of aggressivity. As an example, we observe on figure 3 the deformation of a honeycomb deformable element after the impact test of a vehicle with very stiff longitudinal beams. The obstacle is perforated. In contrary, there is no perforation of the deformable element after a crash test of a vehicle which deformed in a more uniform way (figure4). This comparison let us think that, a priori, monitoting the deformation shape can give informations about the aggressivity of the tested vehicle. A methodology based on this kind of analysis must be developped.

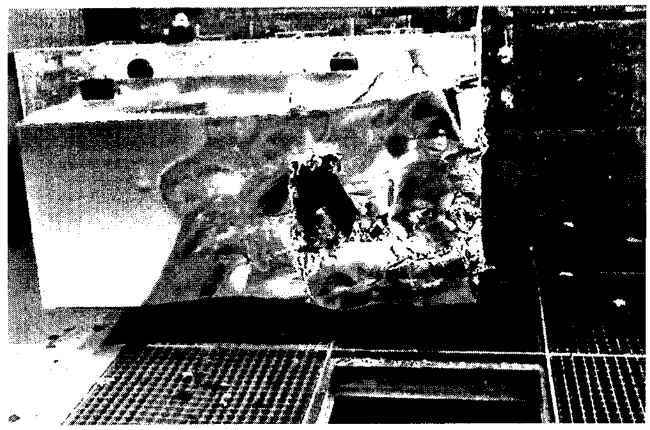

Figure 3. Deformable fixed obstacle after a crash test of a car with rigid longitudinal beams

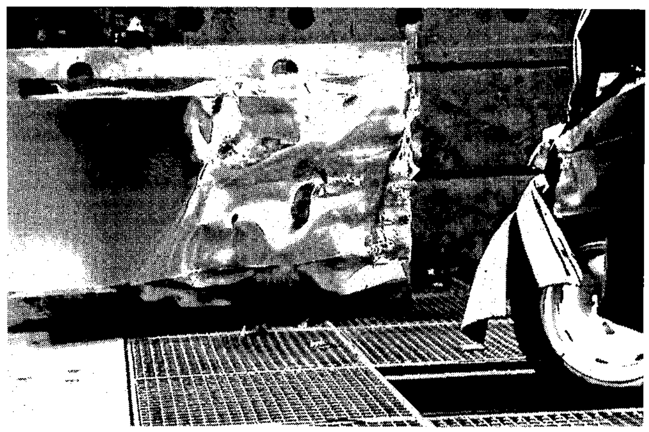

Figure 4. Deformable fixed obstacle after a crash test of a car with with uniform collapse

CONCLUSION

We have seen that the notion of compatibility is one which has still to be defined, to the extent where the indicators are not yet clearly determined. Numerous parameters such as, mass, power, geometry, architecture and vehicle rigidity have to be taken into account. The analysis is even more difficult since these parameters are generally inter-dependant. In evaluating the protection level offered by a vehicle in a crash, we would stress the need for taking the internal protection as well as the aggressivity into account vis à vis the occupants of the antagonistic vehicle. If this evaluation is subjected to a impact test procedure we estimate that it is important to evaluate the consequences that a special test procedure can have on the vehicle's design. Indeed, it would be regrettable if a test procedure encouraged manufacturers to design vehicles which, by improving internal protection would become more aggressive for other users. We think an offset impact test procedure against a deformable obstacle, such as the one developped by EEVC, can take into account this notion of compatibility if the analysis of the deformable element is considered.

ACKNOWLEDGEMENTS

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Assessment of the Safety of Automobiles

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Paper No. 94 S4 O 16

ABSTRACT

A means of assessing the passive safety of automobiles is a desirable instrument for legislative bodies, the automobile industry , and the consumer. As opposed to the dominating motor vehicle assessment criteria, such as engine power, spaciousness, aerodynamics and consumption, there are no clear and generally accepted criteria for assessing the passive safety of cars.

The proposed method of assessment combines the results of experimental safety tests, carried out according to existing legally prescribed or currently discussed testing conditions, and a biomechanical validation of the loading values determined in the test.

This evaluation is carried out with the aid of risk functions which are specified for individual parts of the body by correlating the results of accident analysis with those obtained by computer simulation.

The degree of conformance to the respective protection criterion thus deduced is then weighted with factors which take into account the frequency of occurrence and the severity of the accident on the basis of resulting costs.

Each of the test series includes at least two frontal and one lateral crash test against a deformable barrier, as well as one lateral crash test between two vehicles of the type being tested, thus taking into account both self-protection and protection of the other involved party.

The computer-aided analysis and evaluation of the simulation results enables a vehicle-specific overall safety index as well as partial and individual safety values to be determined and plotted graphically.

The passive safety provided by the respective vehicle under test can be defined for specific seating positions, special types of accident, or for individual endangered parts of the body.

INTRODUCTION

In the frame of the research project "Quantification of Passive Safety of Passenger Car Occupants" on behalf of the Bundesanstalt für Straßenwesen (German Federal Road Research Institute), a procedure has been developed, that investigates and assesses the safety of passenger cars on the basis of accident analysis, statistical biomechanics, and crash tests.

In several expert meetings this procedure has been introduced and developed. Main points of discussion have been the proposed compatibility test and introduction of an offset test.

In many publications, the offset test has been placed in the foreground of the currently performed crash tests. So, in one expert meeting on the assessment method introduced here, it was decided to integrate that test into the procedure.

By introduction of the 50%-offset-test, the procedure comprises four different crash tests:

- Frontal crash according to FMVSS 208 (testing restraint systems)
- 50%-offset-test, frontal, 50 km/h (testing vehicle front structure)
- Side impact according to EEVC-proposal with moving deformable barrier (testing restraint systems as well as vehicle structure)
- Vehicle-to-vehicle crash test (testing compatibility and self-compatibility)

TEST PROCEDURE FOR ASSESSMENT OF PASSIVE SAFETY OF PASSENGER CARS

The newly developed assessment technique tries to combine the methods used so far [2, 3, 4, 5, 6, 7, 8] and provides for inclusion of biomechanics of occupants as well as economic consequences in an experimental-analytical procedure.

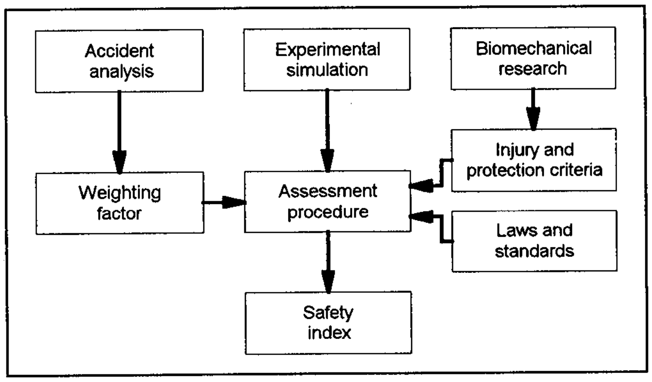


Figure 1: Assessment method

Accident Analysis

The main task had to be solved by the accident analysis, based on the data material [9] of the Medizinische Hochschule Hannover (MHH; Medical Highschool Hannover):

- Provision of input data for numerical simulation.
- On the basis of the material of the accident research unit of MHH, an accident data set has been ascertained, that is used as an input data set for numerical simulation. With this accident data set, in computer simulations assessment functions are established.
- Ascertainment of distribution functions of different parts of the body in order to deduce assessment functions [10, 11]. Numerically evaluated functional relations between accident characteristics and load factor on the one hand and distribution functions of injury severity on the other hand are correlated. Correlation is made according to the EAC-method [12], where the result is made mathematically describable by statistic means.
- Determination of relevance factors for weighting measurements at different parts of the body. Relevance factors are used to compare measurements one to another on the basis of injury costs.

Experimental Simulation

When establishing test procedures for the experimental part of the assessment, it was proceeded from the compulsory homologation test according to FMVSS 208 (a frontal impact against a rigid barrier) [13], an offset test with 50% overlap, and the proposal for a European side impact test with a moving deformable barrier [14]. These three tests serve as a judgement of self- protection.

Partner-protection is paid regard to by an additional side impact test with two vehicles of the type to be examined.

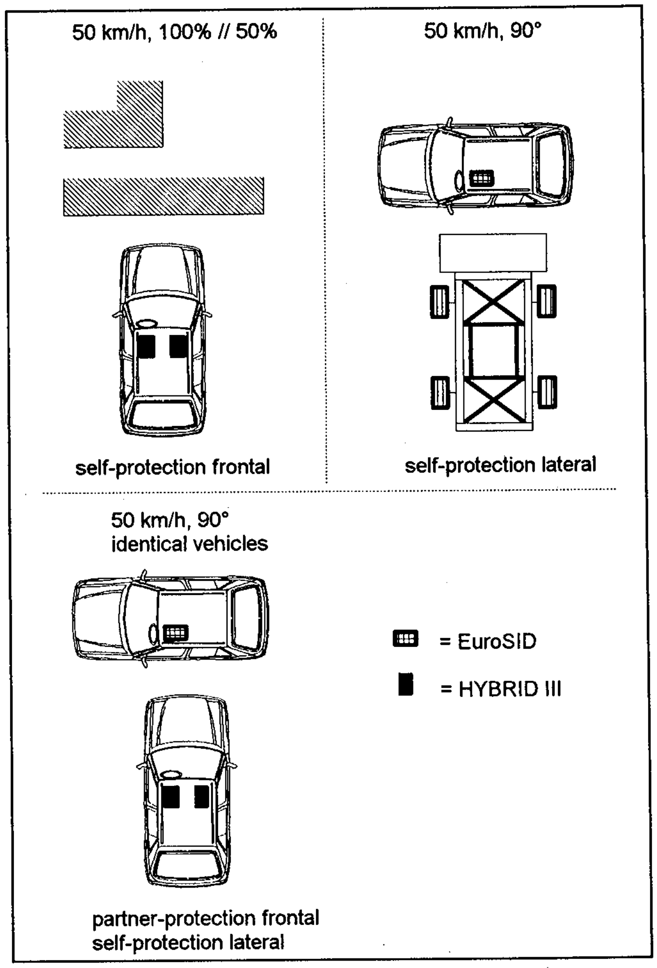


Figure 2: Test-procedure

Instrumentation and loading correspond to FMVSS 208 and the European proposal for a side impact test. Test speeds for all tests are 50 km/h under an angle of 0° and 90°, respectively.

<u>Test Conditions</u> -The following conditions were laid down:

Table 1
Frontal crash according to FMVSS 208

Collision object	rigid barrier
Impact speed	50 km/h
Impact angle	0°
Overlap	100%
Loading	Hybrid III on driver's and passenger's seat

Table2
50%-offset test

Collision object	rigid barrier
Impact speed	50 km/h
Impact angle	0°
Overlap	50%
Loading	Hybrid III on driver's and passenger's seat

Table 3
Side impact according to EEVC-proposal

Collision object	moving deformable barrier (EEVC)
Impact speed	50 -2 km/h
Impact angle	90° left
Impact point	seat reference point
Loading	EuroSID on driver's seat

Table 4
Compatibility test (car-to-car test)

Collision object	test vehicle
Impact speed	50 km/h
Impact angle	90° left
Impact point	seat reference point
Loading of struck vehicle	EuroSID on driver's seat
Loading of striking vehicle	Hybrid III on driver's and passenger's seat

<u>**Measurements and Protection Criteria**</u> - Type and position of transducers are in accordance with the customary equipment used with the respective proposed dummies.

For valuation of intrusion into the foot well, use of 5-axial transducers in the lower leg is recommended.

Table 5
Side impact
Transducers in dummy type EuroSID

Body part	Type of measurement	Protection criterion
Head	acceleration 3-axial	HPC 1000
Thorax	deformation and deformation speed	VC 1 [m/s]
Thorax	deformation of ribs	42 [mm]
Abdomen	force 3-axial	$\Sigma F_{Abd.}$ 2,5 [kN]
Pelvis	force in symphysis	$F_{symp.}$ 10 [kN]

Table 6
Frontal crash
Transducers in dummy type Hybrid III

Body part	Type of measurement	Protection criterion
Head	acceleration 3-axial	HIC_{36} 1000
Head	acceleration 3-axial	a_{3ms} 80 [g]
Thorax	acceleration 3-axial	a_{3ms} 60 [g]
Thorax	acceleration 3-axial	a_{3ms} 60 [g]
Upper leg	longitudinal force	F_{max} 10 [kN]
Lower leg	force X	F_{max} 2 [kN]
Lower leg	force Y	F_{max} 2 [kN]
Lower leg	force Z	F_{max} 10 [kN]
Lower leg	moment X	M_{max} 100 [kN]
Lower leg	moment Y	M_{max} 100 [kN]

Rule of Procedure

A finite number of safety tests is necessary to achieve statistically secured test results. However, only one single test is assigned for tests of homologation and type approval, so, the measured value will deviate from the true value with a certain degree of probability.

In order to reduce test expenditures, a rule of procedure takes this into account.

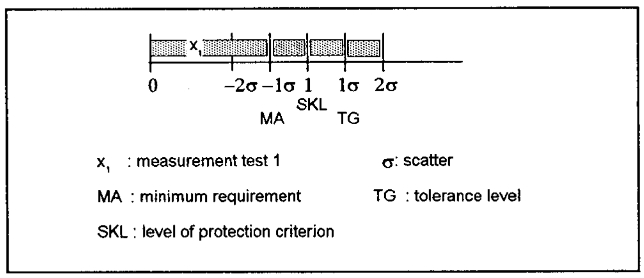


Figure 3: Rule of procedure

The rule includes the definition of a minimum requirement

MA = protection criterion - measurement scatter

and an upper tolerance level

TG = protection criterion + measurement scatter

The relation of the respective loading to these quantities determines whether the values are accepted for assessment, whether one further repeat test with assessment of the mean values is required, or whether the results are excluded from the assessment procedure.

Determination of Assessment Functions

The measurements obtained from a minimum of three or a maximum of six integral safety test, can now be proceeded for assessment.

The physical loading values are first related to the protection criterion, which is the tolerance level of the respective body part. These normalized values are input data to the body part related assessment functions [1].

By combining accident analysis results with those of computer simulation, these functions represent a relationship between the real accident damage and the experimentally deduced loading values.

In the statistical evaluation (figure 4), the severity of the injuries, coded according to the AIS, are plotted for frontal and for lateral collisions (figures 5 and 6) as functions of the equivalent accident characteristics [10, 15], analogous to the values measured by the transducers in the head, thorax, ribs pelvis, and thighs of the dummy.

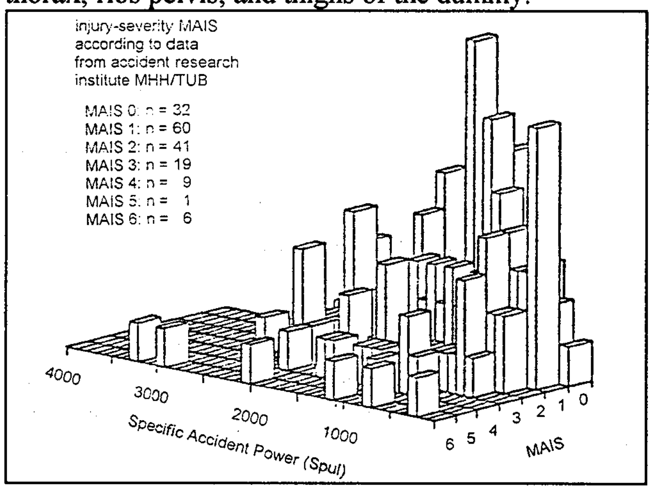


Figure 4: Real distribution of overall injury severity MAIS

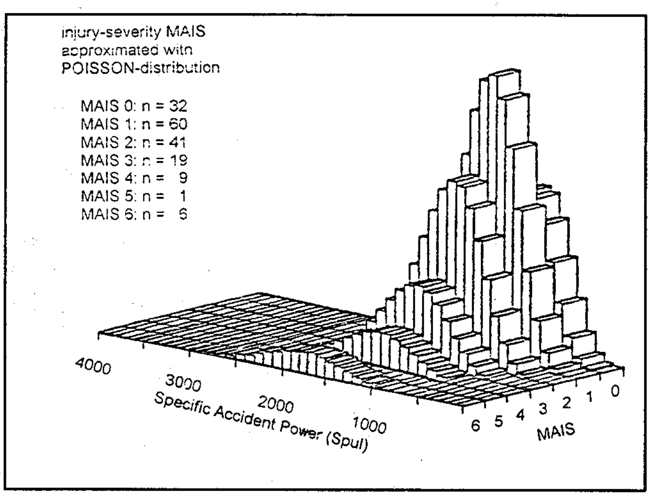


Figure 5: Approximated distribution of overall injury severity MAIS

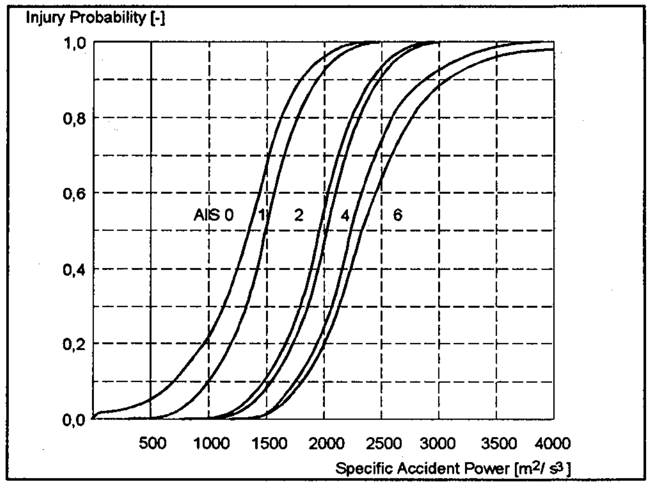


Figure 6: Injury probability of the head (AIS injury scale)

As a result, a distribution function is obtained for the probability of reversible or irreversible injuries to each part of the body in frontal or lateral application of load (figure 7).

The results of this statistical evaluation of real accidents are utilized to determine boundary values as input data for computer simulation, which are to ensure a uniform distribution and to specify the required number of simulation passes.

The physical occupant loading quantities deduced from the equivalent accident characteristics by using occupant simulation models can be correlated to the statistical evaluations. By eliminating the equivalent accident characteristics, which are common to the models, a direct relationship between the loading and the severity of the injuries is established.

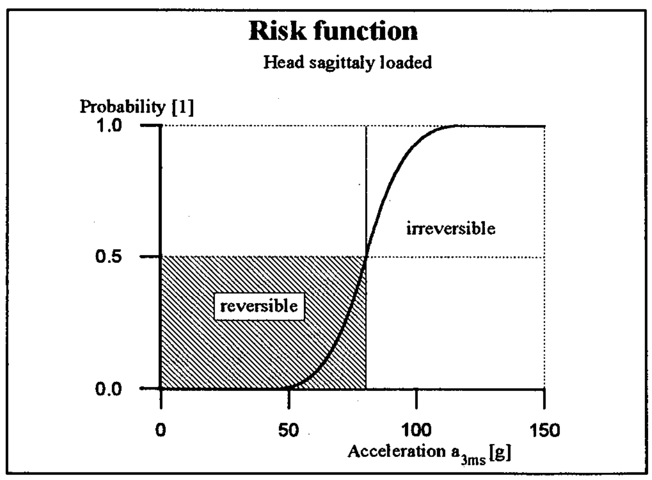


Figure 7: Risk function for occupant loading

Assessment

The assessment function, the central element of the proposed algorithm, provides the ability to carry out a continuous validation of the test results, i.e. the normalized individual measured value is assessed below the protection criterion level within the range defined by the risk function. This degree of compliance with the respective criterion is calculated for every measured value and is weighted with the corresponding relevance factors (figure 8).

The transformation of this method into a computer program [16] enables calculation of both an overall safety index for the whole vehicle and of partial safety indices for the passive safety of the vehicle under test in frontal or lateral collisions. Also, safety values related to seat position and body parts can be established (figure 10).

The areas of safety assessment described before can be expressed in the following formal relation (figure 9).

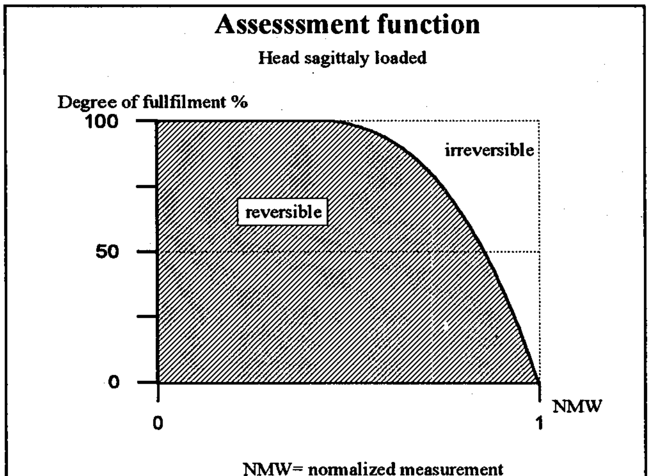


Figure 8: Assessment function

$$\text{Safety index} = \sum_{k=1}^{n}\sum_{j=1}^{m}\sum_{i=1}^{l} RF_{ijk}\left[f_i\left(\frac{MW_i}{SK_i}\right)\right]_{jk}$$

i : point of measurement
j : seating position
k : single test
RF : relevance factor
SK : protection criterion
SK : protection criterion

Figure 9: Algorithm for safety assessment [16]

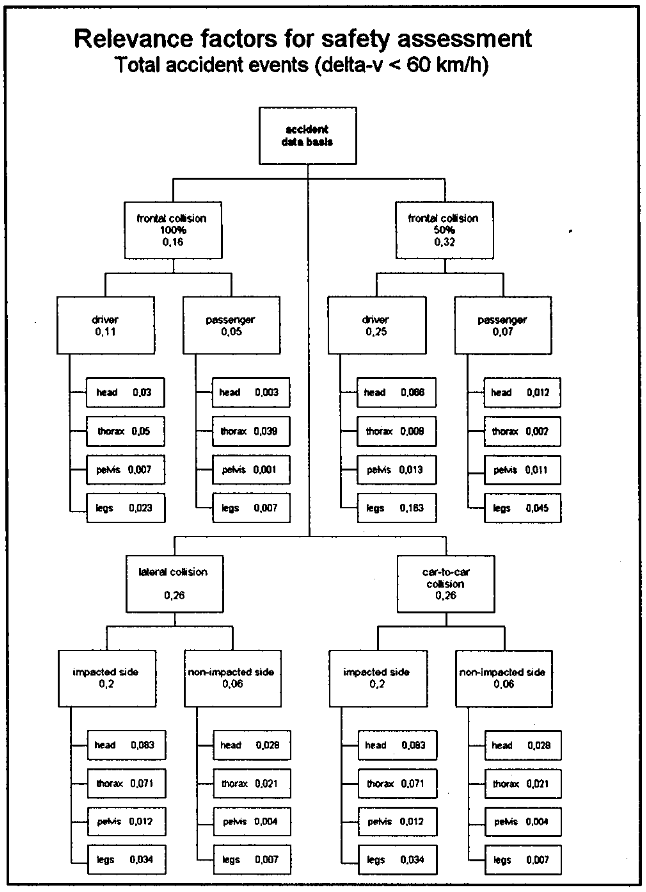


Figure 10: Structure of relevance factors

SUMMARY AND OUTLOOK

Within the scope of this work, the assessment method "Quantification of Passive Safety of Passenger Car Occupants" was extended by a 50%-offset test. Specifications of this test have been set up in the frame of an expert meeting [17]. The procedure was extended by the following items:

- Provision of test conditions for the offset test,
- provision of measurement points, protection criteria and matching assessment functions,
- provision of a new relevance structure according to the extension of the test procedure,
- adjustment of the assessment program BEWAL to the before mentioned changes.

A proposal was developed, which, among other points, includes loading of the lower extremities of the dummy as a means of judging the intrusion behaviour in the foot well. This proposal comprises a 5-axial measurement of the lower legs and an acceleration measurement of the feet.

In the validation phase of the assessment method it should be investigated, if these criteria are capable of describing loads of the occupants. Also the connection of intrusion, accelerations measured at the feet and forces lead into the lower legs has to be investigated with respect to time. Whether these criteria can be a first step of assessment, will then be discussed again.

Special attention was given to the assessment of compatibility by means of a car-to-car test. It has to be investigated, if a less expensive test constellation possibly could give a more complete assessment of the compatibility of passenger cars.

This complete assessment comprises passenger cars only, partner protection of the other exterior road users is not included in this procedure.

A possible test set-up is shown in figure 11.

Physical boundary conditions like

- collision speed,
- stiffness of barrier,
- length of barrier at primary impact,
- length of barrier at secondary impact,
- definition of step depth

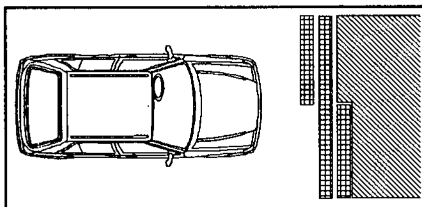
as well as the behaviour of vehicles of different weight, different front structures and driving concepts are investigated by means of an FEM model with the case "impact against a non-moving deformable barrier".

Set-up of such a procedure is currently being investigated at ISS Fahrzeugtechnik (Automotive Engineering), first test have been performed [18].

It will be analysed, whether statements can be made about aggressivity of mass and stiffness of the vehicle as a whole as well as about the aggressivity of members of the front structure, deduced from the deformation characteristic.

It seems possible, that such a test procedure could substitute 0°-test and offset test as well as car-to-car test under the premise of realistic test conditions.

Check quantities are results of frontal tests (0°-test and offset test).



Characteristic:
Barrier: fixed,deformable stepped barrier
Collision speed: V_{koll}>> 50 km/h
Overlap 40%-50% // 100%

Aim of the test:
Investigation of self- and partner-protection

Dummies:
2 HYBRID III-dummies (driver and passenger)

Measurement points on the dummy:
Head, thorax, pelvis, upper leg
(and contact force of the feet)

Measurement points on the vehicle:
Vehicle acceleration in the center of gravity

Deformation behavior:
Vehicle : static deformation before and after crash
Barrier : Determination of proportionate deformation energy
Determination of mean deformation length
Determination of maximum deformation length

Assessment quantities:
self-protection : measurements of the dummy
partner-protection : vehicle deceleration and deformation behavior of vehicle and barrier

Figure 11:Safety test for evaluation of self- and partner-protection

In this way, the procedure can be optimized concerning the number of necessary crash test and the incidental costs of tests and vehicles.

Measurement of forces induced into the rigid barrier with a platform of force transducers was investigated too, but the deformation behaviour of the front structure becomes unrealistic [19].

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How Safe Can Lightweight Cars Be? An Analytical Study of the Limits of Passive Safety

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94-S4-O-17

Abstract

Growing environmental awareness and the desire to preserve fossil fuels have in the recent past led some automobile manufacturers and a couple of small development teams to consider whether this goal can be achieved through, amongst other things, extremely small and light vehicles.

Because of the low weight, the problem of compatibility - i. e. the affect of a collision with a larger vehicle - becomes particularly acute. Furthermore, the requirement that such vehicles be built as compact as possible contradicts the desire to include conventional deformation zones in the design.

Thus the question arises whether such vehicle should be consciously built with lower standards of passive safety or what expense would be necessary to at least partially compensate these physical handicaps. It has been shown that through consequent application of a sieries of complementary measures, and by using the total physically available space, a thoroughly respectable safety potential can be achieved for small vehicles. However, decreased deformation length of smaller vehicles increases the deformation forces and thus the mass of the vehicle. Therefore extremely short vehicles are not necessarily light vehicles.

1. Introduction

As Fig. 1 shows, the development process of a car is characterized by the necessity of taking into consideration a variety of requirements. As a number of these requirements are self-contradictory, it is necessary to accept compromises which, depending on the manufacturer's philosophy and market segment, may result in very different vehicles.

The question which is posed in this connection in a particular way is whether extreme lightweight design has to be paid for with unacceptable reductions in respect of passive safety.

2. Accident statistics

If the risk of being killed in a vehicle is looked at globally, we generally find a trend which reveals a risk which is all the higher the smaller the mass of the vehicle in question (Fig. 2). This correlation is not unavoidable as the relatively large spread shows. What speaks in favour of the trend, though, is that a major share of persons killed is attributable to vehicle/vehicle accidents. There are physical reasons here which explain why the occupants of smaller cars are at a disadvantage.

Fig. 3 shows that in a collision of a vehicle against a fixed wall there is a clear correlation between the deceleration and the deformation length available (Fig. 3, left-hand side). If the deformation lengths available are equally large, equally large decelerations and thus identical occupant loads are attainable - irrespective of the vehicle mass. If the decelerations are identical, the relevant structural force is then, however, proportional to the mass of the vehicle in question.

If two vehicles of differing mass now collide with each other, the theorem of momentum states that the changes in velocity and thus also the decelerations are in the reverse ratio to the masses of the vehicles involved. In the simplified example (rectangular characteristic lines) of Fig. 3, the small vehicle was braked initially with a deceleration which corresponds to that of its own impact against the wall. If the entire deformation zone of the small vehicle is used up, the deformation of the large vehicle begins only now with a deceleration which corresponds to its impact against the wall. For the small vehicle, this phase means an increase in deceleration in the extent of the reversed mass ratio. Only a high structural strength and a particular engineering design effort in respect of the restraint system are now able to offer protection to the occupants.

This physical state of affairs is the main reason for the trend shown in Fig. 2. Small vehicles "protect" the occupants of large vehicles as a consequence of their low mass aggressiveness. If small vehicles were to disappear from the roads and be replaced by heavy vehicles, they would not only be able to protect their own occupants to a greater extent but would, at the same time, injure the occupants of the "previous" large vehicles to a greater extent than before [1, 2].

Such a trend would, of course, be highly undesirable. We can, of course, reverse this argument and demand emphatically that the previously "large" vehicles become lighter in weight in order to produce a better mass compatibility.

If we leave aside at the moment the idea of compatibility between vehicles of differing weight and concentrate our attention on the focal points of injuries from the aspect of an individual vehicle, the situation which we obtain is that shown in Fig. 4.

More than 90% of persons injured in accidents sustain their injuries in collisions in which the vehicle in question suffered an impact in the front or side area. If we analyse only the number of all accidents, rear-end collisions are very frequently represented. The share of rear-end collisions, however, is reduced to 10% if we consider only accidents in which persons suffer injury. The reflections which are presented below are therefore restricted to front and side collisions.

3. Frontal collisions

The criteria which are usual for determining the load to which occupants are subjected are all attributable, directly or indirectly, to the deceleration level with which the speed is reduced. For a fully plastic impact, the deceleration level of the occupant at a given collision velocity v_0 is dependent solely on the deceleration distance s_{tot} in accordance with the equation

$$a = \frac{v_0^2}{2s_{tot}} \qquad 3.1$$

The deceleration distance s_{tot} in this case is the entire stopping distance. It is composed of the deformation length of the vehicle as well as the forward displacement of the occupant relative to the vehicle.

Let it be assumed that the absolute upper limit of sustainable accelerations were to be 60 g. This is the limit which, for example, the US Safety Standard FMVSS 208 (vehicle collision against a rigid wall at a speed of about 50 km/h) requires to be observed for chest deceleration. Were it also possible to maintain this deceleration for the head, this would result in the limit of HIC = 1000 for the time interval 36 ms. In this case, the required deceleration distance would just be 0.16 m. This would be a fantastic value. The available forward displacement distance alone would be adequate to achieve this deceleration level.

A closer look clearly reveals, however, that this value is unattainable. Alone the slightest turn of the head would result in the HIC value immediately rising beyond the limit of 1000.

The question which is thus posed is where are the limits of the required vehicle deformation length if all the possibilities of modern restraint systems are utilized. A study [3] was conducted for this purpose with the aim of obtaining an answer on the basis of simulation calculations with realistic assumptions.

The question to be investigated was whether it is possible to maintain the limits as laid down in FMVSS 208 with a vehicle deformation of only 200 mm and a wall impact velocity of 50 km/h. A prerequisite in this connection was the integrity of the passenger cell.

The parameters available were:

1. Position of the upper anchorage point in x direction
2. Seat belt strain (8%/14%/22%)
3. Seat belt slack (none/25 mm for shoulder and lap belt)
4. Seat belt grabber (yes/no)
5. Airbag type (Eurobag 35 ltr./US airbag 63 ltr.)
6. Triggering time of airbag (6 ms/10 ms/14 ms)
7. Airbag permeability (2x18 mm/2x25 mm/2x30 mm)
8. Seat belt tensioner (yes/no)
9. Seat belt buckle tensioner with force limiter (yes/no)
10. Knee bar (yes/no)
11. Deformability of steering cross member (yes/no)
12. Procon function (retraction of steering wheel, 80 mm)

It proved possible to find a "best" solution for the restraint system by simulating several thousand parameter combinations. This solution is characterized by the load values

HIC value: 603

a_{chest} (3 ms): 52 g

with the parameter constellation:

1. Position of the upper anchorage point: as B-pillar
2. Seat belt strain: 22%
3. Seat belt slack: none
4. Seat belt grabber: yes
5. Airbag type: Eurobag 35 ltr.
6. Triggering point of airbag: 6 ms
7. Airbag permeability: 2x30 mm
8. Seat belt tensioner: yes
9. Seat belt buckle tensioner with force limiter: yes
10. Knee bar: yes
11. Deformability of steering cross member: yes
12. Procon function: retraction of steering wheel, 80 mm

The result, for a deformation length of only 200 mm, can be regarded as remarkable. From the variety and the nature of the measures, it is clear however that, all in all, considerable engineering design effort would have to be pursued in respect of the restraint system.

Of particular interest is a sensitivity analysis of the test result. In this case, individual parameters were modified and the effects on the result presented (Fig. 5). We can see that the seat belt characteristic has a considerable influence both on the HIC value as well as on the chest deceleration. All the other parameters reveal only a slight influence on chest deceleration. The HIC value honours in particular an energy-absorbing support of the legs at a knee bar as well as a harmonized airbag permeability.

The acceleration pulse of the vehicle used in this case assumed a high degree of plastic deformation. The sections which follow look at the influence which plastic and elastic deformation behaviour exert on occupant load. Fig. 6 shows a comparison. The left-hand side presents an ideal plastic behaviour, and the right-hand side an ideal elastic behaviour. In both cases, a linear correlation between force and deformation length is assumed up to maximum deformation. In the case of the plastic deformation, the deformation force drops to zero after reaching its maximum, without any spring-back, while, in the ideally elastic case, the force runs back along the same straight line along which it had risen in the compression phase.

It was again assumed as a simplification that the load to which the occupant is subjected is characterized by the level of the constant deceleration which has to be exerted in order that the velocity of the occupant is adjusted to the velocity of the car at the end of the crash - without any impact within the available forward displacement distance Δs_{max}.

The diagrams show that both processes proceed completely identically up to maximum vehicle deceleration. In the plastic case, the vehicle at this moment has also already come to a final stop. The differential velocity Δv is in total just identical to the impact velocity. In the elastic case, the vehicle rebounds with a velocity which, in terms of the amount, is equal to the impact velocity. The total velocity change Δv is now therefore twice as high. As, in both cases, only the identical maximum forward displacement distance Δs_{max} is available, the occupant deceleration must be higher in order to avoid an impact.

The "Malus" for the occupants in the case of elastic vehicle deformation is all the greater, the smaller the deformation length of the vehicle is (Fig. 7). In the case in question - a deformation length of 200 mm - the ratio is already more than twice as high. In the absence of a deformation length, the ratio increases four-fold. Unfortunately, many an extreme lightweight vehicle tends to a more elastic deformation behaviour.

If one, therefore, attempts to achieve as plastic a deformation behaviour of the vehicle as possible and pursues the high engineering effort described in respect of the restraint system, computer studies at least reveal that, in a collision against a wall at 50 km/h, adequate safety for the occupants appears not completely impossible with a deformation length of only 200 mm. It is clear that high structural forces have to be sustained in the case of such a stiff vehicle (Fig. 8).

On the other hand, the high structural forces would also offer certain benefits. They would improve the compatibility with larger vehicles if these are designed for greater deformation lengths.

Having this aspect in mind it can be stated, that according to computer simulation extremely short vehicles can comply with FMVSS 208. However a "minimal size" design is not necessarily also a lightweight design.

In a study investigating into the influencing parameters on lightweight design a trend was shown for cars based on steel technology (Fig. 9). This trend indicates that for the sake of light weight the optimal length of the frontal deformation structure should be rather in the range of 500 mm than of 200 mm.

Since it was planned to demonstrate the applicability of the computer optimization results it was decided to provide 300 mm of vehicle deformation length instead of 200 mm. On the other hand compliance with frontal NCAP testing was also desired. Therefore the impact speed had to be increased from 50 km/h to 56 km/h (35 mph) which is still not as severe as the combination 50 km/h + 200 mm deformation length.

The results (Fig. 10) were obtained from a sled test with a deceleration pulse close to rectangular shape. Unfortunately due to disengagement of the rod potentiometer the chest deflection could not be measured. The corresponding value obtained from computer simulation is about 70 mm [4].

Having this draw back in mind it is obvious that all dummy loads meet FMVSS 208.

This result was achieved with the following restraint system provided by [4]:

- US type airbag with increased permeability
- belt with low strain
- belt pretensioner with belt force limiter
- lap belt force limiter

In summary: extremely short vehicles which have to meet high safety standards for frontal impacts are likely to have more mass and also tend to be more expensive than mass optimized vehicles.

4. Side collisions

In contrast to a frontal crash, it is no longer possible to proceed from the integrity of the passenger compartment in the case of a side impact. A number of estimations have been conducted on the basis of the American Side Test FMVSS 214 in order to be able to investigate the effect of the vehicle mass m_V on occupant safety in the event of a side impact. In this test, a barrier with a mass m_B of 1368 kg impacts in a "crabbed" movement with the side of the vehicle under study. The lateral velocity component is v_B = 48 km/h.

If, in a first approximation, we assume a fully plastic impact, the common velocity u of barrier and vehicle after the impact is

$$u = \frac{m_B}{m_B + m_V} v_B \qquad 4.1$$

The total converted deformation energy in a fully plastic impact is then

$$E_{Def} = \frac{1}{2} m_B v_B^2 - \frac{1}{2}(m_B + m_V)u^2$$
$$E_{Def} = \frac{1}{2} \frac{m_B m_V}{m_B + m_V} v_B^2 \qquad 4.2$$

The deformation energy is absorbed almost completely by the vehicle. The vehicle portion is about α = 0.95. The NHTSA barrier absorbs only some 5%. Hence, the energy absorbed by the vehicle is

$$E_V = \alpha \frac{1}{2} \frac{m_V m_B}{m_V + m_B} v_B^2 \qquad 4.3$$

The energy absorbed by the impacted vehicle is identical to the product from the mean deformation force and the maximum deformation length

$$E_{Def} = F_{mean}\, s_{\max} \qquad 4.4$$

The equation which then applies to the mean structural force is then

$$F_{mean} = \frac{1}{2} \frac{\alpha}{s_{\max}} \frac{m_V m_B}{m_V + m_B} v_B^2 \qquad 4.5$$

The mean structural force is a lower limit for the maximum structural force. Because of the rather degressive curve of the structural force over the deformation length, the maximum force of a triangular force-distance curve can be regarded as the upper limit. The upper limit is then just twice as great as the mean structural force.

$$F_{\max} = 2\, F_{mean} \qquad 4.6$$

A further point to note is that the test mass m_F does not correspond to the unladen mass, but in accordance with the formula

$$m_V = m_U + 2 * m_D + m_{PL} - n_S * m_{SU} \qquad 4.7$$

with

m_U	= Unladen mass	4.8
m_D	= Mass of dummy (75 kg)	
m_{PL}	= Payload	
n_S	= Number of seats	
m_{SU}	= Seat unit (68 kg)	

Fig. 11 shows the correlation between unladen mass and test mass for a number of vehicles, while Fig. 12 shows the maximum deformation. We can see that there is a trend to greater deformation as vehicle size increases. If we use the fitted straight line, the estimations which we obtain for the deformation forces are in accordance with the equations 4.5 and 4.6 (Fig. 13). A remarkable aspect here is the flat curve, i.e. the maximum deformation forces are approximately independent of the vehicle size. A plausible explanation for this is supplied by Fig. 14. This shows that, in the first moment of the barrier impact - in other words in the phase relevant for the occupant - the A-pillar of small vehicles contributes to a large extent to the support of the structure. In a number of cases, even the front axle plays a role.

The remarkable result which thus exists is that, with approximately identically large structural forces, smaller vehicles tend to suffer less deformation and thus display stiffer side structure characteristic curves.

When it comes to the load to which the occupant on the impact side is subjected, it is not alone the structure strength which is the decisive factor, however. Rather, occupant protection is determined to a considerable extent by the energy-absorbing properties of the impact area in the interior of the vehicle.

The theorem of momentum with the assumption of a concentrated mass for the vehicle is no longer adequate for estimating this influence. Fig. 15 shows a simple side impact model which provides for two individual masses each for the occupant and the vehicle.

The mass facing toward the barrier is identified with "door". It represents the part of the vehicle deformed by the collision, i.e. the door in the narrower sense as well as the adjoining parts. The "door" is connected to the remainder of the vehicle - in other words the undeformed main section - by the structure characteristic of the vehicle.

The occupant in this model is represented in a simplified form only by the upper part of the body. The entire mass is concentrated in the "ribs" as well as in the "spinal column". The data are based on those of US-SID. To simplify the presentation, the pelvis has been left out as we are only concerned here with a trend statement.

The padding characteristic is located between the door mass and the ribs. It describes the complete force-deflection curve as it is represented from the point of view of the occupant during the collision. This contains not only the energy absorption capacity of the door upholstery in the narrower sense, but also the structure compliance within the door.

The investigation now takes two vehicles with clearly different mass as an example of determining the influence which a vehicle size exerts on occupant load.

The two vehicles are characterized by the following masses:

	Large vehicle LV	Small vehicle SV
Unladen mass [kg]	1200	600
Test mass [kg]	1551	843
Door mass [kg]	36	18

The structure characteristics used are presented in Fig. 16.

In the case of the large vehicle LV, it was assumed that the clear distance between occupant and door is 100 mm, and that a linear correlation exists between contact force and deformation (Fig. 17a,). This results in a TTI value in conformity with FMVSS 214 at a level of 52 g as well as a VC value (formal use of the planned EEVC standard) of 0.81 m/s. Both load values are below the limits (85 and 90 for TTI and 1 for VC).

If the small vehicle is assigned the same padding characteristic as the large vehicle (with the sole restriction that a significantly smaller distance between occupant and door has to be assumed for small vehicles), this reveals that the occupant loads are only slightly higher. The clear mass and stiffness differences between LV and SV are thus scarcely noticeable.

It is unrealistic to assume, however, that it is possible to achieve in a small vehicle similarly large deformation lengths in the door padding/door structure area as in the large vehicle. Fig. 17b shows a deformation characteristic which, although it still has a linear curve, does not permit such a large deformation length. This is represented by a steep stop which prevents further energy absorption ("bottoming out"). The consequence is a sharp rise in the load values beyond the limits (TTI = 95 and VC = 1.24).

A solution to this problem is presented in Fig. 17c. As a result of a "more voluminous" deformation characteristic line, it is possible to absorb the energy within the available deformation length - without getting to the stop.

Such a characteristic line can only be achieved however by taking suitable measures not only in respect of the padding itself but also within the door.

5. Summary

This paper has shown that a small vehicle is afflicted from the outset with certain handicaps. These handicaps stem, on the one hand, from the smaller mass if it collides frontally with large vehicles and, on the other hand, from the smaller dimensions which make it difficult to provide deformation zones (free crash length in the case of a frontal crash or "padding depth" in the case of a side impact).

Mathematical studies have also revealed, however, that these problems should not be regarded from the outset as insoluble. The frontal impact can be sustainably structured by means of airbags, in conjunction with a soft seat belt and also a knee pad. The front structure itself should have as plastic a behaviour as possible.

It has been demonstrated that for small vehicles with reduced deformation length adequate safety can be achieved with high engineering effort. The then correspondingly increasing structural forces (in order to prevent collapse of the passenger compartment) would offer certain benefits. They would improve the compatibility with larger vehicles if these are designed for greater deformation lengths.

However higher structural forces of smaller vehicles in turn increase the mass of those vehicles. Therefore, extremely short vehicles are not necessarily lightweight vehicles.

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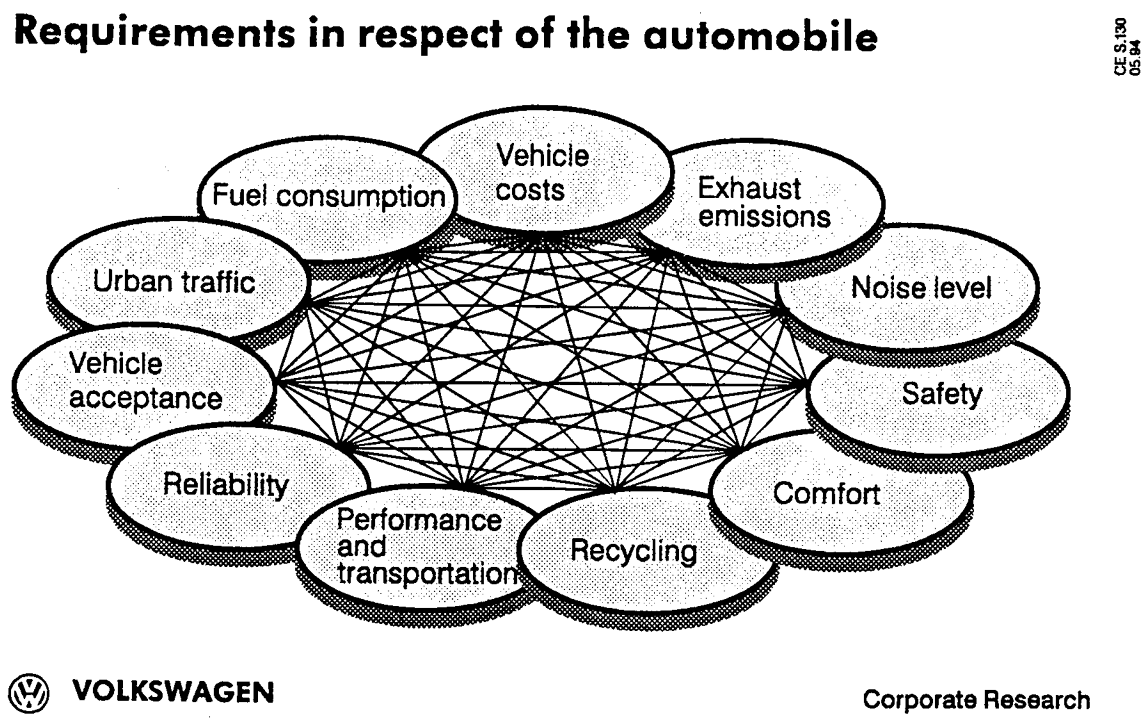


Fig. 1: Requirements in respect of the automobile

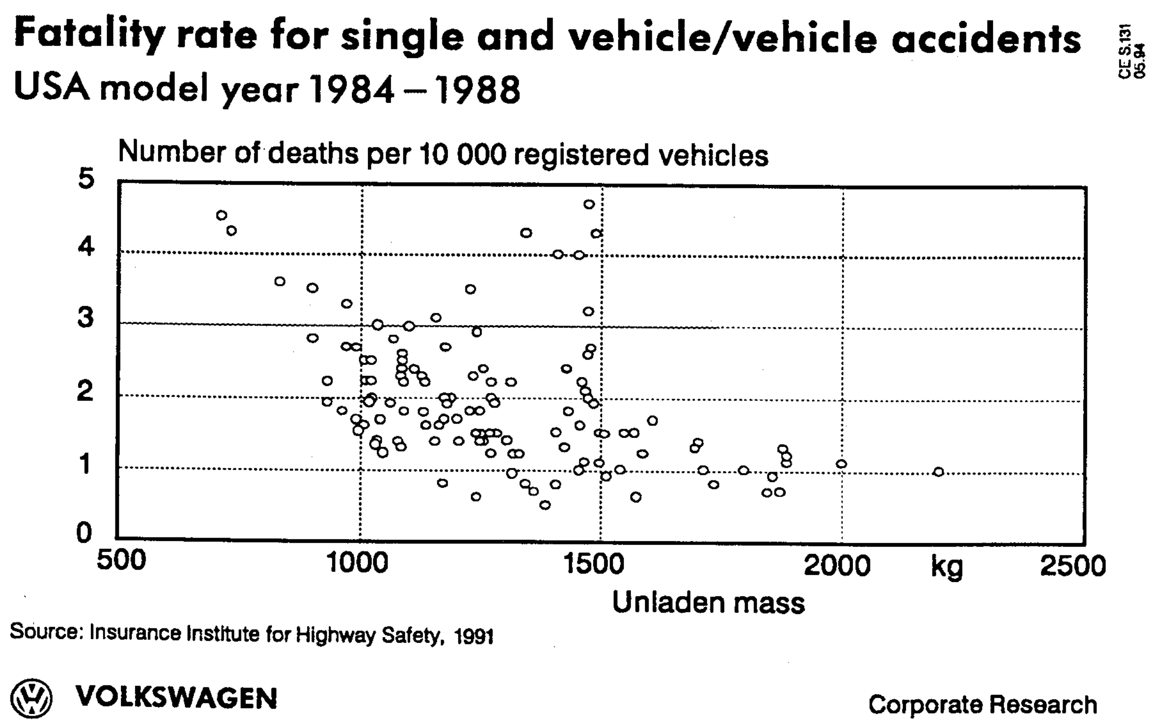


Fig. 2: Fatality rate for single and vehicle/vehicle accidents

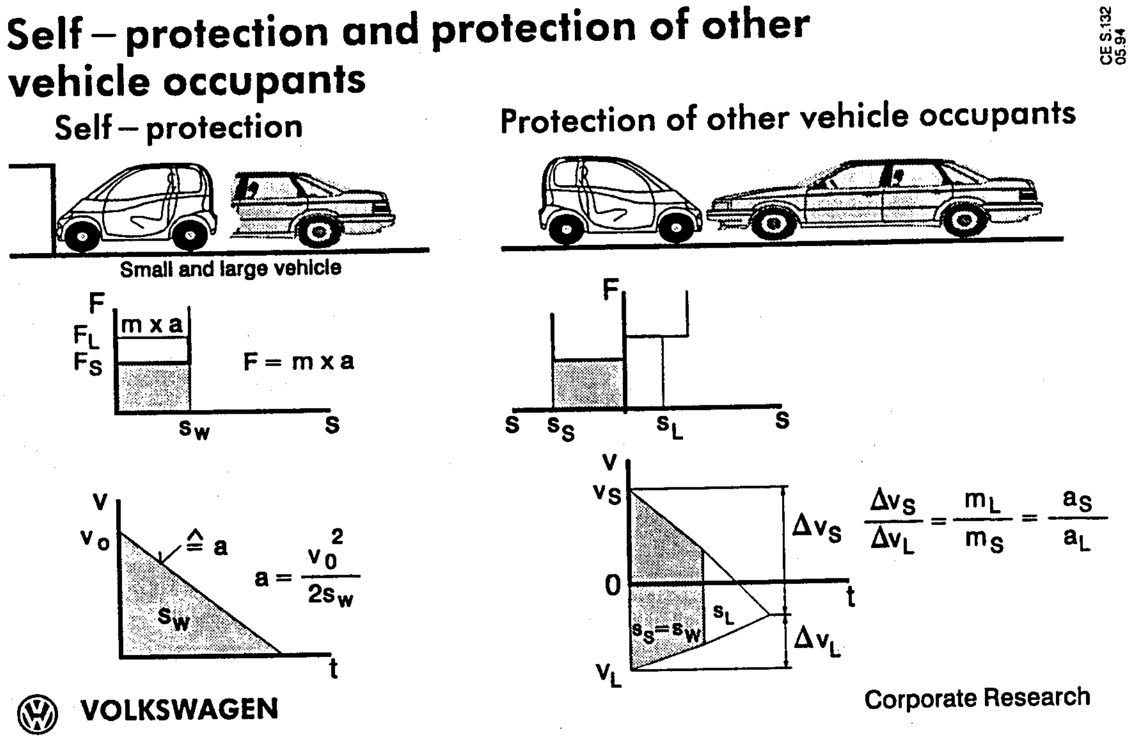


Fig. 3: Self-protection and protection of other vehicle occupants

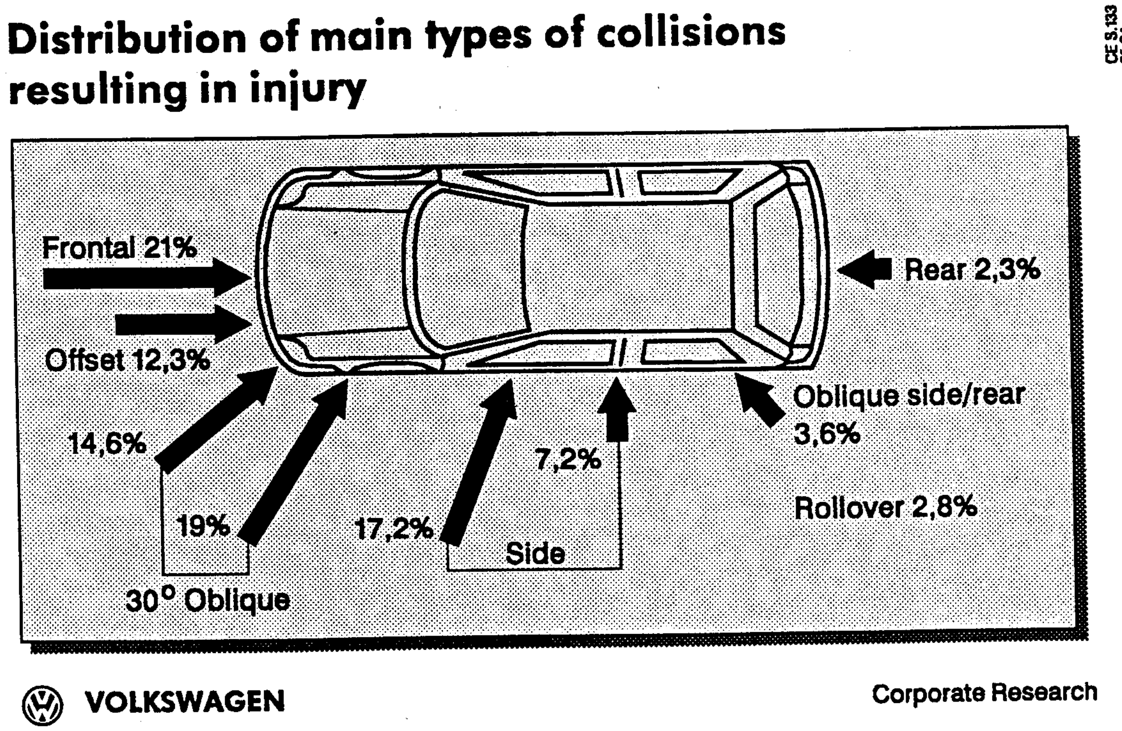
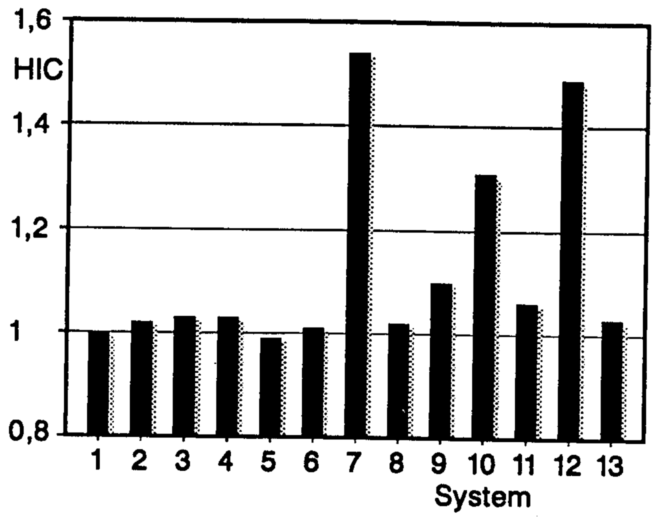


Fig. 4: Distribution of main types of collisions resulting in injury

Sensitivity analysis of the "best" restraint system

Sensitivity analysis of head load HIC

CE S.134 05.94



1 Best result (reference)
2 Without seat belt tensioner
3 Without seat belt buckle tensioner
4 Without Procon
5 Without seat belt grabber
6 Integral anchorage point
7 Seat belt strain 8% (< 22%)
8 Seat belt slack 50 mm (> 0 mm)
9 Infinite cross member stiffness
10 Minimum airbag permeability
11 US airbag
12 No knee bar
13 Triggering time 14ms (> 6 ms)

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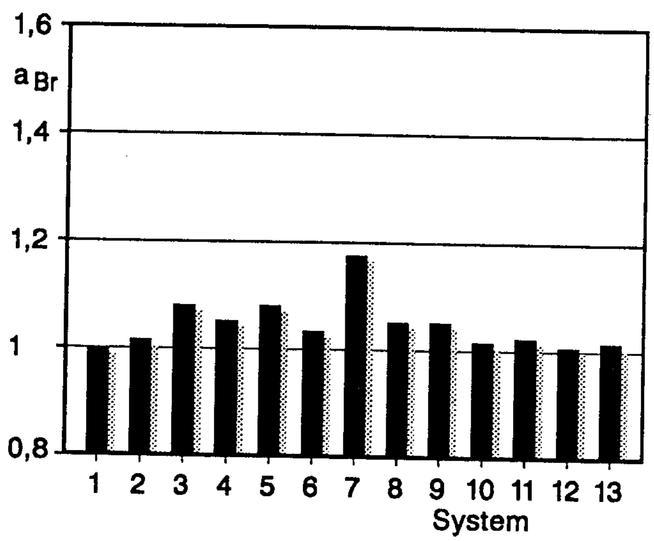
Sensitivity analysis of the "best" restraint system

Sensitivity analysis of chest load a_{Br}

CE S.135 05.94



1 Best result (reference)
2 Without seat belt tensioner
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5 Without seat belt grabber
6 Integral anchorage point
7 Seat belt strain 8% (< 22%)
8 Seat belt slack 50 mm (> 0 mm)
9 Infinite cross member stiffness
10 Minimum airbag permeability
11 US airbag
12 No knee bar
13 Triggering time 14 ms (> 6 ms)

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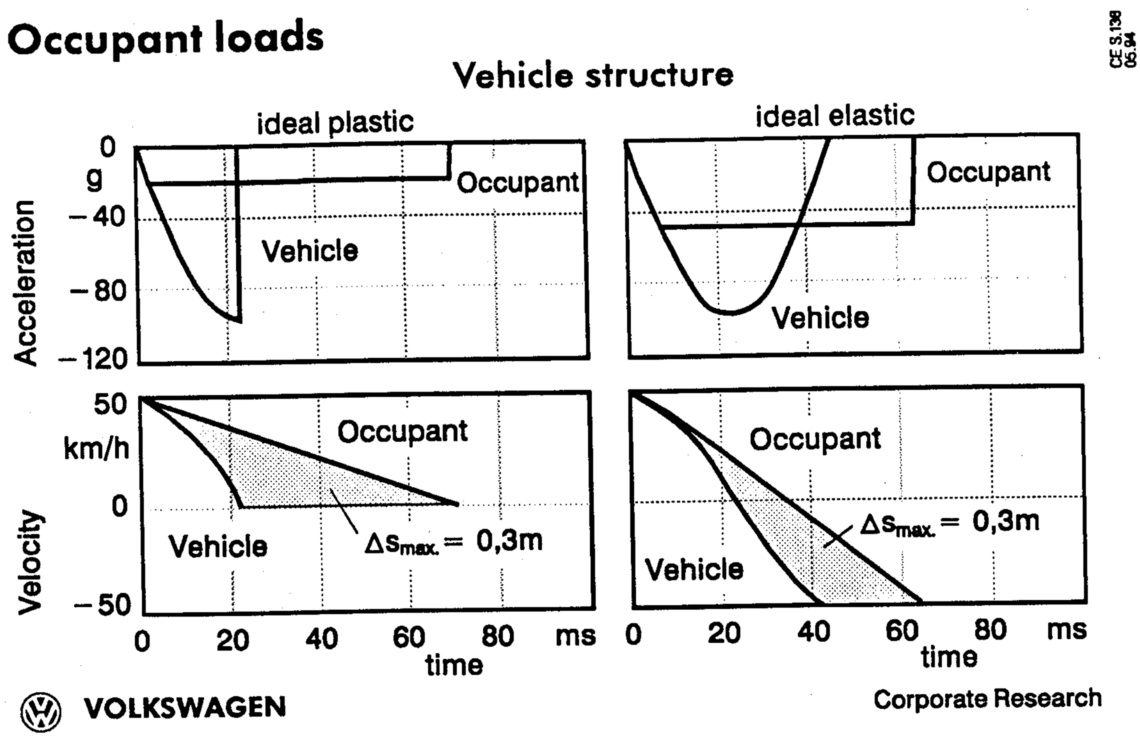
Fig. 5: Sensitivity analysis of the "best" restraint system



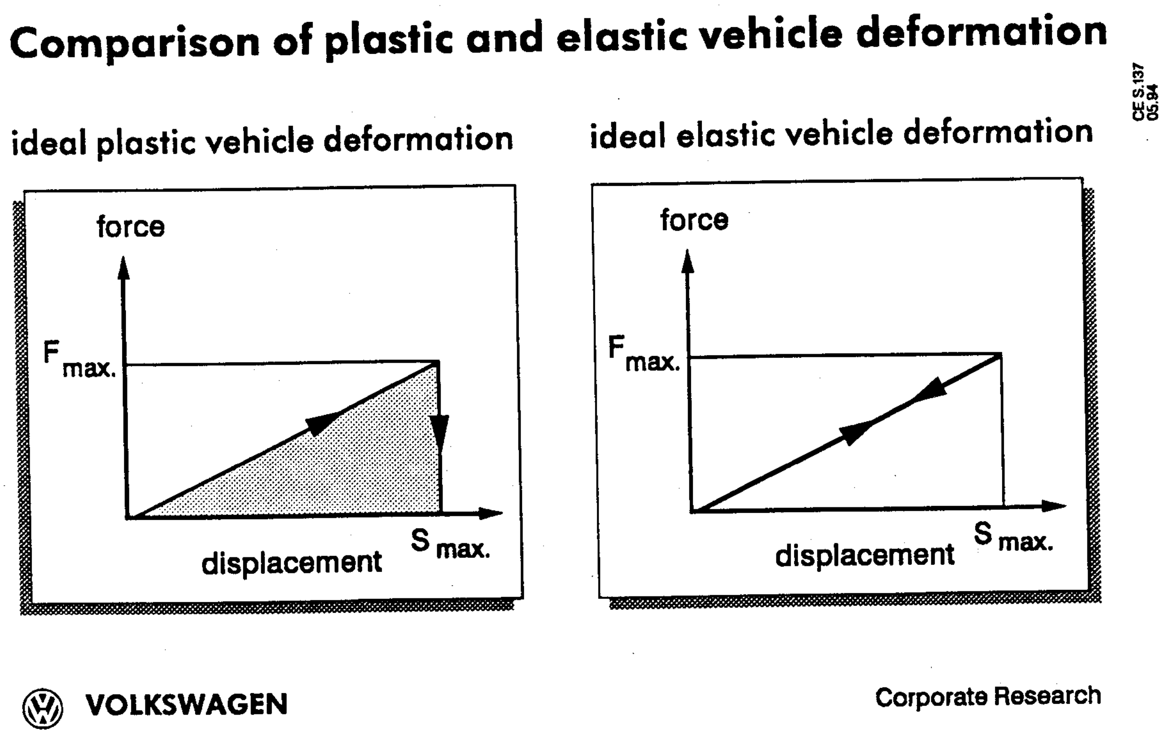


Fig. 6: Comparison of occupant loads with plastic and elastic vehicle deformation

Influence of vehicle deformation length on the ratio of occupant loads in the case of elastic and plastic deformation

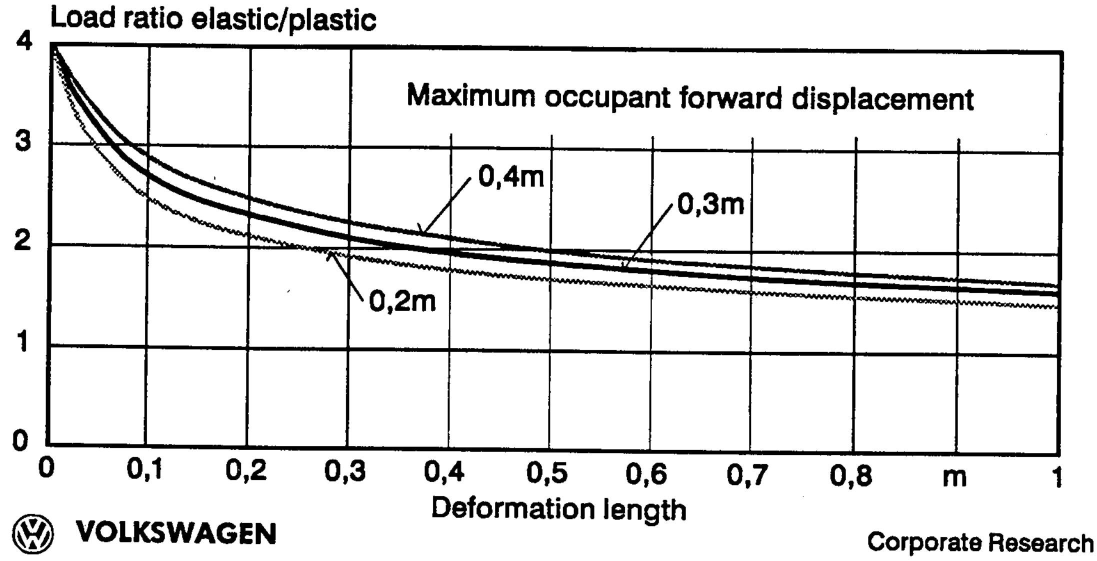


Fig. 7: Influence of vehicle deformation length on the ratio of occupant loads in the case of elastic and plastic deformation

Influence of vehicle deformation length on maximum structure force

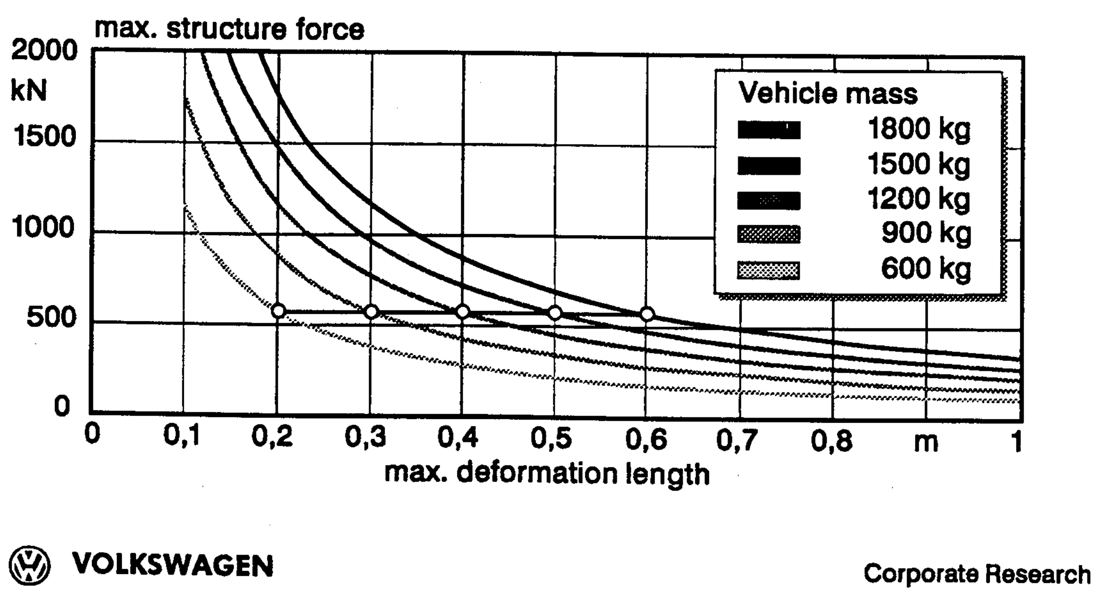


Fig. 8: Influence of vehicle deformation length on maximum structure force

Mass of vehicle structure
as a function of vehicle deformation length

CE S.140 05.94

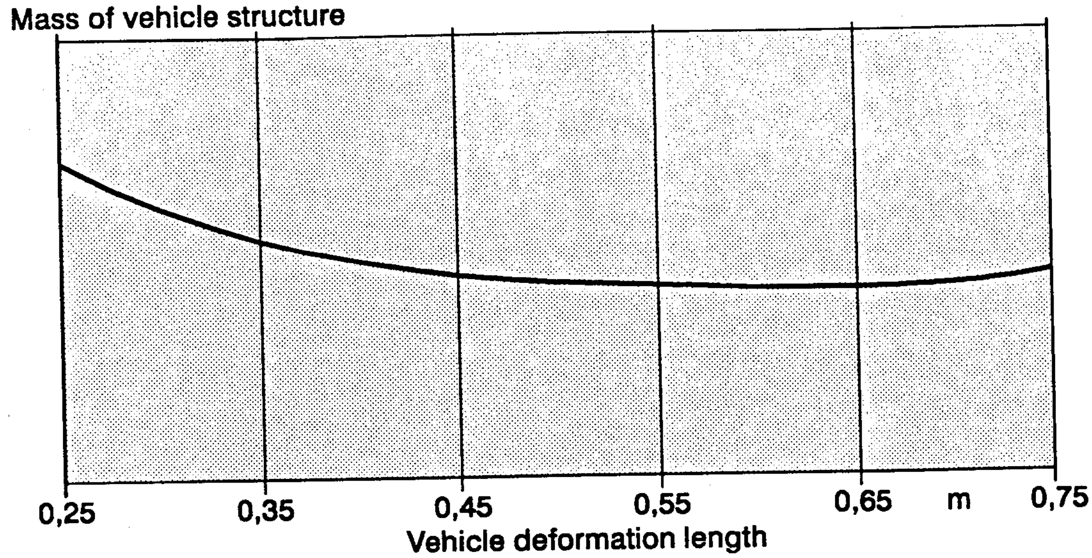


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Fig 9: Mass of vehicle structure as function of vehicle deformation length

Hybrid III driver dummy loads in 56 km/h frontal sled test with 300 mm front structure deformation

CE S.141 05.94

HIC_{36}	:	607
Chest acceleration (g) a_R (3 ms)	:	57,8
Chest deflection (mm)	:	defect *
Femur loads		
left (kN)	:	2,5
right (kN)	:	2,5

Restraint system:
- US type airbag with increased permeability
- belt with low strain
- belt pretensioner with belt force limiter
- lap belt force limiter

* disengagement of rod potentiometer

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Fig 10: Driver dummy loads in 56 km/h frontal impact and 300 mm vehicle deformation length

Test mass conforming to FMVSS 214 as a function of unladen mass

CE S.142
05.94

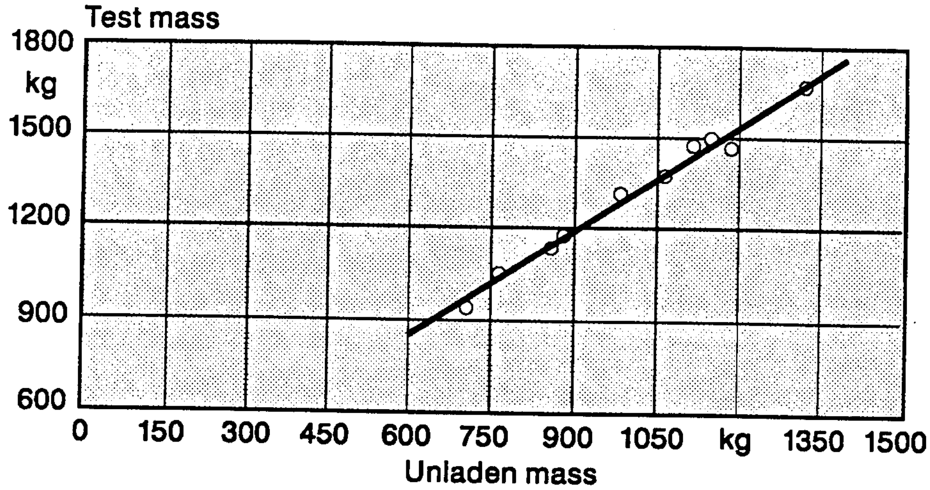

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Fig. 11: Test mass conforming to FMVSS 214 as a function of unladen mass

Vehicle deformation in FMVSS 214 side impact as a function of unladen mass

CE S.88
05.94

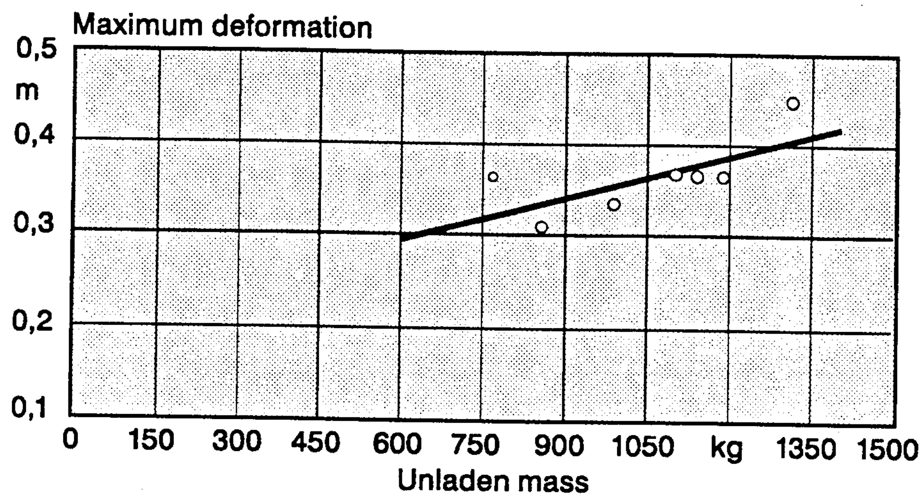

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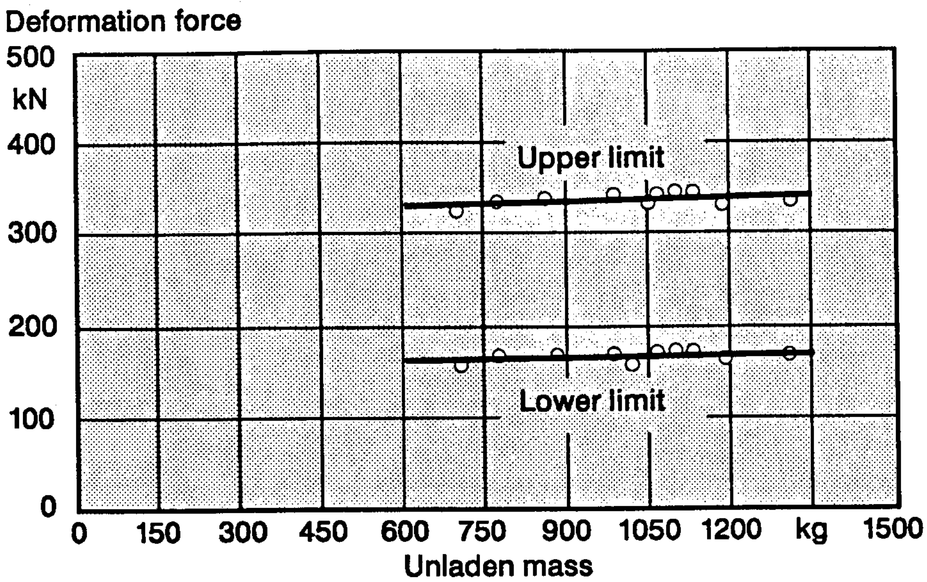
Fig. 12: Vehicle deformation in FMVSS 214 side impact as a function of unladen mass

Deformation force as a function of unladen mass



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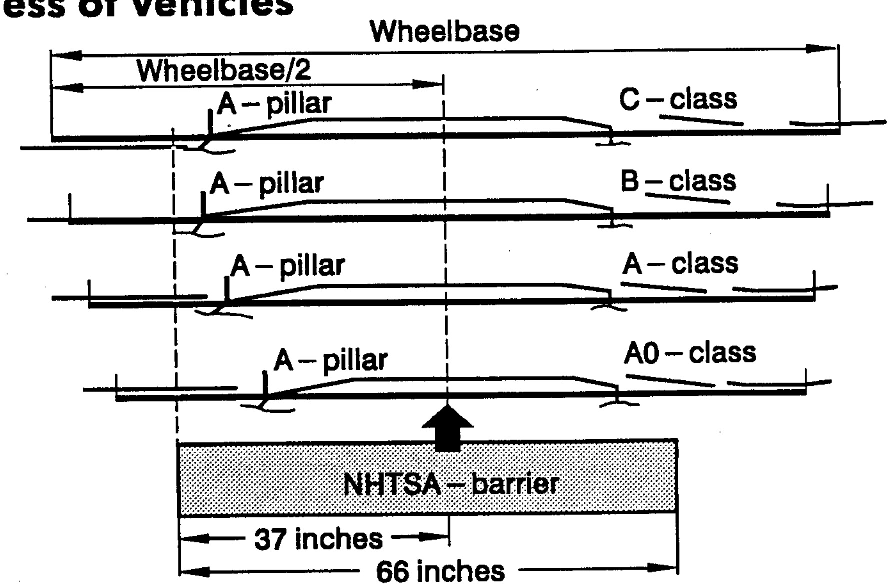
CE S.147 05.94

Fig. 13: Deformation force as a function of unladen mass

Influence of structure geometry on the side stiffness of vehicles



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CE S.87 05.94

Fig.14: Influence of structure geometry on the side stiffness of vehicles

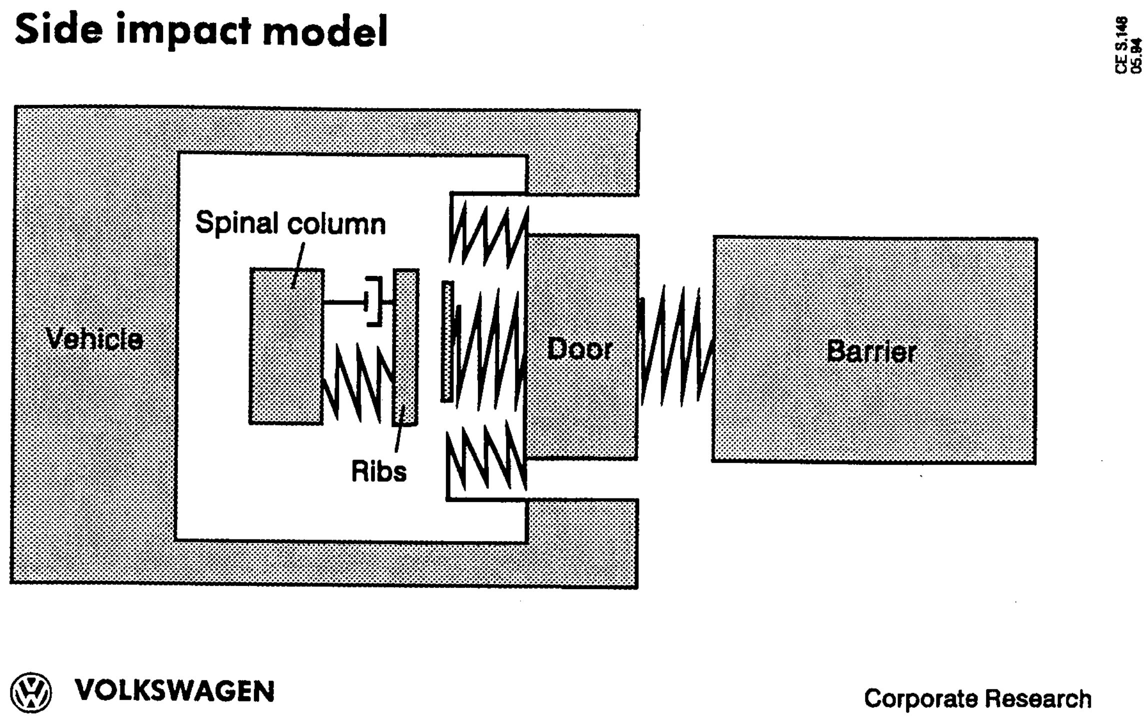

Fig. 15: Side impact model

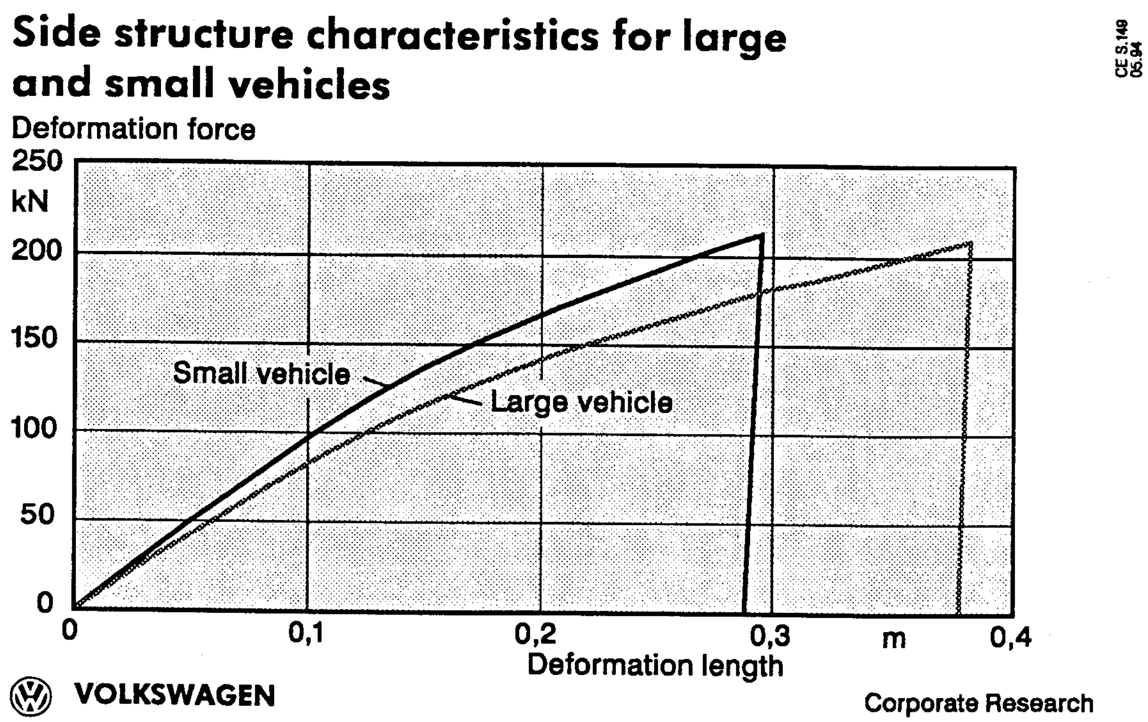

Fig. 16: Side Structure characteristics for large and small vehicles

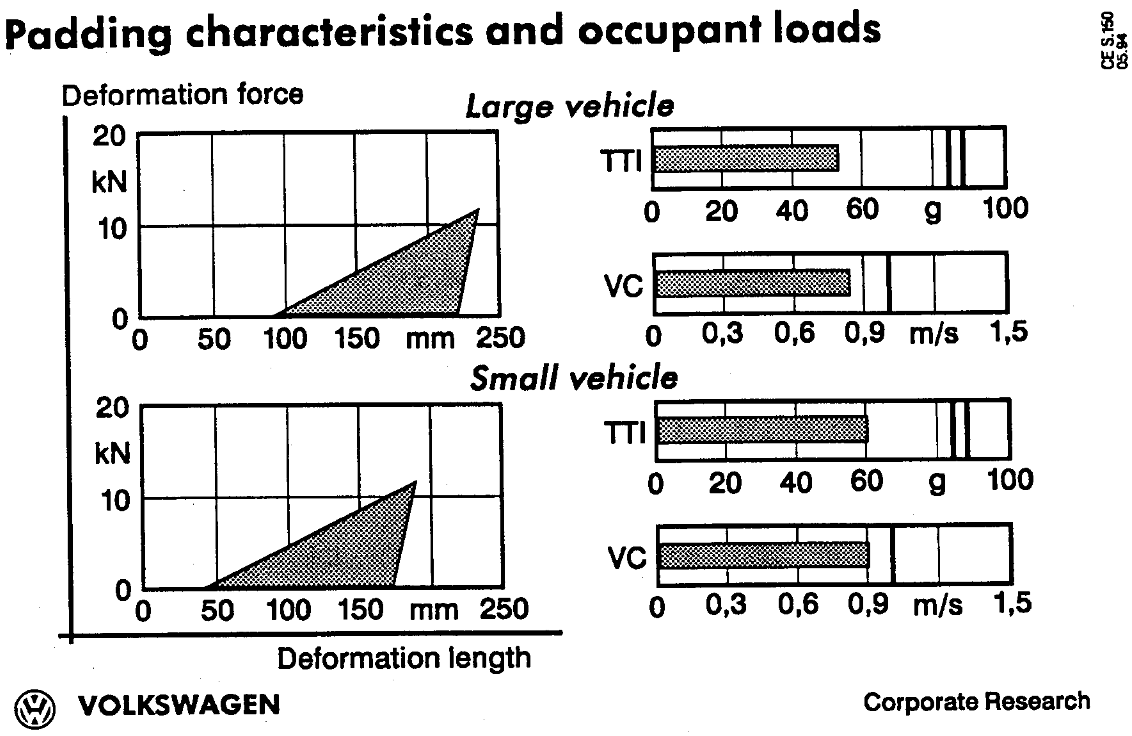

Fig. 17a: Occupant loads with the same padding in small and large vehicles

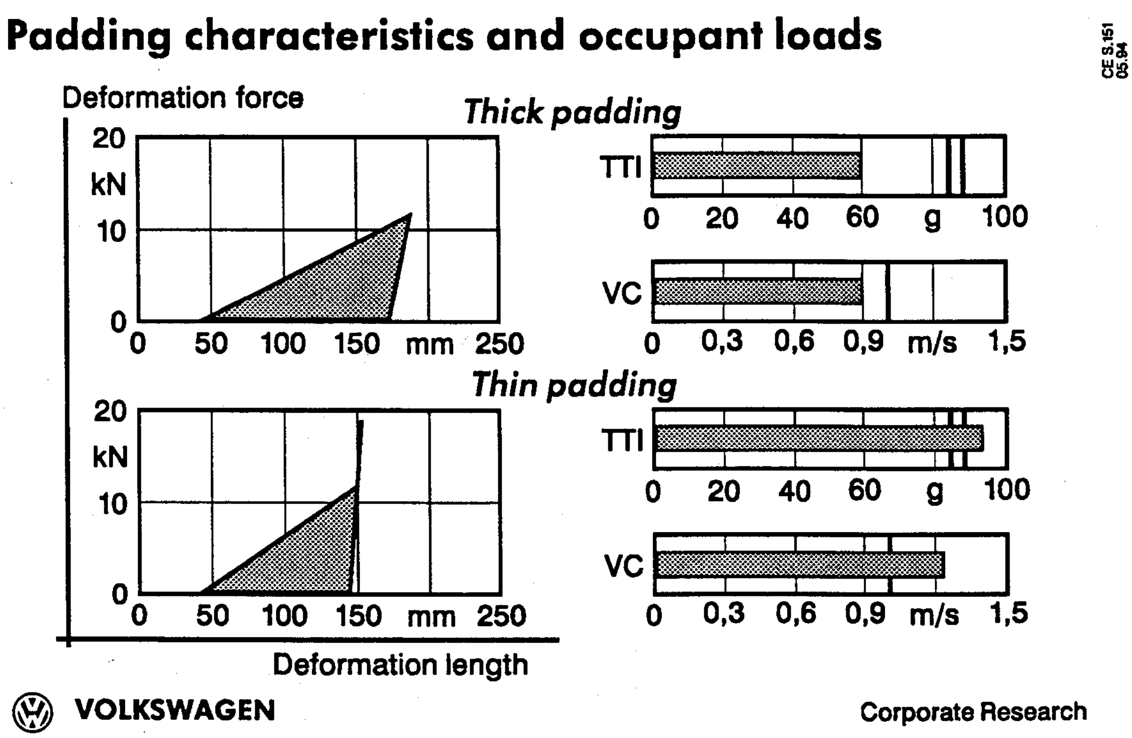

Fig. 17b: Increased occupant loads in small vehicles with reduced padding thickness

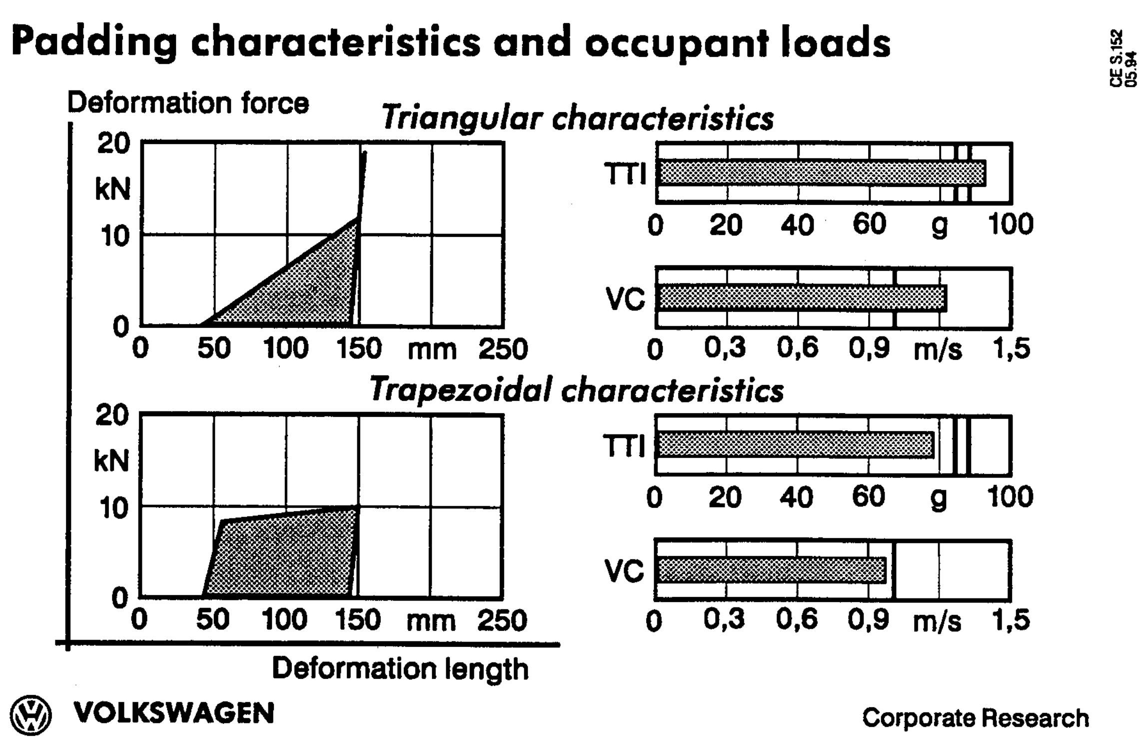

Fig. 17c: Reduced occupant loads in small vehicles and modified padding characteristic

Injuries Sustained by Air Bag Occupants in Frontal Crashes

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ABSTRACT

A multidisciplinary, automobile crash investigation team at the Jackson Memorial Hospital/Ryder Trauma Center in Miami, Florida, is conducting a detailed medical and engineering study. The focus is restrained (seatbelts and/or air bag) occupants involved in frontal crashes, who have also been severely injured. More than 60 crashes have been included in the study to date. Analysis of the initial data indicates that restraint systems are working to reduce many of the head and chest injuries which unrestrained occupants suffer.

However, internal injuries among air bag-protected occupants may be unrecognized in the field providing new challenges in triage and injury diagnosis. In other cases, survival in extremely high severity crashes presents trauma management challenges due to the extent and complexity of the multiple injuries which result. The paper provides case examples to illustrate types of chest and abdominal injuries associated with air bag cases. Two types of cases are presented: Jackson Study Involving Occult Chest /Abdominal Injury and Special Investigation Cases sponsored by the National Highway Traffic Safety Administration, U.S. Department of Transportation

To assist in recognizing the extent of injuries to occupants protected by air bags, it is suggested that additional evidence from the crash scene be used in the triage criteria. For the occult chest/abdominal cases observed in the Jackson study, deformation of the steering system was the vehicle characteristic most frequently observed. The challenges of recognizing injuries to air bag-protected occupants are discussed. The presence of steering wheel deformation may be a sufficient signal of caution to justify transporting the injured victim to a Level 1 or 2 trauma center so that a close examination for occult injuries can be made.

INTRODUCTION

Air bags first became available in passenger automobiles about twenty years ago. During the present decade, the penetration of these devices in the new car fleet will approach one hundred percent. It is estimated that by the year 2000 more than five hundred thousand air bag deployments will occur each year. To date, there is limited medical literature detailing the injury patterns of air bag-protected occupants involved in crashes [1]. Anecdotal reports exist particularly on minor injuries associated with air bag deployments such as abrasions of the cornea of the eye and lacerations of the face [2]. Werner and Sorenson at State Farm Insurance, examined insurance claims and found a 35% reduction in moderate and severe injuries, and that recent air bag design improvements produced a marked reduction of air bag induced abrasions, lacerations and contusions [3].

Because air bags are less than 100% effective, injuries will still occur. The medical community will be challenged by occupants who avoid head, chest or abdominal trauma but experience injuries of their un(air bag)-protected extremities. Of similar concern, occupants may sustain trauma to the chest or abdominal organs through impacts with the air bag or through collisions with internal components like the steering wheel. The mechanisms of injury may include overwhelming the air bag's energy management capabilities due to very high crash forces or multiple collisions wherein the air bag is deflated during some of the collisions. Occupants out of position at the time of air bag deployment may not be protected or may be injured by the deploying air bag. In any event, the injury patterns in air bag-protected occupants must be discerned so that treatment strategies can be optimized and hopefully injury countermeasures can be developed.

This paper summarizes the detailed investigation of a number of air bag-protected individuals involved in crashes whose injuries warranted admission to a trauma center.

METHODS AND PROCEDURES

A research protocol for addressing seriously injured, restrained occupants of frontal automobile collisions was implemented at the University of Miami/Jackson Memorial Medical Center in Miami, Florida beginning July, 1991. In August, 1992, all trauma services were moved into a newly constructed, dedicated trauma care facility named the Ryder Trauma Center. The Center includes unique capabilities to perform injury research. In particular, a computer system has been developed and implemented throughout the Ryder Trauma Center to address the challenge of acquiring and analyzing the enormous amount of information associated with injuries. The CARE system is designed to be integrated with the clinical, administrative, research and educational components of the center. Innovative technologies such as radio-linked terminals, computer-compatible cameras and multimedia electronic displays are incorporated into the system [4]. The research data elements include reconstructions of the automobile crash scene and the vehicular damage, description of the patient's clinical course and outcome status and definition of the economic implications. The database encompasses electronic images such as x-rays, digitized voice and video segments in addition to conventional elements.

Every automobile crash-related admission to the trauma center was considered for possible inclusion in the study. Once a patient was determined to meet the study criteria, complete vehicle and occupant injury data was collected so that it is compatible with the format specified in the current NASS [5]. In addition, in depth data on the victim, the exact nature of the injuries, the outcome and the costs were recorded in the CARE system. The protocol for the data collection is described in detail in an earlier paper [4].

DESCRIPTION OF DATA COLLECTED TO DATE

The study to date includes 62 injured occupants. All occupants were protected by some type of restraint system. Table 1 shows the distribution of restraint systems.

TABLE 1
Restraint Distribution

TYPE OF RESTRAINT	NUMBER
LAP & SHOULDER BELT	39
SHOULDER BELT ONLY	6
AIR BAG ONLY	10
LAP & SHOULDER BELT, AIR BAG	7

One of the criteria for admission to this study is that the vehicle occupant was admitted to the Ryder Trauma Center. In most cases, the victim was suspected on admission of having one or more severe injuries. The cases collected are suitable for developing hypotheses regarding the cause and mechanisms of the injuries and possible injury reduction countermeasures. However, population-based crash studies are required to assess the overall effectiveness of the safety belt and air bag systems. Many such studies have been reported in the literature. The National Highway Traffic Safety Administration (NHTSA) recently reported that safety belts were about 45% effective in reducing moderate to critical injuries.. Air bags in conjunction with safety belts are reported to be between 55%-68% effective in reducing moderate to critical injuries[6].

A general observation of the injured occupants in the study to date confirms other findings that air bags and seat belt systems are doing are very effective in reducing the severity of injuries. The severity and extent of the head and chest trauma suffered by restrained occupants are generally much less than has been observed for the unrestrained population which made up most of the motor vehicle trauma admissions in years past.

This reduced extent of trauma still carries with it the need for careful examination and diagnosis of the residual trauma. Especially for air bag cases, the physiological response of the victim at the crash site does not consistently predict the gravity of their trauma.

The analysis to follow will address the residual injuries observed in air bag cases and will focus on the occult (not immediately obvious) chest and abdominal injuries observed to date.

The 17 occupants protected by air bags who were entered into the study to date had a total of 101 injuries. The distribution of injuries by body region is shown in Table 2. This table also shows the Harm distribution. In the Harm accounting procedure, weighing factors are applied to the injury data, with each injury described according to its threat to life and weighted in proportion to its monetary cost. The procedure was pioneered by Malliaris [7,8]. The monetary weighing factors are based on cost data developed by Miller [9].

TABLE 2
Injury Distribution in Air bag Equipped Cars
17 Cases

Region	# of Injuries	Harm %
Head/Neck	28	22%
Chest/Abdomen	22	38%
Lower Extremity	35	36%
Upper Extremity	16	4%
TOTAL	101	100%

Table 2 shows that head/neck injuries constitute 28% of the injuries, but only 22% of the Harm. In contrast, chest/abdominal injuries comprise 22% of the injuries, but 38% of the Harm. This result suggests that the chest/abdominal injuries are generally more serious than the other injuries for the cases collected to date.

The most common vehicle feature which was associated with chest/abdominal injuries was a bent steering wheel or a compressed steering column. Ninety-five percent of the Harm to the chest/abdomen region was associated with a steering wheel/column deformation.

CASE STUDIES

In the sections to follow, seven selected air bag cases will be summarized. These cases are divided into two groups. The first group are Jackson cases at impact severities of 20 to

37 mph which exhibit occult injuries. The second group are SCI cases in which the driver was fatally injured, and the crash severity was less than 20 mph.

Four cases in the Jackson study involved occult chest/abdominal injuries. All of these cases sustained multiple impacts. In three of the cases, no impact exceeded a delta V of 23 MPH. The fourth case involved a 37 mph delta V. All cases displayed steering wheel deformation of one inch or more.

Three Special Investigation Cases were found which had fatal outcomes in crash severities less than 20 mph. All displayed steering wheel/column deformation of at least one inch.

JACKSON OCCULT INJURY CASES

Case # 92-004

FIGURE 1

A 1992 Lincoln Town Car (Fig. 1) was traveling on a two lane road through a swampy region at a speed of 60 MPH when the left front tire blew out. The posted speed was 45 MPH. The time was 8:42 PM, the weather was rainy and the road was wet. The Lincoln swerved left of center, across the path of a 1982 Mercury Marquis. The two vehicles impacted left-headlight to left-headlight, with a contact width of 8". The Lincoln, directed to the left by this impact, continued along the left shoulder until it sustained a centerline impact with a concrete utility pole, approximately 350' from the first impact. The displacement measurements were as follows: Maximum vehicle crush - 30", Left "A" pillar intrusion -3.25", Left instrument panel intrusion - 3", Steering wheel deformation - 2". The estimated delta V for the car-to-car impact was 19 MPH and for the pole the impact was 22 MPH.

The driver was a healthy 83-year-old retired male who weighed 200 lbs. and was 5' 10" tall. Protection was provided by an air bag and manual lap and shoulder belts. He sustained the following injuries:
AIS-5 Hematoma, subdural, bilateral
AIS-1 Laceration, ear, left
AIS-2 Fracture, ribs, left (3)
AIS-4 Rupture, spleen with hemorrhage
AIS-2 Laceration, descending colon mesentery
AIS-1 Laceration, elbow, left
AIS-2 Fracture, navicular, left
AIS-2 Fracture, acetabulum with dislocation femur, left
AIS-2 Fracture, ankle, left

The EMS personnel at the scene of the crash found that the driver did not meet any of the objective criteria which would have mandated transport to a trauma center (trauma center admission criteria) [10]. Because of suspicion of severe injury, EMS transported the patient by helicopter to a Level 1 trauma center. The patient had a multi-week stormy hospital course wherein he underwent multiple surgical procedures. He was discharged to a nursing home.

Case #92-023

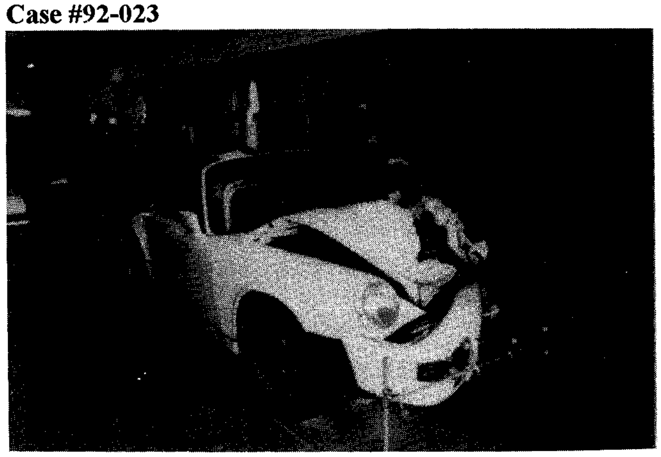

FIGURE 2

A 1990 Porsche Carrera (Fig. 2) impacted the rear of a 1985 Pontiac Fiero which was parked for a tire change in the fast lane of a busy three lane divided highway. The travel speed prior to impact was at the speed limit, about 55 MPH and the delta V is estimated at 22 MPH. The time was 3:30 PM, the weather was clear and the surface was dry. A van traveling ahead of the Porsche blocked the view of the parked Pontiac until the last instant, preventing timely evasive action. The Porsche sustained two impacts. The major impact was with the rear of the parked Pontiac. A second impact occurred with the left front fender of the Porsche impacting the median barrier at a low delta V. The Porsche sustained a maximum frontal crush of 28.5" and a left toe pan intrusion of 4.5". The steering wheel was deformed 1". The driver was a 50-year-old male businessman. He was 5' 11" tall and weighed 220 lbs. He was protected by an air bag and manual belt.
His injuries were:
AIS-2 Fracture, ribs, left (3-5)
AIS-2 Laceration, liver
AIS-1 Contusion, antecubital fossae, bilateral
AIS-2 Fracture, acetabulum, left

At the scene, the patient did not meet trauma center admission criteria and was transported to an emergency room, not a trauma center. After a number of hours in that facility, the patient's condition deteriorated and he was transferred to a trauma center. He had a complex hospital course during which he underwent numerous surgical procedures. During his hospital care he developed a number of complications. A year after the crash the patient was unable to resume his pre-injury activities largely due to psychological problems.

Case #92-006

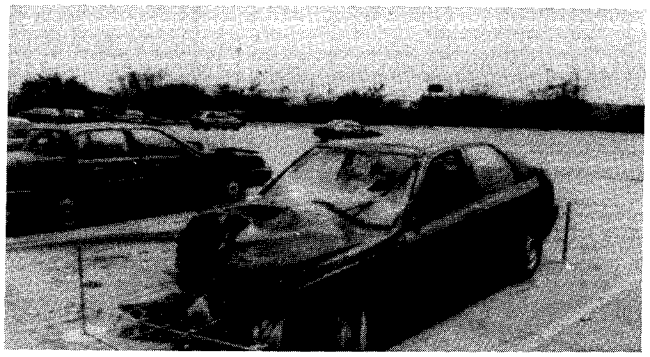

FIGURE 3

At 5:00 AM, a 1992 Honda Civic DX (Fig. 3) approached a right angle intersection in a residential area. The vehicle was traveling at 40 MPH, 10 MPH above the posted speed limit. Unable to negotiate the 90 degree turn to the left, the driver locked the brakes and proceeded straight ahead, leaving 45 feet of skid marks. The vehicle crossed a 5.0" high curb and a sidewalk, crashed through a wood fence and continued another 20' across a grass lawn before impacting a cement block stucco house. The left side of the car went through the sliding glass door but the right side impacted the cement block exterior wall and the inside bedroom wall which was parallel to the direction of travel (Fig. 4).

FIGURE 4

The vehicle continued into the house striking an occupied bed in the master bedroom and coming to rest inside the house. The maximum vehicle crush was 23.0", the right toe pan intrusion was 8.0" and the steering wheel deformation was 4.0". The estimated delta V was 23 MPH. The driver was a 34-year-old male who weighed 134 lbs. and was 5' 6" tall. His BAC was .079, measured 12 hours after the crash. He was wearing the manual belt system and the air bag deployed. He sustained a single injury:

AIS-2 Laceration, liver with hematoma

The patient did not meet trauma center admission criteria and was transported to the nearest hospital, not a trauma center. He developed severe abdominal pain, suggestive of intra-abdominal injury, a number of hours later. He was then transferred to a Level 1 trauma center. The liver injury was treated non-surgically. The patient was discharged home a few days after admission and has done well.

Case #92-017

FIGURE 5

A 1991 Mercury Grand Marquis (Fig. 5) was traveling northbound on a two lane road. The posted speed for this area is 50 MPH. At 8:24 PM, the weather was cloudy and the road surface was dry when a 1989 Chevrolet pick-up truck had to brake suddenly to avoid striking a slower moving vehicle in the same lane. The pick-up truck swerved to the left into the northbound lanes. The Mercury struck the pick-up truck in the front end with the front bumper. After the initial contact, both vehicles rotated and sideslapped. The Mercury came to rest facing in a northeasterly direction. There was 65.0" of direct contact across the front bumper of the Mercury and the maximum extent of crush for this impact was 37.75". The vehicle sustained a left toe pan intrusion of 8.0" and a left instrument panel intrusion of 4.0". The steering wheel deformation was 3.0". The delta V was calculated to be 37 MPH.

The driver was a 63-year-old male engineer who weighed 175 lbs. and was 5' 10" tall. Protection was provided by an air bag as well as lap and shoulder belts. He sustained the following injuries:

AIS-3 Fracture, ribs, left (6-8) right (1)
AIS-3 Contusion, lungs, bilateral
AIS-4 Contusion, cardiac
AIS-2 Fracture, calcaneus, right

This crash occurred in an area not served by a trauma center. The patient was transported from the scene to a local hospital. His injuries led to cardiac and respiratory insufficiency. These problems were not adequately treated. A number of days after the crash he was transferred to a Level 1 trauma center in a critically- ill state. The patient had a multi-week critical course which included a number of operations. He was discharged home and within two months had resumed all his pre-injury activities.

SELECTED SPECIAL CRASH INVESTIGATION OF FATALITIES INVOLVING CHEST/ABDOMINAL INJURIES

Case #91-12

A 1990 Dodge Shadow impacted a 10" diameter utility pole on the left side of a rural two lane state route where the speed limit was 35 MPH. The impact was at 12 o'clock and at the centerline of the Dodge's bumper. It produced a maximum of 14.5" of bumper crush. The resulting delta V of 14.4 MPH deployed the air bag. The steering wheel was bent .25" and the shear capsule was compressed 1.6".

The driver was a 36-year-old female, 5' 3" tall, weighing 112 lbs. She had a history of epilepsy. She was wearing her 3-point belt system. Her injuries were:
AIS-3 Fractures, ribs, bilateral
AIS-3 Rupture, spleen
AIS-5 Rupture, abdominal aorta

The patient was reportedly unconscious at the scene and she was transported to a local hospital. Shortly after admission, the patient's condition deteriorated. She was taken to the operating room wherein she died presumably of the aortic rupture.

Case # 92-4

The driver of a 1986 Ford Tempo lost control of the car during a coughing attack. The Tempo traversed a 5" curb and impacted a wooden utility pole located on the right side of an urban street. The driver was wearing a three point belt and the air bag deployed. The maximum depth of bumper crush was 14.8" which produced a delta V of 17 MPH. The steering wheel was deformed 3.3" forward.

The driver was a 57-year-old female, 5' 6" tall, weighing 150 lbs. Her seat adjustment was 3" from the full forward position. Her injuries were:
AIS-3 Rupture, spleen
AIS-1 Contusion, abdominal wall
AIS-1 Contusion, breast bilateral
AIS-1 Abrasion, chin
AIS-1 Laceration, lower lip

The crash victim was conscious at the scene and reported no pain. She was transported to a local hospital where on admission she was reportedly stable. Four hours following the crash she expired. There was concern by the case reviewers that the injuries to the spleen were not initially recognized.

Case #91-10

A 1991 Pontiac Firebird ran through a T-intersection in a residential area and impacted an 18" diameter tree with its center front. The estimated impact speed was 21 MPH with a delta V of 19 MPH. The vehicle sustained a maximum depth of crush of 22" from the 12 o'clock direction of force impact. The steering wheel was deformed 2" forward and the steering column shear capsule was separated 3".

The driver was a 46-year-old male, 5' 11" tall and weighed 230 lbs. He was wearing manual lap and shoulder belts. He temporarily lost consciousness as he approached the T-intersection. The impact with the tree caused the air bag to deploy. The driver sustained the following injuries:
AIS-4 Fractures, ribs, bilateral (2-9)
AIS-4 Contusion, heart
AIS-1 Ecchymosis, legs, distal to the knees
AIS-1 Abrasion, chin
AIS-1 Abrasion, forehead with ecchymosis

The driver remained conscious post-crash and was transported to a local hospital where he expired several hours following the crash. The apparent cause of death was the contusion of the heart. However, the apparent loss of consciousness prior to the crash opens the question of a heart attack at that time. Acute and/or chronic heart disease could have exacerbated the problem of the contusion, according to the case reviewers.

Table 3 summarizes data from the Jackson air bag occult injury cases discussed earlier. Note steering column deformation ("DEF") occurred in all these cases.

TABLE 3
AIR BAG OCCULT-INTERNAL INJURIES

CASE #	CAR	DEF	INJURY	TRIAGED
92-004	92-Lincoln	2.0"	4-Spleen	Trauma Ctr EMS Susp.
92-023	90-Porsche	1.0"	2-Liver	Hosp.
92-006	92-Honda	4.0"	2-Liver	Hosp.
92-017	91-Mercury	3.0"	3-Lung	Hosp.

Table 4 summaries the NASS data for air bag cases. Note that steering wheel deformation was reported in 23 cases. Of those 15 admitted to the hospital, nine had AIS-3 or greater injuries.

TABLE 4
NASS DATA 1989-1991- AIR BAG DEPLOYMENT FRONTAL CRASHES

135 Cases of air bag deployment
626 Injuries to occupants
23 Cases with reported steering wheel deformation
9 Occupants suffered AIS 3+ Injuries

DISCUSSION

Occult Injuries-The air bag may have ushered in a new era in injury management. Strategies for dealing with severely injured people emanate from military approaches. The methods of assessing injuries on the field, stabilizing life threatening derangement's in physiology and anatomy, rapidly transporting patients to hospitals wherein definitive diagnostic and therapeutic interventions can be provided have continued to improve throughout the history of American military conflicts. The concept of "triage" is fundamental to these processes. It involves the allocation of resources to injured individuals based on the severity of the injuries and the likelihood of survival.

Injuries which occur in military situations are typically related to the penetration of one or more body parts by bullets and shrapnel. The presence of a life- or limb-threatening injury is obvious by the degree of physiological compromise, such as shock, and/or the entry location of the projectile and its presumed path in the body. In automobile related injuries the damaging forces are typically blunt. At the scene of a crash the presence of an internal injury, such as a laceration of the liver, is suggested if there is external evidence of contact (over the area of the liver) such as bruising or pain, and/or if there is physiological abnormality such as shock.

The clinician dealing with blunt trauma must always maintain a high level of suspicion of injury; the failure to recognize injuries can lead to loss of life or limb. Decisions on whether a trauma victim needs to be taken to a hospital and the level of trauma care expertise of the receiving hospital is based on triage criteria mandated typically by state governments. The most capable trauma centers are designated Level 1 or 2 according to the American College of Surgeons Committee on Trauma (ACSCOT) standards [9].

ACSCOT and other organizations have developed criteria that largely are the basis for local trauma system's criteria. These are typically based on physiological abnormalities such as systolic blood pressure below 90 millimeters of mercury or Glasgow Coma Score below 13. Location of injury is also included in some systems' criteria, such as bullet wound to the abdomen. Another group of criteria is mechanism of injury such as a fall of more than two building stories or ejection from a vehicle in a crash. The last group of criteria is called "index of suspicion". These are based on the opinion of EMS personnel at the scene. Even though other objective criteria are not present, the patient does not "look right" and therefore should be evaluated in a trauma center. The criteria which are utilized in Dade County, Florida, wherein the Ryder Trauma Center is located, are listed below.

ADULT TRAUMA CRITERIA
USED IN DADE COUNTY, FLORIDA

- Systolic BP< 90
- Respiratory rate <10 or >29 BPM
- Glasgow Coma Scale < 13
- Penetrating injury to head, neck, chest, abdomen or groin
- Paralysis
- Second or third degree burns > 15% TBSA
- Amputation proximal to wrist or ankle
- Ejection from motor vehicle

Most studies have shown that the combination of criteria that are utilized by individual trauma systems work well [11]. Quality of care analyses, which are mandated for trauma systems, typically show very few cases where injured individuals did not receive adequate treatment. One way of evaluating the quality of care in a system is to evaluate deaths and determine if any were preventable. Most well organized trauma systems have low preventable death rates [12].

The air bag may affect the ability to successfully evaluate crash-involved occupants utilizing existing criteria. The air bag-protected occupant typically will not have physiologically compromising head, chest or abdominal injuries nor the facial lacerations, bruises and fractures that often make crash victims "look" seriously injured. Personnel at the scene may not send occupants, who later turn out to have serious injuries, to trauma centers.

In most cases, the injuries to occupants protected by air bags are less severe than to occupants without airbags, but the problem is that the residual injuries may not be recognized by EMS or emergency room personnel. It is not that the air bag contributes to injury, but that it changes a very serious, obvious injury into a less serious, but less obvious injury. If this less obvious injury is not treated, it may become a serious problem.

What kinds of injuries may not be initially obvious but become life threatening? Any chest or abdominal injury wherein the immediate physiological implications are minimal fall into this category, such as contusions and lacerations of the lungs, aorta and heart. In the abdomen tears of the solid organs, in particular of the liver and spleen, can initially cause limited bleeding with little blood pressure loss and minimal abdominal pain. The mesenteries which connect the bowel components to their central blood supplies can be torn with limited initial bleeding. The bowel can also be torn. Bleeding is less problematic with bowel injuries; contamination of the abdominal cavity with irritating and often infection producing components is the problem. Continued loss of blood and/or contamination of the abdomen typically leads to very serious problems.

Even minutes of uncorrected shock and contamination can lead to death or failure of other organ systems such as the lungs or the immune system.

How can the air bag contribute to serious abdominal and chest injuries which are not initially noticeable? There appears to be three mechanisms:

The air bag may contact the chest or abdomen directly during deployment with enough force to injure internal organs. This appears to be a rare event. It occurs mainly when the occupant is in close proximity to the bag as it deploys.

The occupant's position and size, and/or the velocity of the crash may exceed the air bag's protective capability allowing the occupant to contact an internal component of the automobile, particularly the steering wheel. The examples to date of this include large occupants and crash velocities in excess of 35 miles per hour.

There may be multiple collisions wherein the air bag has partially or completely deflated after the initial external collision. Thus, the occupant can contact internal objects such as the steering wheel.

The problem is that the occupant may not meet existing trauma center admission criteria after one of these types of events. However, the individual may have sustained some chest or abdominal internal injury as previously described. It appears that suspicion of injury must occur if these potentially injured occupants are to receive a full evaluation in the hospital. In present trauma centers the determination that an individual has an internal abdominal or chest injury is based on a combination of available historical information, physical examination and diagnostic tests. The latter include: x-rays (which are particularly useful in evaluating lung injuries), ultrasound (to examine the heart for internal injury and/or bleeding into its surrounding sac), CAT scanning (which is useful mainly for abdominal injuries and in a limited fashion chest injuries), angiography (which is particularly useful for evaluating the most potentially life-threatening occult injury-partial tear of the thoracic aorta) and diagnostic peritoneal lavage (which is extremely useful for discovering bleeding in the abdominal cavity).

Dealing with injury in the era of the air bag is dramatically different than in the setting of the battlefield. The injuries in the air bag setting will often not be obvious and the receiving hospital may evaluate many patients who turn out to be injury-free. In the military scenario the injuries are obvious and hospitals are for the clearly life-threatened patient.

The challenge is to find reliable indicators of potential injury that are available at the crash scene. Deformation of the steering wheel in frontal collisions appears, in the small number of cases studied to date by the Jackson investigation team, to be a useful indicator of possible abdominal or thoracic injury. As Table 3 indicates, all four of the Jackson cases with occult injuries, also displayed steering wheel deformation of 1 inch or more. In all of these cases the crash severity was greater than 20 mph, and the vehicle was subjected to multiple impacts. The combination of crash severity and occupant kinematics was such that impact with the steering wheel and steering wheel deformation might be expected.

However, the three fatal cases with severity less than 20 mph also sustained steering wheel/column deformation ranging from 1.85 to 5 inches. All these crashes were single vehicle frontal impacts with a narrow rigid object. Such large steering system deformations at low crash severities need additional explanation.

It is possible that the occupants in the three fatal cases were positioned close to the steering wheel at the time of air bag deployment. Melvin 1993 [13] and Horsch 1990 [14] have conducted tests with dummies to assess air bag deployment loads. The test results show dummies located close to the deploying bag can sustain chest acceleration higher than 40g.

To further understand the forces on the steering wheel/column for the kinds of tests reported by Melvin and Horsch, a model of a typical air bag system was exercised. The model applied is the generic air bag configuration available for the Fitzpatrick Engineering [15]. This model has been used extensively by the developer and others to predict air bag performance [16]. The model used was of a 50% Hybrid III dummy in a frontal crash with a severity of 15 mph. The dummy position was varied and the steering system forces were observed. The model results showed that for occupants located very close to the air bag at the time of deployment, the forces on the steering column easily exceed 2,000 lbs for a period of 30 ms., causing more than 1 inch of steering wheel deformation. The deployment forces on the steering system were negligible when the occupant was properly positioned. The maximum force on the steering wheel for a properly positioned occupant was less than 1,000 lbs.

These results provide a technical basis for the large steering system deformations observed in the SCI cases. Drivers positioned close to the air bag at the time of deployment can cause high forces to be transmitted to the steering system, even in low severity crashes. The research of Melvin and Horsch also suggests the possibility of injury under certain positions of the body relative to the air bag, at time of deployment. However, many other positions which would produce steering system deformation have a very low probability of injury. Consequently, steering column deformation in low severity impacts might be used as an index of suspected injury, but not as a certainty of injury.

Steering wheel deformation has been observed in 17% of NASS cases with air bag deployment An examination of Table 4 shows that 1989-91 NASS contains 135 cases of frontal crashes with air bag deployment. Among these cases 23 reported steering wheel deformation. Occupants from 15 of the 23 cases were admitted to the hospital for treatment.

Based on these observations, a Research Note was developed by NHTSA suggesting that EMS evaluate the steering wheel in these cases [17]. The Note recommends that deformation of the steering wheel be considered as a criterion for further evaluation, in a hospital setting, of the stable, air bag-protected driver involved in a frontal crash.

Other potential sources of information about possible internal abdominal or chest injuries in air bag- protected crash occupants are the amount of deformation to the exterior of the automobile and/or intrusion of internal components. Occupant stature and position at the crash moment may turn out to be very predictive, particularly if the occupant is out of position or on top of the air bag as it deploys. Crashes which include multiple collisions may correlate highly with injuries.

Continued, detailed study of air bag-involved crashes wherein occult injuries occur is necessary. Traditional analyses of real-life crashes, such as NASS, do not provide precise definition of the clinical course. For example, the timeline from the crash to injury discovery and treatment is of real importance. Hospital-based studies involving multidisciplinary teams such as the ones ongoing at the Ryder Trauma Center and the Maryland Institute for Emergency Medical Services are necessary to provide these data [18].

SUMMARY

The number of air bag-involved crashes wherein difficult triage decisions need to be made is unknown at this time. As previously stated, it is estimated by NHTSA that by the year 2000 more than five hundred thousand air bag deployments will occur yearly. To avoid missing injuries, triage strategies err on the side of transporting patients, who may have serious injuries, to trauma centers for evaluation. Applying this to air bag-protected occupants, there may be many admissions to trauma centers for work-up of occult injuries. On the other side of the equation, admissions of severely injured occupants may decrease as a function of air bag protection.

Determinations need to be made as to whether evaluations of initially stable crash victims, with suspicion of major injury, can be performed in the most sophisticated trauma care arenas (Level 1 or 2 trauma centers). They have the expertise and equipment to work-up these patients and treat their spectrum of injuries. At this time, however, these centers concentrate on treating individuals with obvious threat to life or limb and are often functioning at or above capacity [19]. In the air bag era, the role of the trauma center may need to be broadly expanded to include the evaluation of stable patients who may have incurred occult injuries.

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Offset Frontal Impacts - A Comparison of Real-World Crashes with Laboratory Tests

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ABSTRACT

A review of 1990-92 National Accident Sampling System data found that frontal crashes with direct damage involving two-thirds or less of the front-end of the car are at least as common as crashes with direct damage distributed across the front-end. The role of intrusion in these asymmetric or offset crashes in injury causation — especially to the lower-limbs — supports the need for frontal crash testing that goes beyond the well-established full-width-barrier tests. A series of car-to-car, car-to-rigid barrier, and car-to-deformable barrier crash tests support the use of deformable faces in offset tests as a way of providing a reasonable approximation of actual car-to-car crashes. The results support the growing consensus that a minimum of two tests is needed to assess car crashworthiness in frontal crashes: a full-width-barrier test to assess restraint system performance and an offset test into a deformable barrier to assess structural integrity.

INTRODUCTION

Protecting occupants against serious injury in frontal crashes has been a priority in vehicle safety for more than 30 years, and full-scale vehicle crash tests are an integral part of this effort. Since the late 1960s, when the first U.S. Federal Motor Vehicle Safety Standards (FMVSS) were introduced for new cars, the performance of a number of vehicle safety systems, such as steering assemblies and high penetration resistant windshields, has been assessed in 48 km/h (30 mph) full-width-barrier crash tests. In the 1970s, the National Highway Traffic Safety Administration (NHTSA) proposed adding instrumented dummies to the 48 km/h barrier tests to assess the performance of automatic restraint systems. Although the mandatory requirements for automatic crash protection were delayed, a few cars sold in the 1970s had optional automatic restraints, and these were the first models required to meet injury criteria measured with instrumented dummies. Frontal crash testing with instrumented dummies became much more prominent in the late 1970s with NHTSA's New Car Assessment Program (NCAP). In this program, which continues today, a number of cars are tested each year in 56 km/h (35 mph) barrier tests using instrumented dummies. The results of this program are released to the public to provide new car buyers with comparative crashworthiness information.

The first time large numbers of new car models were required to meet specified injury criteria measured using instrumented dummies in 48 km/h barrier tests was in 1987 with the beginning of the phase-in of the automatic restraint requirements. All new passenger vehicles — cars, light trucks, and utility vehicles — are now required to meet the dummy injury criteria of FMVSS 208 in 48 km/h barrier tests.

The full-width-barrier test used in the NCAP and specified in FMVSS 208 is now generally recognized as a demanding test of a vehicle's restraint system, and there is no question that the NCAP testing and the automatic restraint system requirements of FMVSS 208 have resulted in significantly improved restraint systems in recent model cars sold in the United States.[1,2] Today, virtually all new cars produce relatively low dummy injury criteria results in the 56 km/h NCAP tests.

In recent years, interest in the use of comparative testing of new cars as a way of assessing and comparing crashworthiness has spread from the United States to Europe, Australia, and Japan. Crash tests have been sponsored in different countries by a variety of organizations including car magazines, consumer associations, motoring clubs, and consortiums of these, as well as government agencies.[3,4,5]

Consumer interest in car safety ratings is one of the reasons that comparative assessments of new car crashworthiness have become more common. Safety features, such as air bags, now play a prominent role in new car advertising in many markets as interest in safety has increased in importance for new car buyers. With safety prominent in the minds of consumers, manufacturers cannot afford to have models receive poor rankings in comparative tests.

Despite the obvious success of NCAP testing and FMVSS 208 in improving restraint system designs, questions have been raised about the validity of assessing crashworthiness in frontal crashes with a single crash test. Mercedes-Benz has for more than a decade argued that, although the flat-barrier test used in NCAP and FMVSS 208 is a good test of restraint systems, it is not an appropriate test of structural integrity.[6,7] Mercedes-Benz claims that structural integrity is important because in many real-world collisions only part of the front-end of the vehicle is contacted, and the crash forces are concentrated on part of the front-end rather than spread across the front structure as in flat-barrier tests. In crashes involving only part of the front-end, the structural integrity of the vehicle design becomes especially important.

The limitations of full-width-barrier tests for assessing structural integrity were less important in the earlier days of the NCAP program when large differences among the results for various cars were common. In recent years, however, virtually every new car produces NCAP results that are below the injury criteria thresholds established by FMVSS 208. This raises valid questions concerning the relevance to consumers of relatively small differences in the NCAP injury criteria results, when differences in structural integrity in other types of crashes may be more important. Mercedes-Benz argues that somewhat higher injury criteria results (but still below the FMVSS 208 thresholds) are a necessary consequence of designing front-end structures to resist intrusion in real-world crashes where only part of the front-end structure of the vehicle absorbs the energy of the collision. That is, cars designed to take into account partial front-end involvement in crashes may get poorer ratings in NCAP tests than cars whose designs have not addressed this issue.

To address the question of intrusion and structural integrity, Mercedes-Benz and others have suggested that offset-barrier crash tests are needed in addition to full-width-barrier tests for assessing frontal crashworthiness.[8,9] A number of European manufacturers routinely run such tests to assess the structural integrity of their designs, even though they are not mandated by any safety standards.[10,11] In recent years, there has been growing interest in offset testing, and there are now active programs in a number of countries. NHTSA has been running a series of car-to-car offset crash tests as part of a research program, but these tests were not designed for the purpose of providing comparative information on new cars.[12,13]

In Europe, and more recently in Australia, offset crash tests have been conducted for the purpose of comparing car crashworthiness.[3,4,5] A variety of offset crash test modes has been used by the various groups sponsoring such tests. The offset-barrier test initially proposed by Mercedes was an impact into a rigid barrier with partial overlap that engaged 40 percent or less of the vehicle's front-end. More recently, there has been growing interest in offset testing with so-called deformable barriers, that is, energy absorbing faces added to the rigid barrier.[12,14,15,16] It has been argued by Hobbs,[8,14] and more recently by Mercedes-Benz as well,[16] that the use of a deformable face in an offset-barrier test provides a much better representation of how front-end structures will deform in real-world car-to-car crashes, while offset tests into rigid barriers can result in inappropriate structural designs for such crashes.

There now appears to be a growing consensus that the best assessment of a car's crashworthiness in frontal crashes can be derived from two tests: an NCAP or FMVSS 208 type test into a full-width-barrier to assess restraint system performance, and an offset test involving 50 percent or less of the front-end of the vehicle into a deformable barrier to assess structural integrity and the ability of the vehicle to resist intrusion. With improved restraint systems, particularly the widespread availability of air bags, the role of intrusion, and hence that of offset testing, becomes more important. Although it is too early to develop reliable statistical findings on the injury patterns in otherwise similar cars with and without air bags, there is growing evidence from individual crash investigations that occupants of cars with driver-side air bags who use lap and shoulder belts are surviving relatively high-speed frontal crashes without significant injuries to the chest and head area, but often sustaining serious, although not life-threatening, leg injuries and that these injuries often relate to significant amounts of vehicle intrusion.[17,18]

Although the importance of offset testing as a complement to full-width-barrier testing is increasingly accepted, there are still a number of questions concerning appropriate test speeds, the particular configuration of the deformable barrier face, the degree of overlap, and the methods of assessing performance. The following sections of this paper will categorize and summarize data from real-world frontal crashes and present results from offset car-to-car test crashes and offset test crashes into barriers. These results from real-world crashes and tests will be related to assess the relevance of different test configurations and impact speeds for the assessment of crashworthiness.

Real-World Crash Configurations

To determine the relevance of the various crash test configurations used for assessing crashworthiness, it is important to know how often real-world crashes relate to the proposed tests. Mercedes-Benz has reported that in Europe the majority of severe real-world frontal impacts are equivalent to offset barrier crashes. An analysis of nearly 2,400 severe crashes involving Mercedes-Benz cars in Europe showed that frontal crashes account for 62 percent of the cases, and among these, 57 percent were equivalent to offset barrier tests, 28 percent were equivalent to full-width-barrier or pole-on-center tests, and 15 percent were equivalent to 30 degree angle barrier tests. To obtain similar information about the United States crash experience, Mercedes-Benz conducted a detailed analysis of every case from the 1988 National Accident Sampling System (NASS) in which there was a fatality with an impact speed of at least 30 miles per hour. According to this analysis, 63 percent of these fatal crashes were equivalent to offset barrier crashes, 30 percent were equivalent to full-width-barrier or pole-on-center tests, and 7 percent were equivalent to 30 degree angle barrier tests.[19]

Although the NASS data provide the most detailed information currently available on crash configurations in the United States, the computer-based data files do not provide sufficient information to identify equivalent crash tests for the NASS cases. To obtain such information, it would be necessary to review each original case report and photographs. However, the coded Collision Deformation Classification (CDC) information[20] does provide some insight into the types of damage occurring in a larger sample of frontal crashes. Table 1 shows the direct damage distributions as coded in the CDC for passenger cars involved in two-vehicle and single-vehicle frontal crashes for the 1990, 1991, and 1992 NASS data files. For 46 percent of the cars, the direct damage was distributed across more than two-thirds of the front-end; in two-vehicle crashes 52 percent of the cars had distributed damage and in single-vehicle crashes 23 percent had such damage. For 52 percent of the cars, the direct damage involved two-thirds or less of the front-end and was offset to the right or left; the corresponding result was 69 percent for cars in single-vehicle crashes and 47 percent for cars in two-vehicle crashes.

Table 2 shows similar results for crashes with injuries where the maximum Abbreviated Injury Score (MAIS) was 2 or greater. For just over half of the cars in these crashes, the direct damage was offset involving two-thirds or less of the front-end of the car. Slightly more of these injury crashes had distributed direct front-end damage in both two-vehicle and single-vehicle crashes than in all towaway crashes, but the proportion of all injury crashes that involved single-vehicles increased significantly, with the result that the overall proportion of cars with distributed damage remained about the same.

Table 3 shows the results for the smaller set of fatal crashes. In fatal crashes, offset direct damage to two-thirds or less of the front-end of the car was less frequent than in all crashes and in crashes with injury for both two-vehicle and single-vehicle fatal crashes. But offset direct damage to two-thirds or less of the front-end of the car still occurred to 50 percent of the cars in fatal crashes because the proportion of single-vehicle crashes increased. Thus, the NASS data indicate that among towaway, injury, and fatal crashes, direct damage to two-thirds or less of the front-end of cars is at least as common as direct damage distributed across the front of the car. Although this direct damage information does not translate exactly to equivalent test types, these results do demonstrate the importance of frontal crashes in which only part of the front-end of the car is involved in direct contact during the collision.

In an effort to understand the role of crash configuration and vehicle intrusion in relation to lower-limb injuries, 19 serious crashes from the Institute's seven-county crash investigation program with AIS-2 or greater foot or ankle injuries were also studied.[21] Among these 19 cases, 11 were offset crashes, 7 were distributed crashes, and 1 was a single-vehicle center impact. Among the 11 offset frontal crashes, 10 of the vehicles experienced some degree of footwell intrusion. In contrast, among the seven crashes with distributed front-end damage, only two involved footwell intrusion. Clearly, frontal offset crashes with intrusion in the footwell area are frequently involved in serious foot and ankle injuries.

Table 1
Passenger Car Direct Damage in Frontal Crashes*
Two-Vehicle and Single-Vehicle Towaway Crashes
National Accident Sampling System 1990 - 1992

Direct Damage	Crash Type: Two Vehicle No.	Two Vehicle Percent	Single Vehicle No.	Single Vehicle Percent	Total No.	Total Percent
Distributed	**1,402**	**52**	**173**	**23**	**1,575**	**46**
Left 2/3	446	17	125	16	571	17
Left 1/3	270	10	90	12	360	10
Right 2/3	354	13	150	20	504	15
Right 1/3	199	7	160	21	359	10
Subtotal	**1,269**	**47**	**525**	**69**	**1,794**	**52**
Center	**10**	**0**	**68**	**9**	**78**	**2**
Total	**2,681**	**99**	**766**	**101**	**3,447**	**100**

* Cases with direct damage to the front of the vehicle, a principle direction of force between 11 and 1 o'clock, and an estimated ΔV.

Table 2
Passenger Car Direct Damage in Frontal Crashes*
Two-Vehicle and Single-Vehicle with Maximum AIS of 2 or Greater
National Accident Sampling System 1990-92

Direct Damage	Crash Type: Two Vehicle		Single Vehicle		Total	
	No.	Percent	No.	Percent	No.	Percent
Distributed	**645**	**57**	**199**	**27**	**844**	**45**
Left 2/3	181	16	118	16	299	16
Left 1/3	115	10	100	14	215	12
Right 2/3	115	10	110	15	225	12
Right 1/3	65	6	135	19	200	11
Subtotal	**476**	**42**	**463**	**64**	**939**	**51**
Center	**7**	**1**	**66**	**9**	**73**	**4**
Total	**1,128**	**100**	**728**	**100**	**1,856**	**100**

Table 3
Passenger Car Direct Damage in Frontal Crashes*
Two-Vehicle and Single-Vehicle Fatal Crashes
National Accident Sampling System 1990-92

Direct Damage	Crash Type: Two Vehicle		Single Vehicle		Total	
	No.	Percent	No.	Percent	No.	Percent
Distributed	**82**	**59**	**34**	**29**	**116**	**45**
Left 2/3	25	18	17	15	42	16
Left 1/3	16	11	21	18	37	14
Right 2/3	10	7	20	17	30	12
Right 1/3	5	4	15	13	20	8
Subtotal	**56**	**40**	**73**	**62**	**129**	**50**
Center	**2**	**1**	**10**	**9**	**12**	**5**
Total	**140**	**100**	**117**	**100**	**257**	**100**

* Cases with direct damage to the front of the vehicle, a principle direction of force between 11 and 1 o'clock, and an estimated ΔV.

Much of the current focus in offset crash testing has been on ways to recreate some of the conditions occurring in real-world car-to-car offset crashes with a single-car offset test. A notable real-world car-to-car crash occurred in Culpeper County, Virginia, on March 12, 1990, when two 1989 model Chrysler LeBarons — a convertible and a coupe — collided in an offset head-on crash. The crash received a great deal of attention because it was believed to be the first serious two-car collision in the world in which air bags deployed in both vehicles. It is believed that the actual crash closing speed was about 112 km/h, making it an ideal candidate for laboratory recreation, since much of the focus of both flat-barrier and offset testing has been on impacts in the 56 km/h range, or 112 km/h closing speeds for car-to-car crashes. Both drivers survived this crash with only minor injuries even though there was substantial intrusion in the footwell area. The amount of intrusion was such that it seems very likely that a slightly higher speed impact would almost certainly have resulted in significant leg injuries to both drivers.

Crash Test Program and Results

A frontal crash test program conducted at the Insurance Institute for Highway Safety Vehicle Research Center included a car-to-car test designed to closely approximate the Culpeper County crash, as well as additional car-to-car tests and offset barrier tests using Oldsmobile Cutlass Ciera and Chrysler LeBaron models.

The matrix of crashes in the test program involving Oldsmobile Cutlass Ciera and Chrysler LeBaron cars is shown in Table 4. The nominal test speeds ranged from 56 to 64 km/h and the test configurations included car-to-car crashes with 50 percent overlap, rigid and deformable barrier tests with different amounts of overlap, and deformable barrier tests with different barrier designs. Measurements of vehicle deformation, intrusion, and driver-side 50th percentile Hybrid III injury criteria results were taken for each test. The details of the actual crash speeds and amount of overlap, model years, weights of the test cars, injury criteria results, and a description

Table 4
Crash Test Matrix

Crash Type	Car Model	Nominal Test Speed (km/h)	Nominal Overlap 100%	50%	40%	30%
Car-to-car	Oldsmobile Ciera	56 56 56 64		X X X X		
	Chrysler LeBaron	56 64		X X		
Rigid Barrier	Oldsmobile Ciera	56	X	X	X	
Deformable Barrier: Single-Stage	Oldsmobile Ciera	56 60 64		X X	X X X	X X
Deformable Barrier: Single-Stage with Bumper Element	Oldsmobile Ciera	60			X	
	Chrysler LeBaron	60			X	
Deformable Barrier: Two-Stage	Oldsmobile Ciera	60 64			X X	

Single-Stage Barrier — Aluminum honeycomb, 45 psi (31 N/cm^2)
Bumper Element — Aluminum honeycomb, 250 psi (175 N/cm^2)
Two-Stage Barrier — Aluminum honeycomb, 50 psi (35 N/cm^2) first stage, 250 psi (175 N/cm^2) second stage.

of the intrusion measurement procedures are given in the Appendix. The Oldsmobile Cieras and Chrysler LeBarons tested are similar in size: the Ciera's wheelbase is 266 cm and the test vehicles' weights ranged from 1325 to 1405 kg; the LeBaron's wheelbase is 255 cm and the test vehicles' weights ranged from 1409 to 1427 kg. The Cieras and the LeBarons had manual lap/shoulder belts and the LeBarons had driver-side air bags.

Figure 1 shows the vehicle damage profiles for four 1989 Chrysler LeBarons — the two that were in the Culpeper County crash and a similar pair of cars after a 56 km/h 50 percent overlap car-to-car test. It is apparent from these vehicle damage profiles that the cars in the Culpeper County crash experienced slightly less vehicle deformation than the pair of vehicles in the car-to-car test, indicating that the actual closing speed of the cars in the Culpeper County crash was somewhat less than the 112 km/h in the test crash. The shape

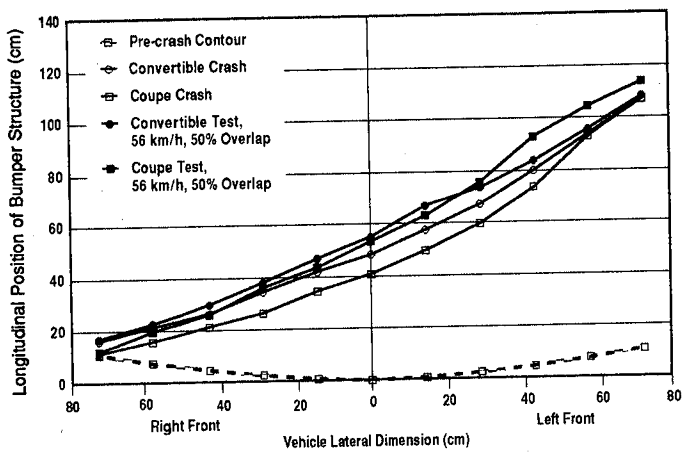

Figure 1. LeBaron Damage Profiles — Car-to-Car Crash and Car-to-Car Test

of the damage profiles, however, was similar, even though the test crash overlap was 50 percent and the Culpeper County crash overlap was estimated to be about 30 percent.

Table 5 summarizes the footwell intrusion measurements for the four LeBarons. Both of the Culpeper crash LeBarons experienced somewhat greater lower dash intrusion than the cars in the car-to-car test. For the convertibles, the brake pedal intrusion was somewhat less for the real-world crash car but about the same for the two coupes. Toe-pan intrusion was about the same in both vehicles.

Figure 2 shows the vehicle damage profiles of six Oldsmobile Cieras that were crash tested in three 56 km/h, 50 percent overlap, car-to-car tests. While the six vehicles exhibited somewhat similar patterns of damage with a generally triangular pattern of deformation and no clear break between the direct and the induced damage, the extent of the damage differed somewhat among the vehicles. The vehicle damage profiles from these car-to-car tests do not resemble the damage profiles from rigid offset tests. In the offset tests into the rigid barrier, the damage patterns were not triangular, the left fronts of the cars that contacted the barrier deformed somewhat uniformly, and the front-ends of the cars that contacted the edge of the barrier had sharp creases. In both the 50 and 40 percent overlap tests into the rigid barrier, there was considerably more direct damage across the left front of the cars than in the car-to-car tests.

The various deformable barriers produced patterns of direct and induced damage that more closely approximate the patterns of damage in the car-to-car tests. Figure 3 shows the damage profiles for the three Cieras that impacted the single-stage deformable barriers at 56 km/h and with overlaps of 50, 40, and 30 percent. In each of these tests, the direct damage on the left front of the vehicle — the side impacting the barrier — was either less than or at the bottom end of the range of damage in the car-to-car crashes. Toward the center and the right front of the cars, the damage pattern for the 40 percent overlap crash was within the car-to-car damage ranges and was the closest overall to the deformation from the car-to-car crashes.

Table 5
Footwell Intrusion in Car-to-Car Crashes
1989 Chrysler LeBarons
56 km/h 50 Percent Offset Test Compared with Real World 30 Percent Offset Crash

Car Model	Crash	Intrusion (cm)			
		Lower Dash		Brake Pedal	Toe Pan (average)
		Left	Right		
Convertible	Real-World	24	14	22	23
	Test	17	10	27	24
Coupe	Real-World	29	16	32	34
	Test	25	13	33	31

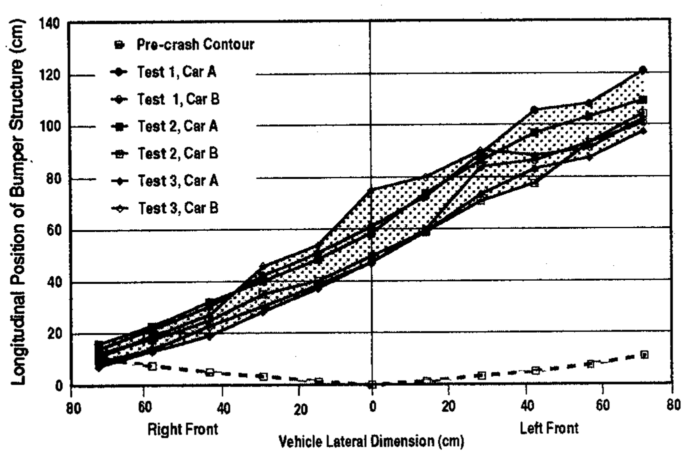

Figure 2. Ciera Damage Profiles — 56 km/h, 50 Percent Overlap Car-to-Car Tests

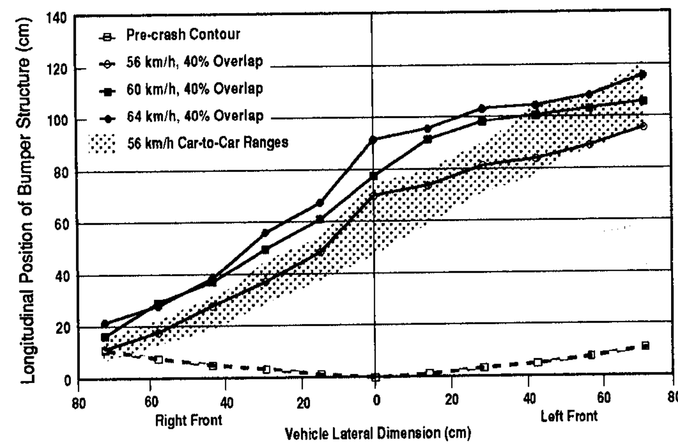

Figure 4. Ciera Damage Profiles — Single Stage Deformable Barrier Tests with 40 Percent Overlap at Various Speeds

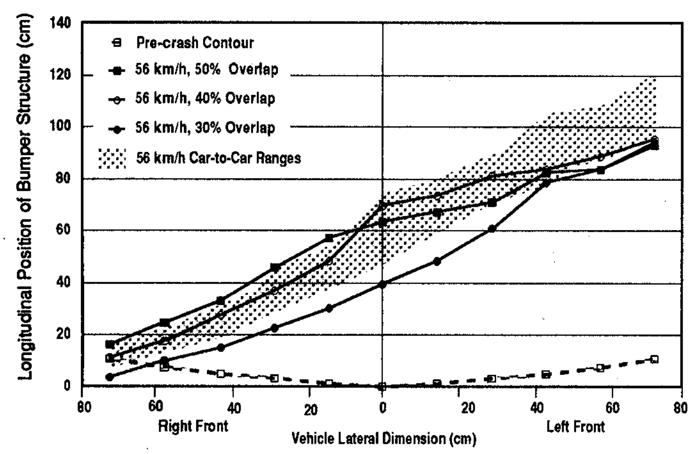

Figure 3. Ciera Damage Profiles — Single Stage Deformable Barrier Tests at 56 km/h with Various Overlaps

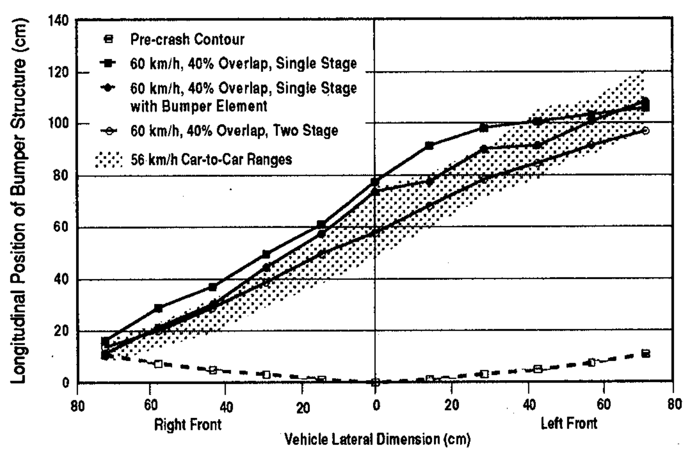

Figure 5. Ciera Damage Profiles — Various Deformable Barrier Tests with 40 Percent Overlap at 60 km/h

Figure 4 compares the damage profiles for the Cieras in tests with the single-stage deformable barrier and 40 percent overlap at three different speeds — 56, 60, and 64 km/h. The 60 km/h test produced a damage profile that was within the car-to-car ranges for the front left of the car, but the deformation toward the center and on the right front was greater than in the car-to-car tests.

Figure 5 compares the vehicle damage profiles for three 60 km/h tests with 40 percent overlap into three different deformable barriers: single-stage, single-stage with the bumper element, and two-stage. In this series of tests, the two-stage barrier produced a damage profile that was within the ranges from the 56 km/h car-to-car tests; however, the maximum deformation at the left front of the car was at the bottom end of the car-to-car ranges. The single-stage barrier with the bumper element produced a damage profile that was close to the mid-point of the car-to-car ranges for most of the area of direct damage, but the area of induced damage was at the top end of the car-to-car ranges.

Figure 6 compares the damage profiles for two Cieras that were in 64 km/h, 50 percent overlap car-to-car tests with the 56 km/h car-to-car test damage ranges. There was almost complete separation of the deformation ranges from the two different speed car-to-car Ciera crashes in the direct damage regions, but the ranges overlaped across the right fronts of the cars. Figure 7 compares the vehicle damage profiles for the three 60 km/h, 40 percent offset tests into each of the deformable barriers with the 64 km/h and 56 km/h damage profile ranges from the car-to-car tests.

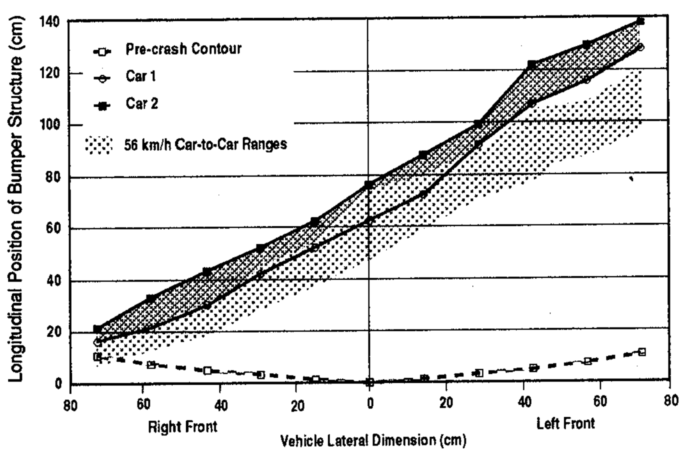

Figure 6. Ciera Damage Profiles — 50 Percent Overlap, 64 km/h Car-to-Car Tests

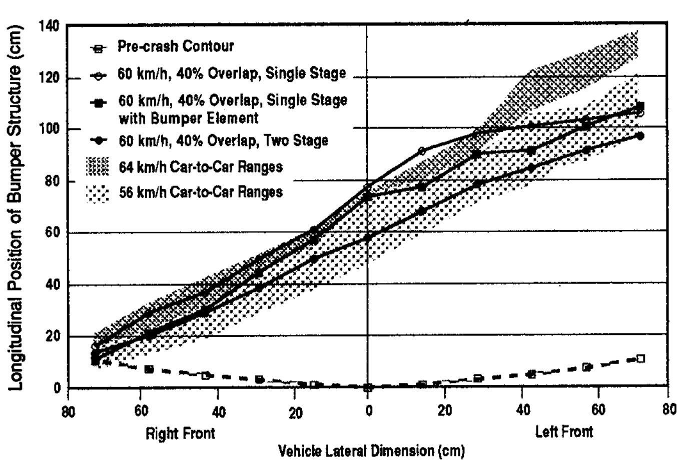

Figure 7. Ciera Damage Profiles — Various Deformable Barrier Tests with 40 Percent Overlap at 60 km/h and 64 km/h Car-to-Car Ranges

Figure 8 compares the damage profiles for the LeBaron convertibles in two of the tests — the 56 km/h 50 percent overlap car-to-car and the 60 km/h 40 percent overlap into the single-stage deformable barrier with a bumper element. As with the corresponding results from the Ciera tests, the damage profiles matched closely on the left front, but the deformable barrier with bumper element produced somewhat more induced damage across the front of the car.

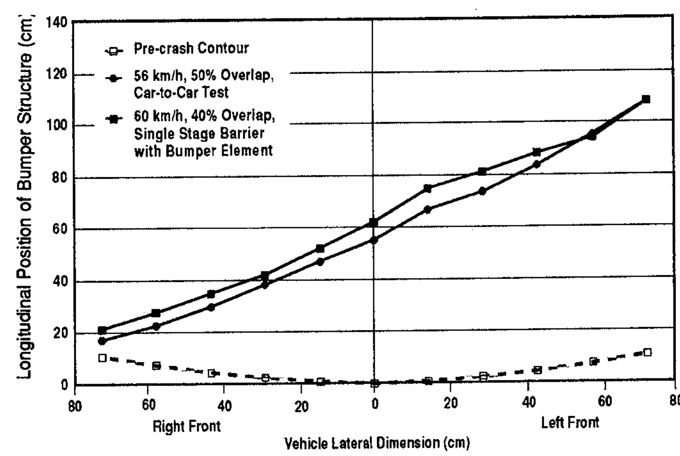

Figure 8. LeBaron Convertible Damage Profiles — Deformable Barrier and Car-to-Car Crash Tests

Table 6 summarizes the footwell intrusion measurements for the car-to-car tests and the 40 percent overlap tests into the deformable barriers. The intrusion in the footwell area in the 56 km/h Ciera test with the single-stage deformable barrier was generally below the intrusion measured in the 56 km/h car-to-car crashes. The footwell deformation measures in the 60 km/h Ciera impacts into the various deformable barriers all tended to be within the range of deformations observed in the Ciera car-to-car tests. Thus, all three deformable barriers produced amounts of footwell intrusion similar to the Ciera 56 km/h car-to-car tests when tested at 60 km/h and 40 percent overlap.

In the case of the LeBarons, however, the picture is not so clear-cut. In the LeBaron car-to-car test at 56 km/h, there was considerably more footwell intrusion than in the comparable Ciera tests; however, in the 40 percent offset 60 km/h LeBaron convertible test into a deformable barrier, the footwell intrusion was comparable to the Ciera tests and much less than for the LeBaron convertible in the car-to-car crash.

Table 7 summarizes the Hybrid III lower-leg injury criteria results from the car-to-car tests and the 40 percent overlap tests into the deformable barriers. In one Ciera 56 km/h car-to-car

Table 6
Footwell Intrusion — Car-to-Car and Car-to-Deformable-Barrier Tests

Crash Type	Car Model	Nominal Speed (km/h)	Nominal Overlap (%)	Intrusion (cm)			
				Lower Dash		Brake Pedal	Toe Pan (Average)
				Left	Right		
Car-to-Car	Oldsmobile Ciera	56	50	18	14	18	18
		56	50	7	6	10	15
		56	50	11	9	13	16
		56	50	7	7	10	14
		56	50	9	8	11	14
		56	50	10	10	13	19
	Chrysler LeBaron	56*	50	17	10	27	24
		56	50	25	13	33	31
Deformable Barrier: Single-Stage	Oldsmobile Ciera	56	40	6	7	7	10
		60	40	13	12	15	17
Deformable Barrier: Single-Stage with Bumper Element	Oldsmobile Ciera	60	40	13	11	16	16
	Chrysler LeBaron	60*	40	13	9	17	15
Deformable Barrier: Two-Stage	Oldsmobile Ciera	60	40	11	8	12	13
Car-to-Car	Oldsmobile Ciera	64	50	23	17	24	28
		64	50	27	20	25	28
	Chrysler LeBaron	64*	50	36	22	36	39
		64	50	31	20	42	40
Deformable Barrier: Single-Stage	Oldsmobile Ciera	64	40	17	18	20	23
Deformable Barrier: Two- Stage	Oldsmobile Ciera	64	40	14	10	14	17

* LeBaron convertible

Table 7
Hybrid III Lower Leg Injury Criteria Results — Car-to-Car and Car-to-Deformable-Barrier Tests

Crash Type	Car Model	Nominal Speed (km/h)	Nominal Overlap (%)	Maximum Bending Moment (Nm)		Maximum Axial Force (N)	
				Left	Right	Left	Right
Car-to-Car	Oldsmobile Ciera	56	50	100	**410**	2,822	**9,610**
		56	50	**410**	**230**	3,760	1,850
		56	50	—	—	—	—
		56	50	—	—	—	—
		56	50	104	142	2,600	2,950
		56	50	200	217	1,970	3,600
	Chrysler LeBaron	56*	50	160	**250**	2,810	**8,660**
		56	50	**290**	90	3,320	7,680
Deformable Barrier: Single-Stage	Oldsmobile Ciera	56	40	80	130	1,800	2,520
		60	40	180	**410**	1,830	2,570
Deformable Barrier: Single-Stage with Bumper Element	Oldsmobile Ciera	60	40	**240**	150	1,485	4,510
	Chrysler LeBaron	60*	40	90	100	1,370	3,230
Deformable Barrier: Two-Stage	Oldsmobile Ciera	60	40	170	120	1,740	2,220
Car-to-Car	Oldsmobile Ciera	64	50	**240**	220	2,740	5,060
		64	50	**240**	**240**	2,590	6,850
	Chrysler LeBaron	64*	50	**330**	**310**	5,180	**10,850**
		64	50	**310**	**350**	**10,390**	**11,490**
Deformable Barrier: Single-Stage	Oldsmobile Ciera	64	40	110	190	2,170	2,410
Deformable Barrier: Two-Stage	Oldsmobile Ciera	64	40	220	100	1,670	1,540

Numbers in bold type exceed the published injury thresholds of 225 Nm for maximum bending moment and 8,000 N maximum axial force.[22]

test, the published tibia bending moment injury threshold of 225 Nm was exceeded on three of the four dummy legs, and one of the legs exceeded the published axial compression injury threshold of 8,000 N.[22] In the other Ciera 56 km/h car-to-car test with data, all of the lower leg results were below the published thresholds.

In the Ciera 40 percent offset tests into the deformable barriers at either 56 or 60 km/h, only two legs out of the eight exceeded the published tibia bending moment injury threshold, and in no cases was the published axial force injury threshold of 8,000 N exceeded.

In the LeBaron car-to-car test at 56 km/h, the right leg of the convertible's dummy and the left leg of the coupe's dummy had maximum bending moments above the published injury threshold. The right lower legs of both driver dummies registered high axial forces, but only the convertible's dummy had a maximum axial force of over 8,000 N. The one LeBaron test at 60 km/h into the deformable offset barrier produced lower numbers than in the car-to-car crash. In the 64 km/h car-to-car crashes all four of the LeBaron driver dummy maximum bending moment results exceeded the published injury threshold and three of the four legs had axial force loads considerably above the published injury threshold. The comparable results from the higher speed Ciera car-to-car crash were considerably lower, although the bending moments also suggested a likelihood of injury. The first 56 km/h Ciera car-to-car crash produced very high lower leg injury criteria results, generally higher than the corresponding results for the higher speed crashes. There are no obvious explanations for these apparently anomalous results.

There was a reasonable degree of correlation between the maximum axial force results and both the brake pedal (0.74) and toe-pan intrusion (0.71) results. In the case of the maximum bending moment results, the corresponding correlations were weak. However, three of the bending moment results for the Cieras were very high and statistical outliers at 410 Nm, two of which came from the crash just discussed; if these scores are eliminated, there are relatively high correlations (0.68 for brake pedal and 0.75 for toe pan intrusion) for the remaining results. Careful examination of the bending moment data in these three cases, however, provides no reason to doubt their validity. The lower dash intrusion results were only weakly correlated with the various lower-leg injury criteria results.

Real-World Crash Speeds

In addition to using test configurations that reflect real-world crashes when assessing crashworthiness, it is also important that the test speeds reflect the speeds in real-world crashes. Test speeds that are too low will not provide adequate assessment of performance in crashes where significant injuries are possible, and speeds that are too high could result in designs that are inappropriate for many real-world crashes. Ideally, test speeds should be equivalent to the real-world impact severities in which serious injuries are possible but where appropriate designs could be expected to reduce or prevent serious injury.

The speeds of 48 km/h and 56 km/h chosen for the full-width-barrier tests for the first FMVSSs and later NCAP tests were somewhat arbitrary; they were chosen in large part because they represented round numbers in English units — 30 and 35 mph. Even though they were chosen somewhat arbitrarily, subsequent in-depth investigations of real-world frontal crashes have justified these choices. Designing restraint systems to perform well in 56 km/h NCAP tests appears to be an appropriate choice for current systems. Future so-called smart restraint systems may be capable of performing well in even higher speed tests without compromising their performance in the 32 to 56 km/h range of crash severity, but for many cars significant improvement in structural designs would be needed before even smart restraint systems could be expected to perform at higher speeds. The fact that structural integrity is one of the factors limiting restraint system performance reinforces the importance of offset tests to complement the full-width-barrier tests. An obvious question, however, is: What are the appropriate speeds to consider for such tests?

The most widely used measure of crash severity in real-world crashes is delta V, or change in velocity. This parameter is used in crash investigation programs around the world, and the values frequently are estimated from post-crash vehicle crush measurements using the CRASH3 computer program.[23] Other crash severity measures that have been used include the Equivalent Barrier Speed (EBS) and the Energy Equivalent Speed (EES).[24,25] In part because the various measures of crash severity produce very similar speeds for single-vehicle crashes with uniformly distributed damage, they are often used interchangeably and are often misinterpreted as being equivalent to test speeds.

This confusion begins with the definition of delta V, which has two components: an approach velocity change that ends when the vehicle is at maximum crush and a velocity of restitution as the vehicle rebounds.[26] The total velocity change is arguably the most appropriate definition of crash severity, because the occupant compartment experiences significant forces beyond maximum crush. However, the CRASH3 computer program estimates only the approach delta V, which is directly calculated from the estimated energy involved in the crush and the principle of conservation of momentum. Investigators have sometimes mistakenly equated delta V from CRASH3 with the total delta V experienced by vehicles in crash tests. But the confusion goes beyond the definition of delta V; it includes the appropriate interpretation of delta V in relation to crash test speeds.

Table 8 summarizes the test speeds and estimated delta V values from CRASH3 for the cars tested in this program. In the full-width barrier test there was reasonable agreement between the impact speed and the delta V. In the offset tests there were substantial differences between the computed delta V's and the test speeds. For the car-to-car tests the computed delta V's average 10 km/h lower than the impact speeds. In the two 30 percent overlap tests the difference was 17 km/h.

Table 8
Test Speeds and Estimated Delta V's from CRASH3
Car-to-Car and Car-to-Barrier Tests

Crash Type	Car Model	Nominal Overlap							
		100%		50%		40%		30%	
		Test Speed	ΔV	Test Speed	ΔV	Test Speed	ΔV	Test Speed	ΔV
Car-to-car	Oldsmobile Ciera			56	45				
				55	45				
				55	45				
				56	45				
				55	46				
				55	46				
				63	55				
				64	55				
	Chrysler LeBaron			56	43				
				57	43				
				64	58				
				64	58				
Rigid Barrier	Oldsmobile Ciera	55	52	56	46	55	49		
Deformable Barrier: Single-Stage	Oldsmobile Ciera			55	50	55	47	55	39
						60	53		
				62	57	63	58	63	47
Deformable Barrier: Single-Stage with Bumper Element	Oldsmobile Ciera					60	54		
	Chrysler LeBaron					60	50		
Deformable Barrier: Two-Stage	Oldsmobile Ciera					60	50		
						63	52		

* The energy absorbed by each deformable barrier was estimated from the volume of the crushed barrier, the compressive strength of the barrier, and the assumption that all of the crushing was produced by compression.

Similar results are available from other crash tests. In a series of five full-width and four partial-overlap frontal crash tests cited in Prasad's validation of a revised CRASH3 algorithm,[26] the delta V's estimated by the current CRASH3 program were lower than impact speeds for the offset crashes by a greater extent than for the full frontals.

These results have important implications when using real-world crash data to establish appropriate test speeds. It is sometimes mistakenly assumed that it is sufficient to look at the distribution of delta V's from real-world serious crashes to directly determine equivalent test speeds. Furthermore, the fact that delta V's approximate equivalent test speeds for full-width barrier crashes but not for offsets can lead to an underestimation of the importance of the latter configuration in real-world crashes if the data are classified by delta V.

Tables 9 and 10 illustrate this problem using NASS data. Table 9 shows NASS data from two-vehicle frontal crashes categorized by delta V. Among the cars in all towaway crashes, 47 percent have front-end direct damage involving two-thirds or less of the front-end of the car, but as the crashes with lower estimated delta V's are eliminated, the proportion of crashes with this asymmetric direct damage decreases. Thus, for frontal crashes with delta V's of 32 km/h or greater, for example, only 33 percent have asymmetric front-end damage in this crash severity range, compared with the 47 percent for all towaway crashes. If delta V's are misinterpreted as indicators of equivalent test speeds, it is possible to mistakenly assume that asymmetric front-end direct damage is less important in higher speed crashes. What is actually happening is that in the asymmetric crashes, the delta V's are substantially less than actual crash or equivalent test speeds, whereas in the crashes with distributed damage the delta V's are reasonable approximations of equivalent test speeds. The same effect is seen in Table 10 for single-car crashes. Here, as before, for the cars with distributed damage, the delta V's can provide a reasonable first approximation of either impact or equivalent test speeds but they underestimate the impact or equivalent test speeds in asymmetric front-end crashes. If test speeds for offset crashes are chosen to match delta V's, they will be too low.

DISCUSSION

In the United States, frontal crashes with direct damage involving two-thirds or less of the front-end of the car are at least as common as crashes with direct damage distributed across the front-end. The NASS data presented in this paper support the claims by Mercedes-Benz and others that full-width-barrier tests do not sufficiently represent the spectrum of real-world frontal crashes to be used as the only measure of frontal car crashworthiness. These data support the view that a minimum of two tests is needed to assess car crashworthiness in frontal crashes: a full-width-barrier test to assess restraint system performance, and an offset test to assess structural integrity.

The crash test results presented in this paper support the use of deformable faces in offset tests as a way of providing a reasonable approximation of actual car-to-car crashes. The results also support the choice of a 40 percent overlap, a single-stage deformable barrier with a bumper element as an appropriate barrier face, and a test speed higher than used for full-width-barrier tests.

However, the appropriate measures of performance to assess crashworthiness in such offset tests and optimum test speeds are still not clear. The offset tests of Cieras and LeBarons produced relatively low head, chest, and femur injury measures on the Hybrid III, even in most of the 64 km/h tests. NHTSA offset car-to-car tests have also produced similarly low injury results.[13] This suggests that the most relevant focus for many cars in the U.S. market will be on the lower-leg injury measures. The current Hybrid III knee, ankle, and foot are simplistic representations of the human anatomy, and the current understanding of lower-limb injury mechanisms is incomplete. In this test program, lower-leg measurements were taken but their relationship to injury potential in these crashes is not entirely clear, although there are indications that they may correlate with appropriate measures of intrusion. Measuring intrusion would seem to be an obvious way of

Table 9
Passenger Car Direct Damage in Frontal Crashes*
Two-Vehicle Crashes
National Accident Sampling System 1990-92

Direct Damage	All Towaways		ΔV ≥ 16 km/h		ΔV ≥ 24 km/h		ΔV ≥ 32 km/h		ΔV ≥ 40 km/h	
	No.	Percent	No.	Percent	No.	Percent	No.	Percent	No.	Percent
Distributed	**1,402**	**52**	**1,260**	**56**	**850**	**62**	**451**	**67**	**227**	**69**
Left 2/3	446	17	385	17	227	17	109	16	57	17
Left 1/3	270	10	185	8	81	6	20	3	9	3
Right 2/3	354	13	287	13	159	12	73	11	28	9
Right 1/3	199	7	128	6	47	3	17	3	4	1
Subtotal	**1,269**	**47**	**985**	**44**	**514**	**37**	**219**	**33**	**98**	**30**
Center	**10**	**0**	**8**	**0**	**7**	**1**	**3**	**0**	**2**	**1**
Total	**2,681**	**99**	**2,253**	**100**	**1,371**	**100**	**673**	**100**	**327**	**100**

(Crash Severity)

* Cases with direct damage to the front of the vehicle, a principle direction of force between 11 and 1 o'clock, and an estimated ΔV.

Table 10
Direct Damage Location in Frontal Crashes*
Single-Car Crashes
National Accident Sampling System 1990-92

	Crash Severity									
Direct Damage Location	All Towaways		ΔV ≥ 16 km/h		ΔV ≥ 24 km/h		ΔV ≥ 32 km/h		ΔV ≥ 40 km/h	
	No.	Percent	No.	Percent	No.	Percent	No.	Percent	No.	Percent
Distributed	**173**	**23**	**169**	**24**	**136**	**25**	**103**	**29**	**58**	**32**
Left 2/3	125	16	121	17	111	20	78	22	43	23
Left 1/3	90	12	76	11	49	9	24	7	12	7
Right 2/3	150	20	140	20	110	20	69	19	31	17
Right 1/3	160	21	140	20	83	15	43	12	20	11
Subtotal	**525**	**69**	**477**	**67**	**353**	**65**	**214**	**60**	**106**	**58**
Center	**68**	**9**	**68**	**10**	**56**	**10**	**39**	**11**	**19**	**10**
Total	**766**	**101**	**714**	**101**	**545**	**100**	**356**	**100**	**183**	**100**

* Cases with direct damage to the front of the vehicle, a principle direction of force between 11 and 1 o'clock, and an estimated ΔV.

assessing structural performance in offset tests, but again some caution is necessary. Absent any energy-absorbing material or designs in the footwell region, it is possible to assert that intrusion is not desirable and that the more intrusion the poorer the structural performance. However, if energy-absorbing material and/or designs are used in the footwell area, then it is possible that some intrusion with energy-absorption designs is better than no intrusion without energy-absorption.

Obviously, more work is needed to definitively resolve these questions; however, there is already a sufficient basis for beginning offset testing programs to assess and compare cars. Such a program has now begun in Australia and the first results have recently been published.[5] The Institute plans similar programs for new cars in the U.S. market for later this year. It is time to begin to expand offset testing so that this important aspect of vehicle design — structural integrity in asymmetric crashes — becomes an important consideration for all manufacturers. It is important for auto manufacturers to focus on this aspect of design as soon as possible if they are not already doing so, because the countermeasures and improvements needed typically will involve structural designs, and as such they are more likely to be implemented for new vehicle platforms as opposed to modifications of existing platforms. The sooner that all new car platforms are designed to perform well in real-world crashes where only part of the front-end of the car is in direct contact during the impact, the sooner we can look forward to reductions in the frequency and severity of many of the injuries — especially lower-limb injuries — that still occur to occupants protected by lap/shoulder belts and air bags.

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APPENDIX

This appendix summarizes the test procedures and the results not included in the main body of the paper.

The cars tested in this program were 1985-87 Oldsmobile Cutlass Ciera four-door models and 1989 Chrysler LeBaron convertibles and two-door coupes. The model years and vehicle weights of the test cars are summarized in Tables A1 and A2.

Table A3 summarizes the nominal and actual test speeds to the nearest km/h. In only one test (Ciera into the single-stage deformable barrier with 50 percent overlap and a nominal speed of 64 km/h) was the actual test speed more than 1 km/h different than the nominal speed.

Table A4 summarizes the nominal and actual front-end overlaps. In general, the nominal and actual overlaps were in reasonably close agreement. There were two crashes (Ciera and LeBaron car-to-car tests) where the actual overlap was significantly higher than the nominal overlap.

Each test car had a 50th percentile male Hybrid III instrumented test dummy in the driver seating position. The seat position, seat back angle, and dummy were set according to the procedures specified in FMVSS 208. The HIC, Chest G, chest deflection, and maximum femur force results are shown in Table A5.

After testing, the vehicle deformation was measured at eleven points across the car at bumper height. In addition, interior intrusion measures were taken, using the following procedures: Several targets were selected to represent various structures that might intrude into the occupant compartment. These included the instrument panel, steering column, brake pedal, and toe-pan. The targets were identifiable and part of the "hard" structure. Examples of the targets included screws into the dashboard; in the case of the toe-pan, there were marks left in the sheet metal by the stamping process. The positions of these targets were measured to a datum line that was stretched between the driver and right front passenger D-ring anchorages on the B-pillars. The distances to the targets were measured along the lines that were perpendicular to the datum line across the car.

The distance between the datum line and the targets, and the angles of the measurements with respect to the horizontal were recorded. The values reported in the tables of this paper are simply the differences between the datum line-to-target measurements made on an untested car of the same model and the datum-to-target measurements made on the test cars.

Figure A1
Deformable Barrier Faces and Diminsions

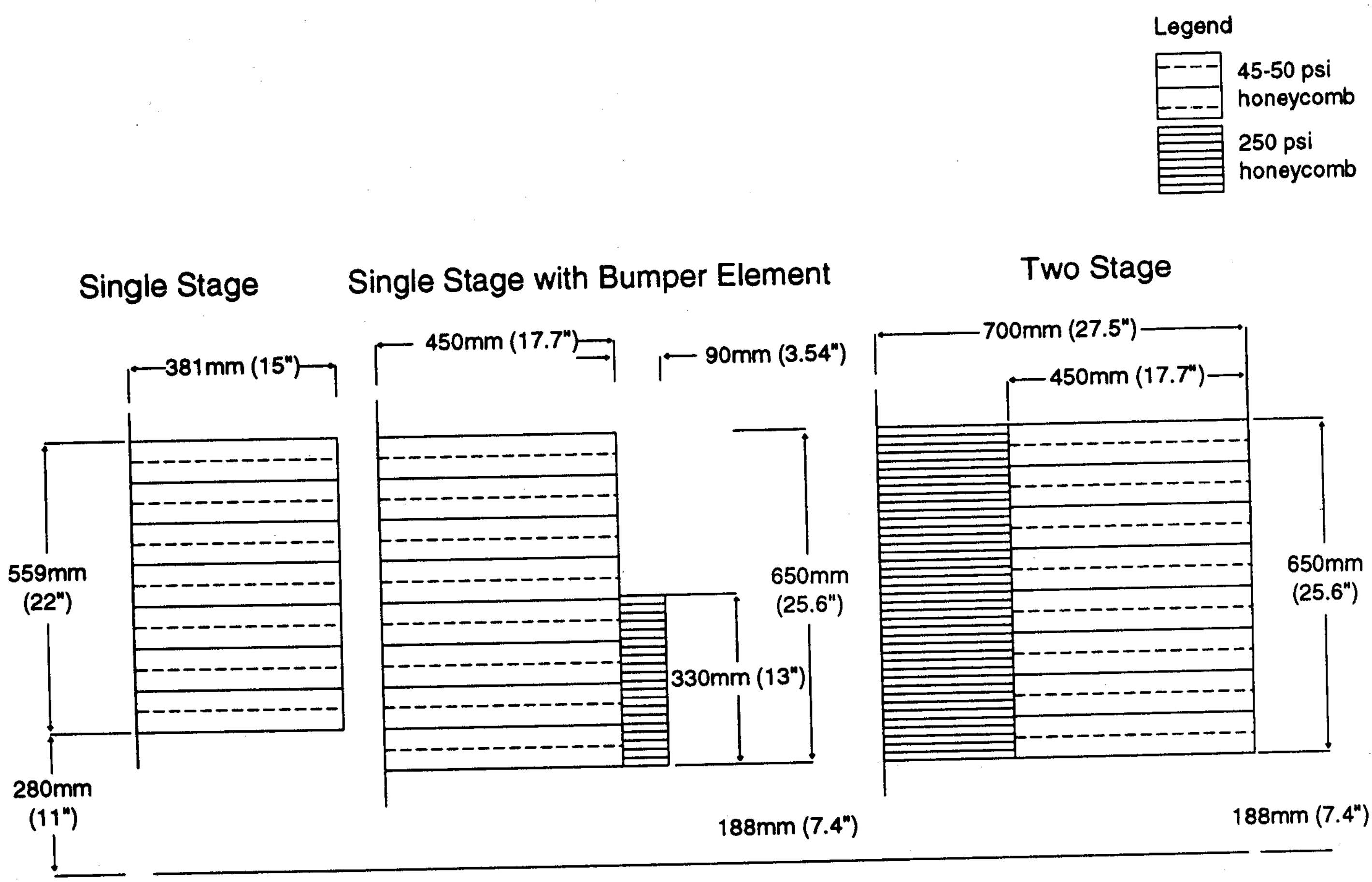

Table A1
Model Years of Cars Tested

Crash Type	Car Model	Nominal Test Speed (km/h)	Model Year			
			Nominal Overlap			
			100%	50%	40%	30%
Car-to-car	Oldsmobile Ciera	56		1989		
		56		1989		
		56		1989		
		56		1989		
		56		1989		
		56		1989		
		64		1988		
		64		1989		
	Chrysler LeBaron	56*		1989		
		56		1989		
		64*		1989		
		64		1989		
Rigid Barrier	Oldsmobile Ciera	56	1987	1987	1986	
Deformable Barrier Single Stage	Oldsmobile Ciera	56		1985	1987	1987
		60			1985	
		64		1985	1985	1987
Deformable Barrier Single Stage with Bumper Element	Oldsmobile Ciera	60			1986	
	Chrysler LeBaron	60*			1989	
Deformable Barrier Two Stage	Oldsmobile Ciera	60			1986	
		64			1989	

* LeBaron Convertible

Table A2
Weights of Cars Tested

Crash Type	Car Model	Nominal Test Speed (km/h)	Vehicle Weight (kg)			
			Nominal Overlap			
			100%	50%	40%	30%
Car-to-car	Oldsmobile Ciera	56		1377		
		56		1377		
		56		1369		
		56		1372		
		56		1359		
		56		1343		
		64		1346		
		64		1347		
	Chrysler LeBaron	56*		1414		
		56		1409		
		64*		1419		
		64		1427		
Rigid Barrier	Oldsmobile Ciera	56	1371	1390	1390	
Deformable Barrier Single Stage	Oldsmobile Ciera	56		1393	1393	1373
		60			1405	
		64		1325	1403	1401
Deformable Barrier Single Stage with Bumper Element	Oldsmobile Ciera	60			1387	
	Chrysler LeBaron	60*			1419	
Deformable Barrier Two Stage	Oldsmobile Ciera	60			1383	
		64			1335	

* LeBaron convertible.

Table A3
Nominal and Actual Test Speeds

Crash Type	Car Model	Nominal Test Speed (km/h)	Actual Test Speeds (km/h)			
			Nominal Overlap			
			100%	50%	40%	30%
Car-to-car	Oldsmobile Ciera	56 56 56 56 56 56 64 64		56 55 55 56 55 55 63 64		
	Chrysler LeBaron	56* 56 64* 64		56 57 64 64		
Rigid Barrier	Oldsmobile Ciera	56	55	56	55	
Deformable Barrier Single Stage	Oldsmobile Ciera	56 60 64		55 62	55 60 63	55 63
Deformable Barrier Single Stage with Bumper Element	Oldsmobile Ciera	60			60	
	Chrysler LeBaron	60*			60	
Deformable Barrier Two Stage	Oldsmobile Ciera	60 64			60 63	

* LeBaron Convertible

Table A4
Nominal and Actual Front-End Overlaps

Crash Type	Car Model	Nominal Test Speed (km/h)	Actual Overlap (%) Nominal Overlap 100%	50%	40%	30%
Car-to-car	Oldsmobile Ciera	56 56 56 64		52 62 57 55		
	Chrysler LeBaron	56 64		48 62		
Rigid Barrier	Oldsmobile Ciera	56	100	49	40	
Deformable Barrier Single Stage	Oldsmobile Ciera	56 60 64		50 50	40 37 43	31 29
Deformable Barrier Single Stage with Bumper Element	Oldsmobile Ciera	60			37	
	Chrysler LeBaron	60*			40	
Deformable Barrier Two Stage	Oldsmobile Ciera	60 64			41 43	

* LeBaron Convertible

Table A5
Hybrid III Injury Criteria Results

Crash Type	Car Model	Nominal Speed km/h	Nominal Overlap %	HIC	Hybrid III Injury Criteria: Chest G (g)	Chest Deflection (cm)	Maximum Fermur Force (N): Left	Right
Car-to-Car	Oldsmobile Ciera	56	50	640	—	3.7	6100	—
		56	50	665	—	4.9	3670	5220
		56	50	921	46	4.8	1050	4940
		56	50	626	44	3.6	710	6580
		64	50	559	49	**5.1**	2090	7430
		64	50	**1240**	51	3.3	2960	**9490**
	Chrysler Lebaron	56*	50	167	28	2.8	1340	3070
		56	50	210	32	1.3	**9790**	5960
		64*	50	592	44	3.6	8770	6420
		64	50	440	58	2.3	2780	7460
Rigid Barrier	Oldsmobile Ciera	56	100	917	37	**5.0**	4740	2530
		56	50	—	—	—	—	—
		56	40	574	41	4.8	3020	5070
Single Stage Deformable Barrier	Oldsmobile Ciera	56	30	321	25	2.3	2150	3530
		56	40	—	33	—	2020	3170
		56	50	673	38	4.1	2220	5550
		60	40	658	41	4.2	1440	6990
		64	30	602	36	4.6	2000	2540
		64	40	**1090**	52	**5.8**	2900	—
		64	50	386	—	2.5	1870	5670
Single Stage with Bumper Element	Oldsmobile Ciera	60	40	620	47	4.5	6080	6370
	Chrysler Lebaron	60*	40	149	18	2.8	2440	1650
Two Stage Barrier	Oldsmobile Ciera	60	40	518	37	4.2	700	4140
		64	40	544	32	3.3	1620	2140

Results in bold type exceed the published injury thresholds.[22]
* LeBaron convertible.

Theoretical Optimization Study of an Airbag System

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Paper No. 94 S4 O 20

ABSTRACT

In this paper we present a theoretical study for an optimization process of an airbag system. We are using simulation methods for this study to show the relevance of different parameters in the development process.

First, we investigate several influence parameters affecting the contact between dummy and airbag, such as contact velocity, contact time, pressure level and vent sizes.

We then present some conclusions concerning the development process, especially under the consideration of different dummy sizes.

INTRODUCTION

The design of an airbag system should satisfy different demands, the most important of which are the effectiveness under various collision conditions and for different sized occupants. These requirements should be taken into account at an early stage of the development process.

In the airbag development, different types of impact are performed as standard tests (50 km/h, 100%, 0°; 50 km/h, 100%, 30° with anti-slide device; 55 km/h, 50%, 15°; 50 km/h pole impact).

The stiffest pulse, which brings the severest requirements for the restraint system, occurs for the 100%, 0° test. This pulse leads to the earliest firing time. It is sensible to use this pulse for the airbag design. The other pulses have to be taken into account for the size of the airbag. It has to be chosen such that the dummy will hit the airbag also in the impact cases with a relevant lateral movement.

In the following investigations, we take the pulse from a 100%, 0° impact against a rigid barrier of an Opel Corsa as a base. We chose the smallest Opel car, since the pulse for a small car is stiffer than for a larger one.

The inflator is a fundamental part of the airbag system. Since this is a theoretical study and we are not concerned with the construction of the investigated inflators, we use constant values for the mass flow rate. For our study only the amount of gas and the filling time are of interest, since we do not consider out-of-position situations. As a starting point we use a mass flow rate, that leads to the same total gas mass and a very similar behaviour of pressure and volume in the airbag as with a standard driver airbag inflator.

Usually, when investigating the restraint effect of an airbag system, the 50th percentile dummy is used. For legal requirements it is the only relevant case, but probably all firms include injury criteria for the 5th and 95th percentile dummy in their in-house crash requirements. In the following, we will identify some important physical events in the airbag-dummy contact. We are interested in the effect on the injury risk of the occupant and we want to show the varying importance of these effects for the three different dummies.

Our investigation concerns only belted occupants. We consider mainly the resultant head acceleration, which is the dummy value most affected by the different airbag parameters. The effect on the upper torso acceleration is less, but its tendency is normally the same as for the head acceleration. The effect on the lower torso is neglectable. With unbelted occupants, the results of the study would possibly differ.

For our simulation studies we used the program MADYMO from TNO with the MADYMO Finite Element airbag.

SOME EFFECTS CONCERNING AIRBAG CONTACT

Velocity of dummy at time of airbag contact

To investigate the effect of the contact velocity, we construct a simple model including only an airbag, with vents and tethers, and an ellipsoid with the effective mass and the geometrical shape of a 50th percentile dummy head. No acceleration pulse is defined. The first contact with the airbag occurs when the mass flow ends, i. e. when the airbag is filled completely.

Figure 1 shows the peak values of the resultant head accelerations at initial velocities of 2 m/s, 4 m/s and 6 m/s. The peaks are in approximately the same ratios as the initial velocities. The head acceleration decreases with decreasing impact velocity.

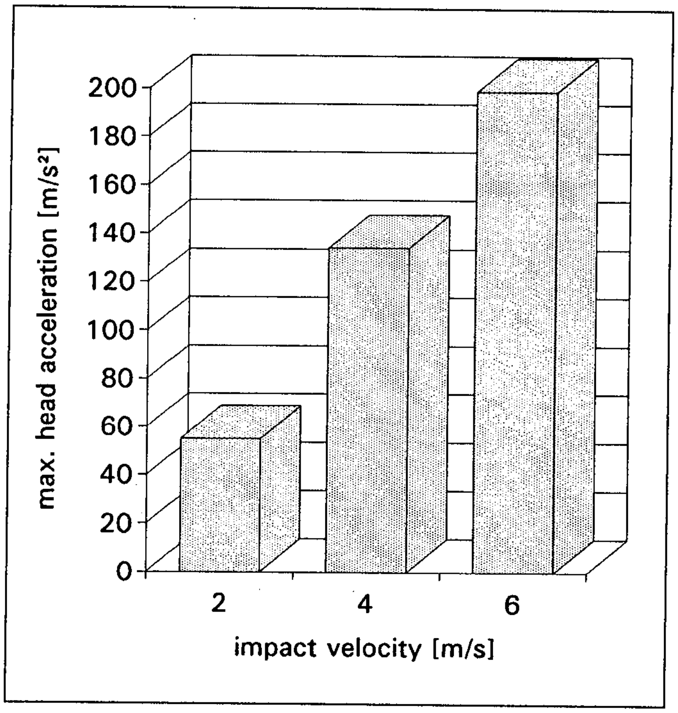

Figure 1: Maximum resultant head acceleration depending on the contact velocity

From this result, we conclude that the first contact with the airbag should be as early as possible since the impact velocity increases with time. Therefore, the horizontal extension of the airbag should be as large as possible in order to minimize the time before airbag contact.

Airbag contact at different times during inflation process

Again, the simple model with only an airbag and a head is used. The head has an initial velocity of 2 m/s. Different initial locations were chosen, causing contact at different times. The mass flow lasts 26 ms, corresponding to a normal filling time for an driver airbag. Figure 2 shows that when contact occurs before the end of inflation, there is a tremendous increase in the maximum head acceleration. The contact which occurs after the inflation has been completed influences the head injuries much less.

To investigate the effect of the contact time for various mass flow rates, in addition, two other mass flow rates were considered, 25% and 50% higher than

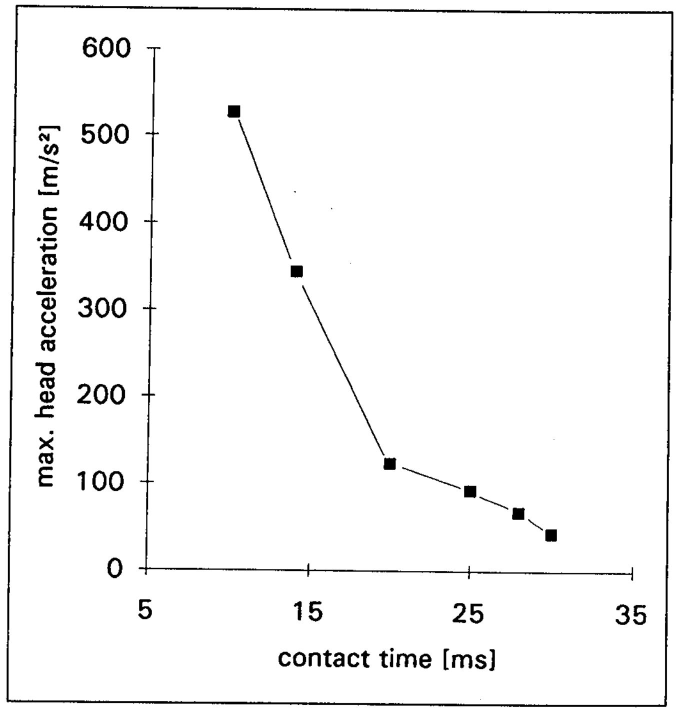

Figure 2: Maximum resultant head acceleration depending on the contact time

the reference rate. In Figure 3, we show that the influence of the contact time grows with the mass flow rate. The higher the mass flow rate, the more important the contact time is for the level of the head accelerations.

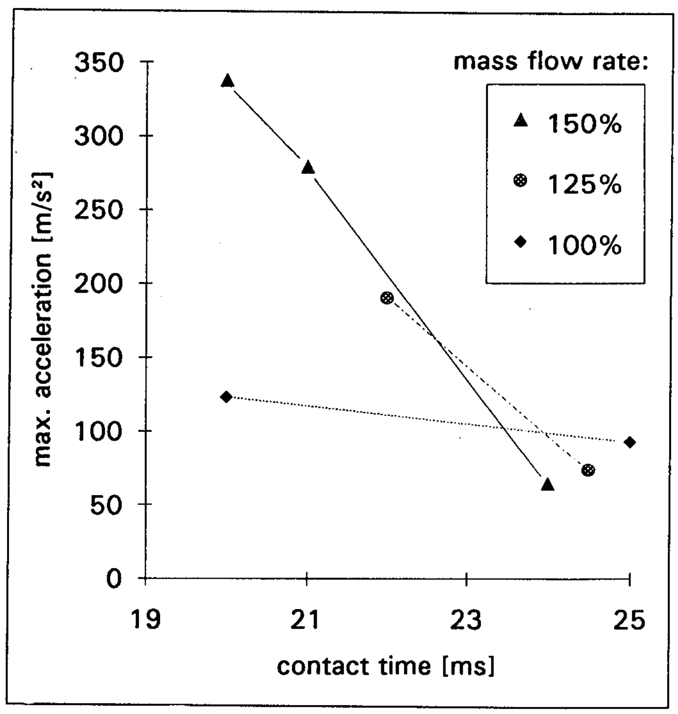

Figure 3: Maximum resultant head acceleration depending on the contact time and the mass flow rate

From this result, we conclude that the first contact with the airbag should not preceed the end of inflation.

Pressure level or total gas mass

In this section we use a driver-side model for the Corsa in a 100%, 0° frontal impact against a rigid barrier. The model includes a 50th percentile Hybrid III dummy, the seat, the floor, the instrument panel, the windscreen, the steering wheel and the airbag. To achieve a higher pressure in the bag at the time of contact, the total gas mass was increased so that the pressure was doubled. The mass flow rate remained the same and the firing time was chosen to ensure that the airbag was fully inflated at the same time. The resultant acceleration increases by 28% (see Figure 4).

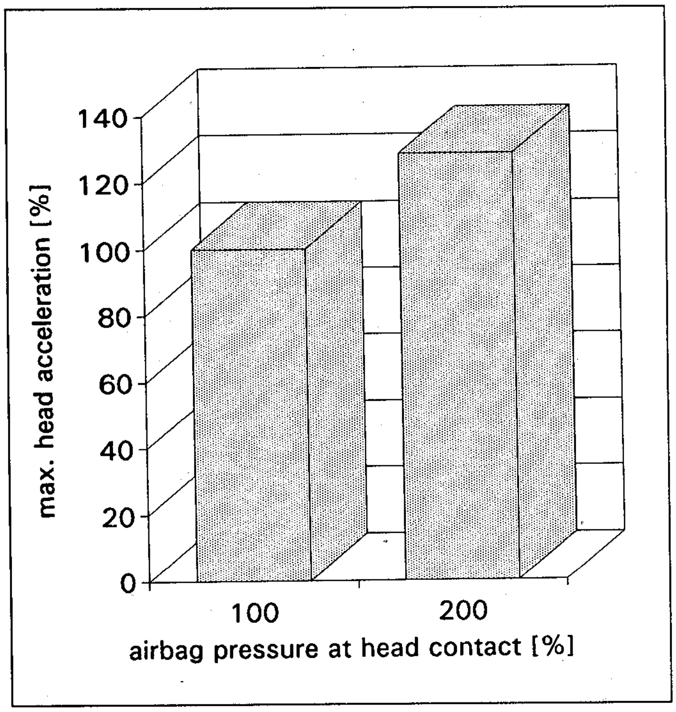

Figure 4: Maximum resultant head acceleration depending on airbag pressure

This result demonstrates that it is preferable to achieve a lower pressure in the bag, which is attainable with a smaller amount of gas mass.

Vent size

Altering the size of the ventholes in the airbag affects the amount of exhausting gas and therefore the pressure in the airbag. The same effect can be produced by altering the permeability of the airbag material. We used the same model as in the section above, with two different gas masses and firing times. In each case the area of the ventholes was multiplied by a factor of 0.5 or 1.5.

Figure 5 shows that the peak resultant acceleration of the head decreases with the increase in size of the ventholes. The effect of the vent size increases with the total gas mass and the pressure in the bag.

We conclude that the ventholes in the bag should be as large as possible.

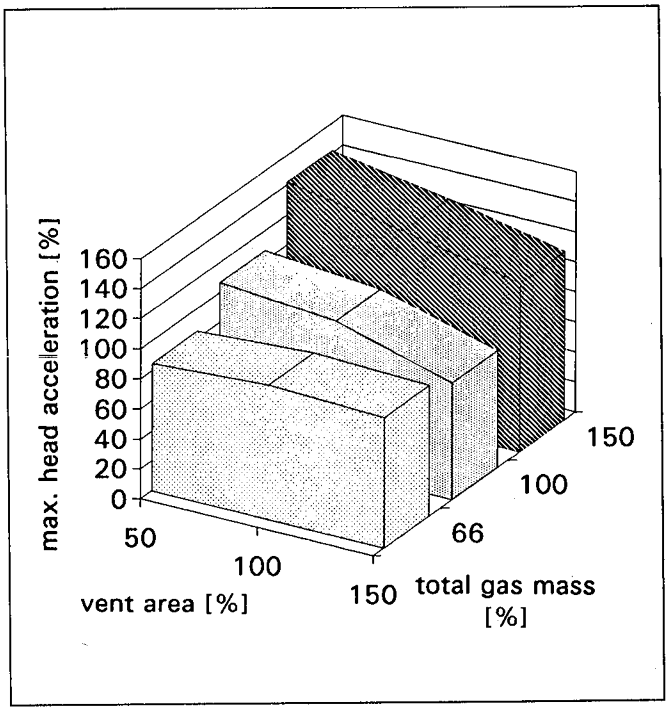

Figure 5: Maximum resultant head acceleration depending on the vent size and the airbag pressure

SUMMARY OF AIRBAG INVESTIGATIONS

The different influence parameters investigated above lead to several conclusions, which are partly contradictory. The most important factor for the head acceleration is the contact time. To achieve contact at a low velocity, the airbag contact has to be as early as possible. On the other hand, the contact has to be as late as possible to avoid contact during the inflation process.

In all circumstances, a low pressure is advantageous. This reduces the head acceleration. In addition, other parameters like vent size and contact time become less important at a lower pressure. This simplifies the design process. The pressure should be as low as possible while preserving the airbag function: to prevent the occupant from hitting the steering wheel. A lower pressure can be achieved by having less gas or larger ventholes. Since it is also desirable to save gas mass in order to have a smaller and cheaper inflator, we suggest a small gas mass coupled with small ventholes rather than larger ventholes coupled with more gas mass.

Considering the different dummy sizes leads to various difficulties. A low airbag pressure, as suggested above, may cause a problem for the large male, since with too small a pressure he may go through the airbag and strike the steering wheel. An even bigger problem is the risk of the inflating airbag hitting the small female. As seen above, this worsens the head injuries dramatically. A further risk induced by hitting the inflating airbag, is the backward neck momentum, which causes severe neck injuries. The effect of hitting the airbag too early is much worse than that of hitting the airbag at some time after the end of inflation. It may be possible to permit a light steering wheel contact, but we have not investigated the effect of a contact with the stiff inflator box.

CONCLUSIONS FOR AIRBAG DESIGN

Since the 5th percentile dummy is in the frontmost seating position there is little space and time to restrain the small females. The high injury risk for small occupants shown above, must be reduced. Therefore the airbag must be optimized for the 5th percentile dummy, subject to the reqirement that the 95th percentile may not go through the airbag and strike the steering wheel.

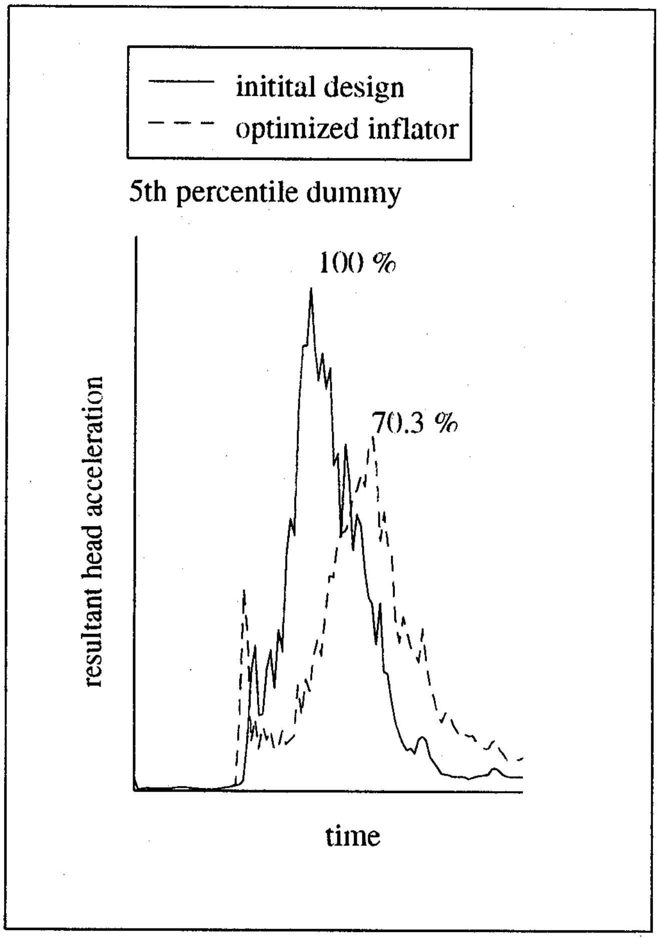

Figure 6: Resultant head acceleration for the small female with optimized inflator

In this paper we want to point out a guideline for the optimization of an airbag for a 50 km/h impact. A basic decision is whether to design the airbag system for this velocity only or also for higher ones. This does not affect our principal conclusions and suggestions, but is just a question of the pulse to be investigated.

Our conclusions for the optimization of an airbag system design are the following:

The standard airbag with a given tether length yields a certain distance between the initial position of the dummy head and the inflated airbag. Integrating the acceleration pulse twice we determine the time for the dummy head travelling this distance. Within this time the airbag should be inflated. Results from out-of-position tests give us a maximum permitted mass flow rate. The inflator should have this mass flow rate during the time period determined above. This results in a particular total gas mass. Figure 6 shows the improvement of the resultant head acceleration compared to the initial design. In this case, we also avoid the high backward neck momentum occurring formerly. If the determined gas mass is too small to fill the airbag, one could have an earlier firing time or change the bag size or tether length.

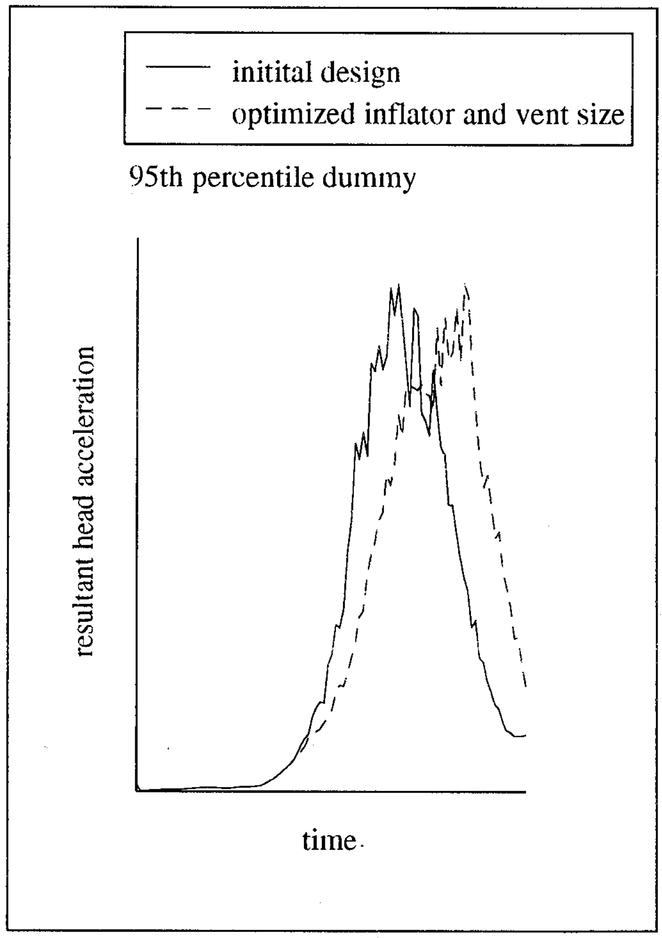

Figure 7: Resultant head acceleration for the large male with optimized inflator and optimized vent size

However, this inflator design does not fulfil the restraint function for the large male. The airbag is insufficiently stiff to prevent him from hitting the steering wheel. Therefore, the vent holes were reduced to prevent the large male from hitting the steering wheel. With the inflator optimized for the 5th percentile and the reduced size of the ventholes the resultant head acceleration is the same as before the optimization, only the time of the peak value varies (see Figure 7).

With this altered design the head injury risk for the 50th percentile dummy remains the same. The effects of the lower gas mass and the smaller ventholes cancel out.

The reduced vent sizes hardly effect the head injury values for the small female because of the low pressure in the bag (see Figure 8).

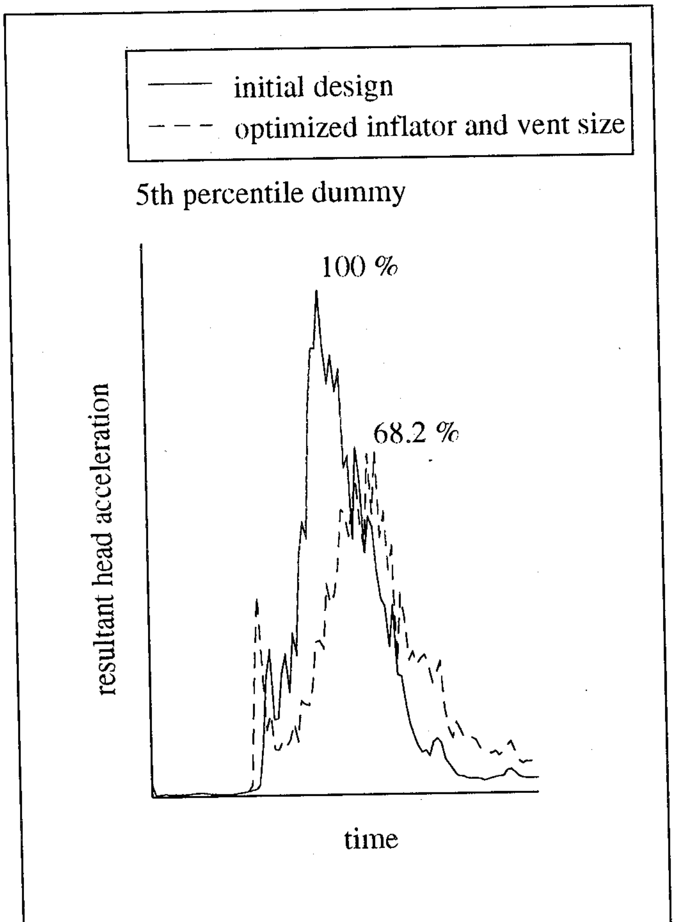

Figure 8: Resultant head acceleration for the small female with optimized inflator and optimized vent size

SUMMARY

In this theoretical study, based on simulation results, we investigated several parameters affecting the contact between dummy and airbag. The severest difficulties are when contact occurs before the end of the inflation process. Since the small female is in the frontmost seating position, the optimization process has to be directed mainly to this case. This study shows that we achieve a injury risk for all dummy sizes with an optimization for the small female. Therefore, we recommend the consideration of the 5th percentile dummy already in the beginning of the development process. Also the development time for an optimal airbag will be reduced with this procedure.

ACKNOWLEDGEMENTS

We would like to thank our colleague Thomas Römer from the airbag center for helpful discussions and several suggestions concerning this study. Günther Schmall from the safety center assisted us with a lot of information concerning safety tests.

In Depth Analysis of Frontal Collisions as Regards the Influence of Overlap and Intrusion on Occupant Severe and Fatal Injuries

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94-S4-O-21

ABSTRACT

Improvements in frontal belted car occupant protection are the first priority in passive safety.

Passenger compartment intrusion is considered by some as one of the main limiting factors of belt effectiveness.

It is proposed to examine the effect of different amounts of intrusion (at the dashboard level but also at the footwell level) on overall severity of injuries ,but also in order to point out the balancing effect between intrusion and acceleration.

The most effective protection of vehicle occupants can only be based on the analysis of real world crashes. This analysis concerns the intrusion but also the overlaps observed in frontal impact for the restrained front belted occupants and uses two sources :

- -detailed survey by the PSA Peugeot-Citroën / Renault L.A.B covering 8,000 vehicles and 14,000 occupants.
- -the study of 1,280 police reports on fatal accidents which occurred in France in the second quarter of 1990.

IMPORTANCE OF FRONTAL IMPACT. TYPES OF COLLISIONS AND OBSTACLES

Protection in frontal impact is clearly the priority (Tables 1 and 2) : 70 % of restrained severe injuries and 48 % of fatalities.

	Cars	Trucks**	Fixed obstacles	Without any obstacle	TOTAL
FRONTAL	44.4 %	9.2 %	16.9 %	-	70.5 %
LATERAL	10.9 %	2.0 %	5.6 %	-	18.5 %
REAR	1.5 %	0.7 %	0.3 %	-	2.5 %
ROLLOVER	-	-	-	6 %	6 %
OTHERS*	0.1 %	0.2 %	0.7 %	1.5 %	2.5 %
TOTAL	56.9 %	12.1 %	23.5 %	7.5 %	100 %

* Full in ravin, drowning, complex rollovers against fixed obstacles

** Including cab over engines and light trucks (20 % of all kind of trucks)

Table 1:Breakdown (%) of impact types and obstacles for severely injured (M.AIS 3-4-5) belted front occupants

	Cars	Trucks**	Fixed obstacles	Without any obstacle	TOTAL
FRONTAL	19.6 %	15.4 %	13 %	-	48 %
LATERAL	12.3 %	8.5 %	11.7 %	-	32.5 %
REAR	0.6 %	1.0 %	0.4 %	-	2 %
ROLLOVER	-	-	-	4 %	4 %
OTHERS*	0.8 %	1.3 %	6.5 %	4.9 %	13.5 %
TOTAL	33.3 %	26.2 %	31.6 %	8.9 %	100 %

* Full in ravin, drowning, complex rollover against fixed obstacles

** Including cab over engines and light trucks (20 % of all kind of trucks)

Table 2:Breakdown (%) of impact types and obstacles for fatally injured belted front occupants

Car-to-car impacts are in the majority both for M.AIS 3+ and for fatalities, at 60 % and 41 % respectively (Tables 3 and 4).

IMPACT CONFIGURATIONS	OBSTACLES			
	Cars	Trucks	Fixed obstacles	TOTAL
Head-on	49 %	10 %	-	59 %
Front-to-side collisions	9 %	3 %	-	12 %
Front-to-rear collisions	2 %	3 %	-	5 %
Fixed obstacle impacts	-	-	24 %	24 %
TOTAL	60 %	16 %	24 %	100 %

Table 3:Breakdown of 336 cars involved in frontal impacts with at least one M.AIS3+ front belted occupant on board according to the crash configuration

IMPACT CONFIGURATIONS	OBSTACLES			
	Cars	Trucks	Fixed obstacles	TOTAL
Head-on	35 %	25 %	-	60 %
Front-to-side collisions	6 %	2 %	-	8 %
Front-to-rear collisions	-	5 %	-	5 %
Fixed obstacle impacts	-	-	27 %	27 %
TOTAL	41 %	32 %	27 %	100 %

Table 4:Breakdown of 436 cars involved in frontal impacts with at least one fatally injured belted front occupant on board according to the crash configuration

The car-to-car head-on collision is the most frequent. It covers 49 % and 35 % of M.AIS 3+ and fatalities.

OBSERVED OVERLAPS AND THE SEVERITY OF RESTRAINED OCCUPANT INJURIES IN FRONTAL IMPACT

Overlaps according to collisions (Tables 5 and 6)

Whether for M.AIS 3+ or for fatalities, the mean overlap against all obstacles is 62%. The high proportion of fixed obstacles such as trees or poles in impacts which often have low offset are not covered by an impact of identical overlap and offset on the left.

In head-on car-to-car collisions, the mean overlap is 64%.

IMPACT CONFIGURATIONS	OBSTACLES		
	Cars	Trucks	Fixed obstacles
Head-on	64 %	62 %	
Front-to-side collisions	78 %	57 %	
Front-to-rear collisions	66 %	59 %	
Fixed obstacle impacts	-	-	46 %*
Average overlap	66 %	60 %	46 %*

The overall average overlap (all kind of obstacles gathered) is 62 %

* 38 % of low overlaps (≤ 40 %) against fixed obstacles (trees, poles) are centered on either longitudinal front beams or the engine (low offsets)

Table 5:Average front-end overlap percentage recorded for 336 cars with at least one M.AIS 3+front belted occupants on board

IMPACT CONFIGURATIONS	OBSTACLES		
	Cars	Trucks	Fixed obstacles
Head-on	65 %	67 %	-
Front-to-side collisions	73 %	68 %	-
Front-to-rear collisions	-	70 %	-
Fixed obstacle impacts	-	-	49 %*
Average overlap	66 %	67 %	49 %*

The overall average overlap (all kind of obstacles gathered) is 62 %

* 30 % of low overlaps (≤ 40 %) against fixed obstacles (trees, poles) are centered on either longitudinal front beams or the engine (low offsets)

Table 6:Average front-end overlap percentage recorded for 436 cars with at least one fatally injured front belted occupants on board

Head-on car-to-car impacts

<u>Overlaps</u> (Tables 7 and 8)

Whether for M.AIS 3+ injuries or for fatalities, most overlaps are <u>greater than 80%.</u>

Overlaps ≤ 40% are in minority : 17 to 20% depending on the severity.

The mean overlap is 65%.

FRONT-END OVERLAPS (%)	Number of cases (%)	
< 20	16 (10 %)	20 %
21-40	17 (10 %)	
41-60	27 (17 %)	
61-80	49 (30 %)	63 %
> 80	55 (33 %)	
TOTAL	164 (100 %)	

The average front-end overlap percentage is 64 %, the median is 69 %

Table 7: Front-end overlap percentage classes for 164 cars with at least one M.AIS 3+ front belted occupant on board (EES between 36 and 65km/h)

FRONT-END OVERLAPS (%)	Number of cases (%)	
< 20	6 (5 %)	17 %
21-40	14 (12 %)	
41-60	26 (23 %)	
61-80	28 (24 %)	60 %
> 80	41 (36 %)	
TOTAL	115 (100 %)	

The average front-end overlap percentage is 65 % the median is 68 %

Table 8: Front-end overlap percentage classes for 115 cars with at least one fatally injured front belted occupant on board

<u>Glance-offs</u> (Tables 9-10 and figure 1)

In car-to-car collisions, one sometimes observes (in 10 to 15% of all head-on collisions) a glance-off of one or both the vehicles.

<u>Definition</u>

The vehicle is considered to glance off (by rotation or slipping) either when:

-its stopping distance after the point of impact is greater than 10 m (provided that the opposing vehicle does not move backwards);

-its stopping distance relative to the final position of the opposing vehicle which has moved backwards is greater than 10 m.

In these circumstances, a large proportion of the impact energy is dissipated by slippage.

<u>Glance-off as a function of overlap</u>

When it occurs, glance-off is observed in nearly every case when the overlap is less than or equal to 40% for M.AIS 3+ injuries and in more than 80% of cases for fatalities when the overlap is less than or equal to 60%.

In fact, for all vehicles with an overlap less than or equal to 40% and on board which there is an M.AIS 3+ injury, <u>glance-off occurs in half the cases.</u> For fatalities, glance-off is <u>observed in 35% of cases</u>.

FRONT-END OVERLAP (%)	WITHOUT ANY glance-off	WITH glance-off
≤ 20	5	11
21-40	12	5
41-60	25	2
61-80	49	-
> 80	55	-
TOTAL	146 (89 %)	18 (11 %)

Table 9: Front-end overlap percentage classes for 164 cars with at least one M.AIS 3+ belted front occupant on board according to glance-off occurence

FRONT-END OVERLAP (%)	WITHOUT ANY glance-off	WITH glance-off
≤ 20	2	4
21-40	11	3
41-60	19	7
61-80	26	2
> 80	40	1
TOTAL	98 (85 %)	17 (15 %)

Table 10: Front-end overlap percentage classes for 115 cars with at least one fatally injured belted front occupant on board according to glance-off occurence

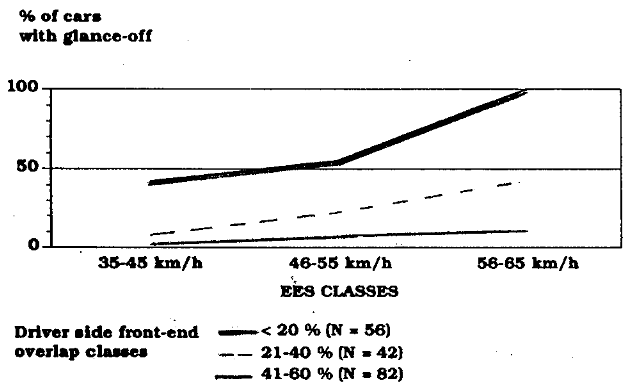

Figure 1: Glance-off frequency according to EES and front-end overlap classes

Meaning of this phenomenon

Glance-off is very hard or even impossible to reproduce against a fixed barrier.

The corresponding injury risk is chiefly located in the legs (foot/knee/femur), but on the other hand vital risks (head/thorax/abdomen) are low for the occupant placed on the offset side;

The passenger is generally unharmed or injured slightly in this configuration.

Angle of collision and overlap (Tables 11 and 12)

The angle formed by the two vehicles is on average 13° for head-on collisions. Overlap is greater for smaller impact angles.

FRONT-END OVERLAPS (%)	0° ± 15° (55 % of all cases)	30° ± 15° (45 % of all cases)
≤ 20	8 %	11 %
21-40	8 %	14 %
41-60	15 %	18 %
61-80	32 %	28 %
> 80	37 %	29 %
Average front-end overlap	79 %	60 %

THE AVERAGE COLLISION ANGLE IS 13°

Table 11: Front-end overlap percentage classes for 164 cars with at least one M.AIS 3+ belted front occupant on board according to the collision angle

FRONT-END OVERLAPS (%)	0° ± 15° (57 % of all cases)	30° ± 15° (43 % of all cases)
≤ 20	6 %	4 %
21-40	6 %	20 %
41-60	18 %	28 %
61-80	23 %	26 %
> 80	47 %	22 %
Average front-end overlap	70 %	58 %

THE AVERAGE COLLISION ANGLE IS 13°

Table 12: Front-end overlap percentage classes for 115 cars with at least one fatally injured belted front occupant on board according to the collision angle

Injuries according to overlap (Tables 13 and 14)

The impacts with the strongest left-hand offset (≤ 40%) represent a majority of injuries of the "femur-pelvis" segment for drivers, while head injuries in particular are insignificant, unlike a more representative impact of overlap ≥ 60% in which the head, the thorax and the femur are injured in the same way.

Offset tests neglect the severe head and chest injuries more frequently recorded in the highest front-end overlap cases

	DRIVER SIDE FRONT-END OVERLAP CLASSES (%)	
	< 40 % (N = 30)	60 % - 100 % (N = 53)
Head/Neck	3 %	25 %
Thorax	17 %	25 %
Abdomen	20 %	8 %
Pelvis/Femurs	43 %	26 %
Tibias/Ankles/Feet	17 %	16 %
TOTAL	100 %	100 %

Table 13: Breakdown (%) of 83 AIS3+ injuries recorded for belted drivers according to two opposite front-end overlap classes

For these overlap configurations, no severe injury is observed for restrained front passengers in the case of low overlap values. On the other hand, the severity is multiplied by nearly 20 for greater overlaps. Nearly all injuries appear at the thorax and abdomen level.

LOCALISATIONS	LESIONS
Head/Neck	7 %
Thorax	50 %
Abdomen	36 %
Pelvis/Femurs	3.5 %
Tibias/Ankles/Feet	3.5 %
TOTAL	100 %

Table 14: Breakdown (%) of 32 AIS3+ injuries recorded for 26 belted drivers according to driver side front-end overlap over 60%

A strongly offset impact therefore does not take into account the potential risks for front-seat passengers.

Conclusions concerning overlaps

Table 15, which summarizes the results of head-on collisions, shows that a representative test shall mandatorily:

-have an overlap with the obstacle of 65% on average (and a collision angle of 13°);

-include two instrumented dummies on the front seats.

It would thus cover 65% of restrained driver/front passenger pairs with injuries of severity M.AIS 3+ involved in possible impacts to be reproduced by testing, i.e. impacts in which all the energy is dissipated against the obstacle.

Front-end overlaps	% of cases (1)	M.AIS 3+ rate			Front seat occupant pair		
		for Drivers (N = 316) (2)	for Front passengers (N=160) (3)	Average for the front seat occupant pair (4) = (2)+(3):2	M.AIS 3+ harm (1) x (4)	M.AIS 3+ frequency	M.AIS 3+ frequency of crash test capabilities
≤ 40 % WITH glance-off	11 %	.52	0	.26	2.9	11 %	NOT feasible
≤ 40 % WITHOUT glance-off	20 %	.33	.02	.17	3.5	13 %	15 %
40 à 60 %	24 %	.25	.13	.19	4.6	18 %	20 %
60 à 100 %	45 %	.31	.36	.33	15.1	58 %	65 %
TOTAL	100 %				26.1	100 %	100 %

Table 15: Summary for belted front occupants involved in car-to-car head-on collisions (driver-side front-end overlaps between 10% and 100%, EES between 36 and 65km/h,speed biases corrected)

Table 16 shows that our conclusions are very similar to those published by Pete Thomas (Loughborough University of Technology) in Proceedings of the ISATA Conference - Aix La Chapelle - September 1993.

		Loughborough University of Technology (Pete Thomas)	L.A.B. PSA - RENAULT
AGAINST ALL KIND OF OBSTACLES GATHERED	Average Overlap		
	- M.AIS 3-4-5	63 %	57 % (65 %)*
	- Fatal	74 %	65 %
	Overlap Frequencies ≤ 50 % - M.AIS 3-4-5	39 %	30 % (26 %)
	- Fatal	29 %	31 %
AGAINST CARS	Average Overlap		
	- M.AIS 3-4-5	70 %	66 % (70 %)
	- Fatal	86 %	72 %
	Overlap Frequencies ≤ 50 % - M.AIS 3-4-5	34 %	25 % (19 %)
	- Fatal	27 %	20 %
	≤ 40 % - M.AIS 3-4-5	22 %	15 % (9 %)
	- Fatal	11 %	16 %

* without glance off

Table 16: Comparison of front-end overlaps recorded in two laboratories for severely and fatally injured front belted occupants

INTRUSION AND SEVERITY OF RESTRAINED OCCUPANT INJURIES

A rough evaluation of the severity (M.AIS 3+) according to the level of intrusion, without taking into account speed biases observed in each class, tends of course to show that severity is linked to the level of intrusion.

Figure 2 illustrates clearly what is mentioned in many publications. Without correcting for speed biases, our results are of the same order.

It is therefore essential to correct this bias so as to obtain an equivalent speed distribution for each class of intrusion.

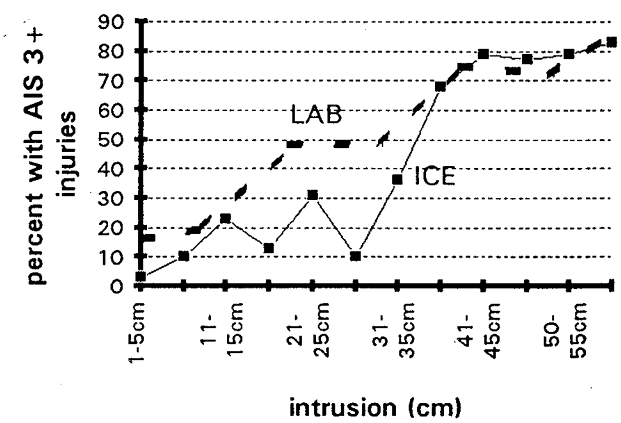

Figure 2: Comparison of percentages of M.AIS3+ front belted occupants according to the level of upper intrusion(I.C.E and L.A.B)

Injury severity for restrained drivers and intrusion

The very great majority of cases with intrusion occur on the driver side (83 %). A selection was therefore made of 354 restrained drivers involved in impacts with overlaps in the range between 10% left and 100%, and for delta-V values in the range between 36 and 65 km/h.

Figure 3 shows that:

- for the first two classes of intrusion, the injury severity and fatality rates are equivalent;
- for the third and fourth classes of intrusion (151-250 mm and 251-350 mm), injury severity increases but there is no change in fatalities;
- for strong intrusions (> 350 mm), the fatality rate becomes unacceptable.

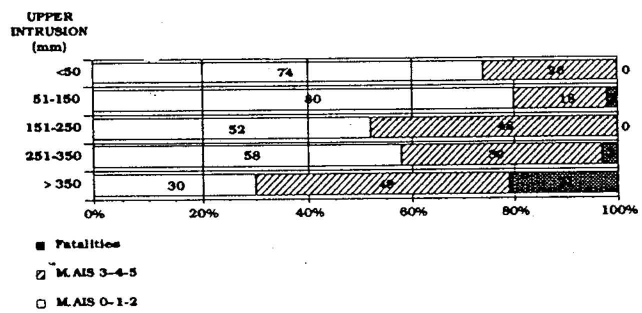

Figure 3: Increased risk for belted drivers as a function of upper intrusion in frontal impacts (corrected sample of 354 drivers between 36 and 65km/h of delta V, driver-side front-end overlaps between 10% and 100%)

This increase in severity for the two intermediate classes is due chiefly to an increased risk of injuries of the knee/femur/pelvis segment, as can be seen in Figure 4. For the other body areas, there is no increase in risk below 350 mm of intrusion; one even observes a reduction in the risk of thoracic injuries for intrusion in the range between 150 and 350 mm.

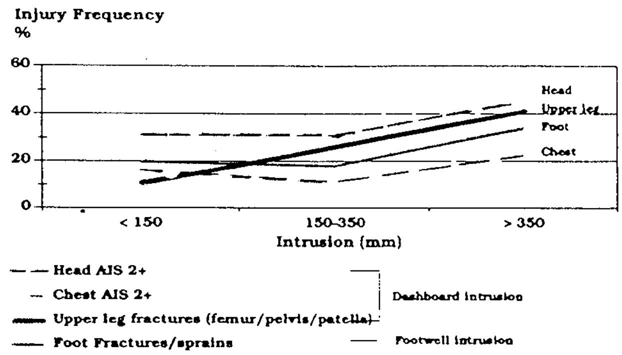

Figure 4: Body area injury risks for belted drivers(same frontal delta V distribution between 36 to 65 km/h,driver-side front-end overlaps between 10% and 100%)

Concerning foot injuries, one observes (Figure 5) that for intrusions of less than 150 mm or between 150 and 350 mm, the risk is identical. Moreover, from cases with a low intrusion level (< 150 mm), which represent 39 % of the injured occupants, around one half of the injuries are attributed to lateral movements occurring when the foot presses and slips off the pedals (sprains, malleolus fractures). One can also notice that the right foot sustains more injuries than the left does, due to direct impacts, (metatarsal fractures caused by the brake pedal impacting the foot).

BREAKDOWN OF 132 INJURIES

Footwell intrusion (mm)	% of cases	LEFT Ankle	LEFT Foot	RIGHT Ankle	RIGHT Foot	Injuries frequencies (%)
< 150	39	13	4	12	22	20
150 to 350	31	7	8	12	14	18
> 350	30	8	13	9	10	34

Ankle injuries : malleolus fractures, ankle sprains or dislocations.
Foot injuries : fractures of the metatarsals, cuneiform bones, navicular, talus, calcaneum and tibia pilon.

Figure 5: Ankle and foot injuries for the drivers

Finally, Figure 6 demonstrates that a large proportion (63%) of the 95 drivers with an injury level of M.AIS 3+ are observed without intrusion or for moderate intrusions (< 250 mm). If we were to take all drivers of M.AIS 3+ for all overlaps together (right and left offset), this percentage would reach 66%, of which half occur with no intrusion.

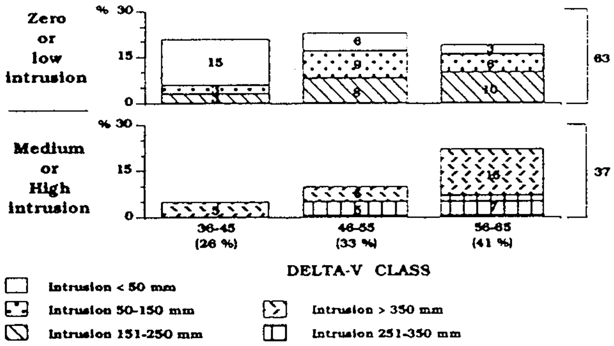

Figure 6: Breakdown(%) of 95 M.AIS 3+ belted drivers according to deltaV class (36 to 65km/h) and upper intrusion (driver-side overlaps between 10% and 100%)

Severity of restrained driver injuries and vertical movements of the steering wheel

It is important not to draw hasty conclusions with respect to neck risks due to vertical movements of the steering wheel. Figure 7, for example, shows that for 448 belted drivers including 290 with head impact against the steering wheel for the delta-V between 36 and 65 km/h (after correction of the observed speed variations for each displacement class):

-the frequencies of head to steering wheel impact (AIS 1+) rise significantly with increasing vertical displacement (measured by static testing).Thus, between displacements not in excess of 50mm and displacements greater than 120mm:

-the frequency of AIS 1+ rises from 53 to 87%,
-the frequency of AIS 2+ from 21 to 41%,
-the frequency of AIS 3+ from 0,5 to 6,6%

-for head impact, the proportions of AIS 2+ increase as well, rising from 40 to 47% (test chi 2:significant difference at the threshold of .20 only), the proportions of AIS 3+ increase, for their part, from 1 to 8% and so a significant difference at the .07 threshold is observed (test chi 2 with Yates correction)

-cervical fractures (AIS 2+) remain very uncommon (7 cases, corresponding to 1,6%), and these risks cannot be associated with vertical displacement of the steering wheel (3 cases without signification ascent, 2 in the intermediate class and 2 cases of ascents in excess of 120mm)

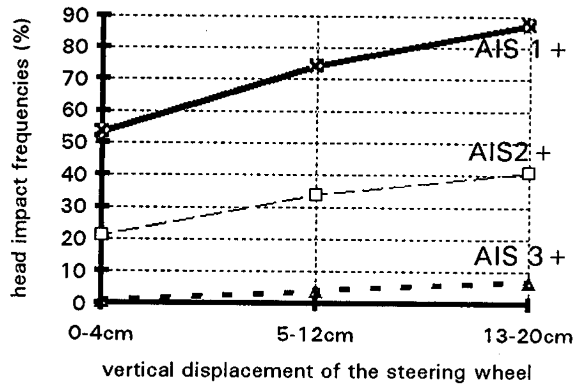

Figure 7 : Frequency and severity of head impacts against steering wheel according to vertical displacements of the steering wheel for 448 drivers

Severity of restrained passenger injuries

For left-offset frontal impacts, for an identical impact violence, the greater the intrusion on the driver side, the lower the risk for the passenger. Hence, injury severity goes from 0.31 to 0.21 for driver side intrusion below and above 250 mm respectively, and the fatality rate from 0.07 to 0.

Deceleration is the main cause of injuries, since taking all overlaps together, for half of the 12 front-seat passenger fatalities, there is no intrusion (< 50 mm) and in the case of ten intrusions it does not exceed 250 mm. Moreover, for all M.AIS 3+ injuries, the thorax and abdomen are the body areas most frequently injured, nearly always without intrusion. One can observe in Figure 8 that 58% of passengers with injury severity M.AIS 3+ sustain no intrusion and that for 84% of them this intrusion does not exceed 250 mm.

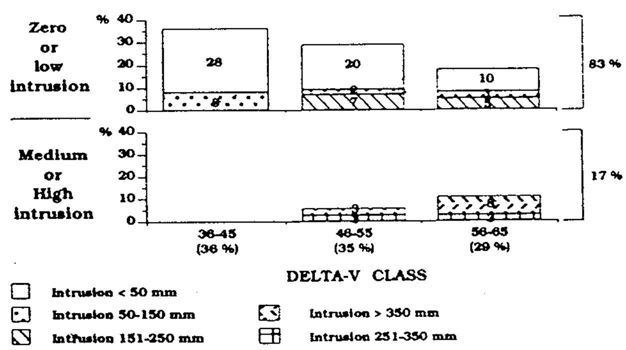

Figure 8: Breakdown(%) of 61 M.AIS 3+ belted front passengers according to deltaV class (36 to 65km/h) and upper intrusion

CONCLUSIONS CONCERNING INTRUSION AND SEVERITY OF RESTRAINED OCCUPANT INJURIES.

For a given impact speed, intrusion up to 350 mm does not alter the fatality rate for restrained drivers, which remains very low, and only the severe injury rate increases above 150 mm of intrusion. This additional risk is due chiefly to an increase in injuries to the knee joint/femur segment, while for the other body areas the risk in unchanged and even decreases for the thorax (weaker deceleration).

The frequencies of head to steering wheel impact rise significantly with increasing vertical displacement, but the risk for the neck remains very low (1.6 %) and not in relation with the amplitude of the steering wheel movement.

The injury severity and fatality level for passengers is chiefly affected by the restraining loads of the seat belt. These are thoracic and abdominal injuries, and more rarely head injuries, which are not attributable to intrusion, but chiefly to deceleration mechanisms. The higher is the deceleration, the higher is the head injury risk.

For a given vehicle and impact speed, rigidification of the front structures to reduce intrusion and the potential risk for the femur will tend (for a given restraining system) to aggravate the risk of injury to other body areas due to higher deceleration. A good balance must therefore be struck between the deformability of the vehicle and the loading of the occupants (especially the chest) by the restraint system. This load increases when the deformability decreases (and the acceleration inside the vehicle compartment increases).

City Cars - A New Challenge for Occupant Safety Systems

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ABSTRACT

As new technologies for light vehicles are being developed and first city cars are appearing on the market, the necessity to provide adequate occupant protection becomes apparent. First crash tests have revealed the problems involved in the design of ultra-short vehicles and the need to shorten the frontal crash zones. However some designs have shown to be able to absorb the impact energy on very short distances and thereby preserving the structural integrity of the occupant compartment. Short crash zone, however, result in high deceleration levels on the occupant compartment. The restraint system of such vehicles therefore requires special consideration, since the occupant is not capable of carrying the loads of the ride-down of the compartment. The study to be presented, has used simulation methods to find an optimised restraint system by studying the equivalent of 2000 sled tests. It could be shown, that with the proper combination of off-the-shelf restraint system components, an occupant safety system for a city car with an extremely short crash zone is feasible.

INTRODUCTION

Public opinion and statistical data correlate well in the assessment of small car safety: small cars are less safe than large cars [1,2]. This fact however cannot be accepted in the future if downsizing of cars will result in a large percentage of small and light vehicles which may even have masses of less than 600 kg. Occupants of small cars who contribute to society by riding a low-consumption vehicle will not accept a discrimination in safety.
In a highly publicised series of full-scale barrier crash tests low-mass vehicles were tested by a group of Swiss researchers [3]. These tests showed that small cars in the mass-class of 500-600 kg can be designed such that the structural integrity of the passenger compartment is fully preserved in a 50 km\h head-on barrier impact. The tests also demonstrated that existing occupant injury criteria can be met with vehicles that exhibit only a very short crush zone which in these cases was less than 200 mm. Such short deformation zones result in considerably high acceleration levels on the compartment which in one case approached 150 g's.
Based on data and observations of these tests computer simulations of the occupant behaviour were conducted in order to answer the following questions:

- Can current restraint system technology handle extreme loading as we find in this new breed of small vehicles ?
- What is the optimal combination of restraint system components?
- What will be the restraint system of the future for small vehicles?

METHODOLOGY

A planar occupant simulation model was established on the basis of MADYMO2D. The reason for choosing a 2D-approach is simple: only with a CPU-efficient 2D-model it would be possible to investigate a large set of parameters at different levels and their combinations.

The model (Fig. 1) consists of the Hybrid III occupant model and individual models for seat, safety belt system, airbag, steering assembly, knee bolster and interior. In addition the outer shape of the vehicle is shown for visualisation purposes. The model input is set up in a modular way in order to make parameter studies easy.
Altogether 13 parameters were studied at 2 or 3 levels (Table 1). A full-factorial study would have

resulted in approx. 42000 individual simulations which would have included all possible parameter combinations. This large number was reduced to 2000 simulations by employing a Taguchi test plan. All simulations were completely controlled by a governing program which set up the individual data sets, ran the simulations and extracted the relevant data from the calculated results.

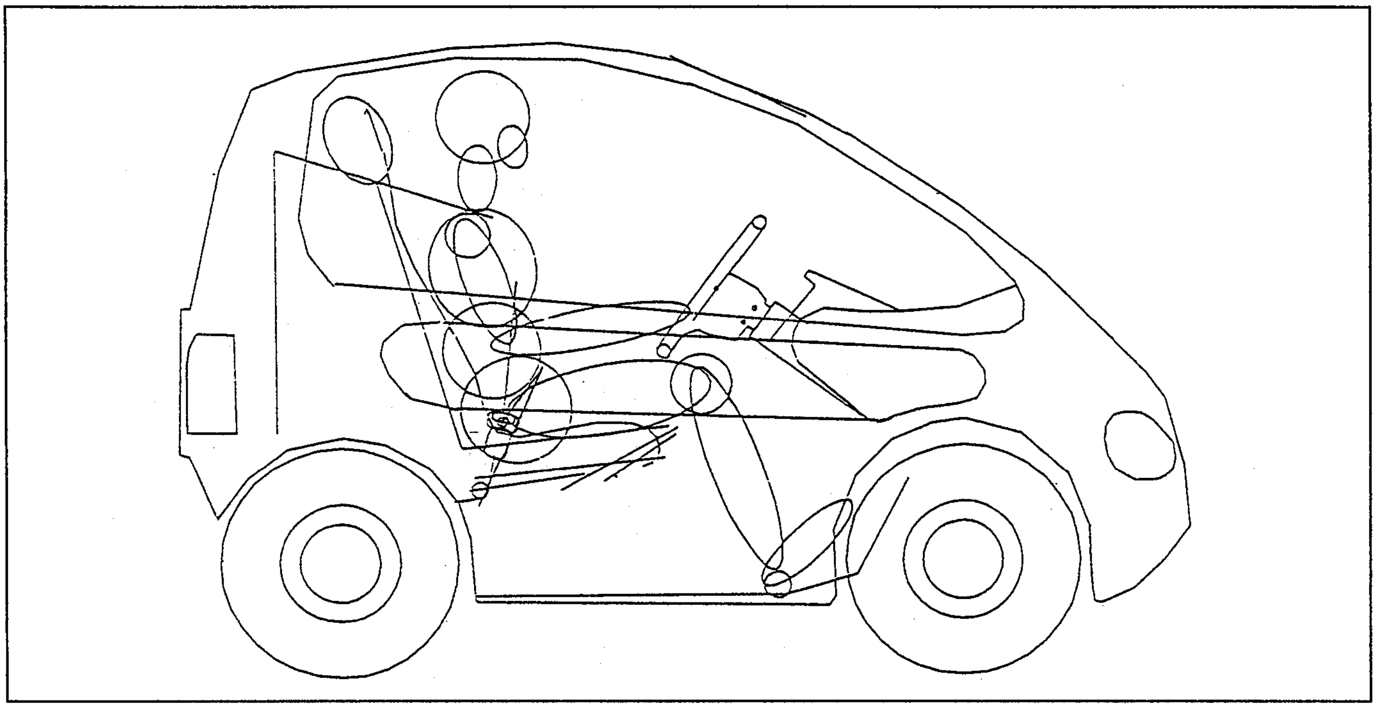

Fig 1: Simulation Model

	Level A	Level B	Level C
1. Position of D-Ring	seat integrat.	at B-pillar	
2. Seat Belt Stiffness	8 %	14 %	22 %
3. Seat Belt Slack	no slack	25 mm	
4. Webbing Grabber	yes	no	
5. Type of Airbag	EURO 35 ltr	US 63 ltr	
6. Airbag Trigger Time	6 ms	10 ms	14 ms
7. Airbag Venting	2x18 mm	2x25 mm	2x30 mm
8. Belt tensioning at retractor	yes	no	
9. Belt tensioning at buckle	yes	no	
10. Knee Bolster	yes	no	
11. Compliance of Steering Bracket	yes	no	
12. Contracting Steering Column	yes	no	

Table 1: List of Parameters and Parameter Levels

RESULTS

The results of this study will not be discussed in detail here, since they have been published elsewhere [4]. The study showed that with existing, off-the-shelf restraint system components it is well feasible to design a restraint system which is capable to protect an occupant in a short-crush-zone vehicle within the legal limits. It is important to note, that these results are based on a single crash severity and one occupant size and seating position. The best parameter combination found in the study is shown in Table 2. It is obvious that two factors contribute most significantly to the success of this particular combination:

- An optimised interior travel distance, allowing large forward displacements of the head, chest and pelvis without hard contacts.
- An energy management via multiple restraint systems whose energy absorption is staged in its timing.

Parameter Combination with best result:

		Level
1.	Position of D-Ring	at B-pillar
2.	Seat Belt Stiffness	22 %
3.	Seat Belt Slack	no slack
4.	Webbing Grabber	yes
5.	Type of Airbag	EURO 35 ltr
6.	Airbag Trigger Time	6 ms
7.	Airbag Venting	2x30 mm
8.	Belt tensioning at retractor	yes
9.	Belt tensioning at buckle	yes
10.	Knee Bolster	yes
11.	Compl. of Steering Bracket	yes
12.	Contracting Steering Col.	yes

Table 2: Best Parameter Combination

DISCUSSION

The results suggested that in a crash test with such a small, short-crushzone vehicle, occupant injury parameter would be high but tolerable.

The test performed in Switzerland (Test No. 5 in [1]) however demonstrated that the injury values for the driver were much less than predicted (HIC 302; Head 3ms 43 g). This may have been attributed to the lower impact speed, however considering the high rebound velocity a delta-v of 13.9 m/s was found which related to the delta-v used in the simulation.

A close observation of crash films and still photos revealed that the little car underwent a significant pitch during the impact phase. A pitch of 7° at 85 ms after initial contact could be measured from the photographic data. This new information was used in the occupant simulation by adding a pitching movement to the vehicle coordinate system (see Fig. 2). This additional movement will add loading to the occupant's pelvis, but the positive effects stems from the fact that the steering wheel and instrument panel will move away from the occupant. Also, the shoulder belt D-ring will move in impact direction, i.e. giving extra travel distance for the chest. The simulations showed that, assuming identical parameter sets, the additional pitching movement could reduce HIC by 600 and Chest 3ms-Acc. by 12 g.

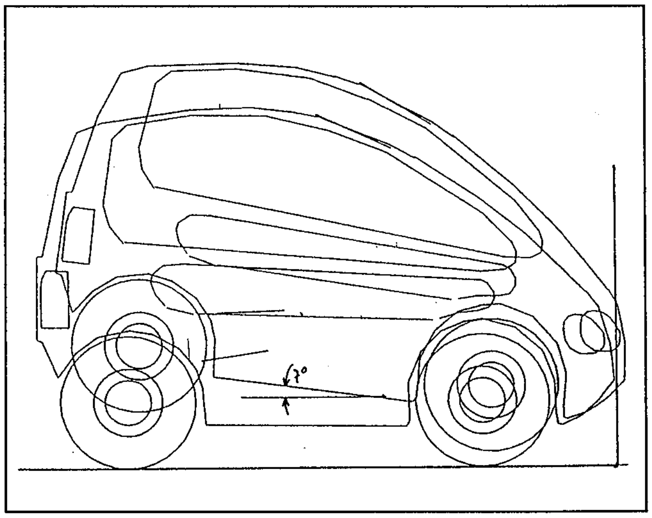

Fig. 2: Pitching Movement

A sequence of plots (Fig. 3) shows the pitching movement of the vehicle exterior w.r.t. the ground and the occupant kinematics. The pitching starts at 30ms, which is after the main acceleration peak on the vehicle and continues through the rebound. The maximum pitching angle of 7° is reached at 85 ms.

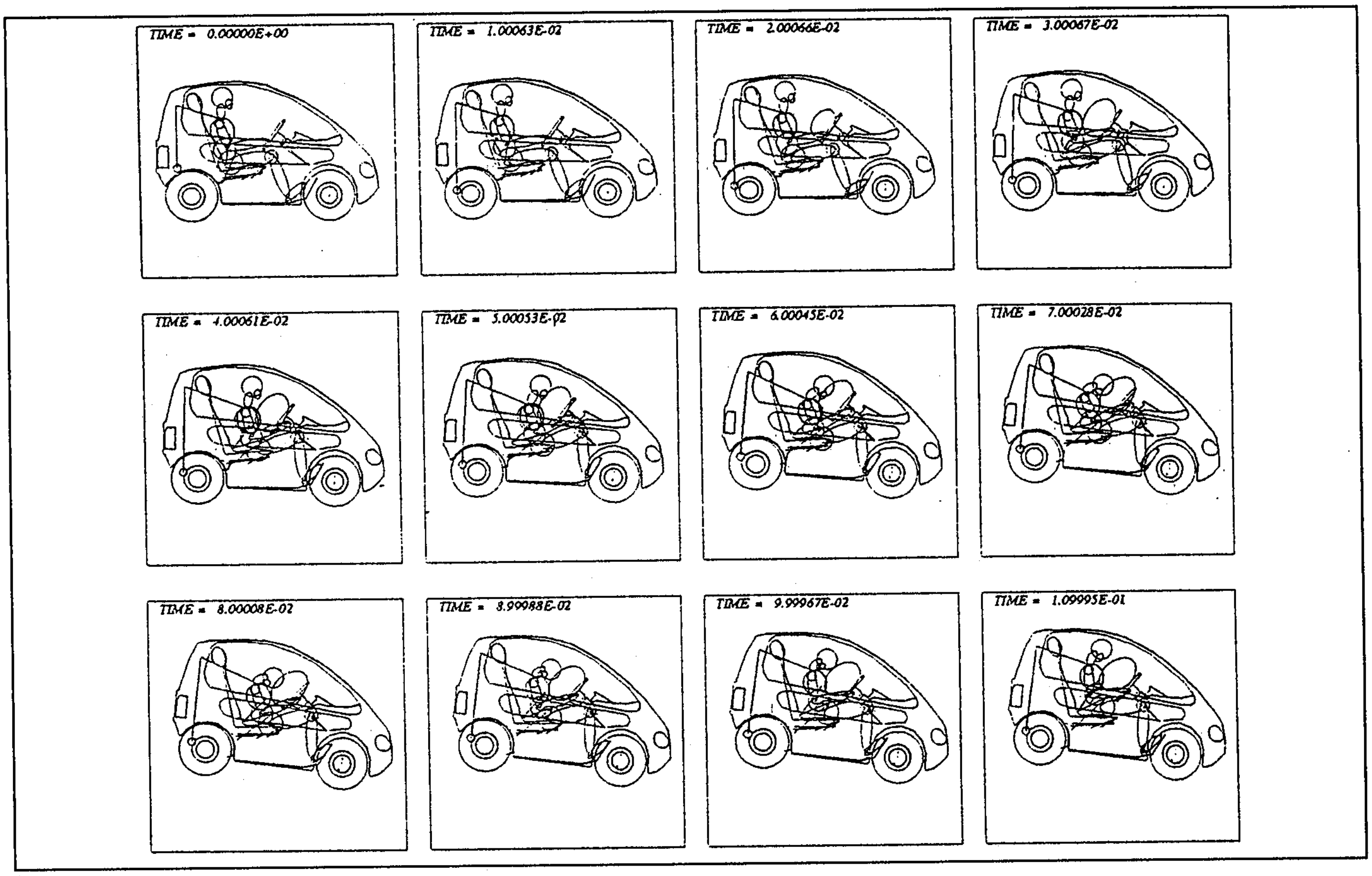

Fig. 3 : Kinematics of Vehicle and Occupant

CONCLUSIONS

Occupant Simulations were performed for a small, short-crushzone vehicle. The simulations shows that it is feasible to design a restraint system which can handle the occupant loading in this case were no ride-down is possible due to high compartment decelerations. However the restraint system has to employ all currently available technology to keep the injury values within given legal limits.

Experiments and subsequent simulations show that additional effects like the pitching of the whole vehicle in the barrier impact can have a positive effect on occupant loading. Although such a pitching movement may not be feasible in a real world situation, its effects may well be included into the design of a restraint system. This can be achieved by translating a purely one-dimensional energy absorption system in a two-dimensional system involving rotational movements. Such systems have been proposed for the seats as well as for the vehicle structure [5].

ACKNOWLEDGEMENTS

This study was in part sponsored by Volkswagen Research. The support of Drs. Scharnhorst and Richter and Mr. Sinnhuber is acknowledged.

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Laboratory Assessment of the Potential for Airbag-Induced Skin Abrasion

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ABSTRACT

Eight airbag configurations were tested using a laboratory test procedure developed to predict skin abrasion potential. Abrasion is predicted when airbag fabric impact with a pressure-sensitive film produces pressures exceeding a threshold value. The effects of airbag design parameters on the fabric velocity and abrasion predictions were investigated. For the airbag modules studied, abrasions were predicted when the airbag fabric impact velocity exceeds 50 to 70 m/s, and when the peak inflator tank-test pressure slope exceeded 160 to 180 kPa/10 ms. Differentiation of airbag modules with respect to abrasion likelihood was found to be fairly insensitive to a range of abrasion-prediction threshold values.

INTRODUCTION

Since the implementation of the passive restraint requirements in FMVSS 208, the number of vehicles in the U.S. market that are equipped with at least one airbag has shown a rapid increase, and is estimated to have exceeded 10 million vehicles (State Farm 1992). The accompanying increase in accidents involving airbag-equipped cars has provided data for estimates of the field effectiveness of airbags in preventing serious injury. Various investigators have found that driver-side airbags are effective in reducing the risk of serious injury by protecting the driver from the secondary impact in the event of a frontal crash. When seat belts are also used, airbags have been found to reduce driver fatalities by an additional 21% (IIHS 1993).

Although the life-saving benefits of airbags have been demonstrated, injuries caused by the deploying airbag have also been reported. These have consisted primarily of abrasions and lacerations to the face, neck, and forearms (State Farm 1992). To address the problem of airbag-induced skin abrasion, University of Michigan Transportation Research Institute (UMTRI) has conducted laboratory deployments with human volunteers (Reed *et al.* 1992). In the UMTRI study, the effects of inflator capacity, tethering, fabric yarn, and target distance on abrasion severity were investigated. These experiments led to the development of a laboratory test procedure for predicting the skin abrasion potential of driver-side airbags by deploying the airbag into a pressure-sensitive film (Reed and Schneider 1993).

This report describes static deployment tests conducted with a variety of airbag configurations using the UMTRI test procedure. The effects of several airbag design factors on the predicted abrasion severity were investigated, and directions for airbag engineering changes to reduce abrasion potential are indicated.

METHODS

Abrasion Prediction Procedure

Airbag-induced abrasions have been found to be caused primarily by high-velocity impact of fabric with the skin (Reed *et al.* 1992). During typical abrasion events, an area of airbag fabric contacts the skin at high speed. The tissue in that area experiences high pressure during the fabric contact, causing mechanical injury in the epidermis and dermis. The UMTRI abrasion-prediction procedure is based on observations that the patterns of airbag-induced skin abrasions in volunteer subjects match closely the patterns of peak pressure exerted by the airbag fabric on a rigid target surface under identical deployment conditions (Reed and Schneider 1993).

Fuji Prescale film, a pressure-sensitive material, is placed on a 102-mm-diameter polyvinyl chloride (PVC) cylinder located in the airbag deployment envelope. When the airbag is deployed, high-velocity contact between the airbag fabric and the Prescale film produces an image on the film corresponding to the pattern of peak pressure on the target surface. A Prescale-film calibration is used to relate the density of the color change in the film to the magnitude of the applied pressure. Under the preliminary guidelines established at UMTRI, abrasion is predicted for areas of the target surface in which the airbag fabric produces contact pressures exceeding 175 kg/cm^2. This pressure threshold level was established using comparisons between injury patterns and pressure patterns for four airbag configurations. Subsequent experiments with other airbags may result in the identification of a more accurate threshold, but the 175-kg/cm^2 level is considered sufficiently predictive to be used in the current experiments.

One alternative to the UMTRI procedure was considered. Semiconductor transducers have been mounted in a Hybrid-III-dummy face to record contact pressures. Although the airbag deployment forces could be measured continuously with this device, the method was not considered suitable for this application because of the expense of the apparatus and because the geometric complexity of the dummy face can be expected to add variability to the data, necessitating a greater number of tests.

Laboratory Facilities

Figure 1 shows the laboratory test fixture used in the current study. A standard steering wheel and a 102-mm-diameter PVC cylinder are oriented vertically on mounting blocks. The horizontal distance between the steering wheel and the airbag module is adjusted by moving each block. The alignment of the tube can also be adjusted by threaded rods. The fixture allows the steering wheel to be rotated so that the airbag can be deployed from different orientations relative to the surface of the target cylinder.

High-speed film of the deployment was obtained with a NAC E-10 camera operated at a nominal 3000 frames per second. Ventilation of airbag exhaust gases was provided by a 146 to 166 m^3/min blower drawing through a 500-mm-diameter duct.

Calibration and Measurement Procedures

Fuji Prescale film responds to applied pressure with a color change from white to red. The intensity of the color change is a function of the applied pressure. When exposed to a time-varying pressure, the film indicates the highest pressure applied. A device similar to the UMTRI calibration fixture was used to determine the relationship between the peak applied pressure and the Prescale film response. Pressure pulses with approximately a 1-ms duration at the base of the pulse were applied to the film.

After the film was exposed to pressure, the image on the film was analyzed with a digital scanner and analysis software. The pressure image is converted to an 8-bit grayscale image for analysis. Digital pixel values are expressed as pressure values via the calibration curve. (For additional details on the Prescale film analysis, see Reed and Schneider 1993.)

Airbag Specifications

Table 1 shows the specifications of the airbag modules tested, including peak inflator tank-test pressure, maximum tank test slope, airbag fold technique, module cover material, airbag volume, size and area of module cover opened, presence of tether, and length of tether if applicable. Figure 2 shows a typical tank-test pressure curve for one inflator.

Test Protocol

Prior to testing with Prescale film, a thorough assessment of airbag deployment kinematics must be conducted to determine the areas of the deployment envelope in which high-velocity fabric contact may occur. Airbags were deployed in the test fixture with the target cylinder removed. The deployments were filmed from the side using several different steering wheel orientations. The airbag fold technique, particularly the direction of the final fold, strongly influences the airbag kinematics. For each fold technique investigated, the orientation of the steering wheel for subsequent testing was chosen to maximize the contact between the airbag fabric and the target cylinder during the unfolding phase of the deployment, which is when the fabric velocities are highest.

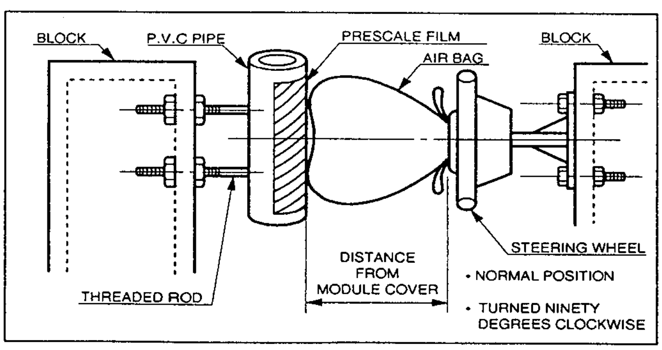


Figure 1. Laboratory Test Fixture.

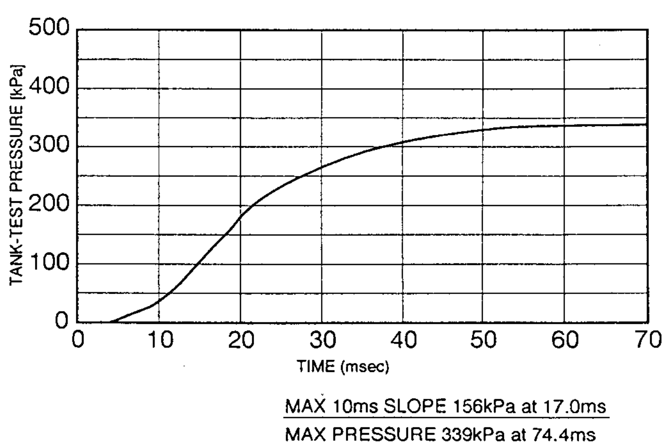
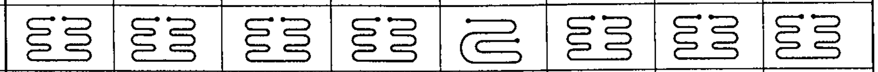
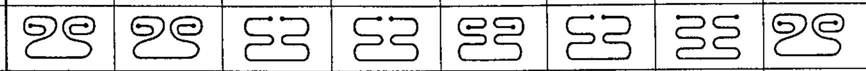


Figure 2. Typical 1 ft^3 Tank-Test Pressure Curve. (Module Type A)

Table 1
Airbag Module Specifications

Module Type		A	B	C	D	E	F	G	H
Peak Inflator Tank-Test Pressure(kPa)		339	328	416	467	312	439	362	309
Maximum Tank-Test Slope(kPa/10ms)		156	165	165	195	148	236	223	110
Airbag Fold Technique	First								
	Second								
Bag Weight (g)		272	269	308	292	238	366	388	241
Bag Material		NYLON 840D	NYLON 840D	NYLON 420D	NYLON 420D	NYLON 420D	NYLON 840D	NYLON 840D	NYLON 420D
Tether (Length in mm)		NONE	NONE	220	220	220	NONE	NONE	220
Module Cover Material		OUTSIDE: POLYVINYL CHLORIDE INSIDE: POLYESTER ELASTOMER		POLY-URETHANE	POLY-URETHANE	POLY-URETHANE	POLY-URETHANE	POLY-URETHANE	T.P.O.
Area of Module Cover Opened(cm²)		211	211	231	238	168	220	200	246
Cover Opening Dimensions Height × Width(mm)		(108)×195	(108)×195	(132)×175	(132)×180	(120)×140	(135)×163	(135)×148	(170)×145

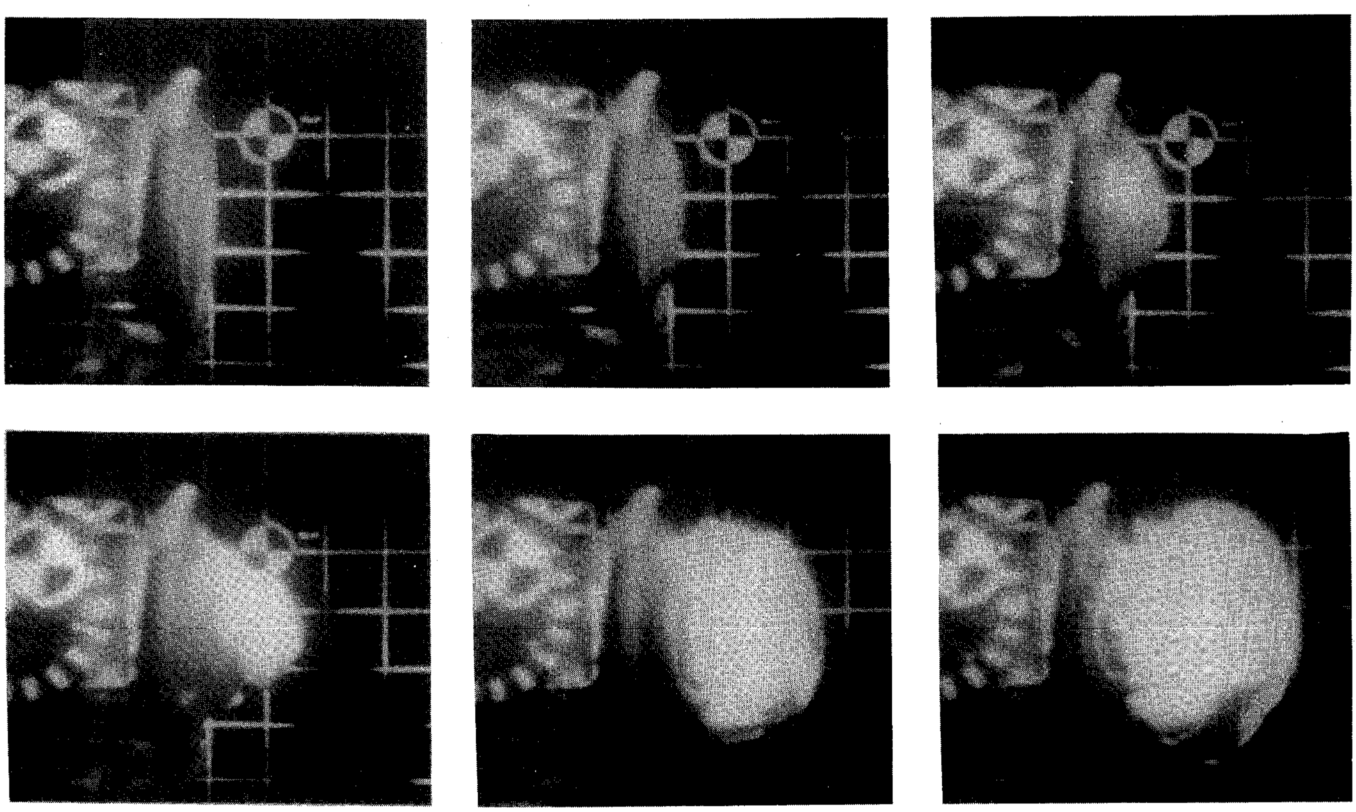


Figure 3. Photo series from high-speed film.

Tests were conducted with the target surface positioned 165, 195, and 225 mm from the center of the airbag module. These distances were selected because the kinematic analysis showed that the test modules generally produced maximum leading-edge fabric velocities (perpendicular to the plane of the steering wheel) at distances from 165 to 225 mm. The Prescale film was attached to the target cylinder with adhesive tape and the airbag deployed. All tests were filmed at 3000 frames per second.

Analysis

Prescale film images were analyzed to determine the area of the film exceeding 75 and 175 kg/cm². The lower value was chosen to investigate the effect of threshold level on the abrasion predictions. The areas of film exceeding the two threshold levels are designated Prescale(75) and Prescale(175), respectively. Measurements of fabric velocity were made using the high-speed film of each deployment, as shown in the film-frame series in Figure 3. The displacement of the leading edge of the airbag fabric perpendicular to the steering wheel plane at each frame was calculated to determine the average velocity for each 1/3000 second.

RESULTS

Figures 4 through 6 show typical Prescale images produced by airbag fabric contact. Table 2 shows the areas of the film images that exceeded 75 and 175 kg/cm² at each of the test distances. Table 3 shows the leading-edge fabric velocity for each module at each of the test distances, along with the inflator performance characteristics.

Velocity Data

Velocities at 165 mm were fairly well correlated with the velocities at 195 and 225 mm, and there was a very high correlation between the velocities at 195 and 225 mm. Table 4 shows the Pearson correlation coefficients (r). There was not a consistent relationship between distance and velocity across airbag modules. Figure 7 shows the leading-edge velocities for all eight modules at the three test distances. The lack of a consistent relationship is probably due to differences in fold technique. Figure 7 also shows the strong correspondence between 195 and 225 mm velocities responsible for the high correlation reported in Table 4. The range of leading-edge velocities observed is substantial. At 225 mm, the velocities ranged fairly evenly from 17.8 m/s for module B to 102.7 m/s for module E.

The peak tank pressure from the inflator tank tests was not strongly related to the airbag fabric velocity, although a regression of leading-edge velocity against inflator slope was significant ($p \leq 0.05$, $r^2 = 0.21$),shown in Figure 8. However, if module E, which had an unusual first-fold pattern, is removed, r^2 for the regression increases to 0.47. Thus, inflator tank-test slope appears to be a reasonable predictor

Table 2
Bag Velocities and Prescale Image Areas

Distance / Module Type	165mm			195mm			225mm		
	Bag Velocity (m/s)	Area Above 175kg/cm² (cm²)	Area Above 75kg/cm² (cm²)	Bag Velocity (m/s)	Area Above 175kg/cm² (cm²)	Area Above 75kg/cm² (cm²)	Bag Velocity (m/s)	Area Above 175kg/cm² (cm²)	Area Above 75kg/cm² (cm²)
A	57.8	0	0.9	55.1	0	3.6	23.2	0	2.2
B	63.8	0	1.3	26.5	0	0.1	17.8	0	1.2
C	53.5	0.03	29.2	56.8	0.03	35.0	54.6	0	23.5
D	30.8	1.8	51.7	59.5	3.0	54.6	62.7	0.3	23.7
E	73.5	12.0	79.6	100.0	9.9	41.8	102.7	7.9	44.0
F	78.0	14.4	125.6	72.5	14.5	153.0	83.0	17.2	126.5
G	82.0	53.9	209.0	90.0	14.7	116.0	94.0	14.8	175.0
H	33.0	0	1.6	42.0	0	0.04	43.0	0	0.4

Table 3
Bag Velocities and Inflator Performance Characteristics

Module Type	Bag Velocity(ms) (m/s)			Max. Inflator Tank Pressure (kPa)	Max. Output Slope (Max.10ms slope)	
	165mm	195mm	225mm		kPa/10ms	Time
A	57.8	55.1	23.2	339	156	17.0ms
B	63.8	26.5	17.8	328	165	14.4ms
C	53.5	56.8	54.6	416	165	15.4ms
D	30.8	59.5	62.7	467	195	13.4ms
E	73.5	100.0	102.7	312	148	14.4ms
F	78.0	72.5	83.0	439	236	13.4ms
G	82.0	90.0	94.0	362	223	14.6ms
H	33.0	42.0	43.0	309	110	15.3ms

Table 4
Velocity Correlations

	Velocity@165 mm	Velocity@195 mm	Velocity@225 mm
Velocity@165 mm	1.0000	--	--
Velocity@195 mm	0.5659	1.0000	--
Velocity@225 mm	0.4851	0.9250	1.0000

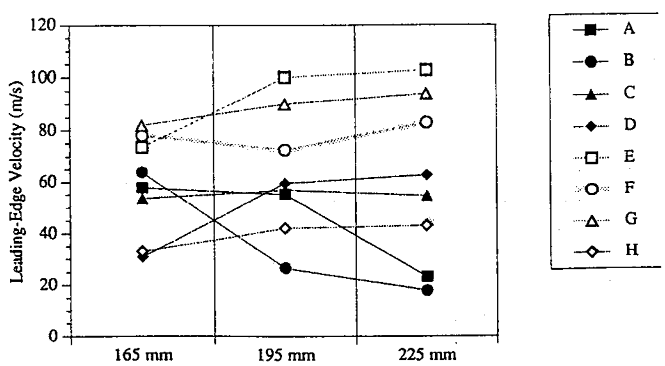


Figure 7. Leading-edge Velocities at Three Distances for Eight Airbag Modules.

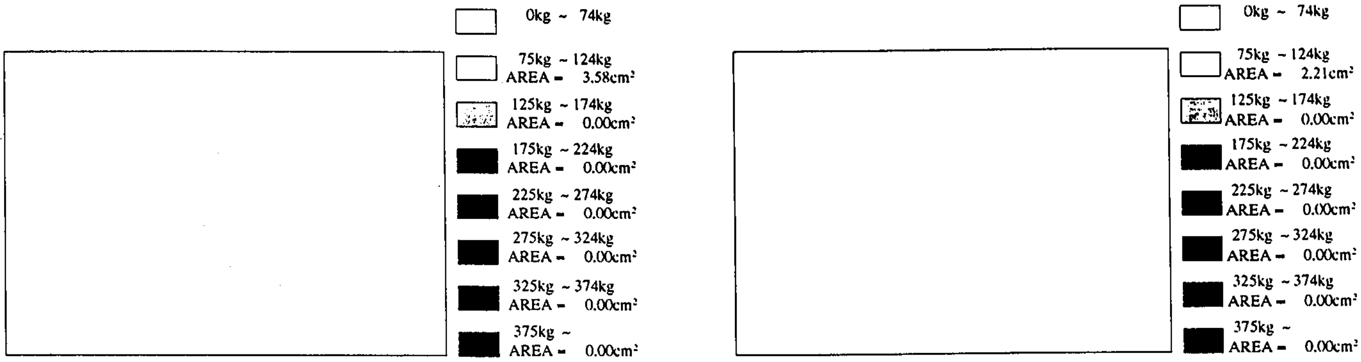


Figure 4. Prescale Image of Airbag Module A at Distances of 195 mm and 225 mm.

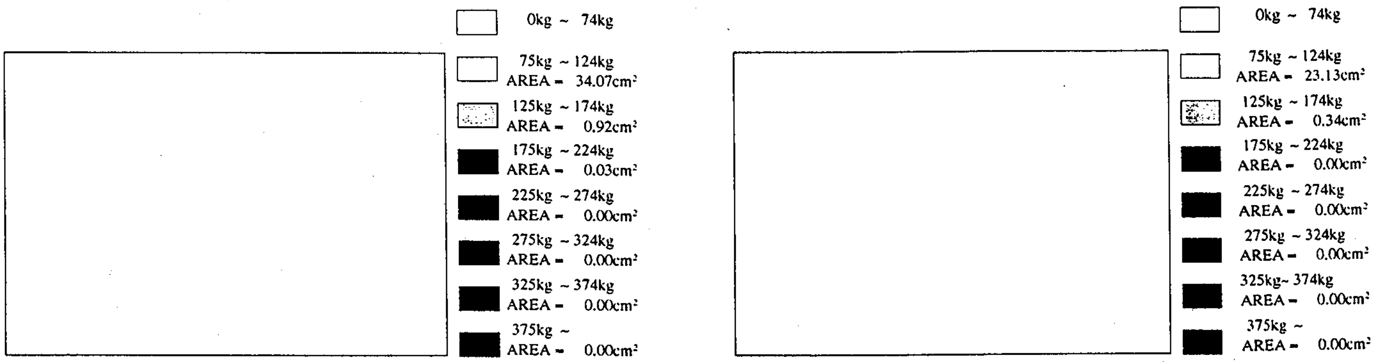


Figure 5. Prescale Image of Airbag Module C at Distances of 195 mm and 225 mm.

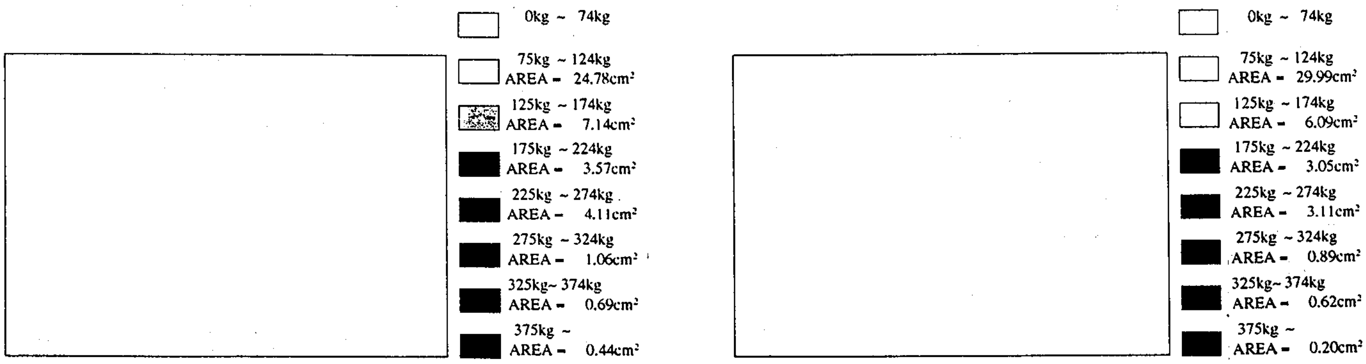


Figure 6. Prescale Image of Airbag Module E at Distances of 195 mm and 225 mm.

of fabric velocity, even when different fold techniques are considered together. If fold techniques and other factors (*e.g.*, module cover material) were uniform, the relationship would likely be stronger.

Prescale Data

Prescale film response above 75 kg/cm^2 was observed in all tests. However, in 10 of 24 tests, Prescale film response did not exceed 175 kg/cm^2. In two additional tests (module C), the area exceeding 175 kg/cm^2 was only 3 mm^2. Figure 9 shows the Prescale film data by module. Since there was no significant effect of distance, data from all three distances are shown together. At the 75-kg/cm^2 level, only modules A, B, and H show no substantial response. At the 175-kg/cm^2 level, modules D, E, F and G show a substantial response, while modules A, B, C, and H do not. Using the preliminary UMTRI abrasion criterion value of 175 kg/cm^2, abrasion is predicted for 4 out of 8 of the airbag modules tested. If the lower, alternative threshold is used, abrasion would be predicted for one additional module C.

There was a strong correlation between the Prescale(75) and Prescale(175) data, with $r = 0.86$ (n = 24). The correlation coefficient was 0.94 at 165 mm, 0.90 at 195 mm, and 0.93 at 225 mm. The relationship would probably have been stronger if not for a floor effect in the Prescale(175) data, where 10 out of 24 data values were zero.

The size of the Prescale-film area exceeding either threshold level is related to the corresponding fabric velocity. Linear regression showed a significant relationship between velocity and the 175-kg/cm^2-threshold Prescale data at 195 and 225 mm, and between velocity and the 75-kg/cm^2-threshold Prescale data at 225 mm (all $p < 0.05$). When data for all tests are combined, the linear relationship is highly significant ($p < 0.01$) for both thresholds, as shown in Figure 10, with $r^2(75) = 0.41$ and $r^2(175) = 0.31$.

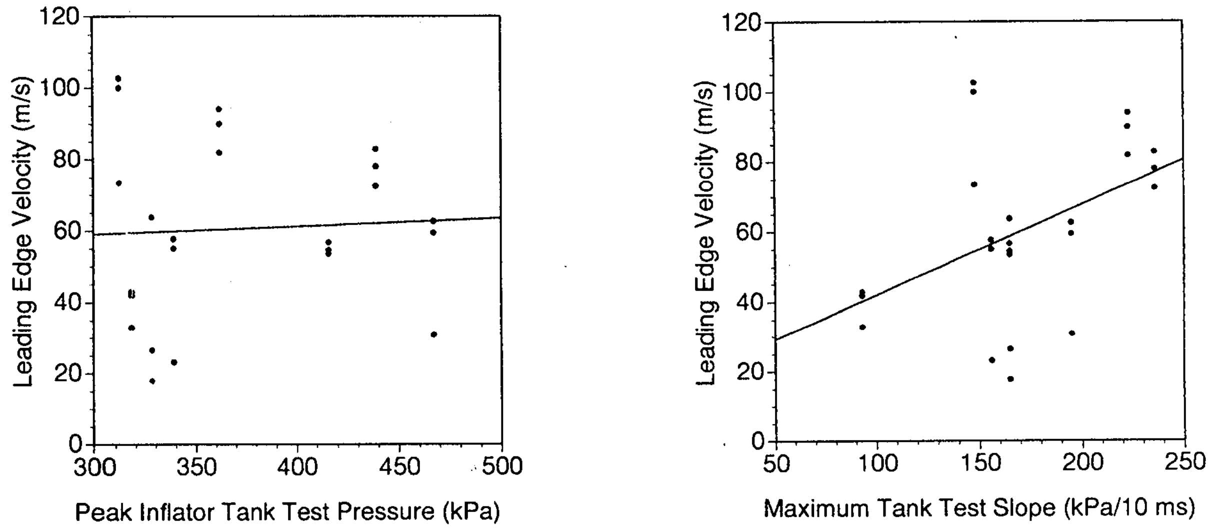


Figure 8. Relationships between peak pressure and peak slope from inflator tank tests and leading-edge fabric velocity. Data from three test distances are combined (n = 24).
Regression for slope is significant ($p < 0.05$, $r^2 = 0.21$).

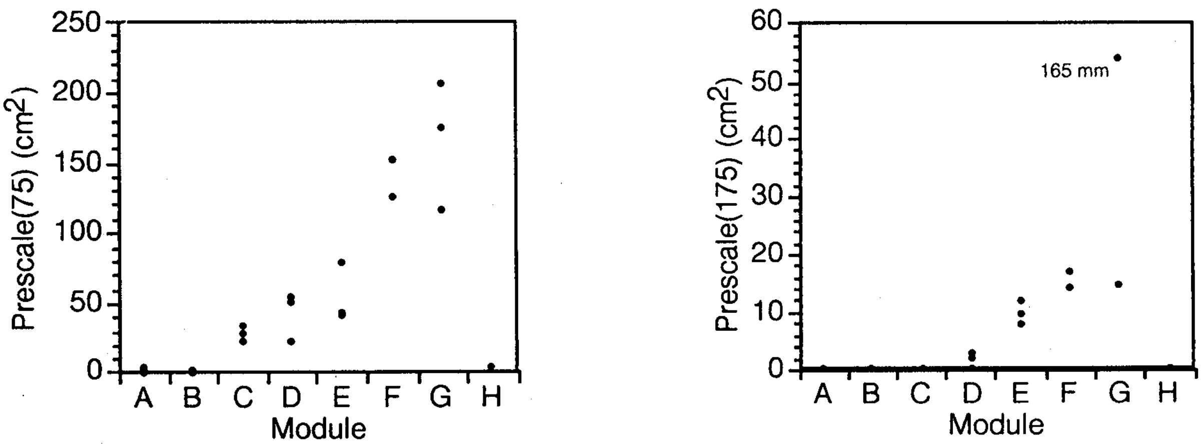


Figure 9. Prescale film data by module.

Figure 10 shows that the area of pressure above 175-kg/cm² is approximately zero until the fabric velocity exceeds about 70 m/s. The relationship at the 75-kg/cm² threshold is less clear, but a fabric impact speed greater than approximately 50 m/s appears necessary to produce target surface pressures above 75 kg/cm².

Since the inflator slope is correlated with fabric velocity, inflator slope is also related to the Prescale film data. Figure 11 shows the Prescale(75) and Prescale(175) data as a function of inflator slope. Once again, module E is an outlier (shown with + symbols). If the data from module E are neglected, slopes above about 160 kPa/10 ms produce Prescale response at the 75-kg/cm² level (four modules), and slopes above 180 kPa/10 ms produce Prescale film response at the 175-kg/cm² level (three modules).

DISCUSSION AND CONCLUSIONS

The previous research at UMTRI showed that impact-level surface pressures were both necessary and sufficient to cause skin abrasion (Reed *et al.* 1992). Abrasion was predicted when fabric actions produced pressures greater than the preliminary threshold of 175-kg/cm² on a rigid target surface. Consideration of airbag fabric dynamics leads to a simplified description of the fabric-skin impact event. The load F applied to the skin is proportional to the change in momentum of the contacting airbag fabric, so that

$$\int F\,dt = m\,\Delta v \qquad (1)$$

where F is the time-varying force, t is time during fabric

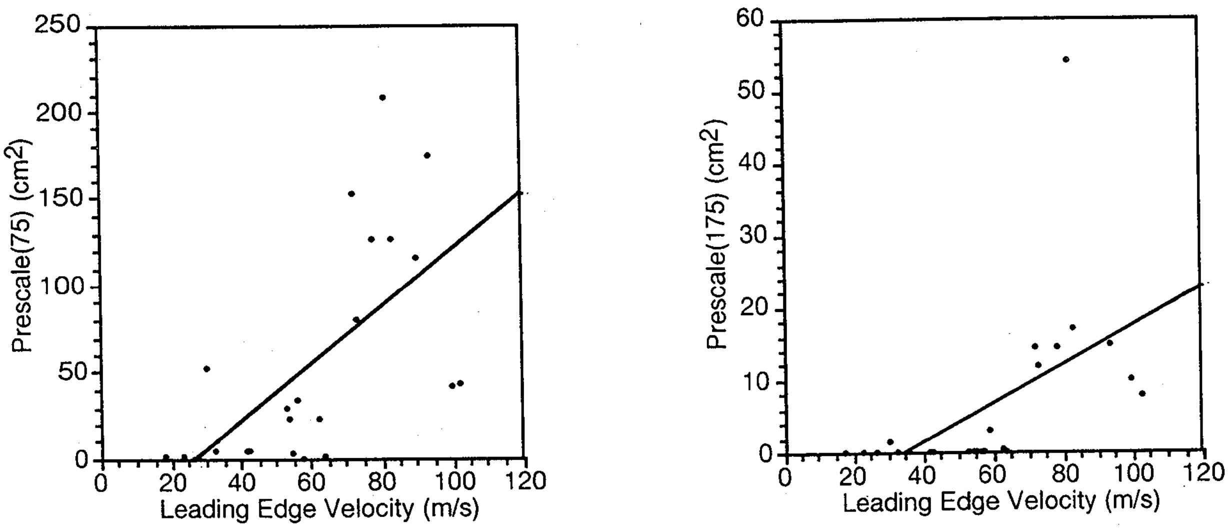


Figure 10. Scatter plots and linear regressions for all velocity and Prescale data. Both regressions are significant ($p \leq 0.01$).

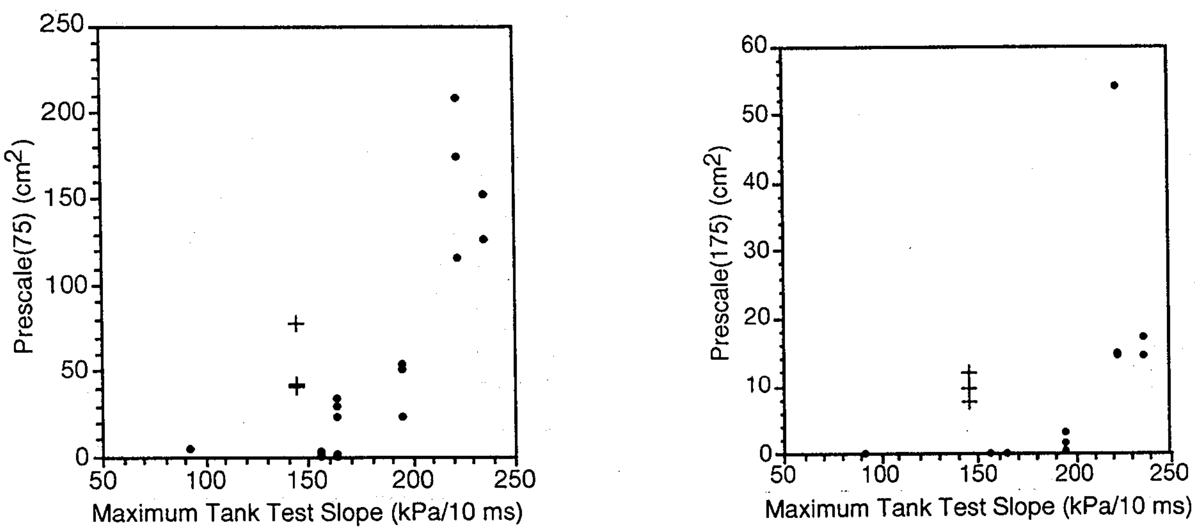


Figure 11. Prescale film data plotted versus inflator slope. Data from module E, which had an unusual first-fold technique, are shown with + symbols.

deceleration, m is the decelerated mass, and Δv is the change in fabric velocity. The force applied to the surface by the decelerating fabric can be expressed as the product of the pressure P and contact area S. If the pressure and area are assumed to be constant during the impact event, and the change in velocity is assumed to be equal to the initial velocity (*i.e.*, the fabric is decelerated to zero) then (1) may be written as

$$P = \frac{mv}{St} \qquad (2)$$

where v is the initial velocity perpendicular to the skin and t is the duration of the impact event. By equation (2), increasing either the fabric velocity or decelerated mass will increase the surface pressure during impact. Conversely, increasing the surface area or extending the duration of the impact would decrease the surface pressure.

The fabric velocity at impact can be measured using high-speed film. The effective fabric mass is more difficult to estimate. The appropriate mass value is related to the size of the fabric region that is decelerated during the impact event. If S is the size of the contact area and also the area of fabric that is decelerated, then the effective mass of the airbag fabric is equal to $S\rho$, where ρ is the planar density of the fabric in kg/m^2. Equation (2) then becomes

$$P = \frac{\rho v}{t} \qquad (3)$$

The duration of the impact event is related to the compliance of the skin and underlying tissue. Because the event is of such short duration, it is difficult to estimate how the duration might vary at different skin target sites, although the impact duration is almost certainly shorter with the rigid target cylinder than with the flesh. However, several experiments with the Prescale film placed over skin showed that only slightly lower pressures are seen with flesh than with the rigid cylinder, suggesting that the skin is fairly stiff at the high loading rates associated with airbag fabric impact (Reed *et al.* 1992). Since the impact duration is difficult to measure or estimate, it is useful to consider that it probably varies primarily with impact velocity. The change in the magnitude of the velocity effect over the range of velocities is probably larger than tissue variability.

By (3), the surface pressure is independent of the contact area. This is an interesting result that bears further scrutiny. For the underlying assumptions to hold, only the fabric actually contacting the skin can be decelerated during the impact event. In actuality, contact is initially made at a very small area at a high impact velocity. Subsequently, the area of contact spreads around the initial point as more fabric reaches the skin. For equation (3) to hold during each local impact sub-event, the local impact velocity of the fabric contacts around the initial point of contact must be independent of the initial contact (*i.e.*, no force is transmitted laterally through the fabric). If the fabric is loose at the time of impact, this assumption may be reasonable. However, if the target is contacted by a flap of fabric that has been made stiff by the pressure of the deployment gases, then the effective (decelerated) fabric mass could be substantially higher than the product of the planar fabric density and the contact area. Thus, m/S will be greater when the fabric is stiffened by internal pressure, and the resulting impact pressure will consequently be higher. This is consistent with previous findings that the highest contact pressures, and most severe abrasions, usually occur at points in the deployment envelope where flaps of airbag fabric with substantial internal pressure contact the target.

The results of the current study support the injury model suggested by equations (2) and (3). Airbag fabric impact velocity was found to be correlated with the predicted area of abrasion, using two different Prescale-film pressure thresholds. However, there was no apparent effect of airbag fabric density. The differences in fabric density were small and were confounded with variations in other factors, so the null result for fabric density is not surprising. In practice, it will be extremely difficult to separate the velocity and fabric density effects, because changing fabric density will inversely affect the velocity if the inflator and other parameters remain constant. Since the velocity has been shown to vary to a much larger extent than fabric density within a set of reasonably configured airbags, the primary focus of abrasion-prevention efforts should be directed at reducing fabric velocities rather than decreasing fabric density.

No attempt was made to correlate the leading edge velocity with the peak pressure at the site of the initial fabric contact. Analysis instead related the area of the target exceeding the threshold pressure level to the initial impact velocity. If the assumptions underlying equation (3) did not hold (*i.e.*, the fabric flaps initially contacting the skin behaved rigidly), then the leading edge velocity might not be correlated well with the predicted abrasion area, since a large portion of fabric would be decelerated by the initial contact and subsequent contacts around the initial point of contact would not be at a velocity sufficient to cause high pressure. However, a significant correlation was observed between the area of predicted abrasion and the leading-edge fabric velocity, suggesting that equation (3) does hold, in that the fabric surrounding the initial point of contact continues forward and strikes the target surface at a substantial percentage of the initial contact velocity.

The peak slope of the inflator tank-test pressure curve was found to be a reasonable predictor of airbag fabric velocity if data from an unusual airbag fold (module E) are neglected. Because of the relationship between velocity and abrasion prediction, high inflator slopes are associated with larger predicted abrasion areas. With fold techniques, module covers, and airbag fabrics similar to those used in this study, abrasion is predicted for inflator slopes greater than 160 to 180 kPa/10 ms, and for fabric impact velocities above 50 to 70 m/s. These velocity thresholds are slightly lower than the 85 m/s level estimated by Reed *et al.* 1992.

A Prescale film threshold level of 75 kg/cm^2, 43 percent of the preliminary value of 175-kg/cm^2 reported by

Reed and Schneider (1993), produced results similar to those obtained with the higher value. Only one additional airbag module was predicted to produce abrasion using the lower threshold level. These findings suggest that, in practical assessment of airbag modules, the choice of threshold level within the range from 75 to 175 kg/cm^2 will not be critical in identifying airbag modules that are likely to cause abrasion. Further validation of the test procedure now under way will likely result in a more accurate determination of the appropriate pressure threshold for predicting abrasion.

Inflator slope and airbag fold technique are primary factors affecting airbag fabric velocity and abrasion severity. Reductions in inflator slope may negatively affect the crash-test performance of the airbag, but changes in airbag fold technique that reduce airbag fabric impact velocity can actually increase the performance of the airbag with respect to deployment time. Consequently, a primary focus of abrasion reduction efforts should be on the development of fold techniques that reduce the potential for high-velocity airbag fabric impact while increasing the overall protection of the occupant.

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Enhanced Safety For Light Trucks and Vans

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94-S4-W-24

ABSTRACT

Small trucks, vans and utility vehicles represent 38% of the current U.S. market. In the designed vehicles of the early eighties, manufacturer's have ignored their full knowledge of the LTV's different statistical accident history as compared to automobiles, and with a minimum of applicable safety regulation, produced and continue to produce, a much less safe vehicle than is practical and economical.

To demonstrate how easy it would be to improve the safety of LTV's, the authors analyzed historical and current accident data bases, investigated and analyzed 11 accident case histories of a GM S-10 vehicle, determined the safety improvements needed, and chose simple and available subsystem design modifications which maximized safety payoff.

The conclusion is that with small running design changes to the seating and restraint system weighing about 15 pounds, about 20 pounds of metal air gap padding, and 15 pounds of composite structural foam filling of roof support sections; an estimated 25% reduction in HARM can be achieved, over and above the reductions resulting from increased restraint usage.

INTRODUCTION

Safety has become an increasingly significant market factor in the United States. This study describes one approach to enhancing the safety of a production vehicle. The design methodology used here is that of the 1982 NHTSA/Minicars Modified Production Vehicle[1]: - i.e. with inexpensive, available modifications.

The choice of vehicle type for this study was based on: the increasing LTV market share; accident data indicating that automotive and LTV societal HARM distributions are considerably different by crash mode; and LTV safety enhancement having little emphasis in the literature. Due to the availibility of data from our investigation of eleven serious injury accidents involving the GM S-10 pickup, this vehicle was chosen as a representitive of a generic LTV. The GM S-10 is used as an example in this paper for subsystem modifications (not a complete redesign), a procedure which is equally applicable and can be applied to any vehicle.

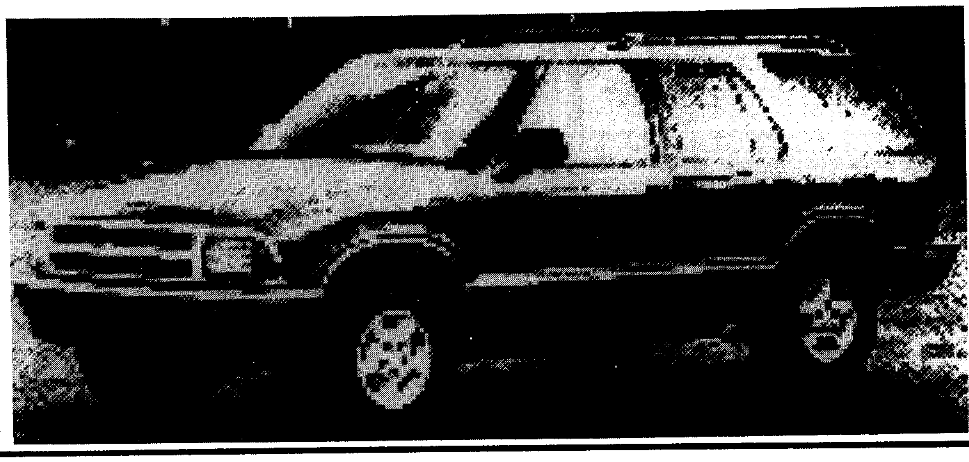
The study first reports on an examination of the history of the available accident statistics, the vehicles product planning, its safety analyses and the available safety enhancement research.

Then each case is briefly described along with the principal design changes which were analyzed to mitigate the injuries. Together, the cases roughly confirmed LTV accident statistical mode distribution, injury mechanisms and demonstrate an alternate enhanced safety design which would mitigate the serious injuries in each mode.

The suggested safety enhancements therefore, are based on the review of 10 years of the as-designed real world severe injury accident experience with this vehicle, available from focused analytical studies and the eleven in-depth case investigations in the primary accident modes.

A global societal HARM and cost comparison has not been made between the original design, the enhanced safety design, and the redesigned 1994 vehicle (Figure 1).

FIGURE 1



However, it is estimated that a twenty five percent reduction in HARM (which the manufacturer had set as a goal in 1982), could have been achieved on top of the gains from increased belt usage for an additional weight of about 50 pounds (and less than $500 per vehicle of consumer cost) by the minimum enhanced safety design, but such gains do not appear to have been achieved in the 1994 redesign.

To satisfy the market demand, a number of smaller trucks were designed, like the 1982 S-10 truck, as a replacement for US marketed Japanese built trucks, but in a somewhat larger configuration. The safety requirements were to meet all applicable FMVSS, although at the time no crash test or dynamic testing regulations had been implemented and those contemplated were not immediately applicable to trucks.

FIGURE 2 **Truck Sales and Production in 1993**

Total Sales of Cars and Light Trucks in the U.S.		13,916,720
Light Truck Sales in the U.S.		5,389,491
Light Truck Sales as a Percentage of U.S. Sales	**38.7%**	
Total Production of Cars and Trucks in The U.S. and Canada*		13,095,138
Truck Production in the U.S. and Canada		5,781,262
Trucks as a Percentage of U.S. and Canadian Production	**44.1%**	

* Includes 'heavy' trucks

HISTORY OF ACCIDENT STATISTICS, PRODUCT PLANNING AND SAFETY

Over the past 25 years, sales of Light Trucks and Vans (LTV's) has risen from 20% to almost 40% of all vehicles sold in the USA2 (Figure 2).

While the original government regulatory effort from 1966 to 1972 covered all accident modes, their focus narrowed towards implementing frontal impact protection in the early 1970's. And the industry did the same, resulting in product objectives which dealt with the restrained and unrestrained protection in frontal barrier crashes, to the virtual exclusion of side, rollover and rear.

The 1976 manufacturer's distribution of HARM from contact with interior surfaces[3] is shown in Figure 3.

FIGURE 3 Societal Loss by Most Probable Contact Area

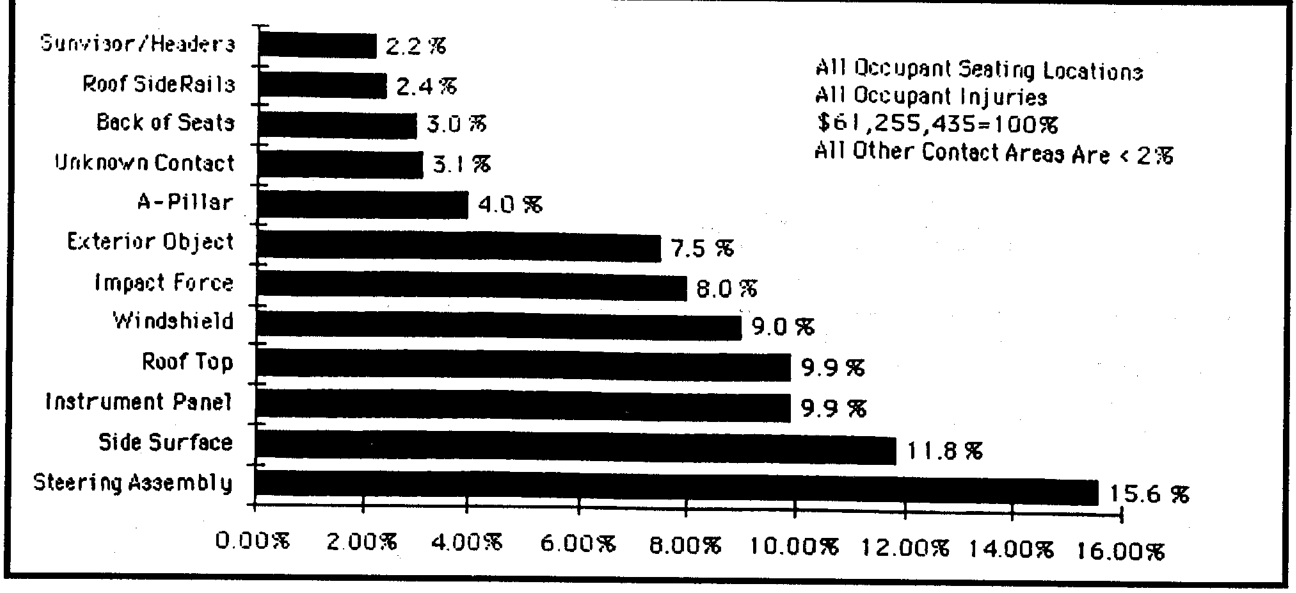


FIGURE 4 Harm by Crash mode

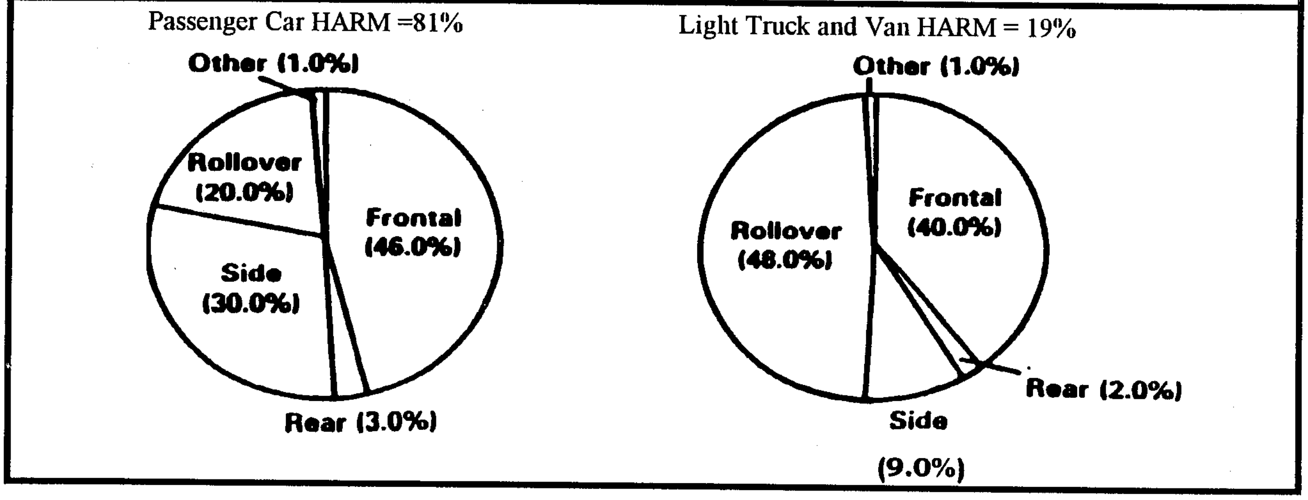


FIGURE 5

% of Occupants with Serious to Fatal Injuries

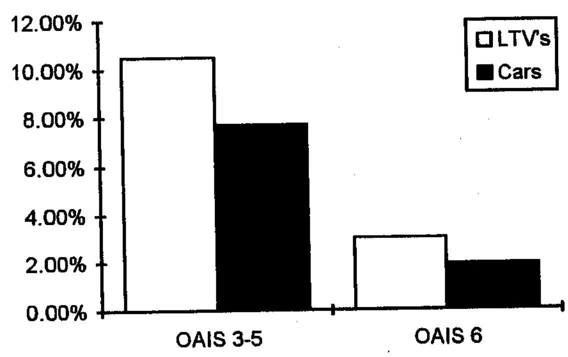
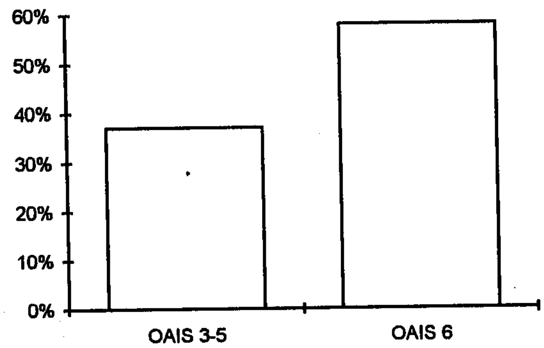


FIGURE 5A

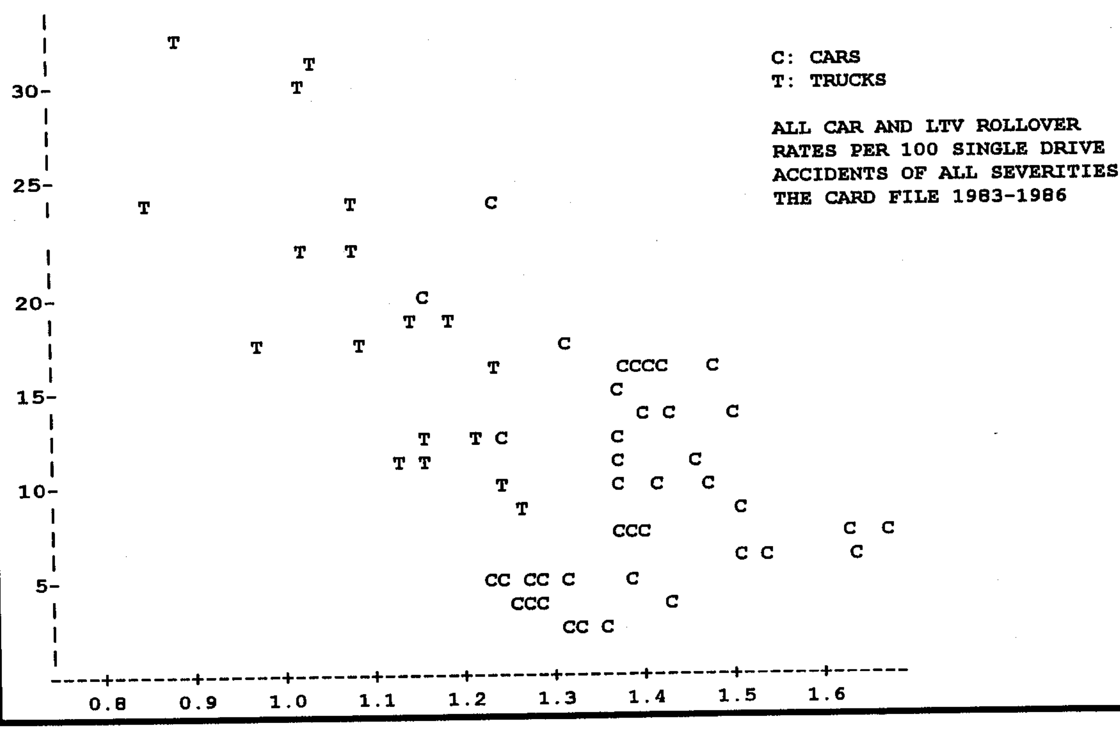
% Greater in LTV's Over Cars



The 1979 safety comparison[4] of truck and passenger cars from MIC data shown in Figures 4 and 5 indicated, as confirmed much later by independent analysis from NCSS and NASS by Malliarus[5], that truck rollovers are almost 2.5 times more frequent and 50% more severe.

"A Comparative Evaluation of Rollover Rates" by Malliarius, shows that the T/2H ratio effects fatality and rollover rates comparably[5]. It appears that LTV's are more prone to rollover than autos, and that there are several possible defining metrics. The difference between passenger cars and LTV, T/2h ratios are shown in figure 6.

FIGURE 6- Rollover as a Function of (T/2H)



Then in the early 80's Malliarius, Hitchcock and Hedlund's " A Search for Priorities in Crash Protection" further refined interior contact, severity and HARM and established a basis for improving crashworthiness[6]. Such priorities resulted in public programs such as the 1980 NHTSA/Industry Side Impact program (leading to the dynamic FMVSS 214), and added emphasis on manufacturer's internal safety improvement projects such as the GM "All Belts-to-Seat", the GM "Vehicle Safety Improvement Program" (VSIP), etc. All were efforts to develop generic safety modifications.

The point about this accident data and the alternative designs is that it was available before the design and production of mid-1980's models and certainly well in advance of 1994 models.

More recently the NHTSA suggested distribution of fatalities and injuries by mode[7] is shown in Figure 7.

FIGURE 7 U.S. SERIOUS TO CRITICAL AND FATALITIES BY ACCIDENT MODE

	SERIOUS/CRITICAL	FATAL
Collisions between:		
Two Passenger Cars	109,000	5,000
Car with Light Truck, Van, Utility	20,000	4,500
Car with Large Truck	10,900	2,500
Single Vehicle non-rollover:	28,000	7,000
Rollover:	15,000	4,500

An NHTSA accident analysis[8] in support of rulemaking on FMVSS 201 provides correlative data on the frequency and severity of head contact injury with upper interior surfaces.

Figure 8 is (A)the distribution of injuries in the US by AIS[9], as well as (B)our own estimate of the numbers of head and neck injuries mitigatable by adjusting the force/deflection characteristics of interior components and finally (C) NHTSA's estimate of head injuries mitigatable by applied padding[9].

FIGURE 8 - SPECIFIC U.S. VEHICLE OCCUPANT INJURIES

#	FATAL	AIS 5	AIS 4	AIS 3	AIS 2	AIS 1
A.	23,600	21,300	23,030	123,800	295,900	2,547,000
B.	8,800 to 5,280	10,650 to 6,390	11,515 to 6,909	61,900 to 37,140	147,950 to 88,770	1,273,500 to 764,100
C.	3,351	1,616	2,032	3,151	19,205	116,341

A. CAR AND LTV INJURIES BY AIS
B. MAXIMUM TO MINIMUM HEAD, FACE AND NECK INJURIES
C. NHTSA'S ESTIMATE OF HEAD AND FACE PRIMARY INJURIES

Finally Figure 9 is the distribution of NHTSA's mitigatable serious to fatal head injuries by contact surface[9].

FIGURE 9 -SERIOUS HEAD INJURIES / FATALITIES BY IMPACT POINT		
	AIS 3-5	FATAL
PASSENGER CARS & LTV's		
A-PILLAR	3563	1776
B-PILLAR	927	446
ROOF SIDE-RAILS	1112	526
FRONT HEADER	1100	555
REAR HEADER	24	13
OTHER PILLAR	76	35
TOTAL ALL VEHICLES	6802	3351

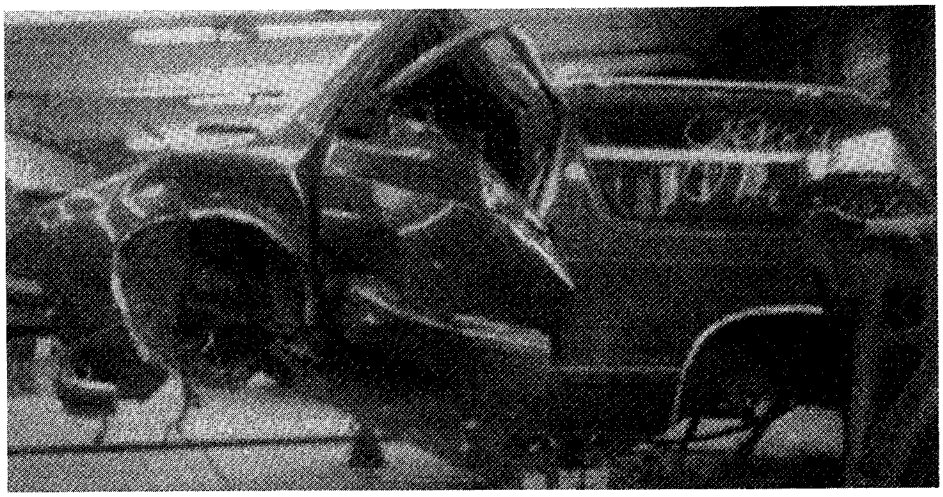
CASE HISTORIES OF S-10 ACCIDENTS IN PRIMARY MODES

In order to evaluate the suggested alternative designs and target the statistically supported problem areas, eleven case histories were studied and computer modeled to represent in sufficient detail the contact injuries sustained and the effectiveness of suggested countermeasures.

Of the eleven case histories, five of the victims (45%) were unrestrained, and three of the impacts were frontal angled; one of the case histories is a side impact, six are rollovers and one is a rear end impact. In contrast, in the recent NHTSA statistical studies about 65% were unrestrained.

A. FRONTAL

1. A car-to-car, frontal angled collision involving a 1984 Chevrolet S-10 Pickup and a 1979 Ford Ranchero. The victim was the driver of the S-10, 5'6" tall, and weighing 125 lbs., not restrained. At impact, the speed was 53 mph and the delta V was 34 mph. The victim died (AIS 6) from chest contact with the steering wheel resulting in an aortic rupture.

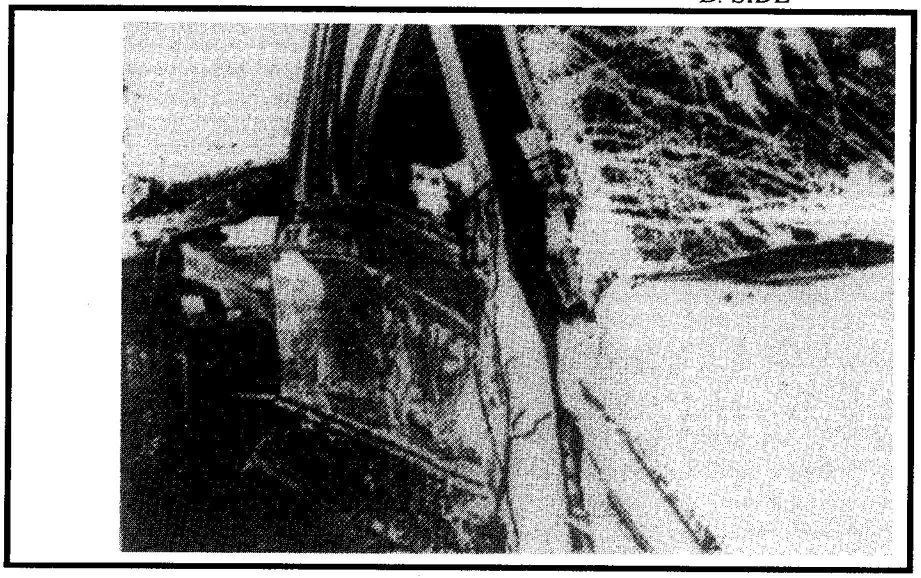


2. A 1989 Chevrolet S-10 Extended Cab Pickup collides with a 1991 Ford F150 Truck in a frontal strongly angled collision, resulting in massive intrusion of the A-pillar. The victim is the driver of the S-10 who was unrestrained and impacted the steering wheel with the chest and the edge of the trim molding of the A-pillar with the head. The victim suffers brain damage, AIS severity 4.

3. Victim is seated unbelted in the passenger seat of a 1987 GMC S-15 when it impacts the side of a 1970 Ford Maverick. The right-side door opens, and he is

ejected from the vehicle. As a result of the accident, he suffers severe head trauma and brain damage of AIS severity 4.

B. SIDE

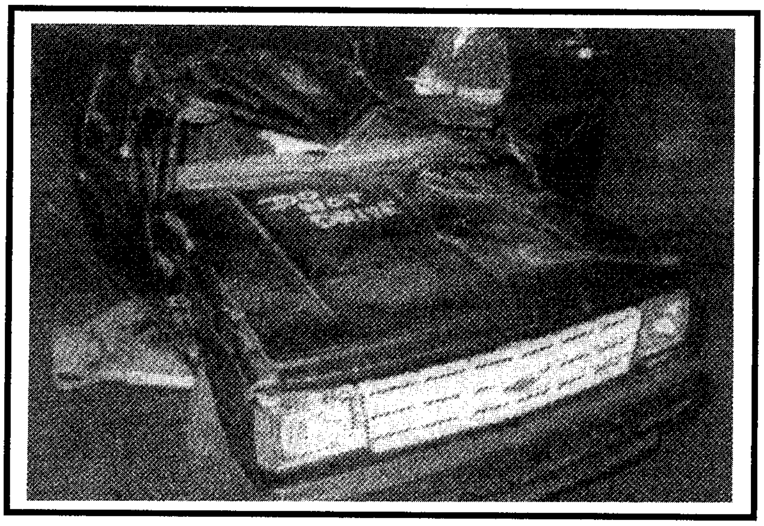


4. The right side towards the front of a 1982 Chevrolet S-10 Pickup is impacted at an angle by a 1979 Pontiac Bonneville. The victim is 5'5" tall and 110 lbs., seated unrestrained on the console between two restrained occupants. She is ejected into the roof by a collapse of the drive tunnel and suffers cervical quadriplegia and brain damage with AIS severity 5. Speed at impact is 33 mph. The delta V is near 40.

C. ROLLOVER

5. A case where a 1985 Chevrolet S-10 Pickup rolls over passenger side leading. The victim was the driver, 5'11" tall and 205 lbs., restrained. The pre-impact speed was 45 mph. At roof impact with 1/2 roll, the speed was only 10.8 mph and the vehicle was oriented 173 degrees from the original direction of travel. The roof crush was severe and the victim suffered quadriplegia, AIS severity 5.

6. A 1983 Chevrolet S-10 Extended Cab truck travels off the road and rolls over. The victim is 6'2" tall and 140 lbs., seated in the passenger seat, unrestrained under a deformed roof rail. The victim suffers brain damage, AIS severity 3.



7. The victim is unrestrained as the right front seat passenger in a 1985 Chevrolet S-10 Tahoe Extended Cab pickup. The driver loses control going over an icy bridge and the vehicle begins to rotate clockwise. The driver side tires go off the road and the vehicle rolls driver side leading. The victim contacts the roof and suffers quadriplegia, AIS severity 5.

8. A 1983 Chevrolet S-10 Blazer rolls over passenger side leading. The victim is 5'8" tall and 140 lbs., is driving, and is restrained. The victim dies as a result of trauma to the head on a collapsed roof rail, after which he is partially ejected from the vehicle.

9. A 1987 GMC S-15 Pickup collides with a cow, continues off the road and rolls over into a ditch. The victim was the restrained passenger, 5'10" tall, 170 lbs. and suffers quadriplegia, AIS severity 5. At impact with the cow the speed of the truck is 44 mph, while trip speed is 16 mph. Orientation at first impact is -90 (north), yawing at 65 deg/sec. The victim while restrained, contacts the roof rail with his head as the roof collapses and suffers axial forces fracturing the neck.

10. The driver of a 1987 Chevrolet S-10 Blazer travels off the road and rolls. The victim was 6'1", 175 lbs. and was restrained. He is rendered quadriplegic under a collapsed roof at AIS severity 5.

D. REAR

11. The 1989 Chevrolet S-10 Blazer is lightly impacted from behind by a 1981 Ford Pickup. The seat back and floor attachment fail causing the driver to lose control of the vehicle, go off the road and hit a tree head-on severely deforming the frame and the floorboard below the drivers seat cushion. The victim is the driver, 5'3" tall, 140 lbs. who was restrained, with the standard two retractor system. She suffered internal abdominal injuries. The speed at impact (with the Ford) is 37 mph, orientated 180 degrees. The rear delta V is 11 mph and the frontal delta V is 25 mph. AIS severity 4.

DESIGN ALTERNATIVES FOR SAFETY

The two unrestrained frontal head injuries were survivable, while the thoracic injury was fatal. None of the vehicles contained the steering assembly[10] or the padding[11] developed by GM to minimize the specific injuries received. Therefore, our modifications include adding those two features designed to the highest practical head and torso impact speed.

The side impact victim was unrestrained on the console, and therefore did not receive injuries characteristic of the revised FMVSS 214 dynamic test. She interacted with the restrained right front passenger and received head injuries from contacting the front header and a cervical fracture, both of which could have been mitigated with upper interior padding (and improved side structure).

However, the near side occupant in that side impact did receive leg, pelvic and thoracic injuries. Studies[12] in support of the dynamic FMVSS 214 have shown that such injuries may be countered by strengthening the vehicle side structure, moving the occupants away from the intruding surface, and maximizing the load distributing padding between the door and the occupant.

Of the six rollovers, the two who were unrestrained received head and neck injuries inside the vehicle by strikes to a conventionally shaped and unpadded roof rail and roof. Analysis showed that a non-collapsing roof and padding would have mitigated the injuries.

Four of the rollover victims were restrained. Three of the restrained rollover victims were rendered quadriplegic by a collapsing roof and a restraint system which failed to limit occupant motion towards the roof. The restraint system of the fourth allowed his head, after striking the collapsing roof rail, to extend out the side window and into fatal contact with the ground. The non-collapsing roof, padding and a restraint system with an autolocking lap belt with pre-tensioner would have avoided the quadriplegia and mitigated the fatality.

A list of the potential safety features considered for the modifications are shown in Table 8. For this exercise in minimum modification, the choice was prioritized in order of the potential benefit, ease of implementation, and the perceived consumer acceptability. In other words, while all the choices add benefit, engineering judgment was used to maximize the perceived overall safety payoff in the eleven cases. However, other and alternative features are discussed in the Enhanced Safety Design, since a global safety payoff analysis wasn't performed.

FIGURE 10

Examples of Technologies Available to Improve Car Safety

Passive Interior Systems	Emergency Tensioning Seatbelts
Anti-lock Braking Systems	Collision Mitigation Systems
Anticipatory Sensors	Impaired Driver Warning Systems
Alternative Occupant Seating Approaches	Advanced Air Bag Systems
Offset Impact Structural Countermeasures	Advanced Steering Systems
Alternative Engine Location	Improved Side Structures
Improved Side Impact Padding	Side Glazing Retention Systems
Reduced Aggressivity of LTV Front Ends	Improved Rear Impact Sturctures
Improved Roof Support Strutctures and Headliners	

ENHANCED SAFETY VEHICLE DESIGN

The intent is to utilize what is already there, with subsystem modifications or enhancements to improve safety, dealing with the accidents that happened. While ultimately one would redesign the vehicle around the occupants to achieve maximum safety, this exercise allows only minimum low cost modifications with maximum safety payoff.

Certainly there can be many approaches to accomplish equivalent safety enhancement. The safety concept we chose was to use the interior volume most efficiently with safety as the priority, and with comfort and convenience as a close, but second priority. The intention is to maximize the frontal, side and rollover deceleration distances by moving the seating positions as far rearward, downward and inboard as possible.

Another way to describe it is to enhance performance by providing increased occupant survival space from external intrusion into the passenger compartment by rearrangement of the internal seating layout.

This is accomplished by replacing the existing bucket seats with a structurally strong "belts to seat" version[13] moved inboard, rearward and lowered. The seat back is attached to the roof with the clear plastic headrest of the Minicars RSV[14]. The "new" 1989 GM energy absorbing column, with self aligning steering wheel and extended brake pedal, would be installed compatibly with the revised seat location.

At the same time, structural improvements limit intrusion in rollover accidents. The pillars, roof rails and headers are filled with about 15 pounds of structural composite foam[15]. The weight includes filling a crossmember under the seats and bridging the tunnel, which in conjunction with the composite filled pillars help deal with side impacts. The metal airgap interior padding enhances the strength of the roof by increasing the section modulus of the A and B pillars, roof rails and headers, while the doubled roof panel resists lateral buckling.

In addition, restraints are configured to contain the occupants and prevent the head from contacting the interior surfaces at speeds exceeding the capabilities of force limited metal air gap padding. The restraints are integrated into the seat, with autolocking seat belts, high sensitivity torso belt retractors and pretensioners. Padding, as mentioned above and which complies with the FMVSS 201 NPRM and our final submission to the docket, and weighing about 20 pounds covers all upper interior surfaces[16].

If the vehicle were redesigned for maximum safety, the roof rail edges of the roof would be moved inboard and rounded to minimize roll radius contact. The side structure would be improved by door beams, larger opening interfaces and better hinges and latches. Driver and passenger airbags would be added. Also, the vehicle would be powered as a 2 wheel front drive with reduced ground clearance, an extended track width, and 4 wheel anti-lock brakes to maintain directional stability and reduce roll propensity.

BENEFIT AND COST ANALYSIS RESULT

In this design, existing space is reallocated. The change of interior geometry added no cost, and in three cases had the biggest safety payoffs.

The next highest safety payoff comes from the upper interior padding and composite structural foam. This ranks high primarily due to its low added cost and the added improvement to structural strength which reduces intrusion. In six of the 11 cases, reduced intrusion alone would have reduced the injuries to AIS 3 or below.

The integrated seat and restraint system ranks third. This is because there is some significant cost and weight associated with strengthening the seat frame, adding restraint attachments and including pretensioners and other devices while still allowing some reclining.

CONCLUSIONS

After years of real world accident experience with the subject vehicle design, many serious accident injuries are obviously foreseeable. Furthermore, there are a variety of developed low cost modifications which can be implemented to mitigate these injuries. Those suggested here weigh about 50 pounds and are estimated to reduce the HARM by more than 25%. Yet each new vehicle generation contains the same flaws. Presumably this is because marketing has a higher priority than safety in the minds of manufacturers.

The demands of an informed consumer for recognizable devices or features, would appear to be the most effective means of requiring manufacturers to improve safety performance. By suggesting obviously safer vehicle designs and devices and comparing them with the current product, we hope to clearly establish their practicality and effectiveness, provide consumer information for more rational future purchasing choices, and aid in demonstrating improved, less dangerous and practical designs.

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The Application of the Crash Victim Simulation with Airbag to Recreational Vehicle

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Paper No. 94 S4 W 25

ABSTRUCT

In recent years, more importance has been attached to the collision safety performance, and in the United States installation of an airbag in the passenger cars has already been enforced by law. At the same time, it is becoming obligatory to install airbags in recreational vehicles (hereafter called RV). Under these circumstances, ISUZU has also been undertaking development to install airbags in the cars it produces, while conducting research on simulation of the airbags. In this report, we would first like to ensure that the simulation can fully reproduce the conditions of a sled test, and then illustrate the case in which the simulation was applied in order to obtain the optimum specification of the collapse characteristic of the steering column which becomes more important as a restraint system when an airbag is installed. In order to efficiently introduce the optimum system of airbags in RV, we are making attempts to develop and utilize this simulation technique.

INTRODUCTION

As RV is a car whose model is mainly derived from trucks, it is structured with separate body and frame, unlike most of passenger cars with the monocoque structure. Since airbags have been developed mainly for passenger cars, some knowhows from the development cannot be immediately applied to RV. For instance, rigidity of a frame-structured car is mainly governed by the frames. In case of a frontal impact collision, in particular, because the frame is very hard, the body is not easily collapsed,and a greater deceleration is generated. Moreover, as this type of car is tall and its center of gravity is high, a pitching phenomenon in which a vehicle is bent forward in the process of collapsing occurs. This pitching phenomenon significantly affects the possible behavior of occupants.

Furthermore, RV have more weight than passenger cars. For this reason, even though the former collide at the same speed as the latter do, the kinetic energy in proportion to car weight at the time of collision is larger for the former. In other words, as the energy to be absorbed increases, either a greater registance is generated or the extent of collapse of a vehicle becomes more severe. A greater registance is a factor to cause more injuries to occupants and the increased collapse of a vehicle reduces a survival space of occupants.

Such problems can only be solved through repetitious experiments and accumulation of knowhows, and simulation should be utilized to serve for this purpose. Thus, while attempting to improve the accuracy of simulation as well as making sure of the extent to which simulation can be applied, ISUZU has full employed the simulation. As a first step, we began with reproduction of the conditions of a sled test, and then undertook several parameter studies so that we could obtain better characteristics of the airbags, inflator, steering column, and knee bolster by using the simulation model. Here, as one example, we would like to introduce a parameter study that we conducted on the steering column.

MODELING

In this simulation, we used PAM_SAFE. It is the software which can perform a three-dimensional Crash Victim Simulation with airbags , calculate the behavior analysis on occupants or steering with MADYMO, let PAM_CRASH execute the airbag deploying simulation, and do calculation while mutually exchanging information on displacement and load.

Here we would like to discuss the airbag deploying simulation. The airbag to be installed on a driver side is a disk-shaped cloth two pieces of which are sewn together and is folded and accommodated in the steering, while the airbag on a passenger side is in a solid cylinder shape which is folded and accommodated in the instrument panel. At the time of collision, the airbags are deployed by gas emitted from the inflator to protect occupants. In PAM_SAFE, the airbag can be decomposed into finite elements, modeled in a folded condition, and deployed in accordance with the inflator characteristics. In addition, PAM_SAFE can process the airbag in three dimensions and decompose it into finite elements, it can reproduce how the airbag bumps against a dummy or window shield glass and the instrument panel, and transforms itself while taking balance with the pressure inside the bag.

In modeling, the three-dimensional model of HYBRID III which belongs to MADYMO is used as a dummy. Seats, floor, dash and instrument panel (knee bolster) are modeled on MADYMO, and their shapes are roughly drawn by using a plane. Then, as reaction force characteristic caused by the encounter with a dummy, the characteristics derived from the results of testing and simulation of individual parts are input. As for the steering, an ellipse is also used for modeling on MADYMO, but not only the contact reaction force characteristic but also collapse characteristic of a column are derived from the drawing and experiment values. The airbag is modeled with finite elements on PAM_CRASH, as described above. As the window shield glass shows a round shape, it is modeled with finite elements on PAM_CRASH.

SLED TEST

A restraint system is developed not only through a collision test using a real car but also through a sled test simulating the conditions of a collision test. This means that situation of an occupant compartment when the collision occurs is reproduced by placing only the occupant compartment on the sled, and providing it with acceleration which imitates a waveform of deceleration generated from the collision test. We conduct simulations exclusively on a sled test since it has less uncertain factors than collision test does. In this RV simulation as well, we also started simulating the sled test as a first step.

First, by comparing the calculation results with the test results, we could confirm the validity of the model. We created a calculating model having the same specification as a sled test, and, as described above, prepared the characteristics of each unit based on the results of testing and analysis of individual parts. For uncertain or unmeasurable characteristics, we referred to the values used for passenger cars. Dummy's behavior, movement, and acceleration are compared for evaluation Figure 2 shows the head and chest acceleration of a dummy. Figure 3 shows dummy's behavior. Consequently, the results from calculation and experiments of both match very well each other and thus it is determined that

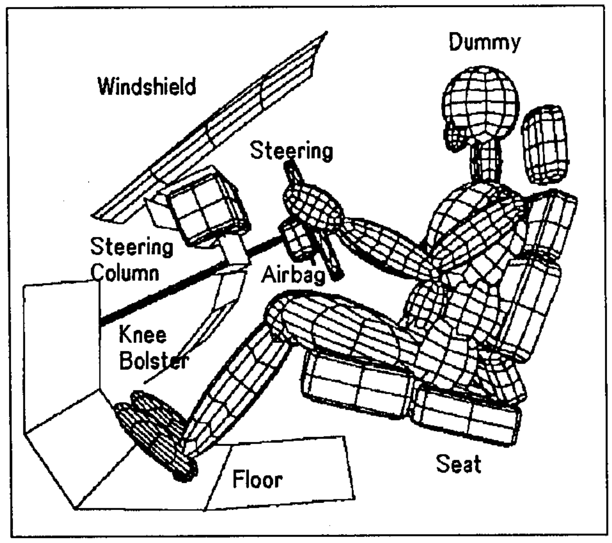

Figure 1. Modeling

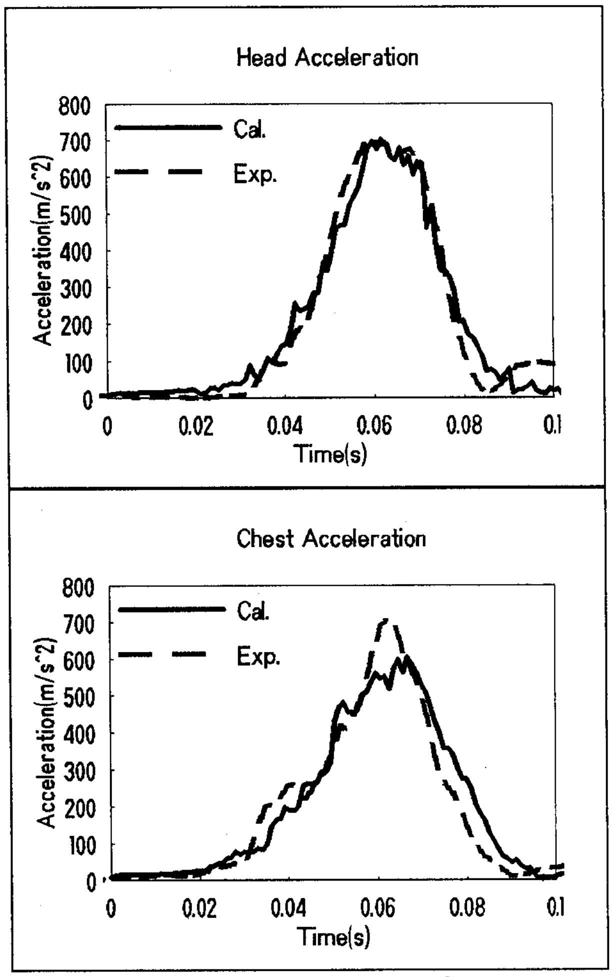

Figure 2. Comparison of Acceleration of Dummy's Head and Chest in Experiment and Calculation

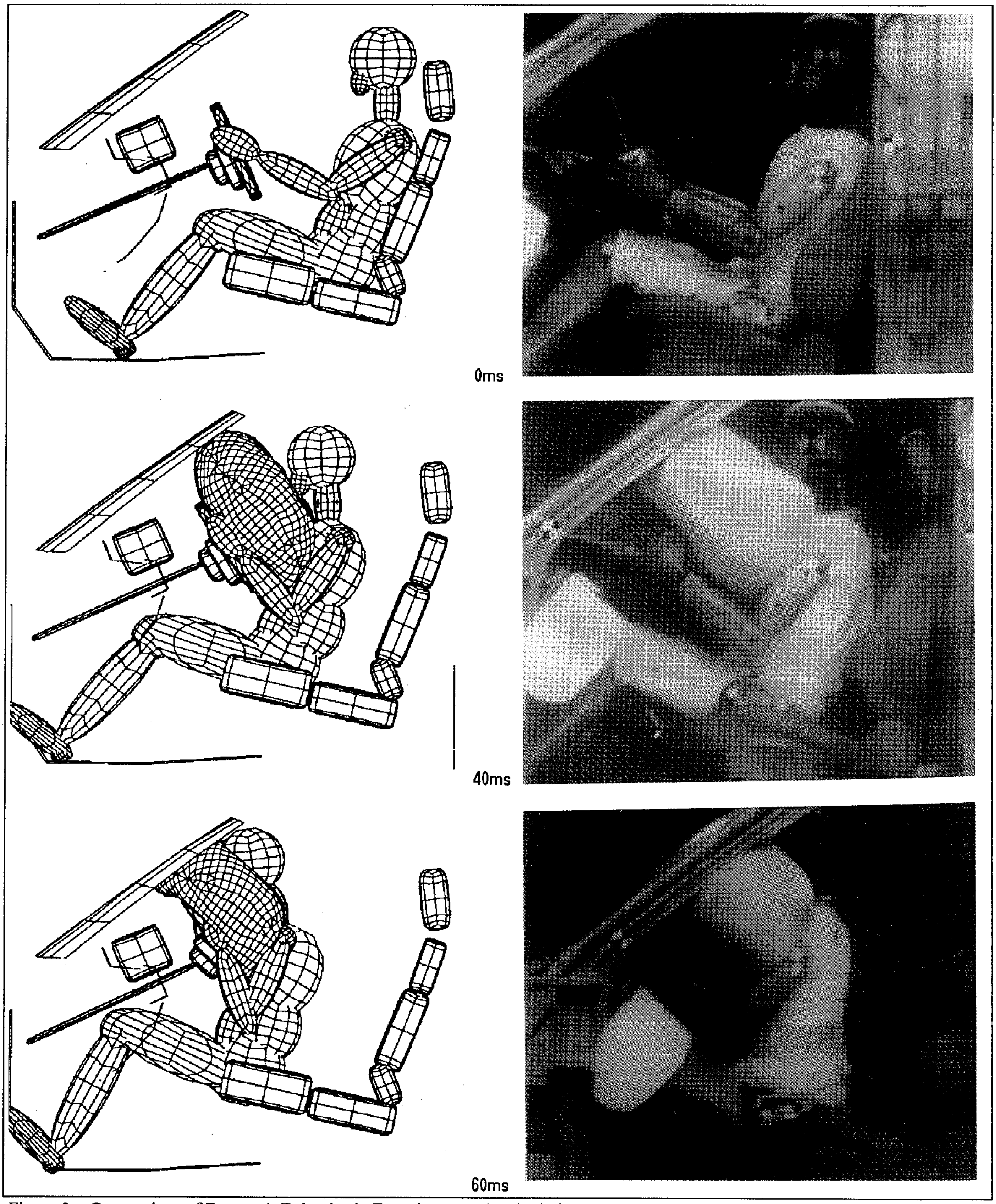

Figure 3. Comparison of Dummy's Behavior in Experiment and Calculation

this model can be usefully employed in the future parameter studies.

PARAMETER STUDY ON STEERING COLUMN

So far we have conducted the parameter studies on the characteristics of the restraint system such as the airbag or knee bolster, etc., by using this model. Here as an example, we would like to introduce the parameter study on the collapse characteristic of the steering column.

Since the airbag is to be installed on the steering on the driver seat, the steering column which supports the airbag considerably affects the performance of airbags. In addition, by being smashed (collapsing), the steering column can alleviate possible injuries of occupants. Therefore, optimization of the collapse characteristic of the steering column is a critical factor in improving the restraint performance. In the model, the steering column is attached to a vehicle by means of POINT RESTRAINT of MADYMO, and the collapse characteristic is expressed as elasticity characteristic of POINT RESTRAINT. The collapse characteristic of the steering column can be divided into the following three sections: the section before the column fixed on the bracket is removed, and the first-step and second-step sections based on how large the registance of the column is. Here, as parameters, we adopted four items of registance of three sections and length of the first-step section (See Figure 4). Following the method of dispersion analysis, as shown in Table 1, we set three levels for each of these four items, laid them out to L27 orthogonal array, and checked the tendency and factors from the calculation results of 27 cases.

Based on the results of dispersion analysis of Tables 2 and 3, each registance generated in the three sections of initial, first-step and second step sections is considered a factor of chest injury criteria(Chest 3ms average G), and it became clear that mutual reaction among registances of all four items, the initial and first-step registances contribute to head injury criteria(HIC). Figures 5 and 6 are graphs averaging the calculation results by an item. From this, we can understand that in order to lower Chest 3ms average G we should decrease each registance, and to reduce HIC we have only to increase the initial and first-step registance, decrease the second-step registance, and shorten the length of the first-step. However, since there is mutual reaction between initial and the first-step registances,the injury criteria is low either when we set the initial registance high and the first-step registance low, or vice-versa. In addition, in the collision test whose specification has been changed with the same direction as the optimum specification obtained here, we could confirm that reduction has been achieved in the injury criteria of 15% for HIC and 24% for Chest 3ms average G, compared with the results obtained so far.

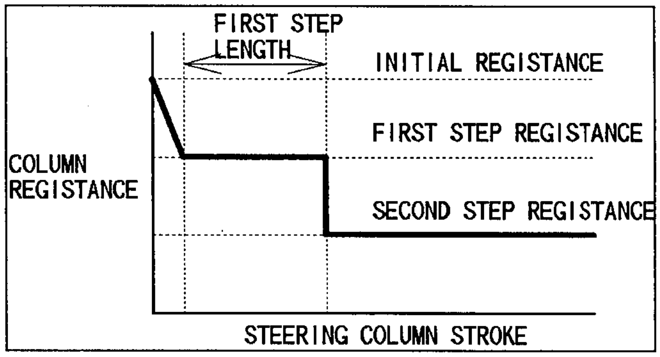

Figure 4. Collapse Characteristic of Steering Column

Table 1
Each Factor ad Level

	INITIAL REGISTANCE	FIRST STEP REGISTANCE	SECOND STEP REGISTANCE	FIRST STEP LENGTH
1	LOW	LOW	LOW	SHORT
2	MID.	MID.	MID.	MID.
3	HIGH	HIGH	HIGH	LONG

Table 2
Table of Dispersion Analysis of HIC

	S	ϕ	V	Fo	F(0.05)
INITIAL REGISTANCE	4422.767	2	2311.384	20.767*	4.10
FIRST STEP REGISTANCE	5162.005	2	2581.003	24.238*	4.10
SECOND STEP REGISTANCE	2324.094	2	1162.047	10.913*	4.10
FIRST STEP LENGTH	3340.583	2	1670.292	15.686*	4.10
INIT. REG. × FIRST REG.	3034.735	4	758.684	7.125*	3.48
FIRST REG. × FIRST LENGTH	597.686	4	149.215	1.401	3.48
error	1064.857	10	106.486		
TOTAL	19946.727	26			

*Factors which became meaningful

Table 3
Table of Dispersion Analysis of Chest 3ms average G

	S	ϕ	V	Fo	F(0.05)
INITIAL REGISTANCE	1172.552	2	586.276	8.931*	3.55
FIRST STEP REGISTANCE	1033.871	2	516.936	7.874*	3.55
SECOND STEP REGISTANCE	1552.198	2	761.099	11.822*	3.55
FIRST STEP LENGTH	65.787	2	32.894	0.501	
error	1181.676	18	65.649		
TOTAL	5006.084	26			

*Factors which became meaningful

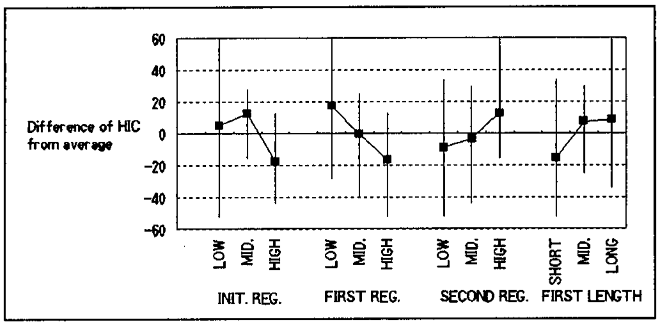

Figure 5. Average Value of HIC by Each Item

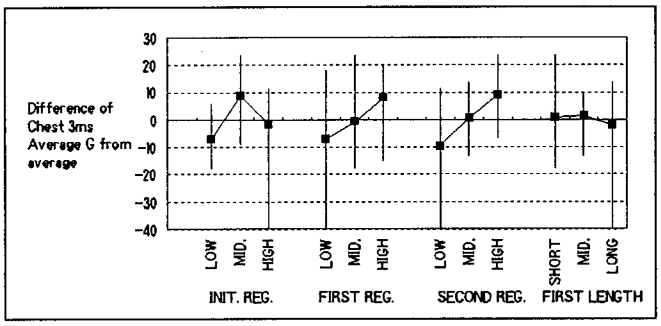

Figure 6. Average Value of Chest 3ms Ave. G by Each Item

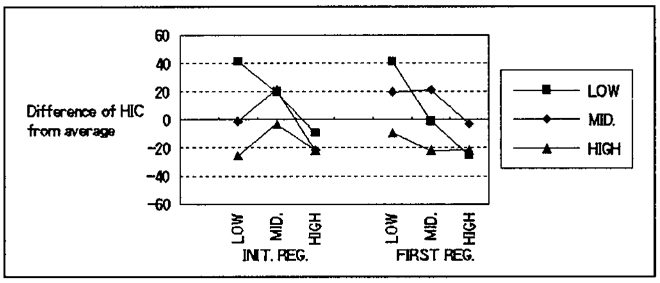

Figure 7. Mutual Reaction of HIC

CONCLUSION

We could reach the following conclusion by carrying out this simulation:

(1) We could confirm that we can reproduce the conditions of sled test with sufficient accuracy, by analyzing the occupant behavior in RV with airbag installed, and comparing it with the sled test on a driver seat.

(2) When undertaking the parameter study on the collapse characteristic of the steering column by employing the above-mentioned model, we could obtain the optimum specification and confirm its validity.

FUTURE DEVELOPMENT

As the sled test can be done more easily at a lower cost in comparison with the collision test, the former is often used for built-in restraint system, but it cannot reproduce the pitching phenomenon unique to RV, as described above. Since the pitching phenomenon greatly influences on injury criteria and the results of the sled test cannot be immediately reflected in the real car collision test, direct reproduction of a collision test tends to be more prevalent. If this method is to be used, the calculation results can be reflected in the collision test without requiring information on correlation between the sled and collision tests. However, when compared with the sled test,the collision test needs more information for implementing simulation and thus works involved become more difficult. Thus, calculation has now been made by modifying a model step by step, and from this attempt some good results have already been achieved. We are further committed to undertake more parameter studies to improve models and reflect them in the design of the future.

Severe and Fatal Lesions in Cars Fitted with Airbags: Case Reports

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94-S4-W-26

ABSTRACT

Airbags promised to usher in a new generation of restraint systems; nevertheless, some Authors described lesions associated to the use of air bags themselves.

Such airbag lesions are described in literature as facial bruising, corneal abrasions, finger distortions; these findings may be rather disturbing for their aesthetic or functional long-term consequences, but they are surely not life-threatening.

This paper describes some accidents involving airbag-equipped cars, in which the driver or the front passenger sustained severe or fatal lesions without severe intrusion of the passenger compartment. Two fatal cases regard drivers, with immediate or delayed exitus; one case regards an unrestrained passenger that was found dead at the scene.

Postmortem data were available for two of the fatal cases; there is strong suggestion that the described lesions have been produced by airbags themselves.

Our data suggest that the airbag alone may not be able to prevent violent contact with the lower part of the steering wheel rim, and that airbag deployment may be dramatically dangerous if the seat belts are not worn. The last assertion is categoric especially for the right passenger, whose body may more easily be displaced within the air bag inflation area during the braking phase that often precedes the impact.

Standard crash test do not foresee that a vehicle might be decelerating before the impact, nor that the space between passenger thorax and airbag surface could not be completely free. Apart from in-depth investigations and adding smart functions to airbags, it seems from our experience that also the testing procedures ought to be trimmed in order to detect chances of out-of-position and therefore prevent potentially fatal outcome.

BACKGROUND

The first airbags have been introduced on cars in the '70s, but only in recent years their number has grown to an appreciable level. Furthermore, penetration of airbags in the new car fleet will approach in the next years one hundred per cent, at least in the United States [3].

In Europe, airbags have reached a status of standard equipment for practically the whole upper and luxury class, at least for what concerns the driver. Passenger airbag is more often offered as optional, while some middle-size cars have begun in 1994 to offer driver airbags as normal outfit.

It has therefore been estimated that by the turn of the century more than half million airbag deployments will occur each year.

Some works in literature deal with the effectiveness of airbags in preventing or lowering impact injuries [2,8,9]. The overall advantage of this passive restraint systems is perhaps beyond reasonable doubts; however, some problems are emerging in particular situations [1,4,8], particularly with malpositioned people inside the car. A characteristic groups of lesions has been described, comprising skin abrasions and bruisings [10], finger trauma [11], corneal abrasions, up to more severe thoracic lesions.

This paper summarizes an investigation upon some accidents involving airbag-equipped cars with very severe or fatal outcome, with particular focus on the correlation between dynamic of airbag deployment and body lesions.

MATERIALS AND METHOD

With the collaboration of a group of Road Police departments throughout Northern and Central Italy, we simply collected any accident with airbag we were able to identify.

The investigation started in Summer 1993 and is going on. For cases identification, we scanned all reported accidents, looking for car models potentially equipped with airbag, such as Volvo, Mercedes-Benz, BMW, Japanese models, or some '94-year-models, checking case by case if the device was actually present.

For each case, we collected any available information about the following data:

- Site, date and hour of the accident;
- Dynamic of the impact;
- Type, model and version of the vehicle;
- Marketing date and provenance of the vehicle;
- Deformation of vehicles, both external and internal;
- Deformation of other colliding vehicles;
- Description of lesions, from clinical and when available autopsical examinations;
- Any other circumstantial information, also from eyewitnesses.

We also directly examined each involved vehicle.

Injury severity was set according to the Abbreviated Injury Scaling, 1990 Edition.

RESULTS

Because of the rarity of airbags on the Italian car fleet, we met only 11 accidents, sometimes with minor consequences to vehicles and no injuries at all.

Relying on memory of Police officers and on newspapers revision, we have knowledge of around a dozen of other cases, generally with moderate or no injuries, but without access to exhaustive or however satisfying data.

All our cases regard cars regularly registered in Italy (with the only exception of the Mercedes Benz 300 CE who wears a Swiss plate) and with Italian drivers and passengers.

In our sample, 2 cases have been reported without any physical consequences; 4 cases are associated with minor abrasions and contusions, or however with lesions AIS ≤ 2, while one case associated with major car damage had fatal outcome.

Ejection from the vehicle despite the airbag deployment was observed in one non-fatal case.

Surprisingly, three other cases had fatal consequences, even if there had been no intrusion of the passenger compartment.

We shall discuss into detail three of the four fatal cases and the case with driver ejection: their main characteristics are summarized in Table I.

Case I.

On an urban road, after midnight, a Jeep "Cherokee" impacted a cement wayside post and went down a scarp, stopping after at least one rollover (Picture 1).

The driver, 42 years-old, male, was ejected and suffered a facial contusion (AIS 1), two bilateral femur fractures (AIS 3 both), with arterial lesion.

The vehicle had been bought in the United States and then imported to Italy; it was equipped with a full-size airbag that deployed regularly.

Vehicle type	*Collision*	*Position*	*Lesions*	*AIS score*
Jeep Cherokee	frontal vs. manufact +rollover	driver	facial contusion	1
			bilateral femur fracture	3
			superficial femoral artery lesion	3
Mazda MX-5 "Miata"	offset frontal vs. car	driver	multiple metatarsal fracture	2
			mesenterial laceration + ileal perforation and emoperitoneum (2000 cc)	3
Mercedes Benz 500 SE	frontal vs. tree	driver	abrasions to forearms and right thigh	1
			sternum fracture	2
			multiple bilateral rib fractures	4
			heart contusion + right atrium lesion	5
Mercedes Benz 300 CE	angled frontal vs. overturned truck	driver	bilateral multiple rib fractures	4
			intrahepatic hematoma + emoperitoneum	3
			diffuse bruisings	1
		passenger	closed thoracic trauma n.f.s.	9
			right arm fracture	2
			facial contusion n.f.s.	1

Table I: *Summary of the main characteristics of the described cases.*

Picture 1: *External view of case I (see description in text).*

There were no other people in the car, nor in the nearbies; the unlucky driver remained at least three hours on the shore of the Adige river, until at dawn a fisher noted him and called for the Emergency team.

Case II.

On a secondary road in the nearbies of Garda lake, a Mazda MX-5 "Miata" (Picture 2) sustained an offset head-on impact on a bend with a Lancia Thema.

The Mazda "Miata", that had been first marketed in the Netherlands, was equipped with a tethered, small-size airbag; its passenger compartment had been not deformed at all (Picture 3). The steering wheel, however, was slightly bent at its lower part (around 10°).

This Japanese car was fitted with a strange type of seat belts, provided with something like a "stress dampener" that will be better described and discussed later (Picture 9).

The unbelted driver of the Lancia Thema, female, aged 51, suffered a large wound at the right knee with ligament transection (AIS 2), multiple rib fractures at the right side (AIS 2), right femur fracture (AIS 3), chin contusion (AIS 1).

The driver of the Mazda, male, aged 45, was able to get down from the car and comment to rescuers that "*the airbag had not worked*". He was admitted into a local Hospital, where he sustained abdominal TC scan and ecography, and rapidly his clinical conditions worsened into shock.

With a diagnosis of haemorrhagic shock due to closed abdominal trauma and closed trauma to left emithorax, the patient was urgently transferred to the Resuscitation Dept. of another hospital, suffering a cardiac arrest in the meanwhile (around four hours after the accident).

An explorative laparotomy documented the presence of a conspicuous emoperitoneum (2000 cc) with disinsertion of a mesenterial root and small ileal perforation (AIS 3). The patient suffered also a right metatarsal multiple fracture, valuable as AIS 2.

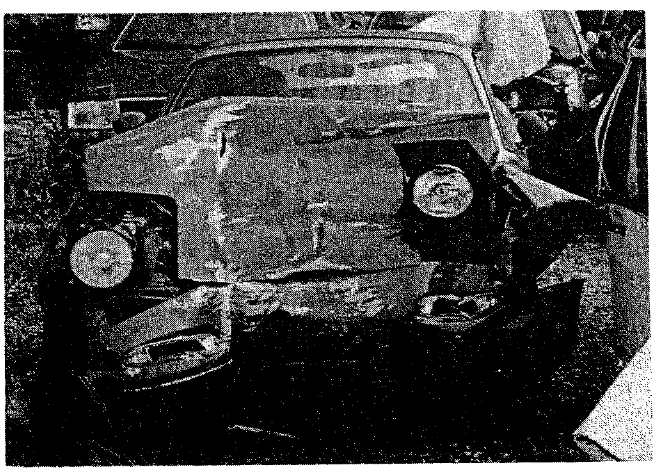
The patient remained in coma (stage III-IV), sustained a second laparotomy at eight days from the accident, and died at 20 days from the traumatic event without leaving coma.

Case III.

On an urban road, in the very first hours of the morning a Mercedes-Benz 500 SE impacted a tree after 12 meters of slippery on grass (Picture 4). No traces of braking were found.

The car had been first marketed in Germany; the airbag deployed regularly (Picture 5). The front of the car had been severely intruded, while the passenger compartment was practically intact (Picture 6).

The driver, male, aged 37, was transported to the Resuscitation Dept. and was declared dead one hour later. The external examination and the autopsy documented abrasions to forearms and to right thigh (AIS 1), sternum fracture (AIS 2), multiple bilateral rib fractures (AIS 4), heart contusion with damage to right atrium (AIS 5). The cause of death has been referred to cardiac tamponade.



Picture 2: *Frontal view of the Mazda MX-5 described in case II (see text).*

Picture 3: *Driver seat of the case II with deployed airbag (see description in text).*

Picture 4: *Scene of case III (see description in text).*

Case IV.

On the motorway "Serenissima", early in the morning, a Mercedes-Benz 300 CE was involved in a slightly offset head-on collision. The car had been marketed in Switzerland; it was equipped with ABS, and as usual in these cases no traces of braking were appreciable.

Both the driver and the full-size passenger airbags deployed regularly; the passenger compartment was slightly intruded from the driver side, but there was no intrusion at the passenger side (Picture 7). The car pavement had been compressed and bent upwards, and the steering wheel had been dislocated in the same direction.

The driver, male, aged 44, suffered bilateral multiple rib fractures (AIS 4), intrahepatic hematoma with emoperitoneum (AIS 3), diffuse bruisings (AIS 1) and was transferred to the Resuscitation Dept.

The passenger, male, aged 53, was found dead at the scene (Picture 8). The cause of death was simply classified as violent traumatic agent ("polytrauma"). From photographs, however, it is possible to ascertain an undoubted fracture of the right arm and an area of contusion around the nose; at the same moment, there is no evidence of bleeding from nose or mouth.

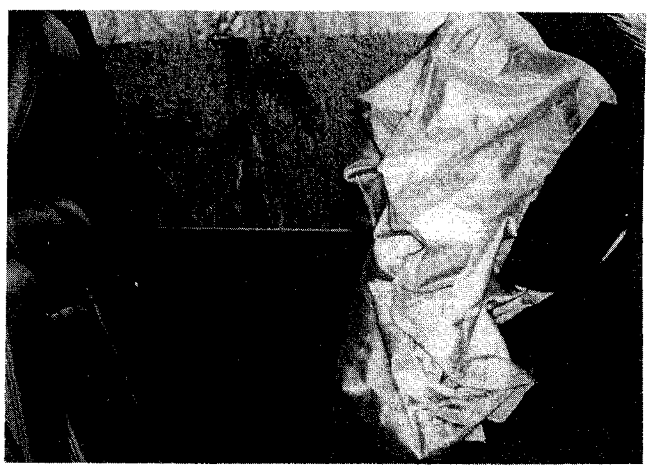
The significance of these pathological findings will be discussed later.

The lesions suffered by the deceased right passenger may be classified as closed thoracic trauma not further specified (AIS 9), right arm fracture (AIS 2), facial contusion n.f.s. (AIS 1).

DISCUSSION

The chance for the driver to receive lesions by the inflating airbag is not new to literature. However, even if the first airbags date so long as twenty years, only in the last two years there has been a significant interest towards airbag traumatology.

The first lesions clearly associated to airbags were considered as actually minor, little more than "bugs" in a context of miraculous preservation of life in road impacts. Moreover, they merely consist in abrasions and small bruisings, abso-



Picture 5: *Driver's seat and deployed airbag in case III (see description in text).*

Picture 6: *Detail of the car structure in case III (see description in text).*

Picture 7: *Scene of case IV (see description in text).*

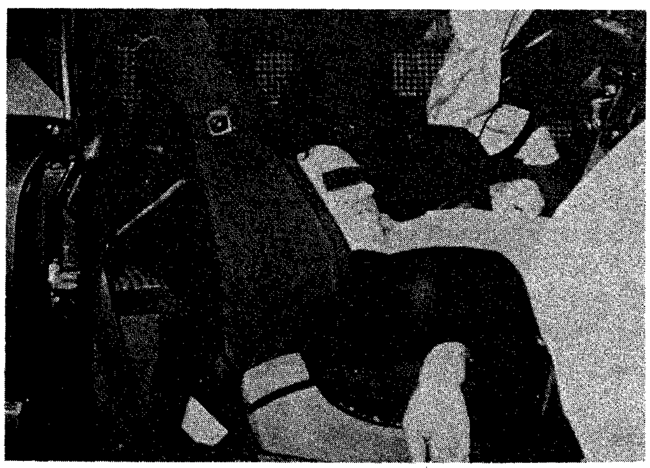
lutely not life-threatening and without feasible chances to give birth to permanent impairment.

Only after in-depth studies on unfolding patterns of airbags it became clear that even these minor lesions are not due to a simple pressure of the skin against a soft cushion, but are rather generated by a "slap" given by the unfolding restraint system [10].

More worrying is the possibility of corneal abrasions by the airbag, not only for the chance of visual impairment and expensive therapy, but of course also because this kind of lesion is inflicted to a body area that would have remained intact without airbag intervention.

The occurrence of severe and fatal lesions in airbag crashes is rare, and for what we know in literature has always been associated with extensive car damage: of course, in extreme situations no restraint system may assure survival.

The cases we describe in this paper share a common feature: they regard cars without passenger compartment deformation, or with only minimal intrusion. In fact, the lesions suffered by the victims may be attributed to airbag loading rather than to rigid car components.



Picture 8: *Body of the front passenger described in case IV (see text).*

The driver of the Mazda had a constellation of lesions very close to a seat belt syndrome, that we think are due to sudden deceleration (induced by the inflating airbag) more than to violent contact with the steering wheel.

In the case of the dead passenger, no autopsy was required by Authorities. An external examinations was performed by a not specialized physician, and this all has resulted in losing precious information on a dramatically important case.

However, from the photographs taken by Police personnel at the scene it is clear how the death has been sudden. The unlucky passenger ceased at once to breathe, as it is demonstrated by the absence of blood around his nose and mouth.

The right arm is frankly broken. Even if it could be possible to hypothesize a "physiological" death, i.e. a cardiac arrest due to the fright of the accident, the occurrence of the arm fracture is a clear marker of something very violent.

Moreover, a possible self-protecting manoeuvre (raising an arm to protect the head and face) could result not only in breakage of the limb by the inflating airbag, but also in compressing it against the thorax, concentrating a strong pressure on a narrow zone.

The autopsical data of the driver of the Mercedes sedan show actually a combination of both compression and deceleration thoracic lesions. The right atrial lesion is closely similar to another case reported in literature, for which the deformation of the car is unknown.

It is important to note that the lesions described in our cases are surprisingly similar to what observed by Horsch, Lau et al. (1990) on experimental animals [1].

Are the situation of our cases extreme or absolutely rare? Surely not. The conditions of these real cases are common: a single vehicle going off-the-road and overturned, a crash against a tree, an offset frontal, a passenger involved in a motorway impact with previous braking.

In all our cases seat belts had surely not been worn; only for the Mercedes Benz sedan case the unbelted condition of the driver has to be considered as highly probable, but not certainly proven.

In the Mazda case, the not wearing of seat belts has been demonstrated by a strange feature of the belt itself. In the lower part of the belt and near to the attachment bolt, the web has been sewn several times, in order to constitute a loop that will be progressively broken under charge. When this loop will disappear under stretching, a red warning "*Replace seat belt*" will come to eyes (Picture 9).

As this instrument was intact in the smashed car, it may be assumed that the seat belt has never been charged during an impact. By the way, it seems very strange that a high-tech car could fit a whatzit that seems designed only to assure some centimetres of slack during an impact: something like a "post-tensioner".

Picture 9: *Detail of the seat belt with dampener, fitted on the Mazda MX-5 described in case II.*

Only in one case (Mazda MX-5) the steering wheel was found in a slightly rotated position; this could however be due to mechanical manoeuvres while picking away the damaged car. That steering wheel is also the only one with appreciable deformation (10° bent at the lower side), while the steering wheel of the Cherokee had been literally detached from the dashboard in one piece with its column.

It is interesting that none of the described cars was initially marketed in Italy: the two Mercedes came from Switzerland and Germany, the Cherokee from the United States, and the Mazda from the Netherlands. For instance, the Mazda MX-5 is not available with airbag in Italy, neither as an optional.

Immediately after the accident, the driver of the Mazda complainted that *"the airbag did not work"*. As we found a completely deployed airbag and there is no proof of tampering of the airbag system after the crash, we may assume that this man had only a partial information upon airbag intervention and thought that it had to remain inflated even after the impact.

It is not possible, from our data, to drive considerations upon the volume of airbags and its influence on the chance of lesions; however, it is instructive how the small airbag of the Miata allowed a deformation of the steering wheel rim.

For what concerns the pathogenesis of lesions, it seems now clear from literature that moderate lesions such as skin and corneal abrasions, facial bruisings, small contusions and hematomas are due to a "slapping" pattern rather than to an open charging of the occupant's body by the inflating airbag.

It is far less clear to define what is happening in more severe injuries. We could recognise the following pathogenic patterns:

- Direct loading by the airbag, at full surface or angled;
- Contact with the steering wheel despite the airbag;
- Secondary thoracic lesions by broken ribs;
- Deceleration (inertial) visceral lesions;
- Transmission of pressure waves to viscera (?)

Other mechanisms of airbag lesions are possible, but do not regard a "normal", rule-observing driving. For instance, in Italy we observed the fatal case of a child travelling on a German-made roadster in the front right passenger's lap and impacted by the airbag in a low-speed crash.

Some of the injuries potentially due to an airbag may present a free interval; therefore, it could be dangerous to ignore the possibility, for instance, of an occult abdominal injury, that could really endanger life some hours after the accident.

One of our cases had actually a short free interval; it is not out of reality to think that a more aggressive diagnostic approach could save lives in such circumstances.

The problems of near-position and out-of-position ought to be better identified and prevented already in crash tests and simulation procedures. Particularly, some tests should include a sharp deceleration before the impact, thus unveiling the movements of the passenger towards the dashboard.

It is questionable if the passenger side airbag complies with the same principles of the driver's one, or if it is rather a different breed of restraint system.

Even if technology and deployment are more or less the same, in fact, the target is different, because of different postures of drivers and passengers while travelling.

In fact, the driver maintains his arms at a distance equal to the diameter of the steering wheel, and the airbag will deploy within them. In other words, the driver is naturally on an "airbag aware" posture.

On the other side, the passenger may assume more comfortable postures, such as crossing arms, or may look for objects around, or and may raise arms to protect himself in the instants preceding an impact. In these cases, and even if belted, the upper limbs may be reached by the airbag and compressed as a club against the chest.

An out-of -position body may act as an "external" tether, modifying the external shape of the bag, but it is highly feasible that the gas pressure may actually cause a rebound of the body, at least in near-position situations. In these cases, deceleration lesions could be possible and regard as well parenchymatous viscera (e.g. liver) or partially mobile structures like mesenterium, or mediastinic vessels.

It could be possible to add "smart" features to an airbag, for instance feeding its processor with data comprising speed, acceleration, belt wearing, distance from occupant's body and so on[6]. With such configuration, the system should decide not only if activate or remain still, but also "how much" activate, achieving the maximum compliance with a given situation and a given person.

It is not clear how an explosive-powered device such an airbag could be triggered in order to give differentiate responses to different inputs; however, it seems that it will be particularly important for threshold impacts, happening around the range of activation of the airbag itself.

In the worst hypothetic configuration, in fact, a vigorous braking at city speed followed by a crash could result in a 200

Permanent (steady)
• Short stature
• Advanced driving posture
Dynamic (pre-impact)
• Braking or slippery before first impact
• First impact not frontal
• Voluntary movement, such as operating a radio or searching objects
Partial (only some body portions)
• Hand upon steering wheel ("claxon reflex")
• Passenger with cross arms
• Self-defense posture (raised arm)

Table II: *Possible causes of out-of-position or near-position.*

km/h impact of the inflating airbag against a not restrained passenger. In this way, a survivable accident could be changed in a fatal one: considering the belting rate in city traffic, this situation may replicate in a high number of case, especially with small cars. It is to note, moreover, that cars like Fiestas and Puntos, recently available with passenger airbags, are more likely to be used in urban service than large cars, and more frequently will host female drivers with more advanced driving posture.

Of course, an algorithm of "smart" airbag activation should considerate a range of current kinematics of car occupants[6], and should integrate with a state-of-the-art seat belt[12] as well as with the overall deceleration pattern of the car.

From our experience, it seems very dangerous to allow airbag inflation when it is not sure there is enough free space for passengers body. From this point of view, also the introduction of side airbags should be carefully studied in order to prevent dangerous contacts with the chest, that could be allowed even to a belted occupant if the car, for instance, had a slope before impacting an obstacle with its side.

According to this discussion, the main risk factors for out-of-position are synthesized in Table II.

Some **forensic aspects** of these cases deserve some further consideration.

For what concerns accident reconstruction, it will be difficult to evaluate a pre-impact braking if the car is equipped with ABS or similar, and usually an airbag-equipped car is.

For what concerns responsibility, it is clear how system or cars manufacturers might be directly involved, if such fatal airbag cases should replicate.

In at least two of our three fatal cases the belts were surely not worn; however, there is little doubt that the lethal injuries were due to the direct impact and loading by the airbag itself.

It is mandatory to provide better informations to car users, by clear and visible warnings that ought to be not confined to a script in the car users' manual or inside the sunvisor.

What is worse, current advertisements and articles on newspapers and magazines are characterising the airbags as the ultimate safety dispenser, without giving adequate informations to the need to wear the seat belts however. This may generate a common feeling that airbags alone are a warranty to survive, so further decreasing the belt wearing rate.

Therefore, responsibility claims against the manufacturer could be carried forward, if the user would have not been clearly informed about the necessity to wear seat belts however.

In Italy, the use of seat belts has always been very low, even after its enforcing by law in April 1989; therefore, it is not surprising that all our cases deal with unbelted occupants. Moreover, driving or travelling in an airbag equipped car may give a presumption of safety, thus lowering again the percentage of wearing. With this scenario, marketing a safety device that requires belt buckling is perhaps not careful when countries with low buckling rates are involved.

Other responsibility issues might regard the driver, if an unbelted passenger had to suffer airbag lesions, at least in those legislation which define the driver as responsible of the belt wearing inside the car (as in the Italian case).

Another group of forensic problems may regard the behaviour of the rescue teams and the medical treatment at the Casualty ward. All the personnel must know that in some conditions airbags may give occult visceral injuries, and must be ready to recognise their first clinical symptoms, providing an adequate observation period for incoming patients.

CONCLUSIONS

Even if the overall effectiveness of airbags seems to be positive, it is hard to accept that a safety measure, even if supplemental, might kickback with so dangerous side effects.

We perceive that airbags, being born to protect unbelted occupants in low-speed (limited at 55 mph) and large size vehicles, need adjustments to fit low- or middle-size, cars travelling at European speeds.

The face bag could obviously be less dangerous, or more precisely could have less probabilities to impact a displaced body. Unluckily, as in one of the case we presented, it may not "fill" enough the survival space to prevent contacts with the steering wheel or forward projection.

To completely eliminate the danger of severe damage to a mispositioned body, we think that some smart functions have to be added to the logic of airbag deployment: for instance, the deployment could be related to variables like speed, peak deceleration, detection of masses in the survival space, biometric features of the occupant, belt wearing or not.

It seems almost impossible, however, to balance a decision diagram with the need to protect always and however even an unbelted occupant.

The mechanisms that lead to the fatal consequences in our cases are simple and susceptible to be reproduced, as long as there will be accidents with unbelted people and decelerations before the impact phase.

Many efforts have been devoted to the increase of seat belt use, but nevertheless an appreciable percentage of drivers and passengers do not accomplish to this rule. In these conditions, the risk of severe airbag lesions is not acceptable.

Compared to seat belts, airbags appear now to be at the "lap-only" stage. Further research and experimentation is needed; our preliminary experience with airbag lesions shows that crash tests themselves have to be improved, in order to provide better informations and help reducing the fatal danger of near- and out-of-position movements.

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Car size and safety:
a review focused on identifying causative factors

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ABSTRACT

In the last few years a number of additions to the technical literature on relationships between car size or mass and occupant risk of fatality or injury have appeared. This new information is reviewed, synthesized and used as the basis for additional calculations aimed at better identifying causal factors. It is concluded that if a car crashes head-on into a 12 000 kg truck, the car driver is 36% more likely to be killed in a 900 kg car than in an 1800 kg car solely as a result of differing Newtonian kinematics. Five studies from two countries consistently support that when cars of similar mass crash head-on into each other, driver risk is inversely related to the common car mass. Size is the dominant causative factor in this relationship, and in the higher rollover risk in lighter cars. Mass and size are causal factors in single-car nonrollover crashes. Mass exercises a dominant causal effect on car driver risk in crashes between vehicles whose masses differ by more than about 10%. All cars becoming lighter/smaller would have only a small effect (most likely an increase) on net driver risk in two-car crashes, such crashes accounting for 22% of car-occupant fatalities. As 70 % of car-occupant deaths occur in crashes involving only one car, and lighter/smaller cars increase driver risk in all of these, a smaller/lighter fleet leads to increased casualties regardless of any interactive effects in the two-car crash component. Because mass is a dominant causal factor in crashes that account for over 50% of car-occupant fatalities, mass reductions (even if size remained unchanged) would lead to casualty increases. Any measure that reduces the mass of cars, even if car size remains unchanged, will increase car-occupant fatalities.

INTRODUCTION

One of the most firmly established effects in traffic safety is that when crashes occur, occupants of smaller lighter vehicles are at greater injury risk than are occupants of larger heavier vehicles. The early studies of Campbell and Reinfurt [1973], Negri and Riley [1974], Joksch [1976], and Grime and Hutchinson [1979] established that when cars of unequal weight crash into each other, fatality and injury risk is greater in the lighter car. Higher risks in lighter, smaller cars are found in data and investigations from many countries: : Germany [Kramer, Scholpp and Otte 1993;

Ernst et al. 1993]; France [Thomas et al. 1990]; the United Kingdom [Jones 1976; Grime and Hutchinson 1979]; Sweden [Koch, Kullgren and Tingvall 1993; Folksam 1990]; Finland [Roine and Kulmala 1994]; and the United States [Evans 1986; Partyka 1988; Partyka and Boehly 1989; Klein, Herts and Borener 1993; Kahane 1993; Insurance Institute for Highway Safety 1987].

Despite an extensive literature, many important aspects of the relationship between occupant risk and vehicle size remain uncertain, particularly identification of causative factors. The size and mass (or weight) of vehicles are closely related, so that any observed relationship between occupant risk and vehicle size does not establish vehicle size as a causative factor; a similarly systematic relationship with mass would have emerged if mass had been chosen as the independent variable. This paper aims at further clarifying such questions by synthesizing results from studies published in the last few years, and by performing some new analyses.

For most purposes mass is the most convenient independent variable because it is, conceptually at least, a fairly unambiguous physical characteristic of a vehicle. It additionally tends to be known, and is often part of the legal description of the vehicle for taxation purposes. In contrast, size is a more nebulous characteristic not quantified by one measurement. Many measures of vehicle size have been used, including overall length, wheelbase, trackwidth (the distance between left and right wheels) and interior volume. In this paper, we examine driver risks versus vehicle mass, but later discuss the findings in terms of relationships between vehicle size and mass, and probable causative factors.

Much of the material to be presented is for fatalities, because reliable information for this highest severity outcome is available from the Fatal Accident Reporting System [National Highway Traffic Safety Administration 1991]. Figure 1 shows that 45 percent of fatally injured car occupants are killed in single-car crashes, and an additional 25 percent are killed in crashes with vehicles other than cars (trucks, vans, etc.). Thus for 70 percent of the car-occupants killed, the only car characteristics related to their deaths are the characteristics of the car in which they were traveling; the mass of the other cars on the road is irrelevant. However, in two-car crashes the mass of the other involved car is important. Much of this paper is devoted to two-car crashes even though they account for far fewer deaths than single-car crashes. This is done because various methods that are not applicable to other types of crashes allow us to focus on detailed aspects of two-car crashes. For single-car crashes, traffic crash data provide information on the striking car, but nothing on the struck object (most commonly a tree). However, in a two-car crash, the struck object is another car, so that important characteristics of it are available in the data set. In many cases precise relationships are obtained which offer insight into the effect of mass in other types of crashes. Physical mechanisms identified in two-car crashes offer possible explanations of mechanisms in other types of crashes.

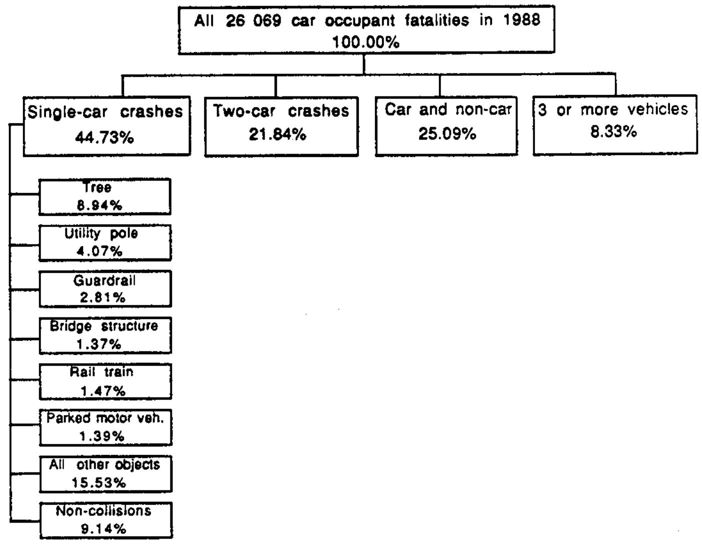


Fig. 1. Distribution of car occupants killed according to the number of vehicles involved. The values in all cells indicate the percents of the total 26 069 car occupant fatalities coded in the 1988 FARS file. From Evan's [1991, p 47].

TWO-CAR CRASHES

Crashes between cars of unequal mass

For every crash between two cars of known mass, we can define a mass ratio, μ, as

$$\mu = \frac{\text{Mass of the heavier car } (m_2)}{\text{Mass of the lighter car } (m_1)} \qquad (1)$$

and a driver fatality risk ratio, R, as

$$R = \frac{\text{Probability of a driver fatality in lighter car}}{\text{Probability of a driver fatality in heavier car}} . \qquad (2)$$

Empirical findings - Using FARS data, Evans and Frick [1993a] examined R versus μ. Figure 2 shows results for head-on crashes (regardless of driver belt use, car model year, driver age, etc.) The relationship fitted to the empirical data is

$$R = \mu^u . \qquad (3)$$

Values of the parameter u, and its associated standard error, are given in Evans and Frick [1993a] for 30 cases (head-on compared to all impact directions, belted compared to unbelted drivers, urban compared to rural, night compared to day, drivers of same sex and similar age, etc.). All the results are inferred from FARS data in a largely assumption-free calculation. The effect of mass ratio is large. For example, Fig. 2 indicates that if one car crashes head-on into another 20 percent heavier, then the driver in the lighter car is twice as likely to be killed as is the driver in the heavier car. If one of the cars is twice as heavy as the other, the driver in the lighter car is 13 times as likely to be killed as is the driver in the heavier car. The finding of so large and robust an empirical relationship invites a search for understanding at a more fundamental and theoretical level, especially with a view to identifying underlying causative mechanisms.

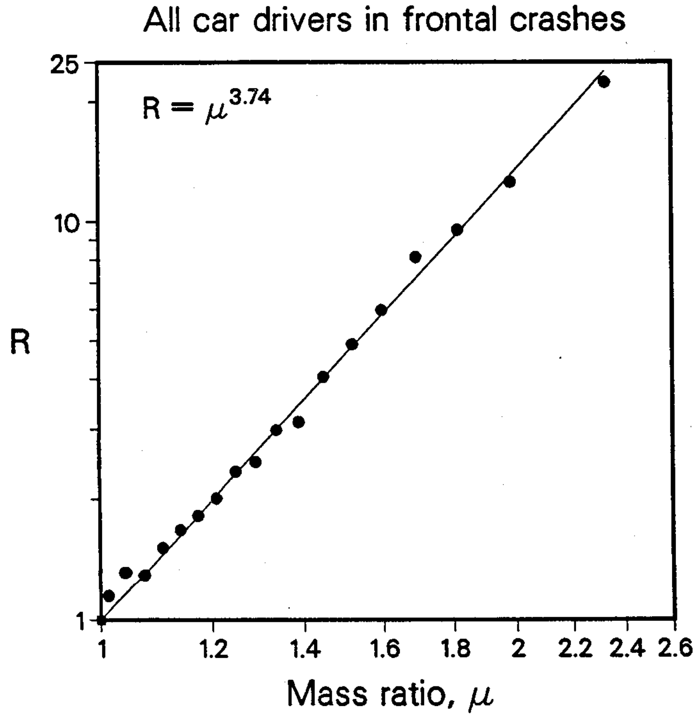


Fig. 2. The ratio, R, of driver fatalities in the lighter compared to in the heavier car versus the ratio, μ, of the mass of the heavier to the mass of the lighter car for frontal crashes (both cars with principal impact point at 11, 12 or 1 o'clock). 1975-1989 FARS data. From Evans and Frick 1993a.

<u>An explanation based on Newtonian Mechanics</u> - Evans [1994] considers two cars traveling in opposite directions crashing head-on into each other, and assumes that the crash is inelastic -- that is, after the crash the vehicles remain in contact as one combined object. Because of the assumed symmetry about the common axis, the combined mass will also travel along this axis. The assumption of an inelastic crash is a reasonable approximation because in most cases crashed vehicles remain relatively close to each other after the crash. By applying the law of conservation of linear momentum, the change in speed, Δv, that each car undergoes as a result of the crash can be computed in terms of the initial speeds and masses of the two cars. The ratio of the changes in speed depends only on the mass ratio, and is given by

$$\Delta v_1/\Delta v_2 = m_2/m_1 = \mu , \quad (4)$$

where Δv_1, Δv_2, are the speed changes of the lighter and heavier cars, respectively.

The speed change a vehicle undergoes in a crash is the best available measure of crash severity for vehicles that have not been specially instrumented for crash testing. It is a measure that has been widely used and studied [Ricci 1980; Roberts and Compton 1993; Joksch 1993]. Figure 3 shows the probability of a driver fatality in a frontal impact crash versus Δv obtained from National Accident Sampling System (NASS) data for 1982-1991 [National Highway Traffic Safety Administration 1988]; corresponding figures for belted and unbelted drivers, but for all crashes regardless of impact direction, are given in Evans [1994]. The curve fitted is the *rule of thumb* suggested by Joksch [1993] with the general form

$$P = (\Delta v/\alpha)^k , \quad (5)$$

where P is the probability of fatality and α and k are parameters determined by a least squares linear regression fit to the log-transformed data. The relationship applies provided $\Delta v \le \alpha$; for $\Delta v > \alpha$ we assume $P = 1$. If P_1 and P_2 are the fatality risks to two drivers involved in the same crash, then the ratio of their fatality risks, R, is given by

$$R = P_1/P_2 = P(\Delta v_1) \div P(\Delta v_2) = (\Delta v_1/\alpha)^k \div (\Delta v_2/\alpha)^k = (\Delta v_1/\Delta v_2)^k . \quad (6)$$

Substituting eqn 4 gives the result that

$$R = \mu^k . \quad (7)$$

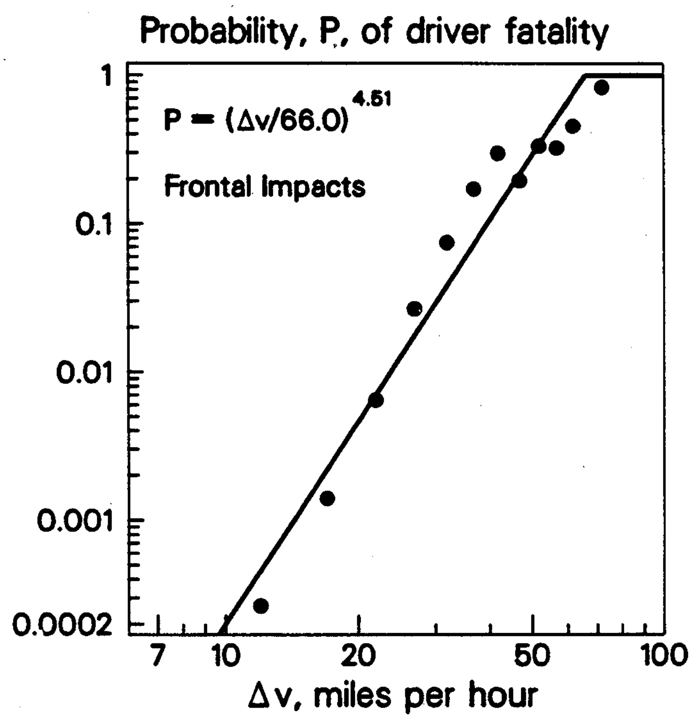


Fig. 3. Probability of a driver fatality in a frontal impact nonrollover crash versus the speed change, Δv. The points plotted are computed from 1982 - 1991 NASS tabulations provided by Susan Partyka.

Thus, the eqn 5 relationship between fatality risk and Δv, combined with simple Newtonian mechanics, generates the empirically derived relationship given by eqn 3 and shown in Fig. 2. The parameter k = 4.51 derived from the NASS data is, given the approximate and general nature of the calculation, in reasonably good agreement with the value u = 3.74 from the head-on two-car crash data in Fig. 2. (For all crashes, regardless of direction of impact, k = 3.80 compared to u = 3.53.)

The comparison presented here is for all driver fatalities, regardless of belt use. The corresponding analyses are given in Evans [1994] for severe injuries (AIS ≥ 3) as well as fatalities, and in each case for unbelted and belted drivers. Separating by belt use so reduced sample sizes that all crashes, regardless of impact direction, were included. The effect of mass ratio for injuries, although still considerable, was substantially less than for fatalities (for unbelted drivers, k = 2.22 for injuries compared to k =3.54 for fatalities; the corresponding values for belted drivers were 4.57 and 2.62). The lower values for injuries finds support in Wood [1993a], who finds an exponent of 2.5 for injuries, based on a calculation using equations relating dynamic and static crush characteristics of cars to injury risk. If one car crashes into another twice its mass, k = 3.54 for fatalities implies that the driver in the lighter car is 12 times as likely to be killed as the driver in the heavier car; k = 2.2 for injuries implies that the driver in the lighter car is 5 times as likely to be injured as is the driver in the heavier car.

Thus simple Newtonian mechanics, together with a relationship between fatality risk and Δv, implies that the risk in the lighter compared to in the heavier car increases as a power function of the mass ratio, as observed directly from data. This agreement definitively establishes that mass causes a large difference in risk, and identifies mass as the main causative factor in the relationship in Fig. 2. Such identification does not exclude the possibility that other factors, such as size, may also be important.

Crashes between cars of the same wheelbase but different mass

Another approach to isolating causative factors in the relationship between relative fatality risk and mass ratio is to examine what happens when cars with identical wheelbases, but different masses, crash into each other. Results of such an analysis [Evans and Frick 1992] are shown in Figure 4. Each point represents crashes between cars coded in the FARS data as having identical wheelbase but different mass. Such a stringent selection criterion leads to few data and large standard errors.

Fitting eqn 3 to the data gives u = 3.8, a value not materially different from u = 3.5 for all crashes regardless of wheelbase. Thus, when cars of the same size, as indicated by wheelbase, crash into each other, the effect of mass is not distinguishably different from the case when no restrictions are placed on size. Size, as indicated by wheelbase, cannot contribute to the effect, so that mass is unambiguously identified as the causative factor. This result fits the explanation above in terms of Newtonian mechanics -- two cars of identical wheelbase crashing into each other will have Δv ratios in inverse proportion to their masses. This and the previous result suggests that increasing the mass of a vehicle reduces the risk its occupants face in a crash, regardless of the source of the additional mass (provided it is not free to move inside the vehicle). Thus adding cargo or restrained passengers reduces your risk when you drive, but increases the risk of those in vehicles into which you crash.

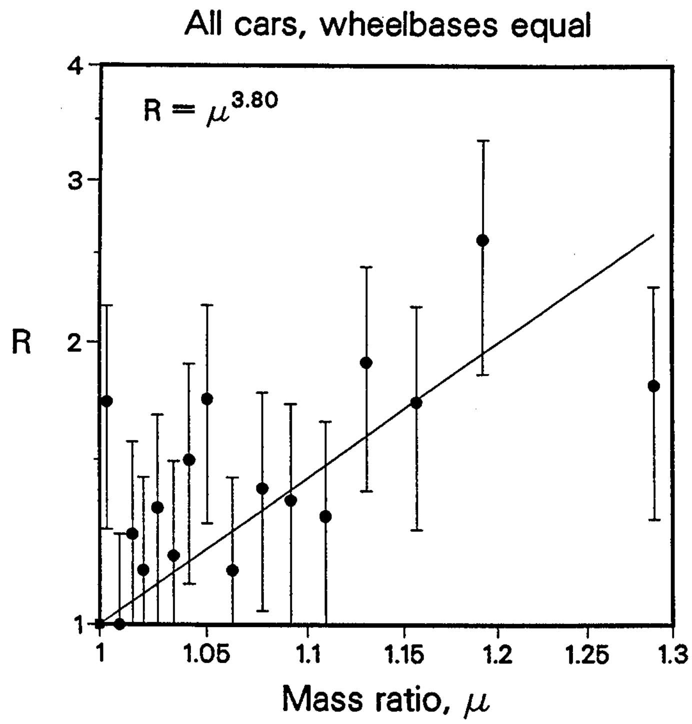
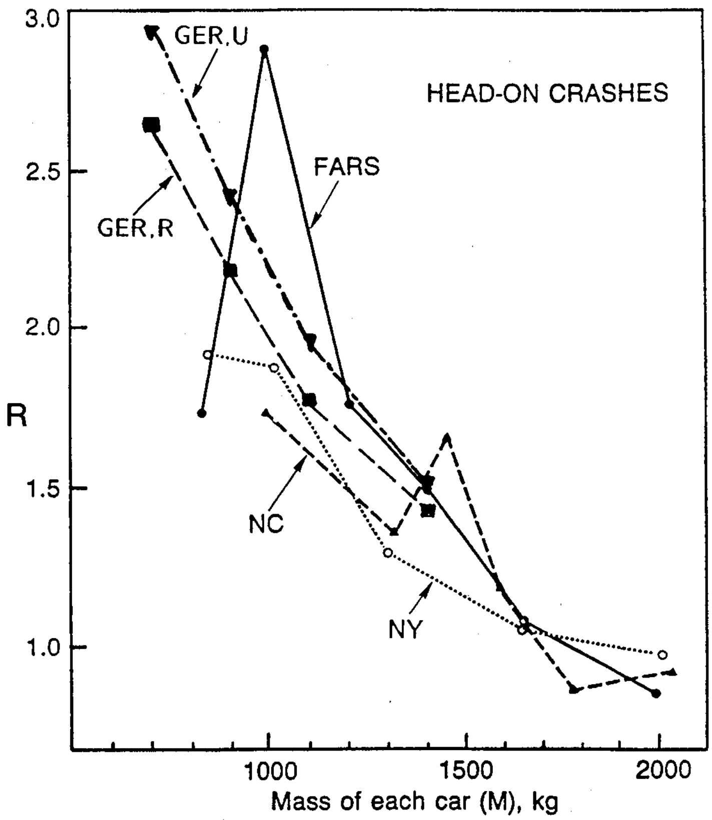


Fig. 4. The ratio, R, of driver fatalities in the lighter compared to in the heavier car versus the ratio, μ, of the mass of the heavier to the mass of the lighter car for crashes between cars with identical wheelbase, based on cars of all model years in 1975-1989 FARS data. From Evans and Frick [1992].

Crashes between cars of the same (or similar) mass

The relationship between driver risk and car mass when cars of the same (or similar) mass crash head-on into each other has been examined using five independent data sets (Fig. 5). The FARS results [Evans and Wasielewski 1987] are for driver fatalities, with exposure being estimated using the *pedestrian exposure approach* described later in the discussion of single-car crashes. The NC and NY results [Evans and Wasielewski 1987] are driver injuries per registered car from data for North Carolina [Campbell and Reinfurt 1973] and New York [Negri and Riley 1974]. The other two sets of results are from Ernst et al. [1993] showing driver serious injuries per driver involved in any type of crash in the German State of North-Rhine/Westphalia, supplemented by Federal data. The Ernst et al. [1993] data are given for rural crashes, and for crashes in built-up areas, giving the two relationships in Fig. 5. All five data sets are scaled using the procedure in Evans and Wasielewski [1987] in which two 1800 kg cars crashing head-on into each other defines a risk of 1.0.



FARS	Fatalities [Evans and Wasielewski 1987]
NC	Injuries in North Carolina [Evans and Wasielewski 1987]
NY	Injuries in New York State [Evans and Wasielewski 1987]
GER.R	Injuries on rural roads in Germany [Ernst et al. 1993]
GER.U	Injuries on roads in built-up areas in Germany [Ernst et al. 1993]

Fig. 5.Relative risk, R, of driver injury or fatality when cars of similar mass crash head-on into each other versus M, the common mass of each car. In all cases the data are scaled so that a regression fit passes through R = 1.0 at M = 1800 kg. The data of Ernst et al. [1993] added to the figure on p 70 of Evans [1991].

All five data sets consistently support that when two 900 kg cars crash head-on into each other, the risk of driver death or injury is about twice as great as when two 1800 kg cars crash head-on into each other. Although Fig. 5 plots the relationships as a function of mass, mass cannot be the causative factor. In terms of the Newtonian mechanics of the crashes, mass is irrelevant when two cars of the same mass crash into each other.

Wood [1993a] investigated injury risk when identical cars crashed head-on using equations relating injury risk to the dynamic and static crush characteristics of cars. He finds that when cars of the same mass crash head-on into each other, driver injury risk increases in inverse proportion to mass; a relationship he notes fits well the same five sets of empirical data displayed in Fig. 5.

Another part of the Evans and Frick [1992] study was an examination of crashes between cars of similar mass, but different wheelbase. While no effect above the noise in the data was observed, the results were compatible with the interpretation that risk increased with decreasing wheelbase in accord with Fig. 5 when the relationship between mass and wheelbase discussed later is taken into account. The similarity between the relationships for injuries and fatalities is supported by the data of Thomas et al. [1990], even though these data, because of exposure limitations, do not support more specific conclusions [Evans 1990].

Two-car crash system-wide effects

Because a driver's risk in a two-car crash depends not only on the mass of the car in which that driver is traveling, but also on the mass of the other involved car, many questions have arisen regarding the overall effect on safety of a general change in the size of cars. Any such discussions should keep firmly in mind the information in Fig. 1 which shows that such considerations are irrelevant for crashes that kill 70 percent of car occupants.

When a driver changes from a heavier to a lighter car:

1) That driver's risk increases

2) The risk that driver's lighter car poses to all other drivers declines.

If the magnitude of the first of these is larger than the second, then the traffic system will be less safe, and vice versa. In order to answer the question whether system safety increases or decreases, we need to know not only the magnitudes of items 1 and 2, but we need to know them with higher precision than the expected small difference between them.

Figure 5 shows that replacing a fleet of identical mass cars with another fleet in which every car was 10 percent lighter would increase casualties by 10 percent. Although this result is simple and relatively reliable, it cannot be generalized in any simple way to actual fleets that contain a wide mix of car sizes.

Klein, Hertz and Borener [1993] applied logit analysis to two-car crashes in Texas and Maryland to estimate the change in casualties that resulted from the reduction in the average mass of a car from 3700 pounds in 1970 to 2700 pounds in 1982 (1678 kg to 1224 kg, a reduction of 454 kg). In their calculations they reduced the masses of all cars by the same proportion to achieve this 1000 pound reduction, so that the same relative mix of cars by mass was maintained. They find that such a change in the average mass of cars in the fleet would increase casualties by 14.3 percent (based on the Texas data) and by 4.3 percent (based on the Maryland data).

Using the *pedestrian exposure approach* described later, Evans and Frick [1993b] estimated driver fatality risk as a function of the mass of each of the two cars involved. They found that replacing any car by a lighter one leads to an increase in net risk for nearly all two-car crashes. The effect was in the opposite direction for some large values of mass ratio, an effect that now appears related to the smaller cars in their sample preferentially benefiting from crashworthiness improvements [Evans and Frick 1994]. However, averaged over the mix of cars into which any particular car might crash, Evans and Frick [1993b] concluded that replacing any car in the fleet by a lighter one always led to a net increase in fatality risk.

While the relationship between risk and Δv in Fig. 3 was useful for investigating large mass-ratio effects corresponding to driver risk ratios that vary by over an order of magnitude, it is unsuitable for examining the small effects discussed here. The Fig. 3 relationship estimates that when cars of identical mass crash into each other, the outcome is mass-independent, in clear contradiction of Fig. 5. If we proceed by making the incorrect assumption that the probability of injury versus Δv is independent of car mass (equivalent to ignoring size effects), then we can calculate the effect of substituting one car with another of different mass. If a crash involving two equal mass cars is replaced by a crash in which one of the cars is 10 percent lighter than the other, the mass ratio change is computed to increase the fatality risk to the driver of now lighter car by 26 percent, but decrease the risk to the driver in the now heavier car by 22 percent. The calculated net effect is that the calculated sum of the risks for the drivers combined increases by 2 percent. If the original mass ratio differs from one, then, in general, decreasing the mass of the heavier car reduces net risk, while reducing the mass of the lighter car increases net risk. As mass ratio becomes larger, the estimated change in combined driver risk increases, so that at some point it will exceed the bias. If vehicles are grossly dissimilar in mass, decreasing the mass of the lighter one generally increases that driver's risk more than it decreases the risk to the driver in the much heavier vehicle. An exception occurs if the crash severity is so great that the driver of the lighter vehicle is killed ($\Delta v > \alpha$); making that vehicle still lighter cannot increase this risk, but will reduce the risk to the driver in the heavier vehicle, for a net decrease in risk.

SINGLE-CAR CRASHES

While single car-crashes account for 45 percent of car-driver deaths, it is not possible to perform the diverse collection of analyses that have been applied to two-car crashes. A central difficulty is that of exposure, made all the more difficult by additional biases that apply specifically to single-car crashes. The probability that a collision with any object immobilizes a car decreases as the mass of the car increases. If the car driver is the only one to observe the crash, and the car is driveable, the crash may never be reported. Accordingly, such measures as fatalities per police-reported crash systematically underestimate how much more likely a driver of a small car is to be killed compared to a driver of a large car in single car crashes.

The *pedestrian exposure approach* [Evans 1991, p 72; Evans 1984a] circumvents these problems. When a car crashes into a tree (the most commonly struck object -- Fig. 1), this crash will generally not be recorded in FARS. However, if a car crashes into a pedestrian, this crash will be in FARS if the pedestrian is killed. If we assume that cars crash into pedestrians at the same rate that they crash into objects such as trees, then the number of pedestrian fatalities will estimate exposure provided that the probability that a pedestrian is killed when struck is independent of car mass. This is likely to be fairly correct, because the lightest car is so much heavier than the heaviest pedestrian.

Figure 6 shows the number of drivers killed in cars of a given mass divided by the number of pedestrians killed in crashes involving cars of the same mass. This is interpreted to indicate the relative probability that a driver is killed in a crash, other factors being equal. Supporting evidence that what is shown is a physical effect related to the car is that the phenomenon is essentially independent of driver age, a factor that has a large influence on crash rates. The effect of car mass in Fig. 6 is substantial -- the driver in a 900 kg car is 2.4 times as likely to be killed as is a driver in an 1800 kg car. Such a difference is much larger than any likely uncertainties in the assumptions on which the exposure approach rests, although these assumptions likely overestimate the effect. In terms of the earlier

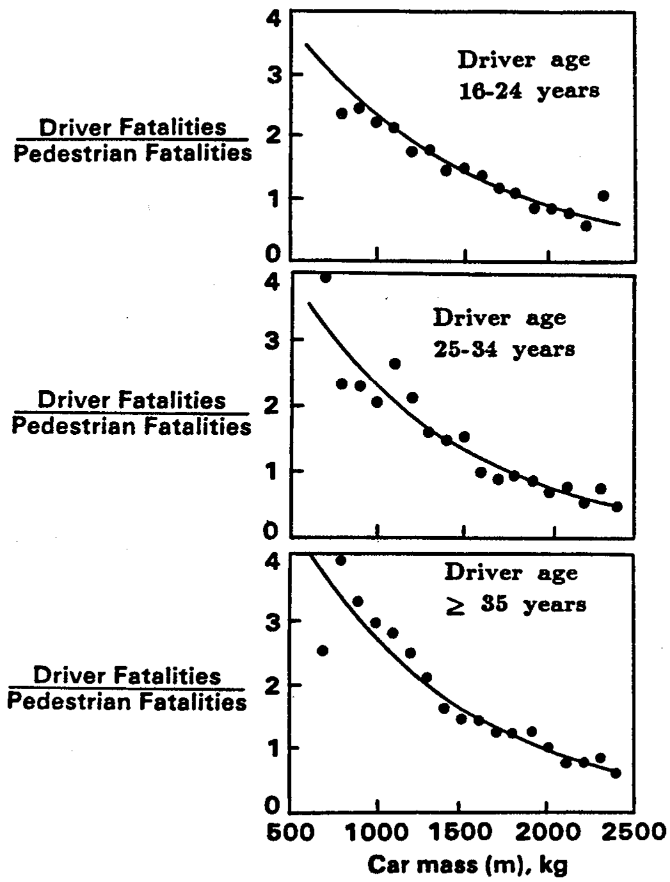


Fig. 6. The ratio of drivers killed in single-car crashes to the number of crashes in which pedestrians were killed versus the mass of the involved cars (FARS 1975-1980). This ratio is approximately proportional to the probability that a driver is killed given that a single-car crash occurs, so the graphs are interpreted to reflect driver fatality risk in single-car crashes versus car mass. From Evans [1984a; 1991, p 73].

discussion of the Newtonian mechanics of crashes, the Δv sustained by a 80 kg pedestrian in an inelastic (not too plausible assumption) collision with an 1800 kg car is 4 percent greater than if struck by a 900 kg car. Applying eqn 6 as a very rough approximation associates a 20 percent greater pedestrian fatality risk with this Δv, compared to an assumption of no effect.

Rollover crashes

We consider single-car crashes as either rollover (account for 18 percent of car occupant fatalities) or nonrollover (27 percent of car occupant fatalities), because different physical mechanisms apply to each. Fig. 7 shows the number of occupants killed in single-car rollover crashes per registered vehicle [Partyka and Boehly 1989]. Although the large effect (an occupant fatality is 1.8 times as likely in a 900 kg car as in a 1800 kg car) is plotted versus car mass, it is not mass, but other vehicle properties correlated with mass, that generate the physical mechanisms. Kahane [1993] writes "Short light cars usually have less directional stability than long, heavy ones. Narrow cars have less rollover stability than wide cars. Since 'small' cars are shorter, lighter and narrower than full-sized cars, they tend to have lower directional and rollover stability." Other factors being equal, the lower the center of gravity the greater is the resistance to rollover. The center of gravity is determined by vehicle function. While geometrical properties of a vehicle are related to resistance to rollover, all other factors being equal, the influence they exercise is small compared to the much larger influences of driver behavior and use patterns. British double-decker busses have far lower rollover rates than sports cars. (My searches failed to uncover a single case of a double-decker bus rolling over -- if any reader knows of such a case, I'd be grateful if they could provide information).

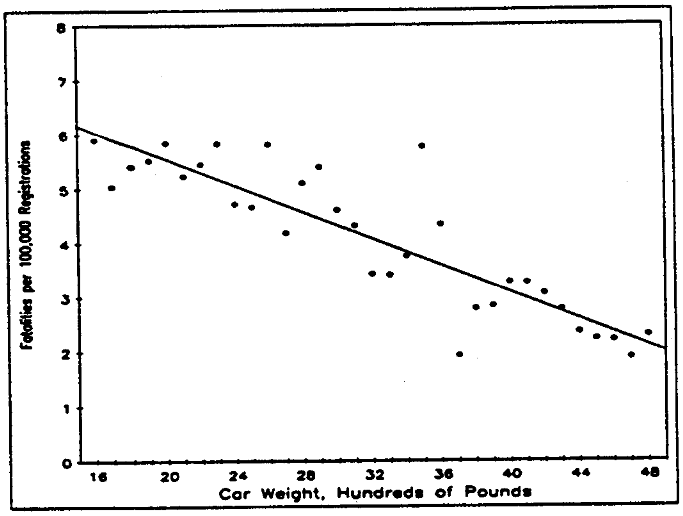


Fig. 7. Occupant fatalities per 100 000 registered cars in single-car rollover crashes. From Partyka and Boehly [1989].

This paper addresses how vehicle size and mass affect risk of death and injury, given that a car crash occurs. The rate *driver deaths per registered car* reflects many properties of the driver as well as of the vehicle. Smaller vehicles are more likely to be driven by younger drivers [Evans 1985a]. Younger drivers have higher crash rates, but are less likely to be killed in a crash of given severity [Evans 1988; 1991], so that these factors will exercise influences in opposite directions. There are indications [Evans 1984b] that smaller cars (corrected for driver age) are associated with lower crash involvement rates, though such an effect is not apparent in insurance claims [O'Neill 1985]. Rothengatter [1988] suggests that larger cars may be associated with higher travel speeds. Even small increases in average speed would have large effects on fatality rates, because fatality rate increases as the fourth power of speed [Evans 1991, p 154]. I consider that the net effect is that *driver deaths per registered car* somewhat underestimates the effect of car mass, given that a crash occurs, especially in view of the results the same measure gives for nonrollover crashes.

Nonrollover crashes

Partyka [1989a] examined driver deaths per registered car versus car mass and found a statistically significant increasing risk with decreasing mass (equivalent to a driver in a 900 kg car being 15 percent more likely to be killed than a driver in a 1800 kg car). The corresponding difference for occupants rather than drivers was not statistically different from zero [Partyka and Boehly 1989]. Concentrating on drivers provides results that are easier to interpret because larger cars have higher occupancy rates, so examining occupant fatality rates adds a non-vehicular confounding factor.

Partyka and Boehly [1989] also applied multivariate methods to the NASS data, and obtained a relationship between car mass and moderate driver injury rate per towaway crash indicating that the risk in 900 kg cars is 30 percent higher than in 1800 kg cars. Quite similar results were obtained in the same study using police-reported data from Michigan, Maryland and North Carolina. The study by Klein, Hertz and Borener [1993] also examined single-car nonrollover crashes, and concluded that a reduction of average car mass from 3700 pounds to 2700 pounds would increase driver fatalities by 9.8 percent, with 95 percent confidence limits from 0.5 percent to 19.9 percent.

CRASHES BETWEEN CARS AND VEHICLES OTHER THAN CARS

The relative risks when cars crash into other vehicles, obtained in a largely assumption-free way from FARS data [Evans and Frick 1993a], show remarkably consistency. For every row the values decrease in every step from left to right, implying a systematic decrease in the relative risk to the car driver as the car's mass increases from light, to medium, to heavy, regardless of the other vehicle involved. The data in Table 1, being for relative risk, do not estimate quantitatively differences in risk faced by drivers of small and large cars (or the differences in risk they impose on others). However, they do lead to the clear conclusion that in crashes with a wide spectrum of other vehicles, drivers of heavier cars are at lower risk than drivers of lighter cars. Thus lowering the average masses of cars increases the net risk to car drivers in crashes with other vehicles. As the great majority of car-driver deaths in crashes with other vehicles that are not cars involve crashes with trucks, we examine such crashes in more detail.

Table 1: Relative driver risks when cars crash into other vehicles. For example, when light cars and motorcycles crash into each other, the motorcycle driver is 42 times as likely to be killed as is the car driver; when light cars and heavy trucks crash into each other, the car driver is 44 times as likely to be killed as is the truck driver. Extracted from the table in Evans and Frick [1993a], which gives all combinations of the listed nine vehicles.

Other vehicle ↓	Mass class* of car		
	Light	Medium	Heavy
Moped	1/139	1/202	1/205
Motorcycle	1/42	1/85	1/153
Light car	①	1/3.1	1/7.7
Medium car	3.1	①	1/2.4
Heavy car	7.7	2.4	①
Pick-up	7.1	2.7	1.3
Van	9.3	3.3	1.7
Medium truck	34	18	12
Heavy truck	44	29	22

**Definitions*

Light car: Mass from 655 kg to 1227 kg, mean 1014 kg
Medium car: Mass from 1227 kg to 1599 kg, mean 1428 kg
Heavy car: Mass from 1600 kg to 2606 kg, mean 1833 kg
Medium truck: Gross Vehicle Weight (GVW) > 10 000 pounds (4536 kg), but not a heavy truck
Heavy truck: GVW > 26 000 pounds (11 794 kg), or tractor-trailer combination, or with cargo trailer(s), or truck tractor pulling no trailer.

Car-Truck Crashes

Klein, Hertz and Borener [1993] examined cars crashing into trucks of gross vehicle weight rating greater than 10 000 pounds (4536 kg). They concluded that a reduction of average car mass from 3700 pounds to 2700 pounds would increase net driver fatalities by 11.0 percent, with 95 percent confidence limits from 0.5 percent to 22.7 percent. Applying the *pedestrian exposure approach* to car-truck crashes showed that car-driver fatality risk was related to car mass not too differently from the Fig. 6 relationships for single-car crashes [Evans 1984a].

The analysis using Newtonian mechanics applied to two-car crashes [Evans 1994] can be extended as follows. Consider a head-on crash between a car of mass m_1 and a truck of mass m_T. The speed change for the car, Δv_1, is given by

$$\Delta v_1 = (v_1 + v_T)\, m_T/(m_1 + m_T)\,, \tag{8}$$

where v_1 and v_T are the pre-crash speeds of the car and truck. Let us imagine this same crash repeated with all factors the same, except that the mass of the car is increased to m_2. The resulting smaller speed change, Δv_2, is given by substituting $m_1 = m_2$ in eqn 8. The ratio of the speed changes for the two cars is given by

$$\Delta v_1/\Delta v_2 = (m_2/m_T + 1)/(m_1/m_T + 1)\,. \tag{9}$$

Comparing 900 kg and 1800 kg cars crashing into a heavy truck of mass 12 000 kg gives a speed change ratio for the cars of 1.070, which, when substituted into eqn 6 indicates that the driver in the lighter car is 36 percent more likely to be killed than is the driver in the heavier car. This effect is due exclusively to the mass-induced difference in the speed change given by eqn 9. In analytical relations giving driver fatality risk as a function of the mass of each of the cars involved, the risk of death in one of the cars still increased with decreasing car mass even when the mass of the other car approached infinity [Evans and Frick 1993b], a case that is conceptually somewhat equivalent to a car crashing into a very large truck. As the mass of the truck becomes infinite, the mass of the car becomes irrelevant in eqn 9. However, the heavier car has safety advantages not reflected in eqn 9. The heavier car, if larger, will provide greater crush space. Because the truck is not a perfectly rigid body, the heavier car will penetrate further into it, thereby providing a longer stopping distance.

Car mass also can affect car-driver risk in sever crashes with much lighter vehicles. If a 200 kg motorcycle and a 900 kg car each traveling at 60 mph crash head-on into each other, the probability that the car driver is killed (from eqn 9 and Fig. 3) is about 1 percent, compared to a fifteen times smaller risk for a driver of an 1800 kg car.

THE RELATIONSHIP BETWEEN SIZE AND MASS

Consider a hypothetical construct (as in Evans and Frick [1992]), in which all cars are made from material of the same density. If cars were of identical shape, differing only by a scale factor, then mass would be proportional to any linear dimension to the power three. However, regardless of their size, cars must be of sufficient height to accommodate seated humans. If all cars had the same height, so that only length and breadth varied, then mass would be proportional to length (or breadth) to the power two. Real cars are likely to be intermediate between these two hypothetical cases, suggesting a relationship between mass and wheelbase of the form

$$M = \lambda W^{\beta}\,, \tag{10}$$

where M is the mass of the car, W is a linear dimension (other than height), and λ and β are constants, with β expected to be between 2 and 3. Figure 8 shows mass versus wheelbase for 3824 unique mass/wheelbase combinations available from the FARS data for cars of model year 1980 or later [Evans and Frick 1992]. The fit to eqn 10 gives

$$M = (6.47\ W)^{2.51}, \qquad (11)$$

thus validating our intuitive understanding that β should be between 2 and 3.

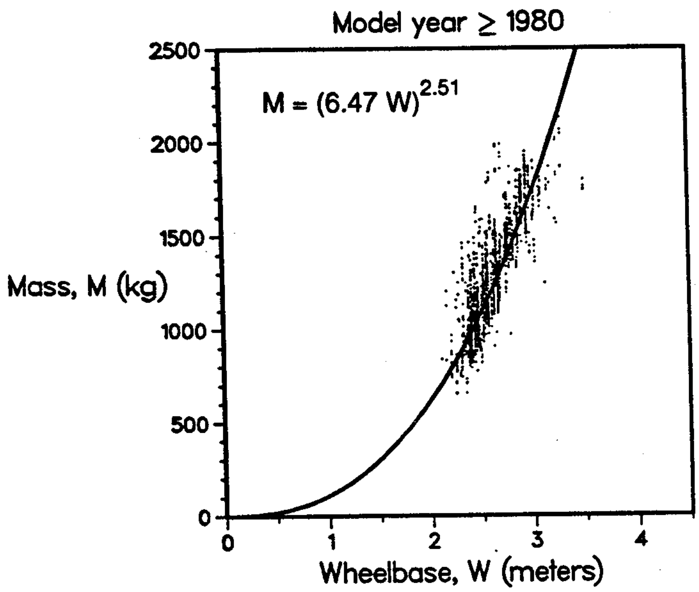


Fig. 8. Mass versus wheelbase based on for MY > 1980 cars coded in 1975-1989 FARS data. From Evans and Frick [1992].

Wood [1993a] fitted data for overall length, L, versus mass for European cars, and obtained an equation that can be expressed as

$$M = (3.89\ L)^{2.48}, \qquad (12)$$

where, consistently with eqn 11, L is in meters and M is in kg. The β coefficients in eqns 11 and 12 agree closely. The constant terms agree provided the wheelbase is equal to 3.89/6.47 times the overall length; that is, the wheelbase is 60.0 percent of the overall length. Wood [1993b] computed the ratio of the wheelbase to the overall length for his data and obtained 59.5 percent.

Additional data on the close relationship between measures of size and weight are provided by Kahane [1993] who finds correlation coefficients between curb weight and wheelbase, curb weight and trackwidth, and wheelbase and trackwidth of 0.93, 0.92 and 0.91 respectively. Any observed empirical relationship with any one of these quantities is going to provide a similarly good relationship with any of the others. In multivariate analyses, simply as a result of eqn 11, parameters associated with length will be about 2.5 times as large as those associated with mass. It seems possible that inappropriately attaching more meaning than this to larger parameters in regressions on size compared to mass could have contributed to suggestions [O'Neill, Joksch and Haddon 1974] that size was a more important causative factor than mass.

SUMMARY AND DISCUSSION OF RESULTS

Table 2 summarizes the results found, in all cases derived for car drivers. Although occupants have different risks depending on seating location [Evans and Frick 1988; 1989], passenger risk is sufficiently closely proportional to driver risk that the results may be assumed to apply, with little additional error, to all occupants in the car. Apart from the 8 percent of car occupants killed in crashes involving three or more vehicles, Table 2 includes all car occupants killed in crashes.

Causative factors

For rollover crashes and crashes between cars of similar mass, size is the dominant causative factor. For all other crash types, mass causally affects outcome, and is the dominant causal factor in crashes between two vehicles whose masses differ by more than about 10 percent. This is to be expected because of Newtonian mechanics. Indeed, the results presented here show that even in crashes between cars and large trucks, kinematic effects due to the mass of the car have a larger influence on fatality risk than was generally assumed previously. For example, if a car crashes into a heavy truck of mass 12 000 kg, the car driver is about 36 percent more likely to be killed in a 900 kg car than in an 1800 kg car solely as a result of the slightly larger speed change the lighter car undergoes.

Mass plays a role in the dynamics of crashes beyond that captured in the speed change calculations. Essentially all objects into which cars crash may break, bend, dent, distort or tear. Each of these effects reduces the forces on occupants. The heavier the striking vehicle, the more likely is a struck object (such as a tree -- the most common fixed object in fatal crashes) to break (assuming car force deflection characteristics are independent of car mass). If the vehicle uproots the tree or breaks it, rather than bouncing back from it, risk to occupants is dramatically reduced. Even the proverbial brick wall from which a light car will bounce back may still be penetrated by a heavier vehicle, with beneficial effects to its occupants. Many of the objects struck have some dynamical properties in common with some members of the wide spectrum of vehicles for which we have definitive information (from mopeds through large trucks). All the mechanisms by which the striking car may move or damage the struck object reduces the speed change the car undergoes, and thereby lower driver fatality and injury risk; small changes in speed change, or the time over which the speed change takes place, translate into large changes in occupant risk.

In nearly all crashes, increased mass, as such, reduces occupant risk. In barrier crash tests, mass is rendered irrelevant. The design goals for the barrier are that it be equivalent to an object of infinite hardness and infinite

Table 2: Summary of how the mass of the car in which a driver is traveling affects that driver's risk in a crash.

Crash Type	Main Causative Factor	Quantification / Comment
Two-car crashes		**22% of car-occupant fatalities**
Cars of dissimilar mass	Mass	$R = \mu^{3.7}$: If one car is twice as heavy as other, driver in lighter car about13 times as likely to be killed as driver in heavier
Cars of same wheelbase	Mass	$R \approx \mu^{3.8}$: If masses differ by 10%, driver in lighter car about 40% more likely to be killed than driver in heavier car
Cars of same (or similar) mass	Size	$R \propto 1/M$: If common mass, M, is halved, risk doubles
System-wide effects	Mass and size	Likely small increase in system-wide two-car crash risk if cars become lighter/smaller; difficult to quantify
Single-car crashes		**45% of car-occupant fatalities**
Overall	Size and mass	Halving car mass multiplies driver fatality risk by about 2.4; exposure method likely overestimates effect
Rollover	Size (length and track width; height of center of gravity)	Halving car mass multiplies driver fatality risk by about 1.8; exposure method likely underestimates effect
Nonrollover	Mass and size	Halving car mass increases driver injury risk by about 30%.
Crashes between cars and non-car vehicles		**25% of car-occupant fatalities**
Overall	Mass and size	Drivers of lighter cars are at greater risk in crashes with motorcycles, vans, trucks, etc.
Car-truck crashes	Mass and size	Halving car mass multiplies driver fatality risk by about 2.4; exposure method likely overestimates effect

Definitions:

R = risk to driver in lighter car divided by risk to driver in heavier car
μ = mass of heavier car divided by mass of lighter car

mass, properties possessed by very few objects into which vehicles actually crash.

The focus of this paper has been the relationship between risk, given that a crash occurs. We have not addressed any changes in driver behavior or use patterns that additionally may be associated with different size cars [Evans 1991; 1985b]. While drivers who chose higher horsepower cars have higher crash rates [Robertson 1993; Evans 1993], horsepower cannot affect injury risk given that a crash occurs (ignoring that, other factors being equal, a heavier engine will in fact reduce risk in a crash). The relationships are for vehicles on the roads, so they may not apply to vehicles using different design concepts. For example, Niederer et al. [1993] describes a low mass vehicle designed with a rigid body belt aimed at preventing vehicle crush, in contrast to the usual design goal of using vehicle crush to absorb crash energy in order to provide the occupants with as much stopping distance as possible.

Total system-wide effects

The least certain relations relate to how reducing the mass of all cars affects the average risk from two-car crashes. If all cars are the same mass, then the lighter this mass, the greater the risk. If all cars become lighter by some percentage, then average risk increases. However, the uncertainty is too great to rule out the possibility that some distributions by mass may lead to lower risk than other distributions with the same average mass.

Of all car occupants killed, 70 percent are killed in crashes involving only one car. For all of these crashes, occupants in lighter, smaller cars are at greater risk than occupants in larger heavier cars. For more than 50 percent of these occupants, mass is an important casual contributor to outcome. These effects are so large and clear that no conceivable effect in the opposite direction in the two-car crash case could come even close to canceling them. The conclusion is unmistakable -- if all other factors are held constant, a lighter car fleet leads to more car-occupant deaths and injuries.

Effect of occupant protection devices

The relationships in this paper were derived mainly for unbelted drivers of cars without airbags. A number of studies allow us to address how different these relationships would be if all occupants were belted and/or had airbags. The computed relative effect of mass on injuries and on fatalities was greater for belted than for unbelted drivers [Evans 1994]. Empirical fatality data suggest (weakly) an effect in the same direction [Evans and Frick 1993a]. No systematic car-mass effects dependent on belt use were found in earlier fatality studies using methods unlikely to uncover small differences. Evans and Frick [1986] and Evans [1985c] found no systematic relationship between belt effectiveness and car mass, whereas Partyka [1989b] found higher effectiveness for very light cars. The more recent finding [Evans 1994] of a larger mass effect for belted drivers implies that if all drivers were belted, the relative disadvantage to drivers of lighter cars would become greater. The finding of Zador and Ciccone [1993] (see also Insurance Institute for Highway Safety [1993]) of a higher effectiveness of airbags for larger cars likewise implies that if all cars had airbags, the relative disadvantage in smaller cars would increase. Although occupant protection devices appear to increase the relative disadvantage in small cars, they of course reduce the risks to drivers in cars of any size. The interpretation is that they reduce the risk in the heavy car by a somewhat larger proportion than in the light car.

IMPLICATIONS

While it has been well recognized that policies which lead to lighter cars increase casualties [Crandall and Graham 1989; Graham 1992], the results presented here demonstrate more definitively, and in finer detail, than hitherto that reducing the mass of cars increases the number of car occupants killed and injured. Increased use of occupant protection devices does not diminish the strength of the relationships between car mass and relative risk. Such devices reduce total casualties, in the same sense that other measures such as reduced drunk driving or converting rural two-lane roads to freeways reduce total casualties, but occupant protection devices do not preferentially reduce the risks in small cars -- if anything, the reverse. By analogy, improvements in safety design or the development of new materials, if equally applied to cars of all sizes, cannot be expected to alter the relative safety disadvantages in the smaller car.

Although there is considerable scientific interest in the question of causative factors, such questions seem less central to policy decisions. For any set of manufacturing materials, a larger car will always weigh more than a smaller car if both cars are similarly designed. If new lower density materials became available, size and mass would still be intrinsically related, but by a different quantitative relationship than applies presently. There is no reason to expect the relative driver risk relationships reported here would be particularly different for cars made from lower density material. If all cars remained the same size, but with reduced mass, rollover risk and risks when two cars made from the lower density material crashed into each other would remain similar. However, car occupant risk in nonrollover single-car crashes, and crashes with other vehicles, which together account for more than half of car occupant deaths, would increase. Most car occupant deaths resulting from crashes with vehicles other than cars are crashes with trucks. As cargo capacity is a crucial determinant of total truck weight, it is not possible to substantially reduce the weight of laden trucks without reducing the flow of goods (or increasing the number of trucks). Thus, reducing the masses of cars leads to an increase in the number of car occupants killed in crashes with trucks even if the size of cars remained unchanged.

Additional mass, as such, increases protection in any crash in which the struck object can move, bend, break, distort, or tear. Increased mass of the striking car increases damage to the struck object, thereby increasing the distance over which the car comes to rest, with consequent reduction in risk to the car's occupants. Reducing the mass of the car fleet by even small amounts substantially increases total traffic fatalities and injuries.

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The Influence of Foot Placement and Vehicular Intrusion on Occupant Lower Limb Injury in Full-Frontal and Frontal-Offset Crashes

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ABSTRACT

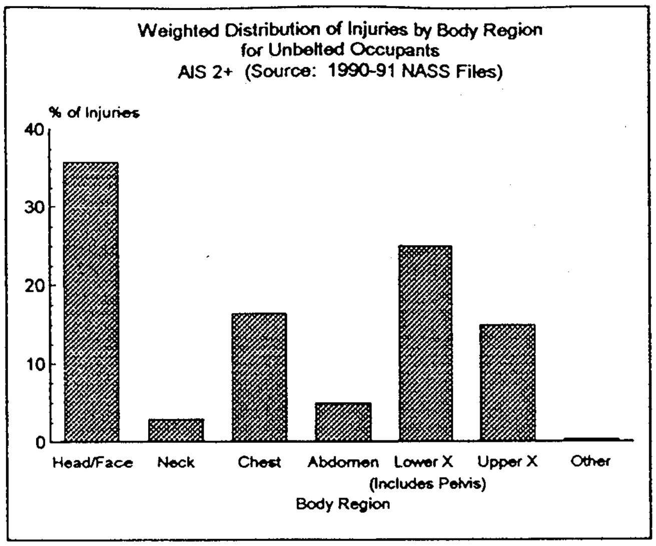
The University of Virginia is investigating the biomechanical response and injury tolerance of the lower extremities in a vehicle crash environment. Studies of accident databases have shown that the widespread use of seat belts and airbags has increased the relative importance of debilitating lower limb injuries significantly. This paper discusses the methods used to address this problem, which include accident investigation, computer simulation, and laboratory testing. A representative accident case has been selected for simulation with the ATB occupant simulator. The results indicate that a strong correlation may exist between foot position on the brake pedal and the load transmitted to the heel of the braking foot. The results are less conclusive with regard to the effects of moderate amounts of intrusion (less than 20 cm). These simulations have set the stage for upcoming laboratory work involving an impact sled fitted with a special buck which provides toe pan intrusion, as well as a compound pendulum which will be used to perform highly controlled, component tests of lower limbs. The laboratory tests will make extensive use of the new Hybrid III Advanced Lower Limb.

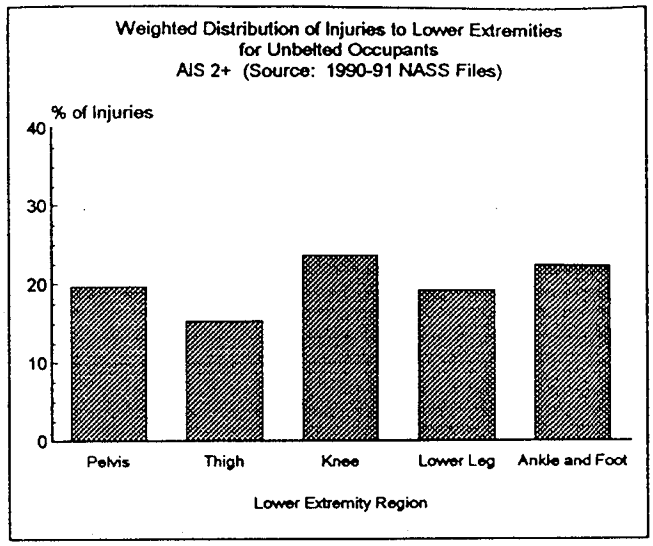
INTRODUCTION

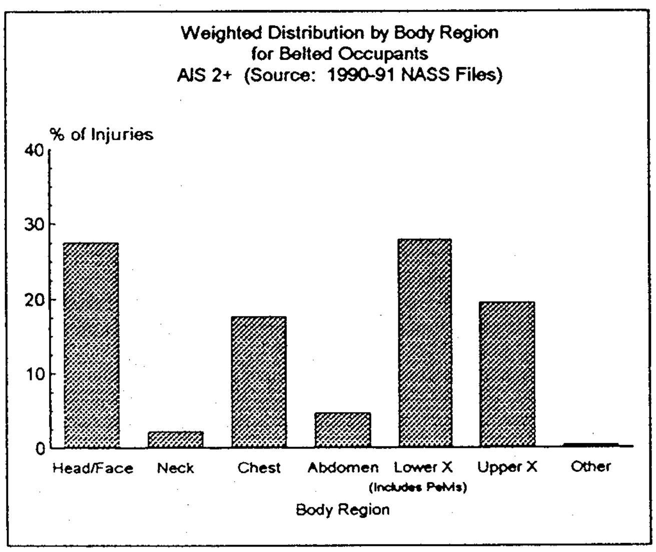
Lower limb injuries resulting from automobile accidents are a significant cause of permanent disability and impairment. The 1990-1992 NASS files indicate the weighted distributions of lower extremity trauma shown in Fig. 1. The search criteria for this figure specified front seat occupants at least 16 years of age, in frontal car or LTV collisions, without rollover or ejection, and with AIS $\geq$ 2. The data indicate that lower extremity injuries account for 32% of all AIS $\geq$ 2 injuries for belted occupants (25% for unbelted). Specifically, injuries to the ankle/foot complex account for 33% of the AIS $\geq$ 2 lower extremity injuries for belted occupants (24% for unbelted) and are the most prevalent injury. Based upon data for vehicle accidents in which there is improved head and torso protection from airbags, the relative importance of lower extremity injuries, and especially ankle/foot injuries, has increased as a result of the decline in head and chest injuries. While there is agreement that ankle injuries are more frequent in frontal collisions than in other crash configurations, there is little agreement on the exact injury mechanisms involved. Originally, distal leg and ankle fractures were thought to occur due to a twisting or bending of the foot at impact [1]. Recently, some researchers have conjectured that movement of the ankle beyond the normal range of motion [2, 3] is the source of injury. Still other research indicates that intrusion of the toepan [4] and subsequent foot contact with the pedals and floorpan [5] are significant factors. Accident data obtained by the University of Virginia suggest that these contact ankle injuries occur regardless of the degree of intrusion and that they seem to be associated with the dynamic characteristics of toepan acceleration [6]. Supporting this hypothesis, 1990-1992 NASS data suggest that 62% of lower extremity injuries below the knee occur at intrusion levels of less than 2.5 cm.

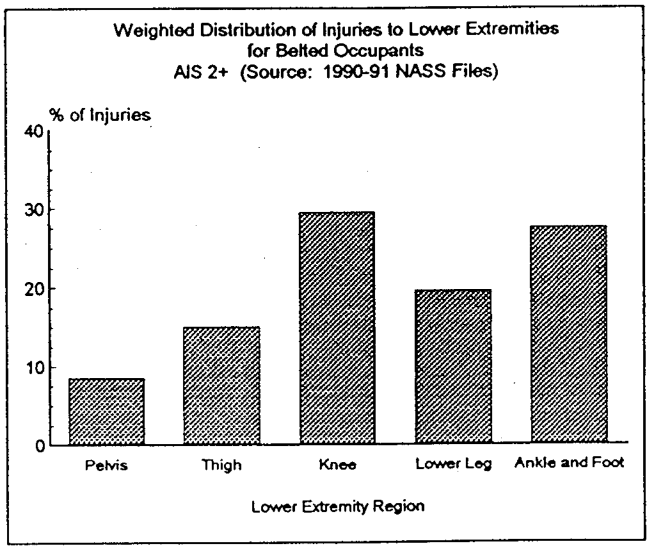
Since contact with the pedals and the floorpan are the primary mechanisms of ankle/foot injury in automobile collisions, intrusion parameters are being incorporated into the cadaver and dummy sled testing. Intrusion is defined as the inward crushing motion of a vehicle's interior structures toward the occupant. This is of special concern in offset frontal collisions where less than the full frontal area of the vehicle is engaged in energy absorption. Current vehicle safety standards (e.g., FMVSS208), however, only test full frontal collisions against rigid barriers, and intrusion is generally minor. In offset collisions, greater vehicle deformations and intrusions occur on the struck side. European researchers [7, 8] have emphasized this as a rationale for specifying an offset frontal test since tests limited to full frontal crashes may produce a false sense of security.

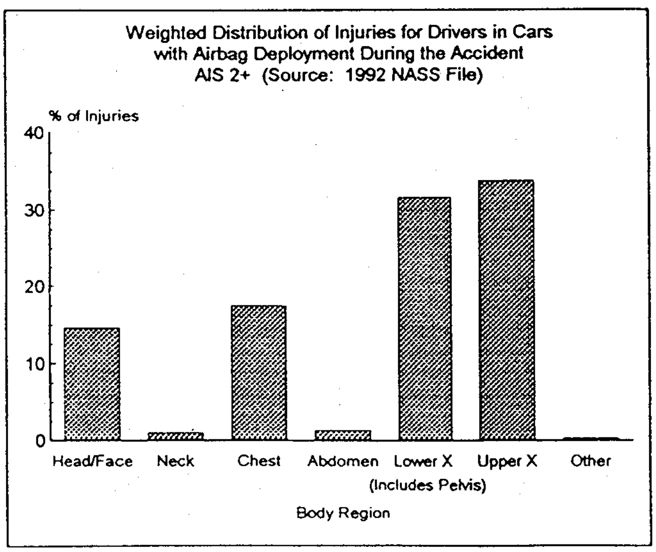
In order to simulate the primary mechanisms of ankle injury (i.e., pedal and floorpan contact [5]), sled and component tests must simulate the strokes and accelerations of intruding vehicle components. Analogous to the crash pulse used to characterize vehicle and sled tests, a "toepan pulse" can be defined to characterize the intrusion. Little research, however, has been done to describe the displacement and the collapse (i.e., buckling) of the toepan's thin metal structure. In addition to the longitudinal translations, large toepan and floorpan rotations occur during the intrusion event. For offset


Weighted Distribution of Injuries by Body Region
for Unbelted Occupants
AIS 2+ (Source: 1990-91 NASS Files)
% of Injuries
40
30
20
10
0
Head/Face
Neck
Chest
Abdomen
Lower X
Upper X
Other
(Includes Pelvis)
Body Region


Weighted Distribution of Injuries to Lower Extremities
for Unbelted Occupants
AIS 2+ (Source: 1990-91 NASS Files)
% of Injuries
40
30
20
10
0
Pelvis
Thigh
Knee
Lower Leg
Ankle and Foot
Lower Extremity Region


Weighted Distribution by Body Region
for Belted Occupants
AIS 2+ (Source: 1990-91 NASS Files)
% of Injuries
40
30
20
10
0
Head/Face
Neck
Chest
Abdomen
Lower X
Upper X
Other
(Includes Pelvis)
Body Region


Weighted Distribution of Injuries to Lower Extremities
for Belted Occupants
AIS 2+ (Source: 1990-91 NASS Files)
% of Injuries
40
30
20
10
0
Pelvis
Thigh
Knee
Lower Leg
Ankle and Foot
Lower Extremity Region


Weighted Distribution of Injuries for Drivers in Cars
with Airbag Deployment During the Accident
AIS 2+ (Source: 1992 NASS File)
% of Injuries
40
30
20
10
0
Head/Face
Neck
Chest
Abdomen
Lower X
Upper X
Other
(Includes Pelvis)
Body Region

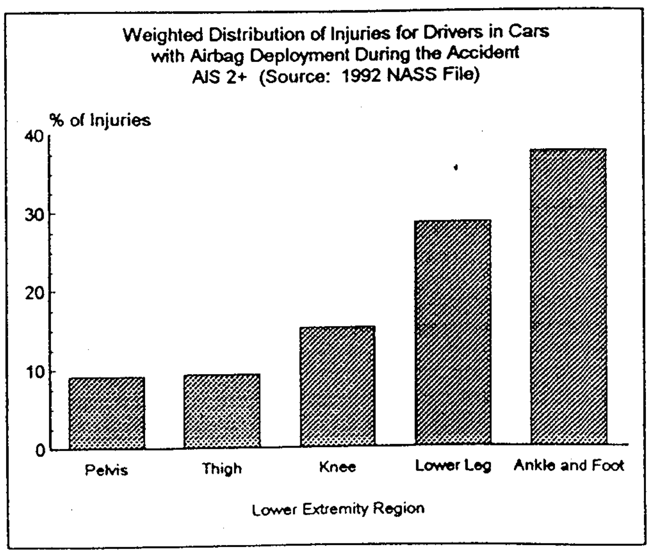

Weighted Distribution of Injuries for Drivers in Cars
with Airbag Deployment During the Accident
AIS 2+ (Source: 1992 NASS File)
% of Injuries
40
30
20
10
0
Pelvis
Thigh
Knee
Lower Leg
Ankle and Foot
Lower Extremity Region

Figure 1.

vehicle tests, the available intrusion data have been obtained from a single uniaxial accelerometer mounted to the toepan. However, as the crash progresses, the toepan rotates and the actual orientation of the axis of the accelerometer becomes poorly defined.

Kuppa and Morgan [9] have addressed this problem by making several simplifying assumptions based on a 58 km/h (36 mph) offset frontal collision between a 1991 Ford Taurus 4-door sedan and a 1991 Honda Accord DX 4-door sedan. They have produced an equivalent toepan pulse and brake pedal pulse designed to preserve the gross characteristics of the original data and to be readily reproducible in a laboratory.

At the present time, it is not known which intrusion parameters (e.g., intrusion displacements and accelerations) are significant in the study of ankle trauma. A major goal of the University of Virginia's research program is to evaluate the correlation of these parameters with observed trauma and to recommend which parameters should be used to define the standard toepan pulse.

CASE STUDY

In order to understand what some of the statistics in the NASS database are really referring to in terms of injury, the University of Virginia and the MIEMSS have been cooperating in the investigation and analysis of lower limb injuries associated with vehicle accidents. The methodology involves four distinct parts. First, the medical personnel in the emergency room document the type of injury and estimate the most likely mechanism, such as direct impact, bending, or twisting. Next, an accident investigation team reconstructs the vehicle parameters prior to impact, such as direction, velocity, and impact point; they examine the interior of the vehicle to measure the intrusion of various components and to locate probable points of impact between the occupant and the interior. The question of whether or not the victim was braking at the time of impact can sometimes be answered by skid mark analysis, post-crash interviews, and an examination of the brake pedal. The third part is to set up a computer model of the crash environment and, through simulation parameter studies, to look for the mechanism of injury. Finally, once various injury mechanisms have been identified, they are studied in a controlled manner using laboratory testing.

To illustrate this methodology, a particular case, designated 399, was chosen from the MIEMSS database. The details of this accident are described in a recent report by Dischinger, et. al. [10]. This case was selected because it represents an "average" crash in many ways: it was nearly head-on (approx. 80% front end engagement), but still involved the considerable front end damage asymmetry associated with offset crashes; the estimated delta-V was high (approx. 64 kph), but not extreme; the 19 cm of toepan intrusion is an intermediate amount; and the victim's lower limb injuries were distinct enough that medical personnel could offer reasonably confident appraisals as to how they occurred. In particular, the victim suffered a right closed medial malleolus fracture and a right closed calcaneus fracture. The trauma center orthopedist postulated that the malleolus fracture was caused by a medial rotation of the foot/ankle, while the calcaneus fracture is believed to have been created by direct, axial impact.

Because the locations and types of injury are known, and because there is good evidence of the injury mechanisms, in terms of the trauma applied to the foot, computer simulation becomes a valuable tool. What is not known from the initial accident data is the mechanism due to the vehicle-occupant interaction which resulted in the trauma.

SIMULATION STUDY

To gain an understanding of the dynamics of the occupant's feet during such a crash, a simulation was set up using a modified version of the Articulated Total Body (ATB) program [11]. The simulation was based on an earlier project for the IIHS in which a model of an offset crash test was developed [12]. The delta-V in that test was about 64 kph, which is very close to the estimated velocity of each vehicle in Case 399. The time to maximum crush observed in the films of the IIHS test was approximately 70 msec, so 70 msec was used as an upper bound to guide the development of a vehicle crash pulse and of component intrusion time-histories.

In particular, the intrusion of the toepan center-point on the driver's side was reported to be 19 cm. Since pure horizontal intrusion without rotation is uncommon, this was modeled as a combination of 12.7 cm of horizontal intrusion plus 23 degrees of rotation. The resulting velocity and position time-histories are shown in Fig. 2. Note that most intrusion is expected to occur between 20 and 60 msec.

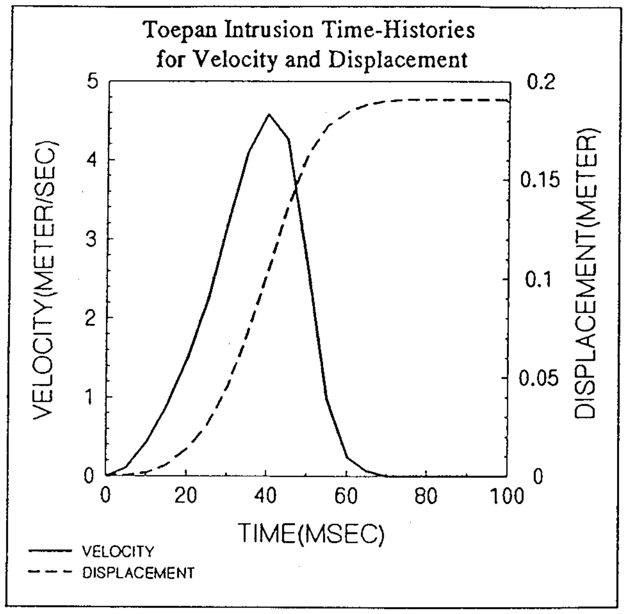


Figure 2.

accident investigation report describes a fracture of the right calcaneus as one of the more serious lower limb injuries, while no injury to the left foot was observed. The right heel injury is postulated to have been caused by direct axial impact; therefore, the initial focus of the simulation study was on the loads to the left and right heels to justify this asymmetry. Because the crash investigation report indicated that the occupant was braking, the right foot was placed on a brake pedal while the left foot was assumed to be flat against the toepan. A pre-load of one body-weight was placed on each foot at the start of the simulation. To maintain initial equilibrium, a small locking torque simulating muscle tension was imposed on the hip, knee, ankle, and foot joints. Most of these joints unlock within the first 15 msec of the simulation. Since no details pertaining to the position of the occupant's foot on the brake are known, a number of possible orientations were tried (see Fig. 3).

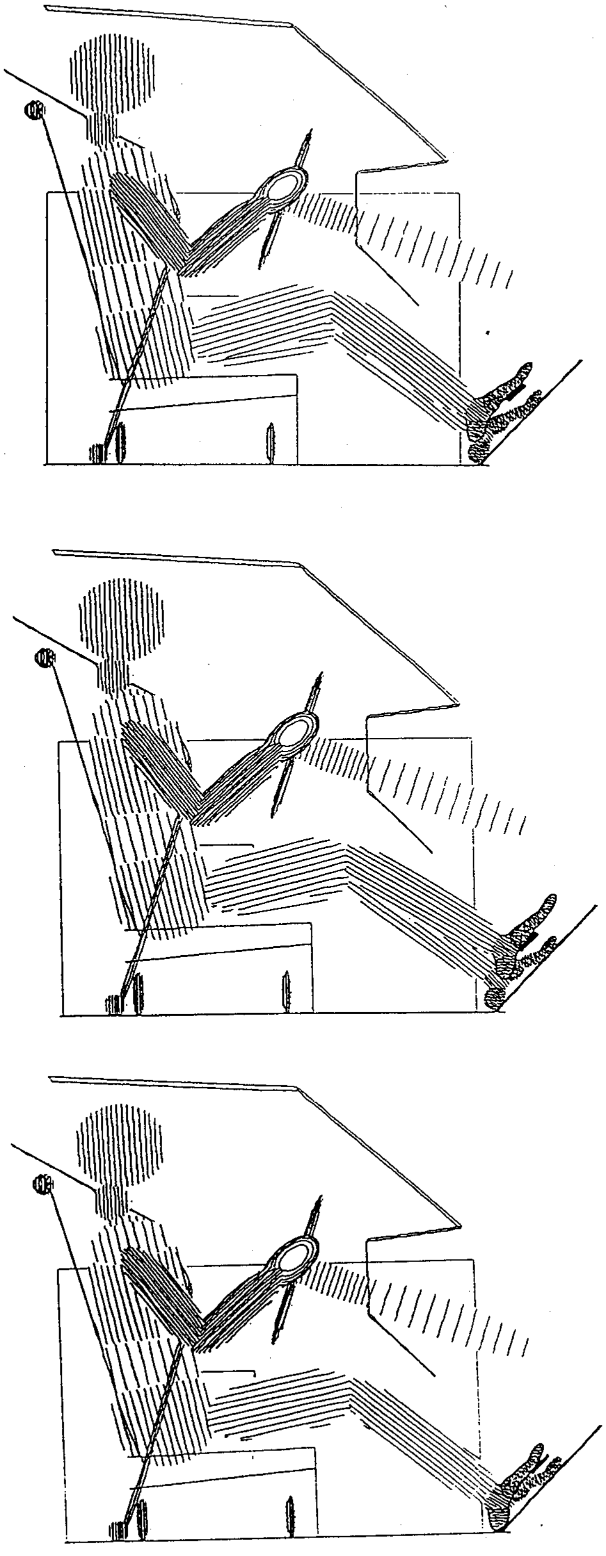


Figure 3.

Figure 4 shows plots of the toepan load time-histories for the right and left heels for several initial right foot positions. Also shown, for comparison, is a case for which the intrusion of the toepan has been removed. Significantly, for those cases in which the right heel is initially out of contact with the toepan, the peak loading on the right heel is significantly higher than that on the left heel. Furthermore, the load on the right heel is experienced as an impact of short duration while the load on the left heel builds up over a time period more than twice as long (7 msec versus 16 msec). On the other hand, when the right heel is initially touching the toepan, the loads on the left and right heels are nearly the same, and the peak right heel load is only 50% of the worst-case result that occurred when the initial contact was between the forefoot and brake only. Note that in all intrusion cases the peak loads on both heels occurs prior to 30 msec, when the intrusion is less than 4 cm.

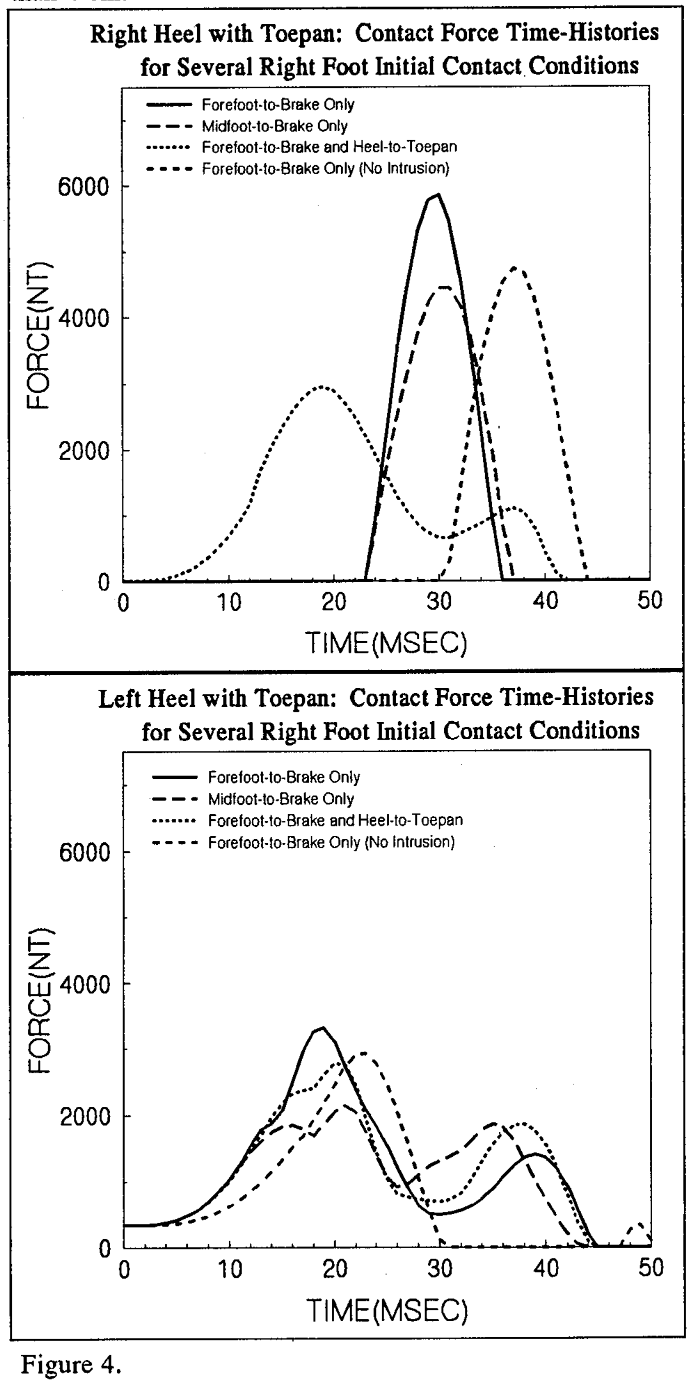


Figure 4.

These results strongly suggest that the act of braking can place the foot in a vulnerable position which enhances the likelihood of certain types of injury. In retrospect, this is not surprising since pivoting of the foot about the point of brake contact causes the heel to impact the toepan with a significant relative velocity. The left foot, however, experiences a smoother "ride-down" and, therefore, lower loads. What is surprising in these results is the relative importance of intrusion.

The no-intrusion simulation was performed for the worst-case right foot position, and, as Fig. 4 shows, the peak load on the right heel does drop by about 1300 N. However, this peak load is still larger than the peaks for either of the other two foot positions and the shape of the load curve is still very much a spike, indicating severe impact. The peak load relationships for the left heel are similar, with the no-intrusion case coming in second worst for that foot also. This suggests that for cases of intrusion less than or equal to this one, the positioning of the foot by the occupant may be of greater significance in determining the peak loads along the foot than the process of intrusion itself.

Figure 5 directly compares the effects of intrusion and initial heel position on the heel load time-history. In each case, the forefoot is on the brake and the heel is off of the toepan, but two heel-to-toepan spacings are considered both with and without intrusion. The results show that moving the brake closer to the toepan has about the same effect on heel load as eliminating intrusion. However, a combination of the two provides the best results and reduces the original worst-case load by almost 45%.

These results suggest several factors that will be considered in upcoming tests at the University of Virginia's Automobile Safety Laboratory. The following section describes the equipment and the methods that will be used in the experimental phase of the lower extremity work.

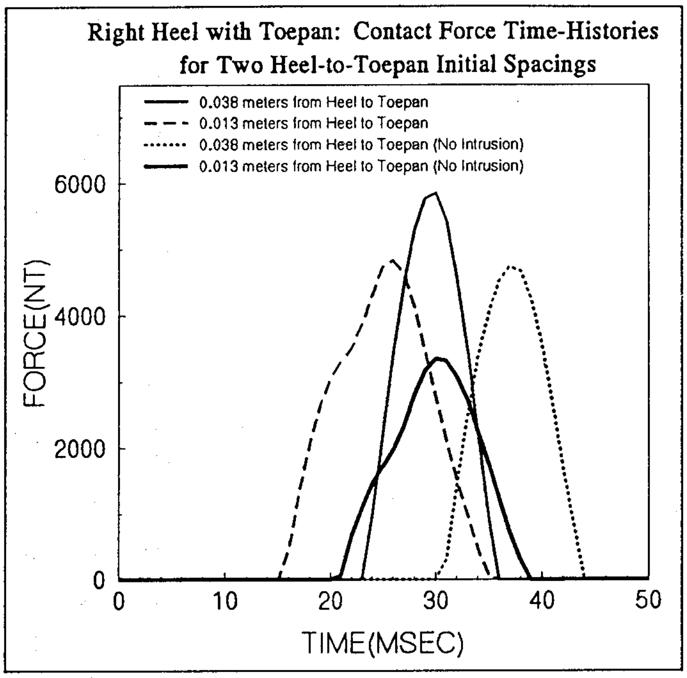


Figure 5.

EXPERIMENTAL TEST PROCEDURES AND EQUIPMENT

Intrusion Buck

In order to simulate the effects of toepan deformation during vehicle crashes, sled components must follow a programmed displacement and time profile. One method to accomplish this is to integrate the action of the toepan components of the buck with the deceleration action of the sled. This is accomplished with a VIA Systems hydraulic decelerator attached to the University of Virginia's test sled.

The hydraulic decelerator is a cylinder provided with an array of discrete orifices over a portion of its length. The orifices are sized to vary the resistance as a function of piston position, so the rate of energy absorption for the system can be regulated. Since the decelerator is attached to the sled carriage, it can be used as a hydraulic pump to power the intruding components mounted on the sled carriage.

Figure 6 depicts the schematic of the integrated hydraulic decelerator and the floor board actuator system. This system uses the two actuators of a double-acting piston. The first actuator (slave cylinder 1) is connected to one or more of the hydraulic decelerator output ports. The other actuator (slave cylinder 2) is connected via a "tee" to two hydraulic decelerator output ports.

As the sled strikes the reaction mass to begin the deceleration pulse, the piston of the hydraulic decelerator strokes into the cylinder. During impact, pressure is developed in the decelerator and transmitted to the two slave cylinders. Since the piston rod is located in slave cylinder 2, slave cylinder 1 has a greater piston area and no initial movement of the push rod develops. Output port 1 serves as the event initiation port and its location along the decelerator cylinder determines the time interval between the start of the impact and the start of toepan motion. After the decelerator piston passes output port 1, the fluid contained in slave cylinder 1 can be exhausted. Thereafter, the slave piston is moved by the pressure in slave cylinder 2 and begins the toepan intrusion sequence.

Output port 2 is used to tailor the pressure and the flow profile of the actuator piston. This is accomplished by adjusting the size of the orifice installed at this port relative to the size of the orifice at port 3. The basic functions of this port are either to increase the flow to the actuator before the decelerator piston has passed it or to decrease the flow and pressure after the decelerator piston has passed it. The toepan movement can be terminated either when the decelerator piston passes output port 3 or the slave cylinder volume has been filled. To develop the orifice profiles simultaneously for both the deceleration and intrusion pulses, a software program has been developed. For the desired pulses, the algorithm determines all the essential pressure and flow information necessary to identify the conditions and hardware configurations of the actuator.

Since contact with the floor/toepan region and pedals of the vehicle appear to be mechanisms of ankle/foot injury, intrusion parameters are being incorporated into the cadaver and human surrogate testing. At the present time, it is not known which intrusion parameters (e.g., displacements or

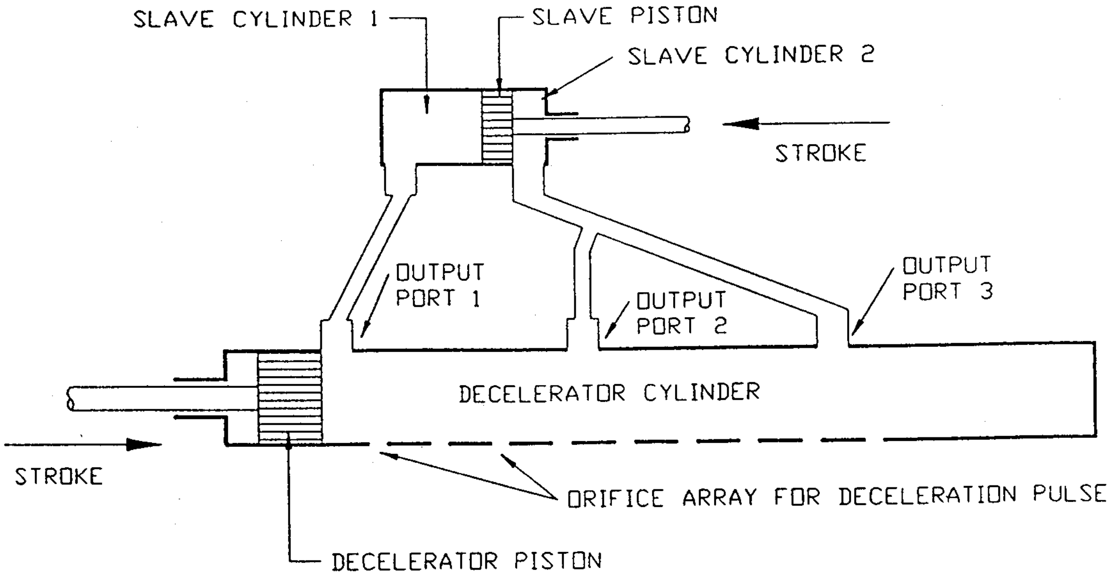


Figure 6.

accelerations) are most significant in producing ankle trauma. Therefore, experimental test devices have been designed and fabricated to determine the susceptibility of the ankle to injury from known impulse loads over the range of ankle motion.

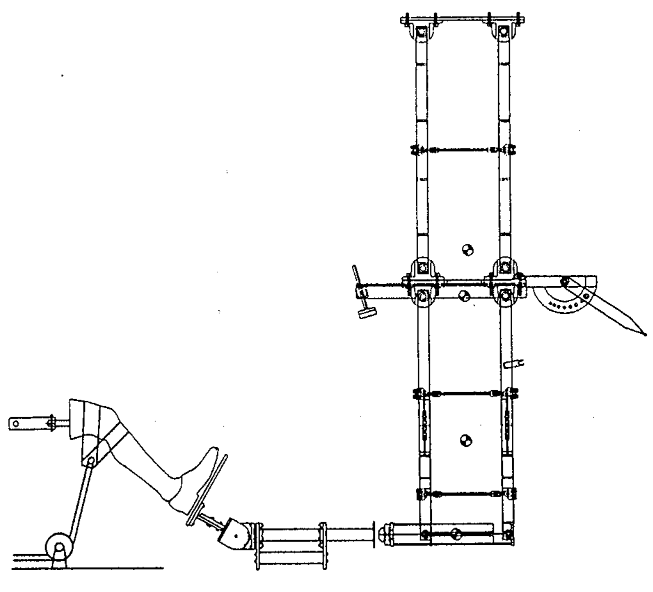


Figure 7.

Lower Extremity Pendulum Tests

Along with the intrusion buck, we have constructed a test apparatus which allows the testing of lower limb response at the component level. This environment is much more controllable than is a full sled test. It will allow us to examine load transmission for precise initial foot positions and orientations, and will allow the applied load to be accurately selected as well. This apparatus consists of two complementary devices, a compound pendulum and an ankle test cell. Figure 7 shows a sketch of the pendulum device and its relationship to a Hybrid III leg. This apparatus was developed to study the effects of a range of impulsive plantar loadings on ankle injury and to verify the functionality of newly developed lower limb instrumentation. The footplate can displace (i.e., intrude) up to 20 cm with pulse profiles of less than 5 millisecond to 40 millisecond duration. The total applied energy applied by the pendulum at the contact pad can exceed 678 N.m for impactor speeds of up to 27.4 km/h.

The pendulum is a double or compound design. The upper and lower arms are raised and released simultaneously. Upon reaching bottom dead center, the upper arm is stopped abruptly using a cable. The lower arm, however, continues to fall until it impacts the contact pad on the ankle test cell's transfer piston. This approach was used to maximize impact velocity for a given drop height.

The ankle loading fixture (ankle test cell) has been developed to assist in the verification and the testing of instrumented legs. It consists of a contact pad, transfer piston, detented universal joint, footplate, and muscle tether. The contact pad is designed to control the shape of the transmitted pulse from the pendulum impactor to the transfer piston. The detented universal joint allows initial positioning of the foot/ankle complex about the flexion and inversion/eversion axes; it allows rotations of $\pm 90^{\circ}$ about two axes. These axes can be aligned with the rotational axes of the foot/ankle complex so that the device can accommodate the full range of motion of the ankle. The muscle tether applies a load to the distal femur and proximal tibia to simulate the straightening of the leg due to muscular contraction when the brakes are being applied. The force versus. displacement profile for this device is programmable. The current version uses a mechanical spring, but provision has been made for the use of other force generating devices. Accelerometers can be attached to the foot support plate to measure values at the plantar surface of the foot.

The dynamic response tests are designed to determine the susceptibility of the ankle to injury from known impulsive

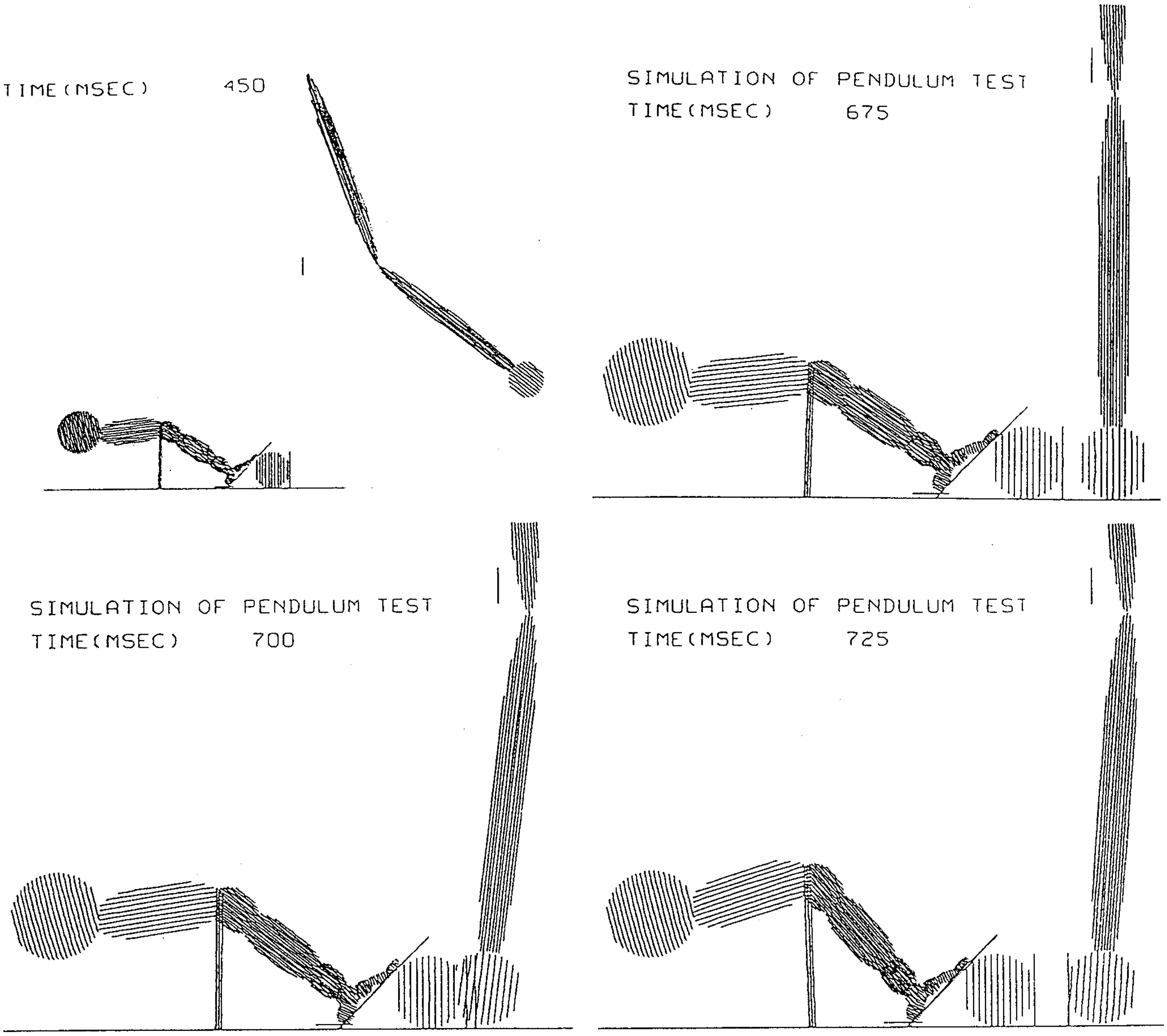


Figure 8.

loads over the range of motion of the ankle. The degree of ankle inversion and eversion are fixed as initial conditions. These tests will provide additional data for interpreting the full-scale cadaver sled tests.

To go with the pendulum test device, an ATB model of the same system has been developed. This has involved modifying the lower leg to have three segments instead of one as shown in Fig. 8. The additional "joints" in the new lower leg are located at the same positions as the tibia load cells in the new Hybrid III lower extremity. Although these joints are locked with respect to the relative motion of the connected segments, the reaction forces and torques which ATB must apply to maintain the locked joint constraint are reported in the simulation output. These quantities should compare favorably with the data from the tibia load cells which are also part of a relatively rigid structure.

Testing of the pendulum/leg apparatus has just begun. After some initial data sets have been obtained for low energy impacts, the simulation will be validated and used to predict the kinematics of more energetic impacts prior to running the pendulum. This will help estimate the loads that we should expect. After a sufficiently large database is obtained for different initial foot positions, the joints torque functions and the stop angles in the foot and ankle model will be updated and incorporated into full-occupant simulations to further improve the biofidelity of simulations, allowing accurate estimation of forces and torques at several foot locations under complicated loading conditions.

CONCLUSION

Results from computer modeling of a real world accident have shown promise as a means of determining the injury-causing mechanism within the occupant c ompartment. In the specific case selected for study, the simulation results for heel loading correlated very closely with the type of injury sustained by the victim, including a pronounced left-right asymmetry.

The conclusion, in this case, is that braking by the occupant placed the right heel above the floor and toepan, making it more vulnerable to an impact injury than the left heel which was in contact with the toepan from the start. Removing intrusion from the model reduced the peak load on the right heel, but a greater reduction could be achieved by modifying the position of the foot. It appears from the simulation results that minimizing intrusion combined with a brake pedal position which allows the heel to remain close to the toepan would be the optimum way to limit impact loading to the foot.

These simulation results clearly point toward specific parameters which should be considered in upcoming experimental work. First, the actual injury tolerance of lower limb components must be determined. The simulation can predict with confidence that the kinematics resulting from the act of braking can lead to a large asymmetry in the loads experienced by the left and right feet, but it cannot say whether these loads will produce injury. For this, an injury database obtained from controlled experim ents is needed. The UVA sled and pendulum devices will soon provide input for that database.

Second, once injury tolerance is established, experimental work can help to verify the effectiveness of design modifications which have been identified from simulation parameter studies. In the above case, moving the brake pedal closer to the toepan might be a simple, inexpensive way to reduce the severity of heel trauma. In may also be very practical since most brake pedals are still about 10 cm. from the toepan, even during heavy braking. This is a subject that will be studied very soon at the UVA laboratory.

ACKNOWLEDGEMENTS

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The air inflator - a contribution to improving the airbag system

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Paper No. 94 S4 W 33

AGENDA

A collision, particularly a collision of the head and chest against the steering wheel, caused by the forward rotary movement of the upper body resulting from the sudden deceleration of the vehicle in the event of an accident, has led to the development of new driver and passenger protection systems.

The introduction of the airbag system meant a considerable improvement in the protection afforded to drivers and passengers. As a result of the short reaction times, modern airbag modules are fitted with pyrotechnic gas generation systems. The drawbacks involved with this, such as the high burning temperature, the splitting of CO and disposal problems have been compensated by KS AS by the development of a gas generation system on the basis of compressed air. This paper reports on the design, function and benefits of an airbag with this system, in terms of its protective function.

INTRODUCTION

Evaluations of accident simulations, such as sled and vehicle crash tests have shown that unbelted persons inside a vehicle are injured most often by impact with the steering wheel, "A" pillar, windscreen and dashboard, Figure 1. An analysis of injuries suffered in road traffic accidents confirm this. In fact, 70% of all fatal accidents are caused by serious skull injuries from colliding with the above vehicle components which are essential parts of the vehicle and therefore cannot simply be removed. The introduction of the seat belt, whose improvement in the form of the automatic belt and belt tensioning systems have led to a 50 - 60% reduction in the severity of injuries caused by impact with the windscreen, "A" pillar and the dashboard, Figure 2. The collision, particularly of the head and chest, against the steering wheel, caused by the forward rotary movement of the upper body resulting from the sudden deceleration of the vehicle cannot be adequately prevented by a seat belt, however. This made it necessary to develop HIC (head injury criteria) optimised steering wheels, but above all, of airbag systems for drivers and front seat passengers. Only these air bags are capable of making a clear reduction in the risk of serious accident injuries and thus to considerably increase passive safety, Figure 3.

KS AS tried from a very early stage to use these benefits and, in conjunction with leading automotive manufacturers, developed solutions to the large number of problems with which the airbag was initially faced. On this basis airbag systems were developed for drivers and front seat passengers for standard installation which met all the requirements in terms of functional reliability to a very large degree.

Almost without exception, all these airbag systems use pyrotechnic propellents which have proven most suitable over the years.
More recent requirements, not least in respect of the recyclability of the components, are presenting airbag module manufacturers with new challenges.

For this reason KS AS has developed a new series of inflators which use a compressed gas, the Ecoinflator. This paper is particularly intended to described the function and design of this new inflator technology in comparison with conventional solutions.

Design of pyrotechnic inflators

The solid propellent gas inflator, of the latest generation, generally consists of an alloy casing which is fitted with gas escape apertures on the side which faces the airbag, Figure 4. It is triggered electrically using the centrally position ignitor unit. The amplifier charge positioned above this is used to build up the high pressure and high temperature required for the reaction of the pyrotechnic propellent which is kept in the auxiliary chambers. When the pyrotechnic propellent is converted into the gases which fill the airbag, solid and liquid reaction products are generated which retained by filter systems which surround the propellent. The high gas temperatures generated during this process may damage the airbag material and certainly constitute a disadvantage for the person who is looking to be protected when the head and chest come into contact with the airbag.
Therefore the filter systems are also used to cool the propellent gases. The by-products of this combustion are harmful gases such as the toxic gases carbon monoxide, hydrocarbons and particles which may escape through the exhaust holes in the airbag and into the passenger compartment.

Gas generation systems

Figure 5 shows an overview of the gas generation systems which are used or possible in airbag inflators.

a) Sodium acide
Sodium acide is a solid propellent which has been used in the past as a gas supplier (nitrogen) for inflating the airbag. The gas is generated by the conversion of sodium acide (NaN_3) with an oxidiser, eg. copper oxide (CuO) or potassium nitrate (KNO_3) and silicium dioxide (SiO_2). It has also been allowed to react with molybdenum disulphide (MoS_2), Figure 6. The gas yield if approx. 30 standard litres per 100 g of propellent with a slag proportion of approx. 60% and a gas temperature is approx. 1500°C means that additional cooling and filtering measures are required. A typical gas analysis is shown in Figure 7. Additional heat protection measures for the bag material are also necessary to prevent the destruction of the bag and also to prevent burning the face when it comes into contact with the bag. However, the ignition of the propellent always develops a certain amount of smoke inside the vehicle. The toxicity of the non-combusted propellent is very high. The disposal of old vehicles therefore presents the appropriate problems and is correspondingly expensive. Environmental risks and the abuse of the propellent can therefore not be ruled out.

b) Nitrocellulose
Although at the beginning of the development of the airbag, every conceivable gas generating propellent was examined in terms of its function and toxicity and the combustion product (nitrogen) from sodium acide was the only one which was not toxic, today inflators with a nitrocellulose base are currently in use. As a result of the high energy density of the NC propellent at high gas temperatures, the inflator may be designed within smaller dimensions as a result of the lower mass of the propellent. However, nitrocellulose propellents have the following properties. Because of the high temperature of the gas of between 2500 and 3000°C, special cooling measures are required. The heat protection measures for the bag material also require special work. Because of the high conversion reaction, residue and particles in the bag are less of a problem. The gas from the nitrocellulose propellent is characterised by its high level of CO (40 - 50%) and is therefore toxic, Figure 8.

The disposal problem, together with environmental risks and abuse, is also one which has to be faced with this propellent. With ambient temperatures of in excess of 70°C, which as may occur within a vehicle, the propellent undergoes chemical decomposition and conversion into nitroglycerine (Ngl) with the risks this involves of self-ignition. As a result of the high proportion of CO in the gas, an inflammable mixture (CO + H2 with air) may be generated inside the vehicle. A vehicle fire, a lit cigarette or some other spark may ignite the gas mixture. Depending on the location and size of the bubble of inflammable gas, the burn off may take the form of an explosion which could be dangerous for anybody inside the vehicle.

c) Other propellents
Other propellents such as HITP, monergols and diergols also generate high gas temperatures when ignited. In the same way, the reaction produces CO and hydrogen gases which may mix with the oxygen in the air to form explosive mixtures.

d) Liquid gas generating systems
The only liquid substances which may be considered are ones which are not toxic in their gaseous state, such as all inert gases, nitrogen N_2, air, carbon dioxide CO_2 and water. The liquefaction of, for example, inert gases, nitrogen and air is only possible at very low temperatures. This means that a permanent cooling system would be required for the entire service life of the gas inflator, which therefore means that these systems are impracticable. Carbon dioxide, liquefied under pressure, cools the ambient area considerably when suddenly relieved and goes into a solid phase.

This means that this system is also not suitable for an airbag. When water is evaporated, an energy requirement of 226 x 10^3 joules must be supplied for 100 g of water in a time of just 20 milliseconds. This corresponds to a rating of 100 MW. This means that this system, too, is not practical for an airbag. When fluids are combusted there is also the problem of uncontrolled conversion as a result of the undefined areas. It is therefore not possible to reproduce the quantities of air in an airbag.

KS Ecoinflator

From the point of an airbag module manufacturer, after analysing the drawbacks described above, the challenge must be to develop inflators with as low a pyrotechnic effect as possible and a working medium which must offer benefits in many aspects. As a result of this KS Automobil-Sicherheitstechnik GmbH has developed a new series of inflators on the basis of compressed gas, the Ecoinflator. Currently this series of inflators comprises four types of inflator which have been adapted to the various requirements for driver, front passenger and side airbag modules. This new inflator technology differs from the inflators used in the past in that they also affect the design of the entire airbag module.

Taking as an example the design for a full-size driver module, the following describes the design and the function of these new inflators, which is the same for all the different versions, Figure 9.

In contrast to the passenger and side bag inflators which have a bottle-shaped volume of compressed gas, the driver inflator has a ring-shaped storage chamber which is positioned around the bursting system. When the airbag is triggered, the air passes through star-shaped ducts around the bursting system towards the inflator outfeed aperture, the diffusor. The entire inflator and therefore also the compressed gas, is sealed by a rupture disk which bursts when a specific pressure is applied to certain points of it, thus releasing the outfeed cross section. The increase in pressure required to burst the rupture disk is achieved by igniting a pyrotechnic starter charge. This is ignited by a conventional igniter unit as used in pyrotechnic inflators.

The energy this releases ignites an amplifier charge, known as the heater charge, and opens the rupture disk by the increased pressure produced by the gas-generating combustion of the propellent. The compressed gas can now escape with the help of a little additional energy from the heater charge which continues to burn and the gas then inflates the airbag to produce its live-saving effect.

Theoretical considerations

High gas temperatures such as those described above used in pyrotechnic propellents, at a similar pressure produce completely different densities of the flowing medium. In the application range of the Ecoinflator of approx. 370 K, the density is around 1 kg/m^3 and if the temperature is increased any further the gas density falls sharply to values of between 0.4 and 0.2 kg/m^3 in the temperature range at which pyrotechnic inflators operate of between 900 and 1800 K, thus, on average, making up around one-third of the gas density of the Ecoinflator, Figure 10. This inevitably leads to increased coordination work in the design of an airbag module which uses the pyrotechnic effect.

In fact it has been shown that pyrotechnic inflators and the Ecoinflator require different airbag modifications with almost identical maximum can pressures pkmax. Compared to pyrotechnic inflators, there are hardly any cooling effects in the air which fills the airbag because of the environment inside the vehicle, which means that the passenger or driver has a longer period of contact. This produces benefits above all for out of position situations. Knowledge of this fact means that it is possible to adjust the optimum outfeed characteristics of the airbag for interaction with the passenger or driver which, with the KS AS model, is initially completed before each module is developed using numeric simulation.

Measurement results

To characterise inflator performances the airbag industry generally uses the tank test. In this test the build up of pressure after the ignition of the inflator is recorded for a defined container. Overall the Ecoinflator showed very low dependence on the temperature throughout its application range which means that it differs immensely from the solid state inflators, Figure 11. Figure 12 shows the tank measurement values for a full-size inflator for the driver's side with the comparable results in terms of the bag inflation properties achieved with a pyrotechnic inflator set at 0.5 bar higher. This is due to the colder gas in the Ecoinflator and the higher density of the medium this produces.

Pendulum impact test
So-called Eurobag systems are designed for passengers and drivers wearing a seat belt, in other

words, they produce a preventative effect against head contact with the interior parts of the vehicle. In the pendulum impact test the impact of the head to the airbag is simulated at a speed of 25 km/h. This test is used to measure the distance travelled by the pendulum into the airbag after it has struck it (deformation distance), the deformation energy, in other words the energy which the bag absorbs from the pendulum and the pendulum deceleration.
Figure 13 shows the measurement results from the pendulum impact as a comparison between an Ecoinflator and a pyrotechnic inflator. We can see that the curves are almost identical. We can therefore conclude that the Ecoinflator even offers a slight advantage.

Sled test
In a sled test corresponding to a vehicle velocity of 56 km/h, tests were carried out using a full-size driver side airbag. As the results in Figure 14 show, the Ecoinflator offers a slight advantage for the chest values whilst the pyrotechnic inflator provides slightly better results for the head values in this test. In this case the coordination potential of the Ecobag had not been used to the full. In further series of tests which will be performed after this article had gone to press, the Ecobag will show that in fact after modification it will be slightly better than the pyrotechnic bags. The influencing parameters to achieve the desired pressure increase gradient or the maximum pressure are shown in Figure 15. By varying the mass of air or heater charge, the parameter can be adapted to meet the specific requirements.

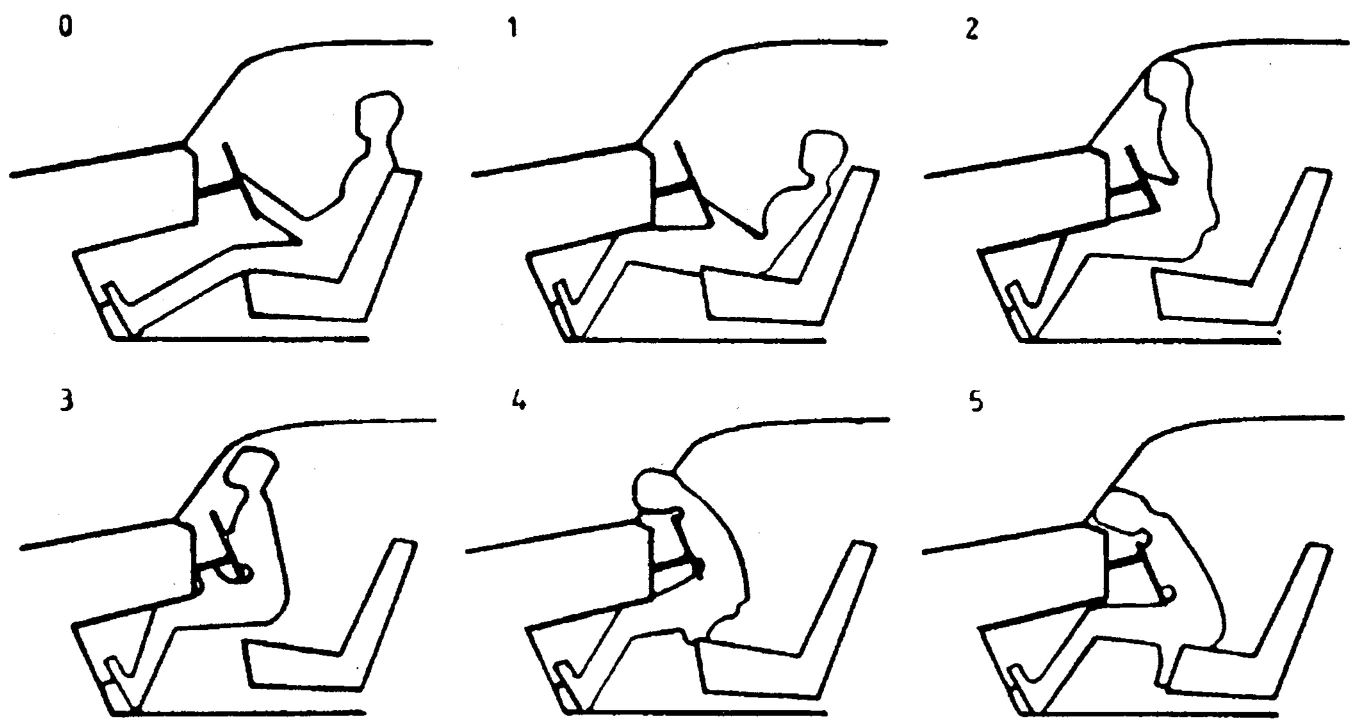
Service life
The container for the KS Ecoinflator is filled with normal air. By restricting the amount of pyrotechnics to an absolute minimum, all the problems concerning toxicity, disposal, environmental risks, abuse, particles in the bag, CO flashing in the vehicle and the decomposition of the propellent have been eliminated. No pressure monitor is required for the KS Ecoinflator. By using special ductile materials the reduction of the storage pressure of 250 bar can be prevented for a period of 15 years. This value was arrived at by means of simulated inflators which were subjected to the ageing cycles specified in the automotive industry. This meant that the inflators were subjected to temperature change, temperature shock, vibration stresses and corrosion tests. The extrapolated pressure reduction of 15 years amounted to a maximum of 1 bar and was therefore almost below the detection limit.

Other applications

Applications on the driver's side both for the Eurobag and for the full-size airbag have been described in the above sections. The front seat passenger inflators shown in Figure 16 work in the same way as the inflator for the driver's side described above. Airbag volumes of between 60 and 150 litres are possible. However, special mention must be made of the use of Ecoinflators for side impact protection. As a result of the lack of deformation zones it is essential that a side impact protection system is built up in the shortest possible time. As a result of its fast reaction times, the Ecobag is absolutely unbeatable for these applications, Figure 17. Special sizes for the seat-integrated version or door installation are possible. As a result of the cold gas it is also possible to separate the inflator and the module by using an overflow duct. This opens the way for new possibilities, particularly in cases when the area available for the accommodation of airbag modules is limited, Figure 18.

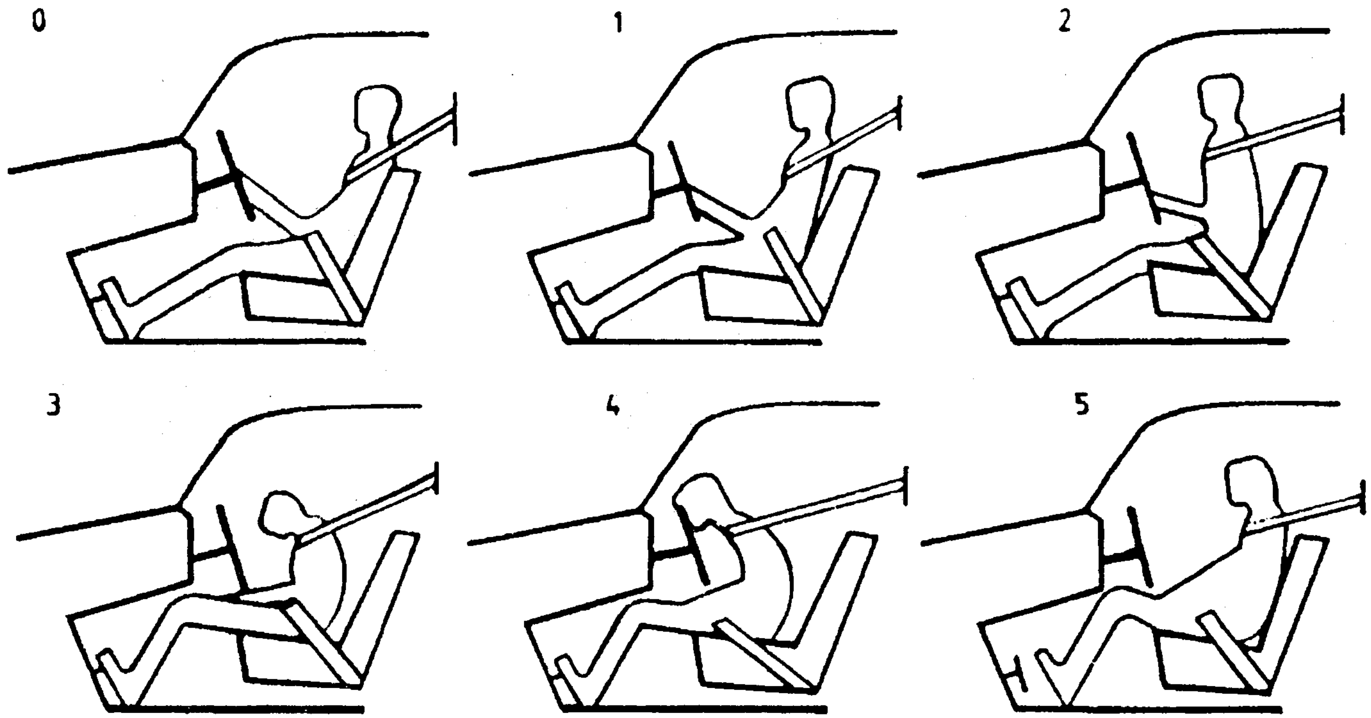
Summary

Starting from the propellent systems currently in use in airbag inflators, it has been shown that if pyrotechnic propellents are used they produce considerable drawbacks in terms of the toxicity of the non-combusted propellent or the toxicity of the gas which fills the airbag. The Ecoinflator from KS AS, on the other hand, is filled with compressed air and represents a real alternative to pyrotechnic inflators. In extensive series of tests it has been shown that inflators of this design have either equalled or exceeded the results achieved by pyrotechnic inflators. Particularly when used for protection against side collisions, the fast reaction time of the Ecoinflator is of great benefit. The possibilities of a constructive separation between the actual module and the inflator by using an overflow duct opens the way for new potential in terms of the use of space in areas which were originally not designed for the accommodation of an airbag. By developing the Ecoinflator, KS AS has managed to supply a further improvement in the field of airbag systems.

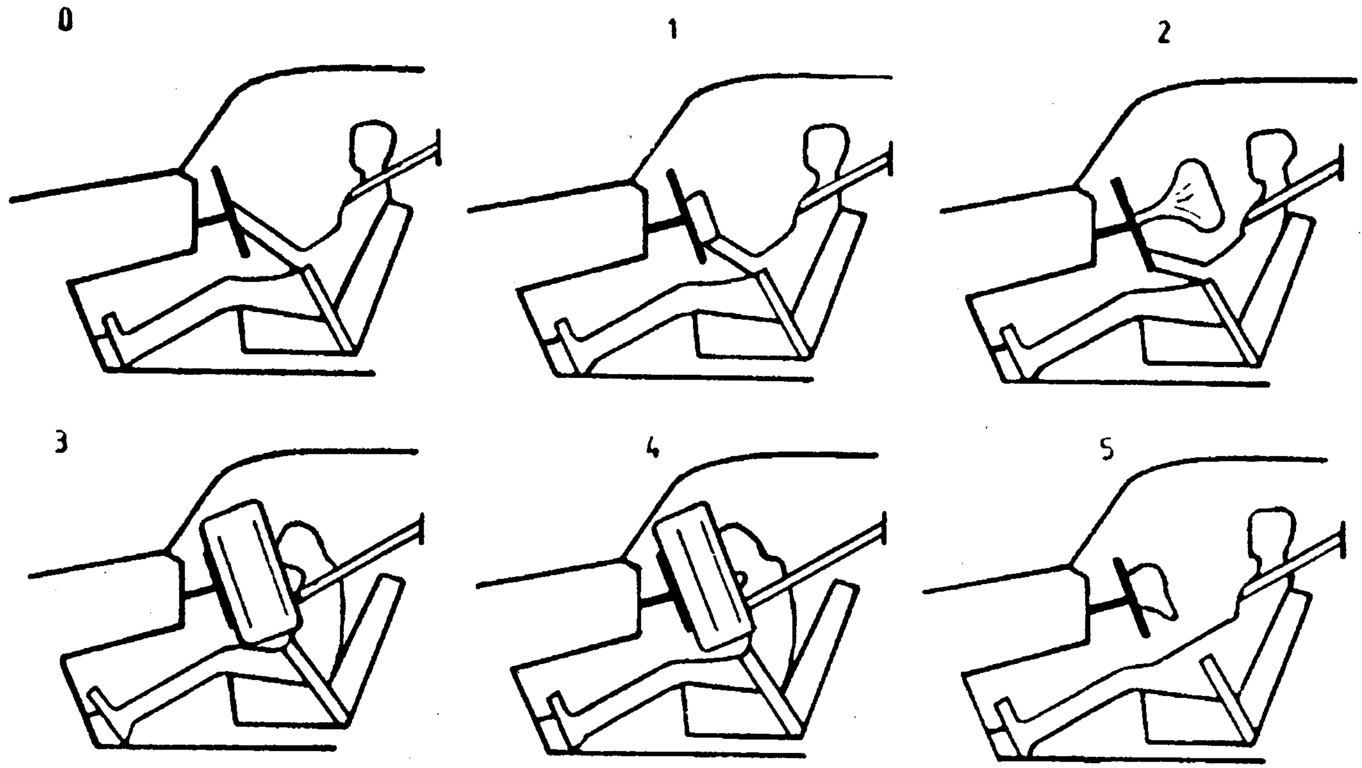


(according Gögler)

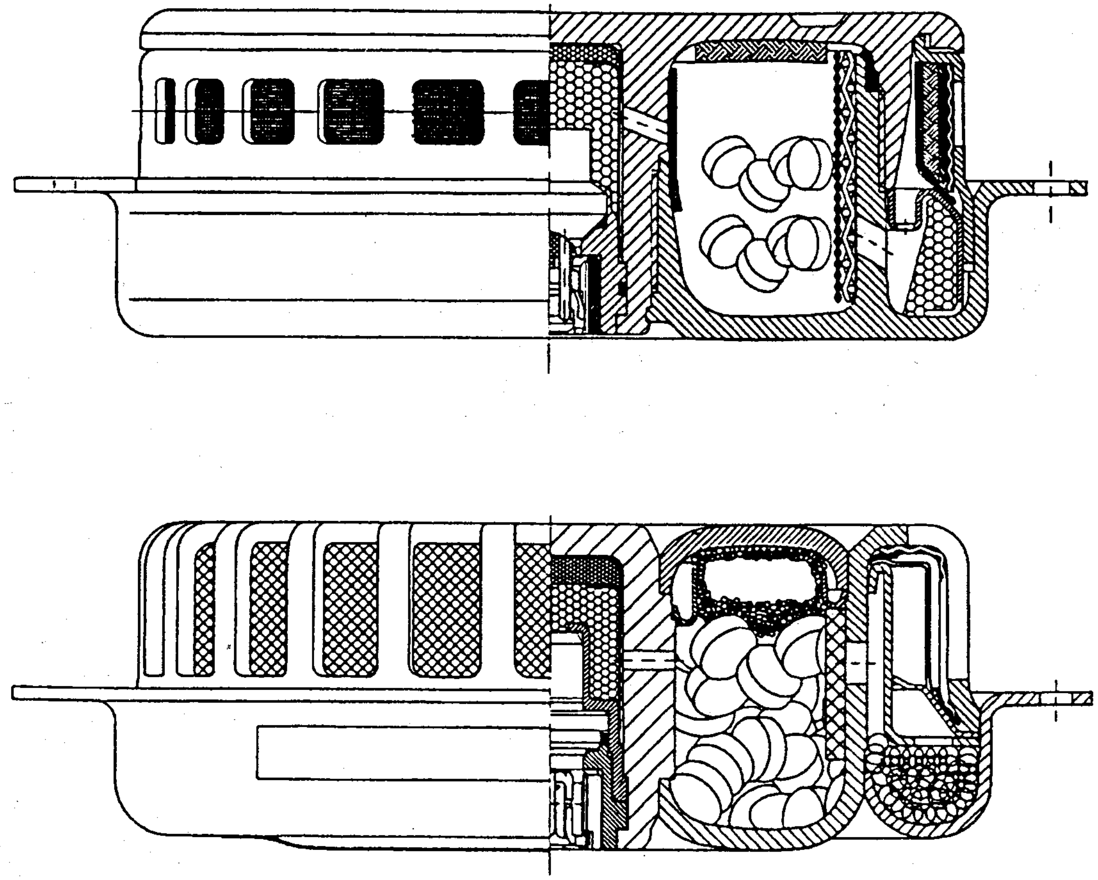
Schematic movements of head and body of an unbelted driver in a frontal crash



Schematic movements of head and body of a belted driver in a frontal crash



Schematic movements of head and body of a belted driver with additional protection from an airbag in a frontal crash



Construction of pyrotechnic inflators

Solid gas compounds

Natriumacid NaN3

LOWA HITP

Liguid gas compounds

Monergole

Diergole

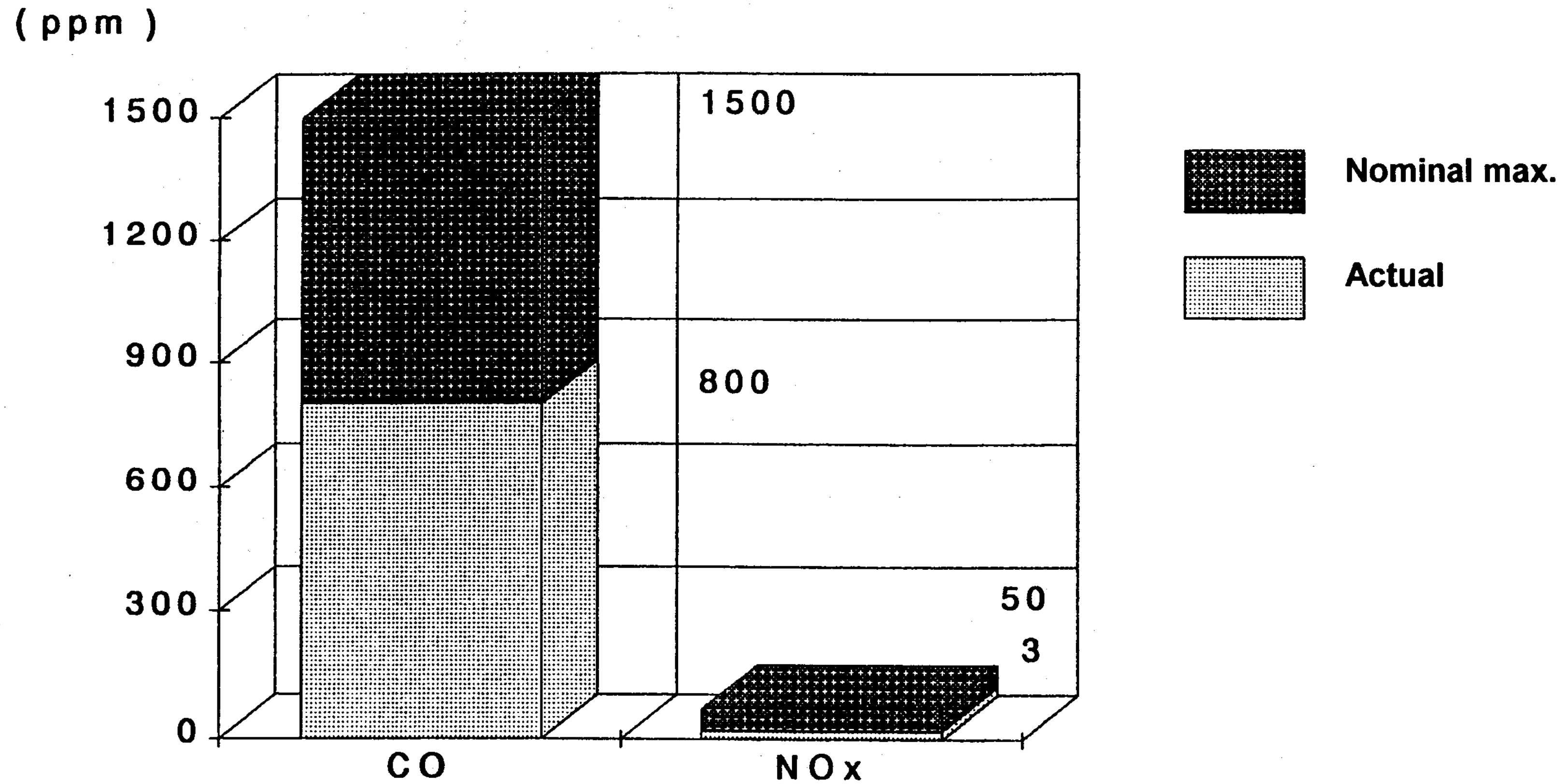
Evaporated liguids

Reaction scheme

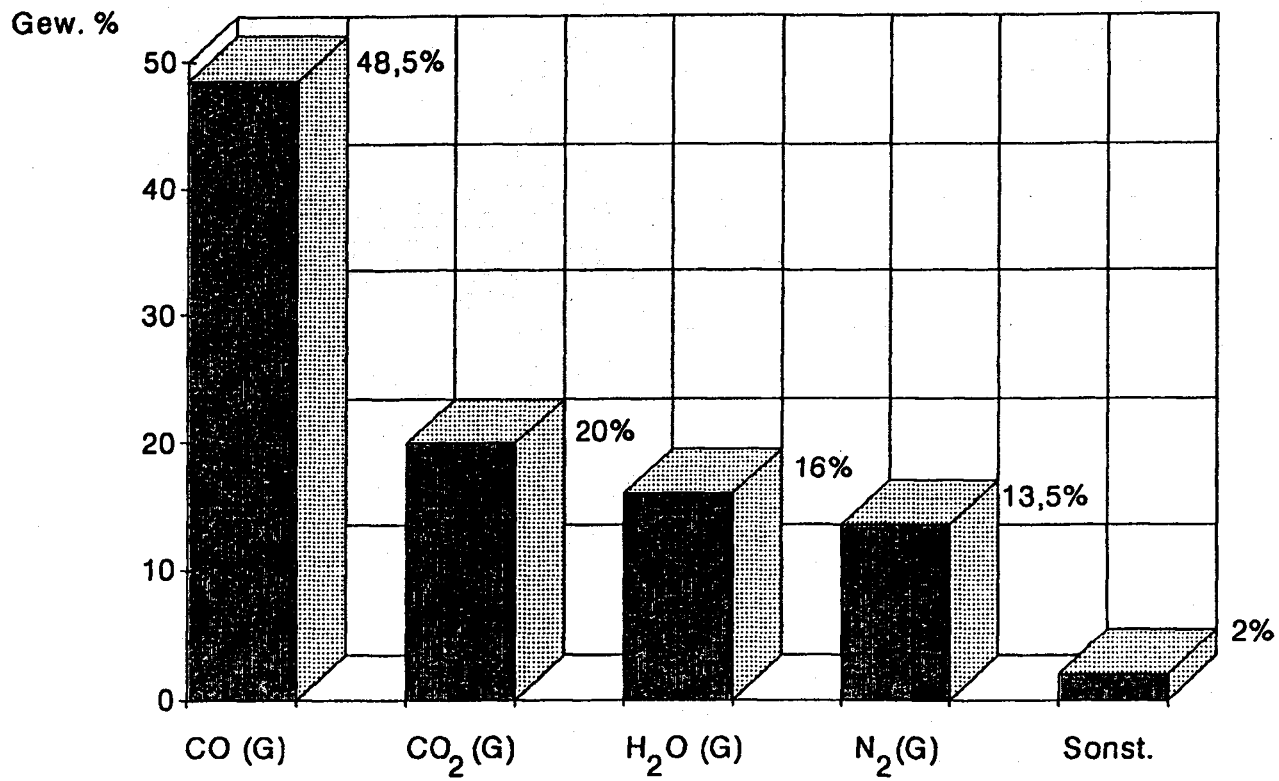
Ignition	:	NaN_3	➡	$Na + 1,5N_2$
Begin to burn	:	$2Na + S$	➡	Na_2S
Deflagrate	:	$4Na + MoS_2$	➡	$2Na_2S + Mo$
Sidereaction	:	NaN_3	➡	$Na + 1,5N_2$

NaN_3	:	Natriumacid
Na	:	Natrium
N_2	:	Nitrogen
S	:	Sulphur
Na_2S	:	Natrium sulphide
MoS_2	:	Molybdenum disulphide
Mo	:	Molybdenum

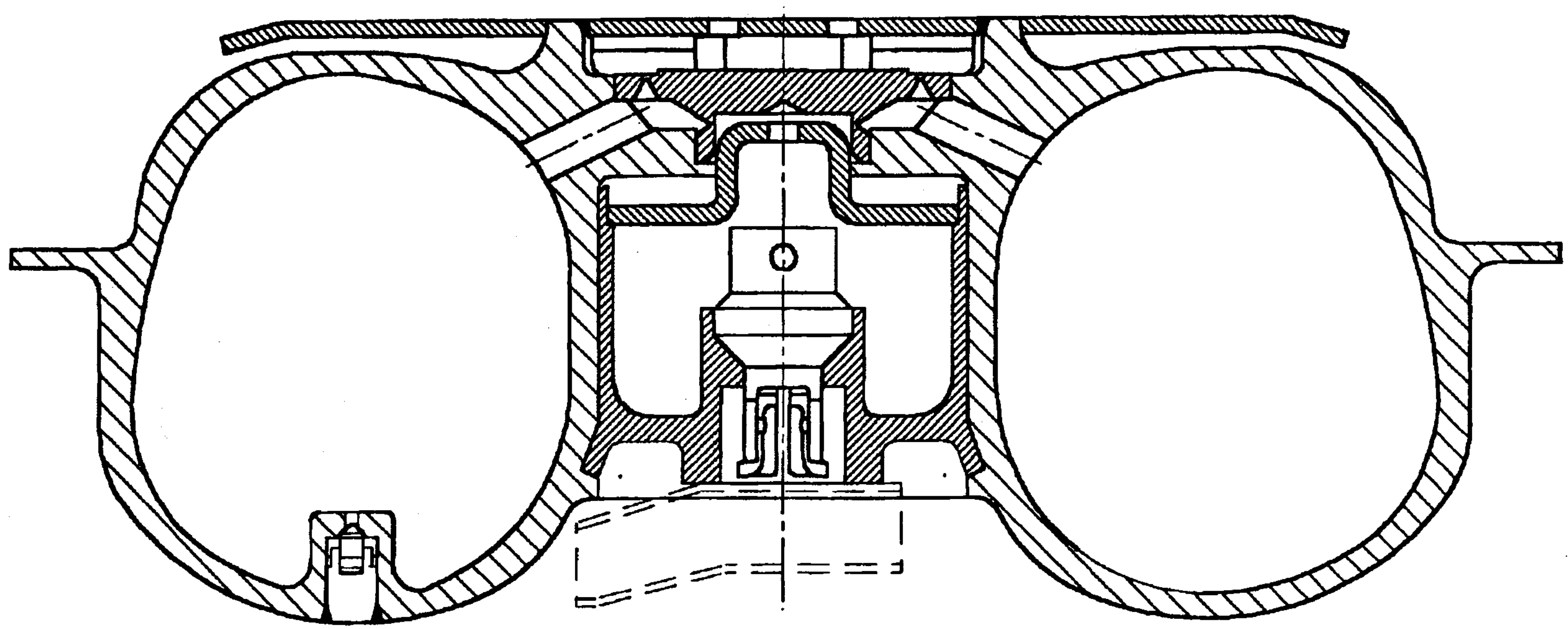
Gasanalysis
(Natriumacid)



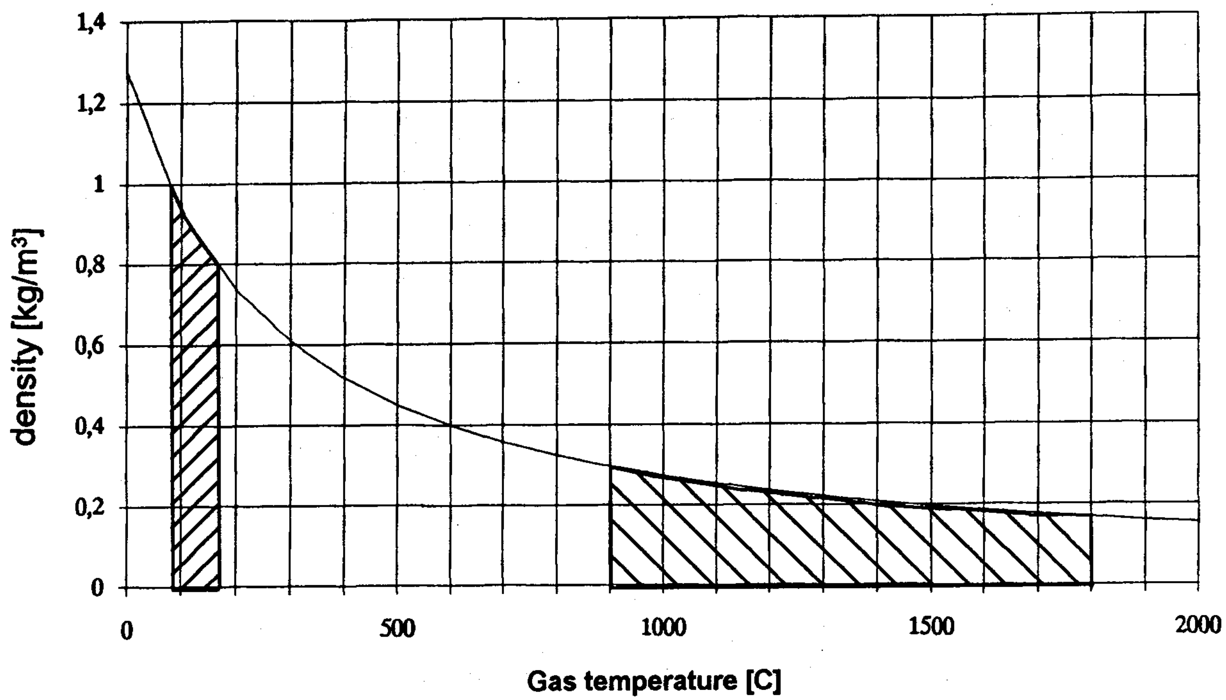
The importend reaction points in weight % using gascompounds based on nitrocellulose



others = O_2, HCN, H_3N, NO

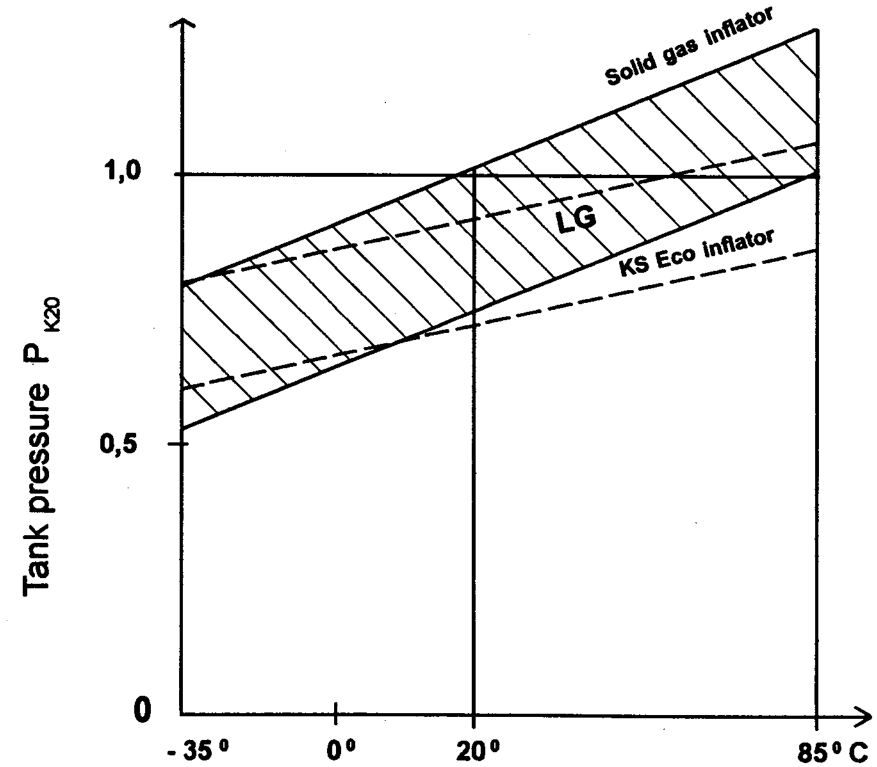


Eco inflator for fullsize driver module with a bag volume of 64 l

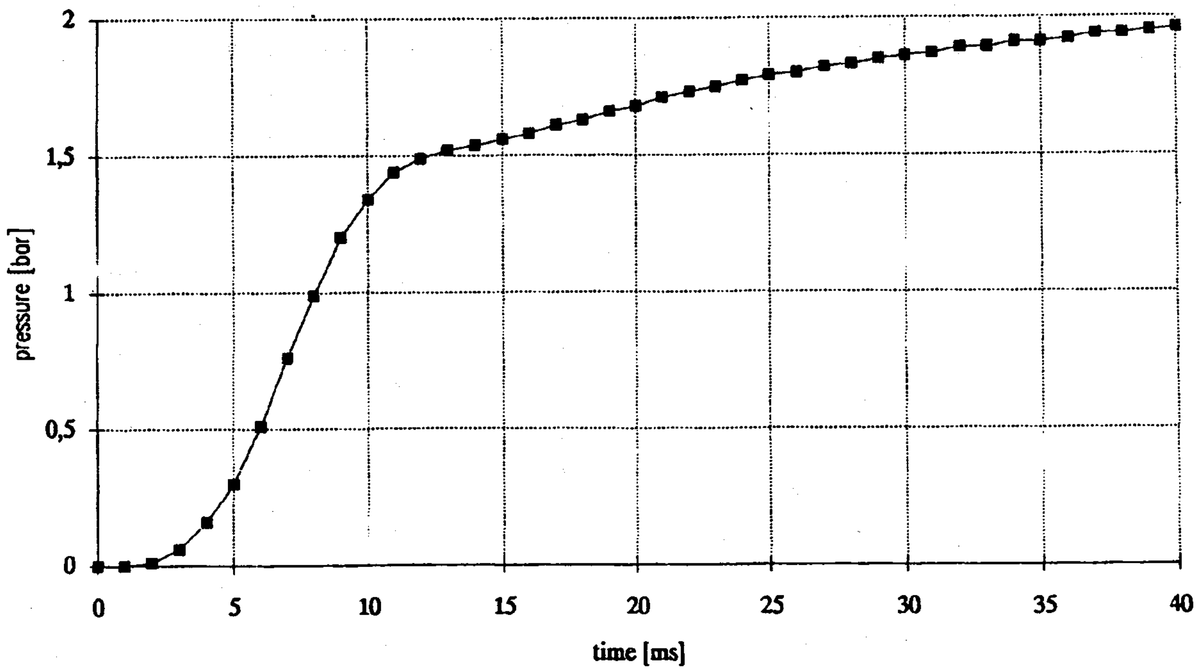


Gas density in dependence of the temperature

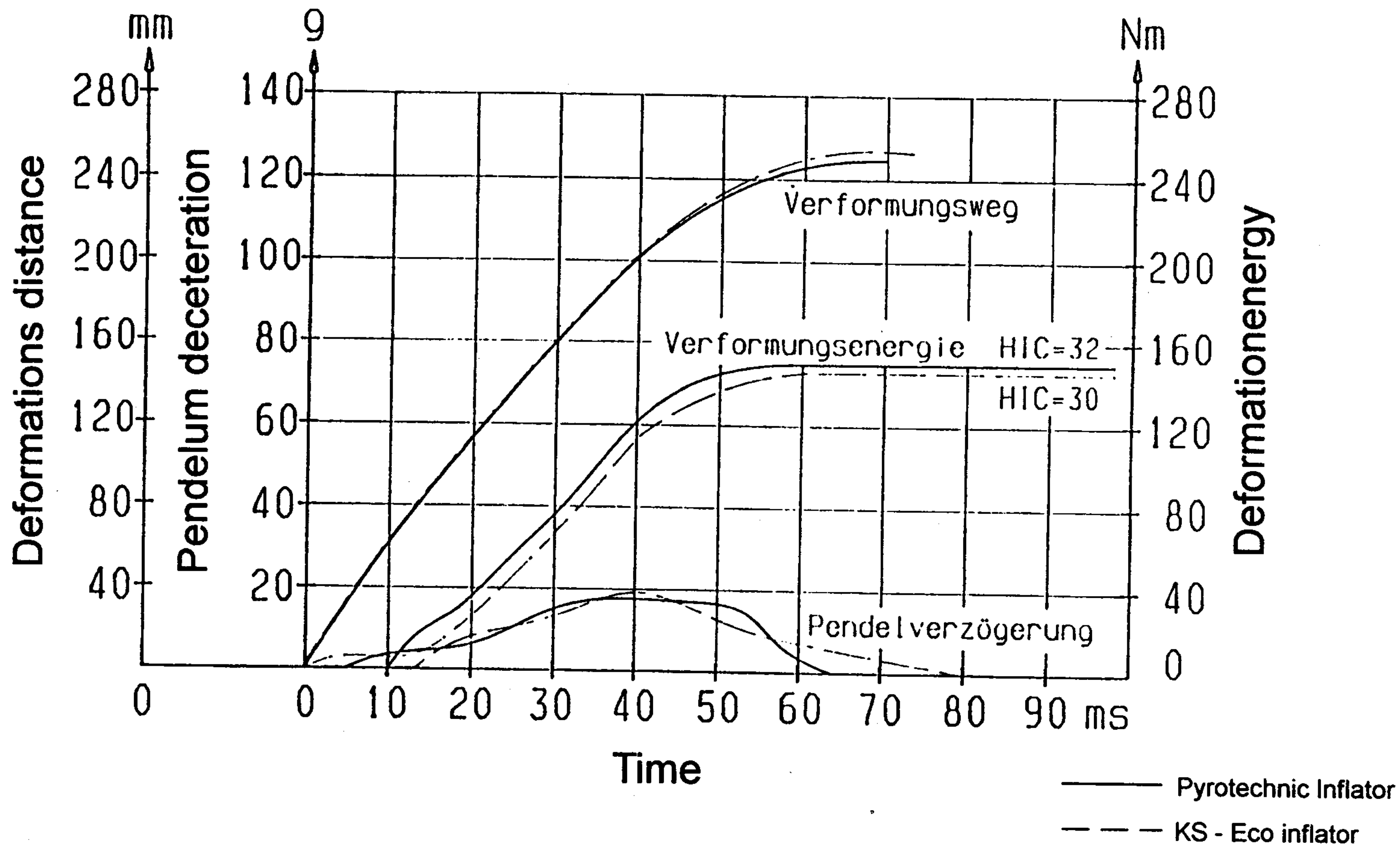
- Solid gas inflator
- KS - Eco inflator



Temperature behavior in the tank



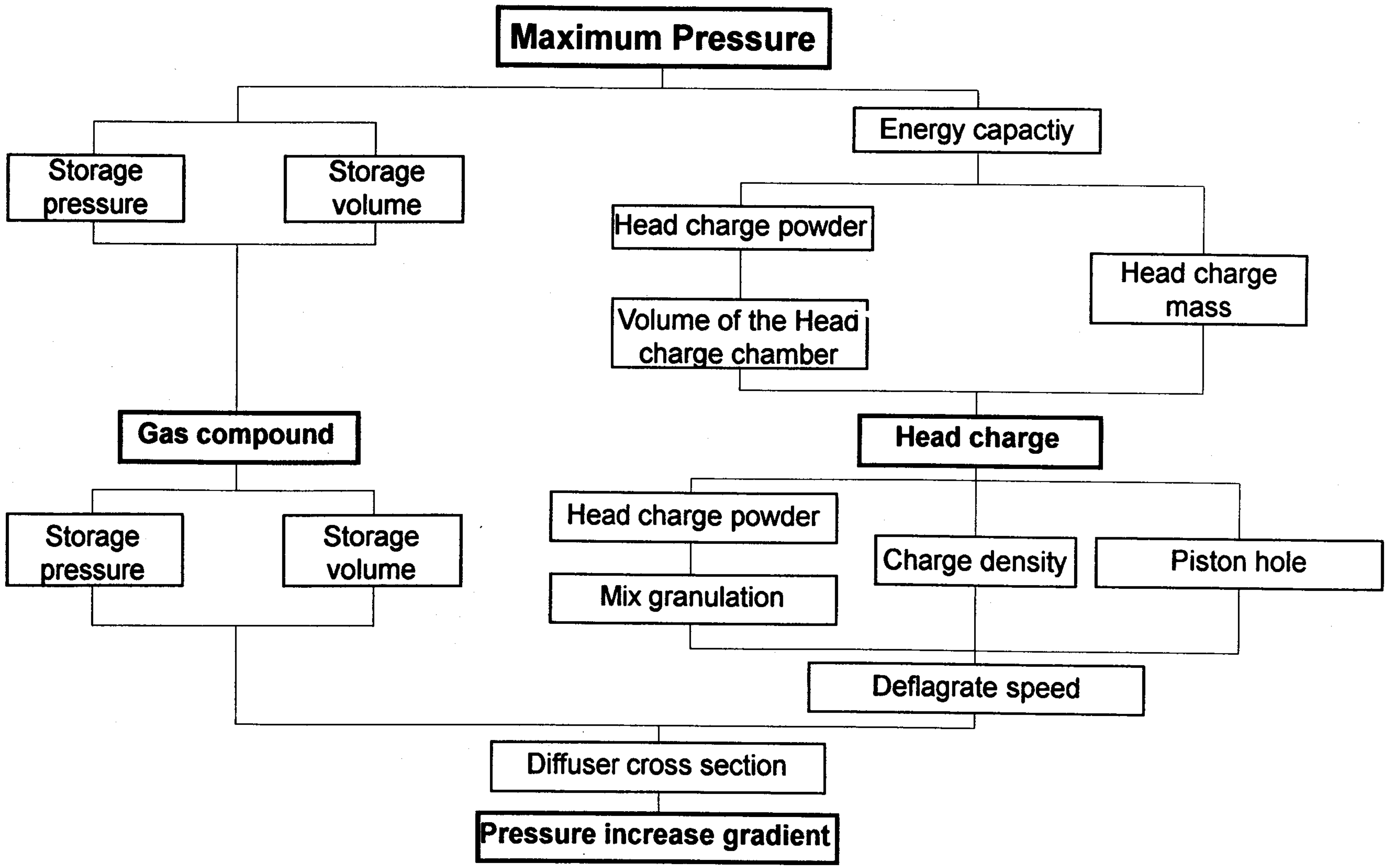
Tank pressure curve of the eco inflator compared to the pyrotechnic inflator

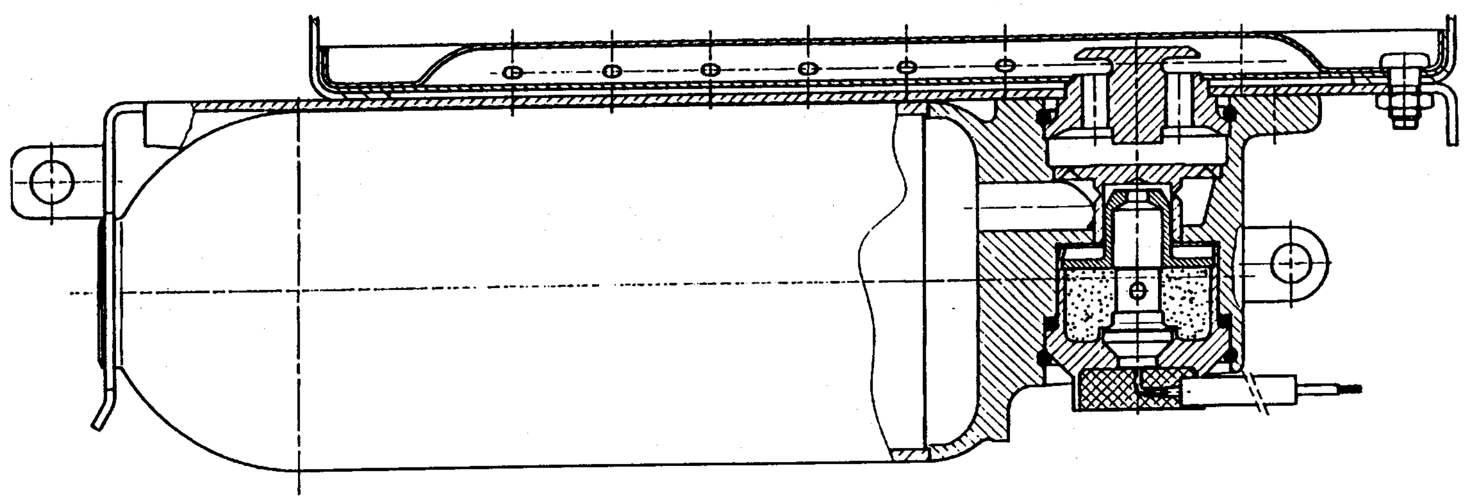


Head Pendelum impact comparsion of the eco inflator with the pyrotechnic inflator **Page: 13**

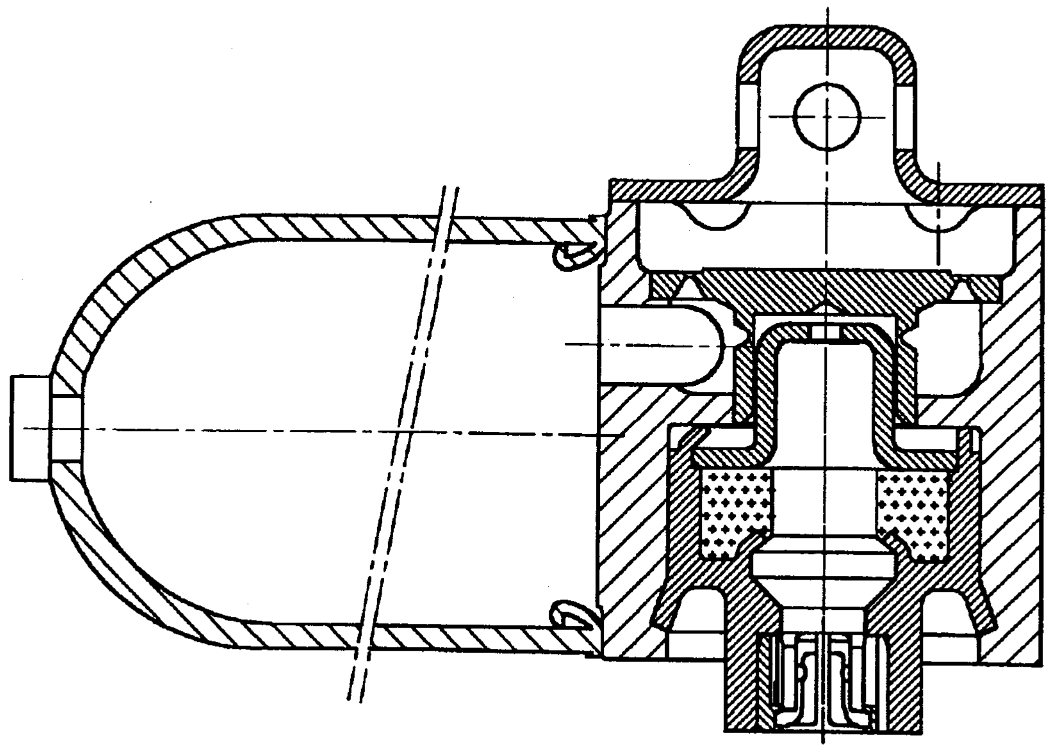
Test number			S004F081	S005F081
Inflator type			MTG5	GDM8 (Air)
Steering connection			supported	supported
Exhaust hole			50 mm	65 mm
Head	a res. max	[g]	52,7	63,5
	a 3ms	[g]	52,2	61,4
	HIC		445	510
	HIC 36		416	501
Chest	a res. max	[g]	94,3	75,3
	a 3ms	[g]	80,2	71,7
	SI		785	727
	Penetration	[mm]	37,2	41,4
Pelvis	a res. max	[g]	73,0	71,0
	a 3ms	[g]	65,2	69,7
Femur left	max.	[kN]	7,0	7,1
Femur right	max.	[kN]	8,8	9,2

Sled test comparsion of a pyrotechnic to a eco inflator in a midsize car body

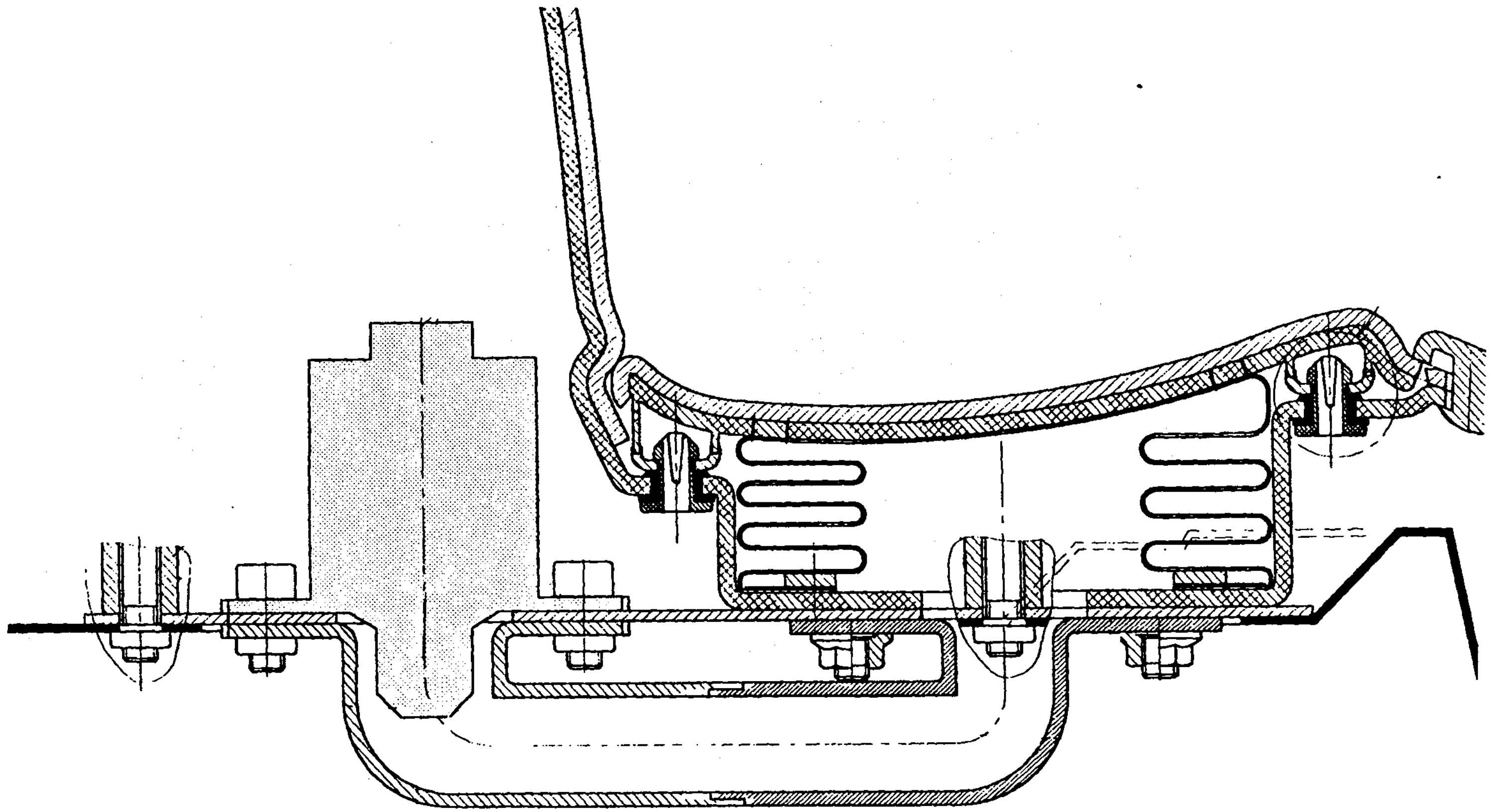

Maximum Pressure
Storage pressure
Storage volume
Energy capactiy
Head charge powder
Head charge mass
Volume of the Head charge chamber
Gas compound
Head charge
Storage pressure
Storage volume
Head charge powder
Charge density
Piston hole
Mix granulation
Deflagrate speed
Diffuser cross section
Pressure increase gradient



Eco inflator for a passenger airbag module with a bag volume of 60 l



Eco inflator for a side protection airbag module with a bag volume of 10 l to 20 l



Eco inflator for a side protection airbag module with overflow duct (door integrated)

Technical Session 5

Crash Investigation and Data Analysis

Chairperson: Claes Tingvall, Sweden

An Estimate of the Long Term Consequences of Motor Vehicle Injuries

Stephen Luchter
National Highway Traffic Safety Administration
United States
Paper Number 94 S5 O 01

ABSTRACT

The Functional Capacity Index (FCI) is a measure of a person's capacity to function following an injury. The index values vary between 0 and 1.00, where no loss of function is defined as 0 and full loss of function is defined as 1.00. When the index is multiplied by an injured person's life expectancy, the product is an estimate of the Life-years Lost as a result of the Injury (LLI). The FCI was applied to the injury data in NHTSA's Crashworthiness Data System for the first six months of 1993 to estimate the LLI in 1993 resulting from police reported motor vehicle crashes in the United States where at least one of the vehicles was towed from the scene. The results are disaggregated by age, gender, body region and AIS level, restraint use, vehicle type, and level of medical treatment.

INTRODUCTION

Until recently traffic safety efforts in the United States focused primarily on reducing motor vehicle fatalities, since motor vehicle injuries have been the fourth leading cause of death. In 1990, more deaths resulted from motor vehicle injury than from all other injuries combined, homicides, chronic liver disease, and HIV infection. Only heart diseases, cancer, pulmonary diseases and diabetes resulted in more deaths.

There has been an increasing awareness that survivors of motor vehicle crashes place a greater overall burden on society than those who die in these crashes. In 1990 there were an estimated 120 injured survivors of motor vehicle crashes for each fatality, roughly 10 percent of whom were injured seriously enough to require hospitalization. Of an estimated $137.5 billion total economic cost to society resulting from motor vehicle crashes in 1990, 51 percent were applicable to injured survivors, 23 percent to fatalities, and 26 percent to property damage only crashes (Blincoe and Faigin).

Allocating resources to develop measures to reduce the number and severity of injuries is a more complex undertaking than allocating resources to reduce fatalities. Whereas fatalities are binary, that is, you are alive or you are dead, describing injuries requires a number of additional dimensions. These include injury severity as measured by threat to life, body region injured, level of medical care required, and, of particular interest here, the long term consequences once the acute phase of injury treatment has been completed.

For some time, the primary metric used to measure the long term consequences of injuries has been the economic cost to society. Two conceptual frameworks are widely used, usually labeled human capital and willingness to pay. Both of these are broadly applicable; however, they are not ideal for all situations. The human capital estimates involve discounting future year costs. Besides the question of what is the proper discount rate to use, there is the problem that the long period at reduced functional capacity for younger people who have been seriously injured is so heavily discounted that it results in relatively lower values than for people in their peak earning years. Although the willingness to pay concept is theoretically satisfying, the assumption of a rational and knowledgeable consumer cannot always be accepted.

A number of other approaches to measuring the long term consequences of injury also have been explored, including various disability and quality of life scales (Luchter 1989). Although each of these approaches has merit, none of them provide a means of quantifying the long term consequences of specific injuries in the motor vehicle crash milieu. To fill this gap, work has been underway for some time to develop such a means.

DEVELOPMENT OF THE FUNCTIONAL CAPACITY INDEX (FCI)

The fundamental viewpoint of the FCI is that life is its own measure of value. If a person's ability to function following an injury is less than it was before the injury, some part of their life is lost. The FCI has been developed to quantify that loss.

Hirsch et al. developed an impairment scale based on the opinions of an expert panel of the time an injured person would experience one of four levels of six attributes intended to encompass full functioning. These values were applied to the AIS 80 injury definitions. The scheme included several time frames, and the effects of the injuries at different age levels. Marcus and Blodgett used the Hirsch et al. scale to determine the short term impairment for a number of injuries based on injury data in the National Accident Sampling System. Carsten and O'Day expanded on the Hirsch et al. effort and developed an Injury Priority Rating. A major innovation in the Carsten and O'Day work was the introduction of the concept of whole body impairment, which collapsed the various time estimates into a single number. This made the scale much easier to apply. Luchter (1987) demonstrated the feasibility of applying the Carsten scale to NASS data. Luchter (1989) also suggested an approach to the problem, which became the basis for the development of the FCI. The actual development of the FCI was accomplished under a Cooperative Agreement between NHTSA and The Johns Hopkins University School of Hygiene and Public Health (MacKenzie et al.)

An important distinction was made at the beginning of the development of the FCI between impairment and functional capacity. This is best illustrated by example. If one's ankle is fractured, that is an impairment. If, as a result of this impairment, one can no longer walk a reasonable distance, that is a reduction in functional capacity. There may also be other reasons why the individual can no longer walk a reasonable distance, such as a spinal cord or lung injury. The FCI focuses on the outcome, that is, the reduced ability to walk rather than on the broken ankle.

To develop the FCI, a panel of experts first developed a set of attributes that in the aggregate would reflect full functional capacity of a healthy adult. These attributes are: eating, eliminating, sexual function, ambulation, hand and arm function, bending and lifting, sight, hearing, speech, and cognitive function. Rigorous definitions for these attributes as well as for appropriate levels of reduced functioning for each of the attributes were developed (NHTSA). These definitions were applied to the injuries in the 1990 Abbreviated Injury Scale listing by the expert panel, assuming the person was between the ages of 18 and 50 and had been in good health prior to the injury. Further, it was assumed that the condition was assessed one year after the injury initially occurred, and that the person's condition was stable. In this assessment, burn injuries were not included.

In order to translate the relative value of these qualitative statements into a numerical scale, the value judgments of a number of population subgroups were determined: the expert panel of health care professionals who developed the attributes, white collar workers, blue collar workers, students, both working and non-working persons with functional limitations, and older persons. The values used in the present analysis are the average values for the entire population, excluding the senior citizens. That group had difficulty with the exercise. To complete the development of the index, an algorithm was developed to combine the values for each attribute into a whole body factor (Damiano).

The bulk of the injuries in the AIS '90 dictionary result in a 0 for the FCI, that is, there is no reduction in functional capacity for these injuries once the effects of the injury have stabilized. In contrast to the Abbreviated Injury Scale (AIS), which is primarily a measure of threat to life, the FCI is a measure of long term effects of an injury on a person's ability to function. Thus the FCI is not monotonic with AIS injury severity level. For example, typical injuries at each AIS level in the present (not clinically validated version) have the following FCI values: Minor facial laceration (AIS 1) FCI = 0, Closed fracture of the radius (AIS 2) FCI = .434, Open fracture of the tibia condyles (AIS 3) FCI = .270, Fracture with separation of the Bronchus distal to the main stem (AIS 4) FCI = .304, and Diffuse axonal injury to the brain stem (AIS 5) FCI = 1.00

DATA

This paper is concerned with the application of the Functional Capacity Index to the data on injured survivors of police-reported tow-away crashes found in the National Accident Sampling System Crashworthiness Data System (NASS CDS). This system collects data on police reported crashes of passenger cars and light trucks in which at least one of the vehicles is towed from the scene. The crashes selected for investigation are based on a stratified sampling scheme intended to mirror the national situation. The data are collected from 26 Primary Sampling Units across the United States. Trained crash investigators complete an extensive listing of data elements that describe the crash, the vehicles, and the occupants. Police accident reports are augmented by inspection of the vehicle and access to hospital records. About 5,000 crashes a year are investigated. In many of these, more than one person is injured.

In 1993, the NASS CDS began to use the AIS 90 injury descriptions. In the analysis presented here, preliminary data for the first six months of 1993 were used. Not all of the quality control checks had been made on these data by the time this analysis was completed, and the final weightings will not be available until the full year data have been collected. Therefore the results reported here must be considered preliminary, and suitable only for an overall estimate of the problem.

Specifically, the NASS CDS data used here comprised those cases in the 1993 Half Year file where a person survived the injury, the age and gender were known, and for which there was a match with the FCI. A total of 3,401 cases met these criteria. An additional 25 cases did not meet the criteria either because the age or gender were unknown (7 cases) or there was not an FCI match (18 cases), and an additional 175 cases did not meet the criteria because the injured person died within 30 days of being injured.

When weighted to the national level, the 3,401 cases represented 857,999 injured persons during the six month period. A comparison of the six month files for the prior three years indicate that the six months data varied only slightly from half of the year's total. Therefore, all incidence values were multiplied by two to obtain the results reported here. The total incidence of police reported injuries in passenger vehicles during 1993 thus is estimated to be 1.7 million.

METHOD

Motor vehicle crashes typically result in multiple injuries, and as noted above, injuries with higher AIS values do not necessarily have higher FCI values. A SAS program was written to select the injury with the highest FCI for each injured person, similar in concept to the use of Maximum AIS values. If more than one injury had identical values of FCI, the injury was selected according to the following priority listing of body region: head, spine, lower extremity, upper extremity, abdomen, thorax, face, and integumentary. For the given age and gender of the injured person, the remaining life expectancy was determined from standard life tables (Statistical Abstract). The listing for the white population was used since neither race nor ethnicity are NASS CDS variables. The life expectancy was multiplied by the FCI to obtain the Life-Years Lost to Injury (LLI).

RESULTS

In order to estimate the consequences of injury from an overall societal viewpoint, it is necessary to consider how many people are injured, a description of their injuries, the long term effects of the particular injuries, and how long the person would be expected to experience those effects. The number of injuries are taken from the NASS CDS data; the long term effect from the FCI; and the length of time from the person's life expectancy. Since life expectancy is a function of the person's age and gender, both of these factors must be accounted for. These factors are considered in the following discussion of results.

Summary

Police reported towaway passenger car and light truck crashes in the U. S. during 1993 resulted in an estimated 1.7 million injuries. The overall average FCI for these injuries was 0.04, the overall average LLI was 1.4 years, and the total LLI was 2.4 million years.

Only 196,732 injuries (11.5% of the total), had an FCI value other than zero. For the injuries with a non-zero FCI, the average FCI was 0.31 and the average LLI was 12.2 years.

Incidence and FCI

The unweighted 6 months NASS CDS file for 1993 had 3,401 total cases, representing a total of 269 different injuries. Most of these injuries were infrequent; in 121 cases the injury occurred only a single time. Only five injuries occurred more than 100 times, and all of these were at the AIS 1 level with a zero FCI. Table 1 shows the number of people in the weighted data base for each range of FCI values. Although the lowest category shown is for 0-.09, these injuries actually had only a zero FCI. The lowest recorded FCI was .143.

Table 1
Incidence of Functional Capacity Index Values

FCI	Incidence	% of Total
0-.09	1519244	88.54
.10-.19	65960	3.84
.20-.29	56164	3.27
.30-.39	530	0.03
.40-.49	53268	3.10
.50-.59	302	0.02
.60-.69	16492	0.96
.70-.79	1172	0.07
.80-.89	1620	0.09
.90-.99	498	0.03
1.00	726	0.04

Age and Gender

Table 2 shows the variation of the average FCI with age.

Table 2
Functional Capacity Index Variation with Age

Age Group	Average FCI
00-04	.0046
05-09	.0017
10-14	.0162
15-19	.0248
20-24	.0359
25-29	.0399
30-34	.0361
35-39	.0203
40-44	.0269
45-49	.0658
50-54	.0210
55-59	.0155
60-64	.0456
65-69	.0215
70-74	.0146
75+	.1966

The average values of FCI are quite low, ranging from 0.002 for those in the 5 to 9 age cohort to 0.2 for those in the 75+ age cohort. The highest values of FCI are not found in the age cohorts with the highest incidence, the 15-29 year olds, but rather in the oldest age cohort, the 75+. The variation of FCI with age is not smooth, with unexplained peaks at the 45-49 age cohort and the 60-64 age cohort.

The variation of incidence with age is shown in Figure 1, and the distribution of LLI by age is shown in Figure 2. The stacked bars in Figures 1 and 2 show the totals for each 5 year age cohort. The line graph inset in Figure 2 shows the average LLI per injury as a function of age.

The average LLI varied from a low of 0.12 years for those in the 5 to 9 age cohort, to 2.0 for those in the 20-24 year age cohort.

The LLI attributable to females is greater than that for males for all ages except between 25 and 39, 45 to 49 and 70 to 75. The male:female ratio for the total LLI is 48:52, compared to a male:female incidence ratio of 52:48.

Injury Severity and Body Region

Table 3 shows the LLI for each body region and AIS injury severity level, and Table 4 shows that the distribution of incidence and LLI by injury severity are very different, with the largest portion of the incidence at the AIS 1 level and the largest portion of the total LLI at the AIS 2 level.

Table 4
Variation of Incidence and LLI with AIS Level

	Incidence	LLI
AIS 1	77	4 percent
AIS 2	16	66
AIS 3	4	22
AIS 4	2	3
AIS 5	0.2	5

There is a dramatic increase in the average LLI per injury as the AIS level increases, except at the AIS 4 level. See Table 5.

Table 5
Variation of Average LLI with AIS Level

AIS Level	Average LLI
AIS 1	0.08 years
AIS 2	5.6
AIS 3	7.4
AIS 4	1.7
AIS 5	40.2

Table 3
Life-Years Lost to Police Reported Motor Vehicle Injuries in the United States in 1993
by Body Region and Injury Severity

Region	AIS 1	AIS 2	AIS 3	AIS 4	AIS 5	Total
Head	0	65	0	35,120	124,791	159,976
Spine	0	2,782	3,980	12,409	3,770	22,941
Lower Extremity	9,206	876,400	352,200	0	0	1,238,806
Upper Extremity	9,850	673,600	160,022	0	0	843,472
Thorax	0	0	0	16,077	0	16,077
Face	82,540	18,198	9,692	0	0	110,430
Total	101,596	1,571,045	525,894	63,606	128,561	2,393,396

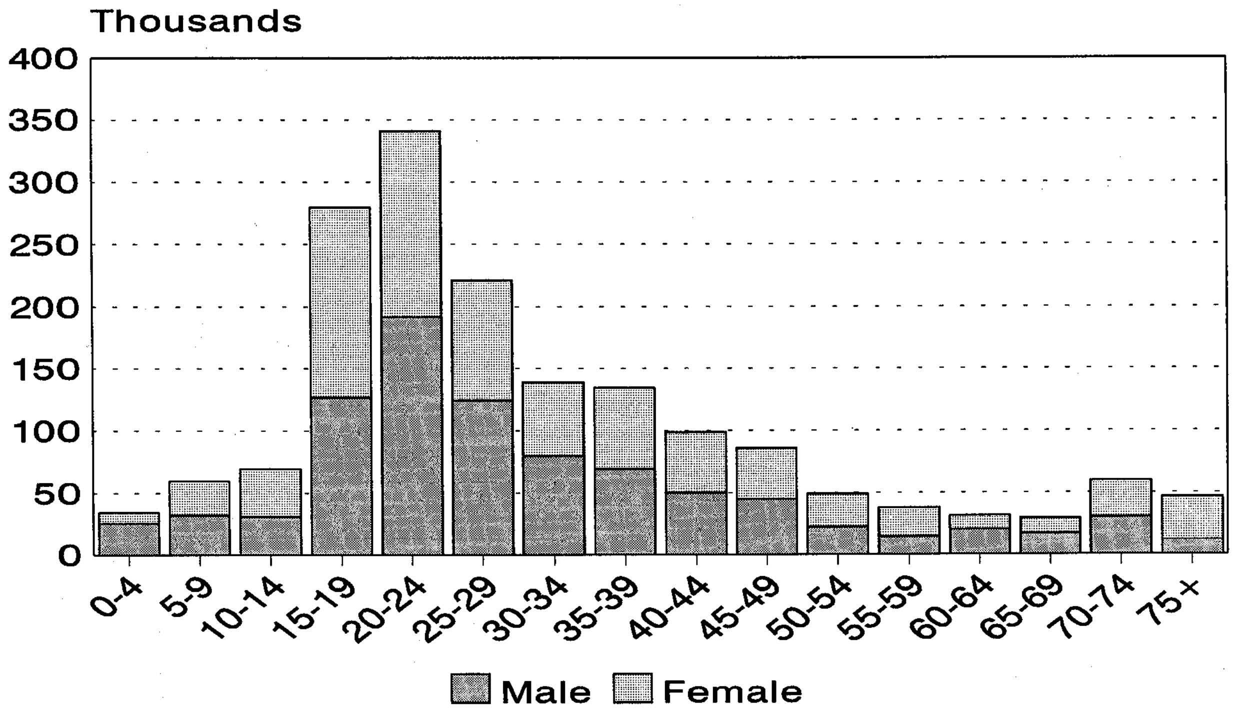


Figure 1 Incidence of Police Reported Motor Vehicle Injuries in the United States in 1993 by Age and Gender.

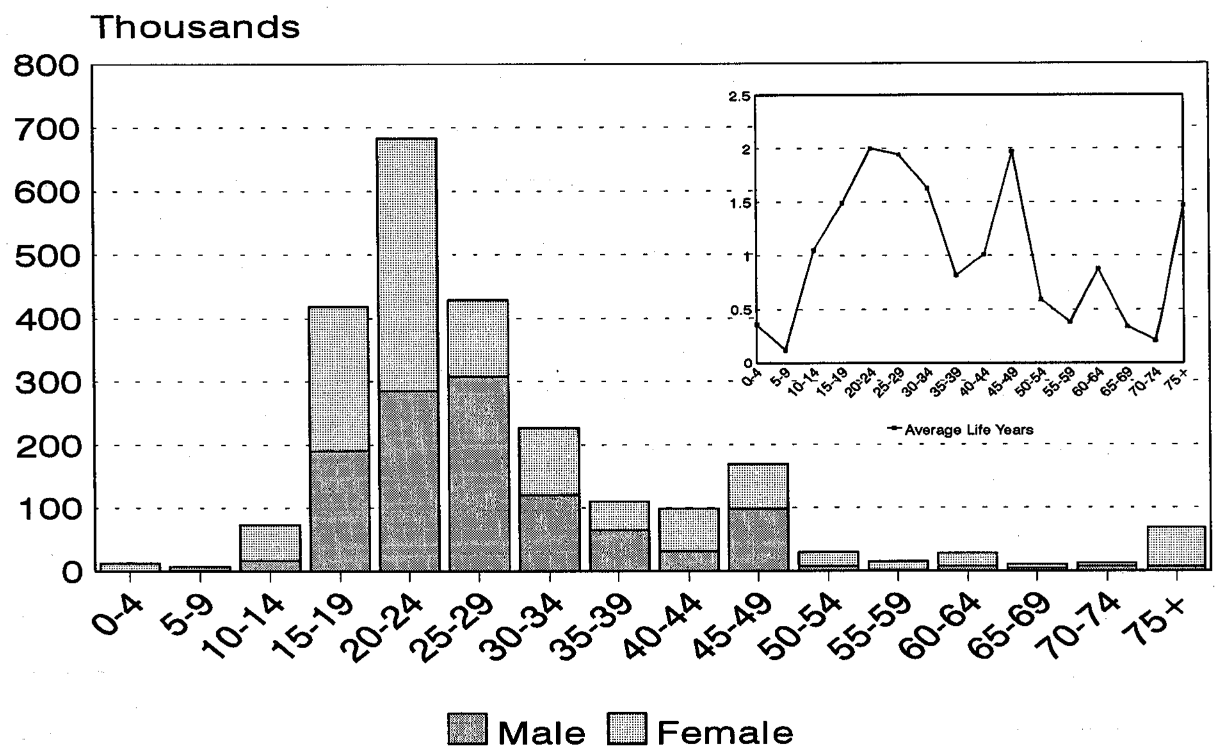


Figure 2 Life-Years Lost to Police Reported Motor Vehicle Injuries in the United States in 1993 by Age and Gender.

The distribution of incidence and LLI by body region is shown in Table 6, where the spine category includes neck injuries. Over 93 percent of the incidence of the spine injuries is at the AIS 1 level.

Table 6
Variation of Incidence and LLI by Body Region

	Incidence	LLI
Head	21.3	6.7 percent
Spine	19.2	1.0
Lower Extremity	30.0	51.8
Upper Extremity	13.6	35.3
Abdomen	1.6	<0.1
Thorax	2.2	0.7
Face	12.1	4.6

Another indicator of injury severity is the level of treatment received. Recall that since the NASS CDS data base focuses on the more severe crashes, the data are not typical of the entire crash spectrum. The relative number of persons who received no treatment, those transported to a hospital but released, and those admitted to the hospital are compared to the relative number of LLI in those categories in Table 7.

Table 7
Variation of LLI with Treatment Level

	Incidence	LLI
No Treatment	13%	<<1%
Transported	55	34
Admitted	25	64
Other	7	2

Other Considerations

Injured drivers comprised 66 percent of the total injured population and experienced 69 percent of the years of functional life lost.

Incidence and LLI for police reported restraint use are shown in Table 8. Restraint usage includes child seats.

Table 8
Variation of LLI with Restraint Usage

	Incidence	LLI
Restrained	59%	49%
Unrestrained	37	50
Unknown	4	2

Passenger car occupants comprised 74 percent of the total number of people injured, and their injuries resulted in 68 percent of the total LLI.

DISCUSSION

Limitations of the Analysis

The results presented here should be considered preliminary. The FCI values used in the analysis are those based on the judgment of an expert panel. There are plans to validate these estimates with clinical data now that the basic development of the index has been completed. Also, the data from the National Accident Sampling System used here are preliminary. Final quality checks may require some revisions of these data. Also, the weights used to develop the NASS CDS incidence are preliminary and only the final weights will be suitable for true national estimates. However, both the FCI and the NASS CDS Half Year file in their current state are judged to be useful for the purposes of this analysis.

Another limitation is that the FCI is not truly applicable to the youngest and oldest part of the population. Since the scale was developed as being applicable to the 18 to 50 year old population, the results for those in the 0-4 year old and 5-9 year old age cohorts cannot be considered accurate for those age groups. The effect of this limitation on total LLI is small, since the incidence for these age cohorts in small, 2 percent and 3.4 percent respectively. It is assumed that the results are reasonably reflective of the population from 10 to 65. There are plans to develop both a pediatric and geriatric version of this index in the future.

Age

The results shown here indicate that the common knowledge that motor vehicle injuries largely affect the young is even more true than can be deduced by looking at incidence alone. Three age cohorts, 15-19, 20-24, and 25-29, account for 64 percent of the total LLI but only 49 percent of the incidence. The 20 to 24 year old age cohort has the largest LLI value, 683,000, 28 percent of the total. This age group had 20 percent of the incidence.

The initial expectation was that the average LLI, that is the total LLI for an age cohort divided by the incidence, would decrease with age in a reasonably smooth fashion, since the life expectancy is greater for the younger population. The results do not support this hypothesis. Rather, there is a general uptrend until age 24, followed by an overall, albeit uneven, downtrend. After age 74 there appears to be another uptrend.

The results reported here do not support the initial hypothesis. On reflection, it is apparent that for the hypothesis to be true the injury pattern would have to be the same for all ages. That would result in the same FCI values. In that case, the total LLI would vary with incidence but the average LLI would vary with life expectancy. An examination of the injury pattern with age shows considerable variation of both incidence and LLI with respect to both AIS level and body region injured. This finding, although not central to the topic being treated here, bears further investigation. It is also possible that the "noise" in the average LLI pattern may be due to the small sample size.

Injury Severity and Body Region

As anticipated, the results show that injuries to the extremities comprise the bulk of the LLI, 87 percent of the total. Lower extremity AIS 2 injuries are the body-region/severity-level category with the greatest number of LLI, 37 percent of the total. This category also represents 56 percent of the total LLI at the AIS 2 level and 71 percent of the total LLI for lower extremity injuries. The LLI for the upper extremities were greater than expected. Unanticipated was the relatively low value of LLI for head injuries. These results will be reconsidered when the full year injury file becomes available.

Comparison with Fatality Data

A life-year lost to death (LLD) is not the same as a life-year lost to injury, however from the societal viewpoint, they have a similar effect. In order to determine the relative magnitude of the LLD, a similar calculation was made with the preliminary 1993 Fatal Accident Reporting System (FARS) data as with the NASS CDS data. The life expectancy was determined for those who died in motor vehicle crashes based on their age and gender. The result of this calculation shows that there were 1.6 million LLD, compared to the 2.4 million LLI. Of the total LLD, males contributed 67 percent. This is not a fully valid comparison, because the FARS data includes all motor vehicle related fatalities, whereas the 1993 NASS CDS data include only passenger vehicle injuries. Thus the relative magnitude of the LLI as compared to the LLD is greater than would appear from this calculation.

An investigation of the reasons for the lower than expected value of average LLI at the AIS 4 level reveals that a large number of those who received an AIS 4 injury died. Although the number of deaths recorded in the weighted CDS file do not agree with the FARS file, it is assumed here that the distribution by AIS is representative. With that assumption, the variation of AIS for those who died is shown in Table 9.

Table 9
AIS Level for Fatalities

AIS 1	9.4 percent
AIS 2	18.0
AIS 3	23.5
AIS 4	32.1
AIS 5	11.6
AIS 6	5.3

Thus it appears that the effect of the large number of AIS 4 deaths is seen in the LLD total rather than in the LLI total.

Comparison with Earlier Work

In a feasibility demonstration of the concept of quantifying the consequences of injuries in terms of reduced functioning, the author (1987) applied factors developed by Carsten and O'Day to an average of the 1982-1984 NASS data base. The results of that analysis were that 571,000 "impairment-years" were lost to AIS 2-5 injuries and 1.78 million were lost to fatality. The effect of AIS 1 injuries were a small part of the total.

Although the details of the methods vary, the basic concept is the same. The fatality life-years lost were calculated in the same way, with the only difference being that the 1987 estimate was based on 44,000 fatalities and the present calculation was based on 39,850 deaths. If the age pattern for fatalities were the same for the two different periods the expected number of life years lost to fatality would be 1.61 million. This agrees with the result found here.

A comparison of the 1987 results for injury with the present work show considerable difference in both the total and the distribution. The current estimate at 2.4 million compares to the 0.6 million found earlier. The distribution of impairment-years in the earlier work was AIS 2 = 12.6%, AIS 3 = 32.7%, AIS 4 = 13.2% and AIS 5 = 41.5%. Also, the earlier work showed the head, face and neck total impairment-years to be 67.9 percent of the total.

There could be a number of reasons for the differences between these two estimates. These include that the AIS 80 injury descriptions do not match the AIS 90 descriptions, that the Carsten factors were significantly different than those used in the present analysis, and that the injury pattern is different between the early 1980's and 1993. The vehicle fleet is also known to be different in 1993 than in the early 1980's, and restraint use is considerably different. These factors could account for the large head injury component in the earlier work and the large lower extremity component in the present work. If both analyses are reasonably accurate, the indication is that the long term consequences of injuries are greater today than they were ten years ago.

CONCLUSION

The Functional Capacity Index (FCI) is being developed as a way to quantify the long term reductions in functional capacity experienced by survivors of motor vehicle injuries. This paper reports on the application of the index to the injury data contained in the six month file of the National Accident Sampling System Crashworthiness Data System (NASS CDS) for 1993 and extrapolated to full year values. The 1993 data base is the initial application of the AIS 90 injury definitions in the NASS CDS.

The results of the analysis are expressed in terms of Life-years of full functioning Lost as a result of the Injury (LLI). These are obtained by multiplying the FCI values for each injury by the life expectancy of those injured based on their age and gender. For cases with multiple injuries, the injury with the maximum FCI was counted.

The results demonstrate that the FCI can be applied to the AIS 90 injury definitions with conventional programming techniques.

A total of 2.4 million LLI are estimated for those who survived injuries received during 1993 as a result of police reported crashes of passenger cars and light trucks in which one of the vehicles were towed.

The results show that in 1993 the pattern of incidence of motor vehicle injury with respect to age is as it has been in prior years - a sharp peak between the 15 to 29 year old population, followed by a slow decrease to age 50, a relatively flat portion until age 70 followed by another rise. The pattern of LLI with respect to age is similar to the incidence pattern but even more pronounced. The LLI for ages 15-29 account for 64 percent of the total LLI but only 49 percent of the incidence. The results also show that the life years lost to injury increases after age 75. Although not the topic of this paper, it appears that the injury pattern varies with age, both as far as AIS level and body region injured.

Females have a slightly higher LLI than expected based on their incidence, and have a greater percentage of the total LLI for a number of age cohorts.

Injuries to the upper and lower extremities, comprise 87 percent of the total LLI. The LLI for lower extremity injuries at the AIS 2 level are in a class by themselves, with 37 percent of the total.

The average LLI per injury increases dramatically with injury severity level as measured by the AIS, from less than 0.1 year at the AIS 1 level to over 40 years at the AIS 5 level. This pattern does not hold for AIS 4 level injuries, possibly due to the high percentage of fatalities with AIS 4 injuries.

The LLI of drivers, occupants of light trucks, unrestrained occupants and those with injuries serious enough to be hospitalized are overrepresented compared to their incidence.

ACKNOWLEDGMENT

Marie Walz prepared the SAS programs to extract the data from the National Accident Sampling System. Ruth Isenberg made a number of valuable suggestions.

DISCLAIMER

The opinions advanced in this paper are those of the author and do not necessarily reflect the policy of the National Highway Traffic Safety Administration.

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Impairment pattern in passenger car crashes, a follow-up of injuries resulting in long-term consequences.

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ABSTRACT

The immediate diagnosis following road accident trauma is the main source for assessing the severity and coding of injuries. The long term consequences are increasingly more focused, but still, methods for assessing impairment are rare. This seems to be a problem as the impairment pattern is quite different from the injury pattern at the scene of the accident or immediately after. This results in a different interest in injury prevention for different body areas and severities, depending when the judgement is made.

In this paper the impairment pattern for road accident injuries 1-5 years after the accident is identified. Different levels of impairment have been recorded as well as the type of road users.

Moreover, the impairment pattern was found to be unique for different types of road users as well as for different ages. It is also obvious that the impairment risk is focused around a few diagnoses. The result can be used for formulating what future priorities that should be set up in the field of crash protection for car occupants as well as for unprotected road users.

INTRODUCTION

There is an increasing interest in assessing impairment, disability and handicap due to injuries occurring in road traffic accidents. Such injuries are costly to society and injuries causing severe permanent disability need to be i dentified to assign priorities for injury control research and intervention programs.

There are several ways to classify injuries. The Abbreviated Injury Scale (AIS) (1) is one of the most commonly used but, basically only mesasures the fatality risk.Also the ICD (2) scale is used for describing the injuries. The scaling is done in close connection to the trauma occurence. In addition, there are scales that take into account the entire injury sequence in terms of the cost to society, etc., such as the Injury Cost Scale (ICS)(3) and "Harm"(4). The predictiton of long-term consequences of injuries has presented a more difficult problem because more variables are involved (5). For this reason, the development of a scale that could cover most, if not all, variables has been eagerly awaited. The Injury Impairment Scale (IIS)(6,8) was developed in an attempt to fulfill this need by rating individual diagnoses and their associated impairment risk from the AIS. However, the validity of IIS is already being qestioned (7).

There are three different types of long-term consequences that have been formulated (9):

Impairment is the loss of function or abnormal function of an organ, tissue or organ system resulting after healing has occurred.

Disability is the effect or consequence of an impairment on a person that restricts the individual from performing at or near the pre-injury capability. Age, education, family and community support, personal financial resources, the availabilty of rehabilitation programs, and pre-existing conditions are determinants of disability relative to impairment.

Handicap is social dysfunction that is the total disadvantage resulting from impairment and disability causing impaired performance at the cultural, social level.

This paper will only focus the level of **impairment.**

The aim of the study was to:

- Reflect the impairment pattern for road accident injuries and type of road users.
- To identify some injuries that cause medical impairment more often than others.

MATERIAL AND METHOD

In Sweden all traffic injury victims with 10% medical injury or more, after a certain period of time, have their injuries judged by a special committee in which all insurance companies are represented. One criterion for having the injuries judged by this committee is that the medical impairment is claimed to be 10% or more. If the expected level of disability is below 10% , the case is handled by the individual insurance company. All jugements and associated diagnoses are gathered in a book (10) with the level of impairment for each diagnosis. Normally the degree of medical disability is not permanently settled until 3-5 years after the accident. A preliminary degree is settled around one year after the accident.

The criteria for determining the extent of the medical impairment are related to the loss of function, pain, and/or mental dysfunction. There should not be any relation to the patient's occupation or social situation. The economic compensation is not primarily linked to the level of disability.

Examples of medical impairment degree:

	Medical impairment
- Completely blind	100%
- Quadriplegia	100%
- Paraplegia	100%
- Loss of one hand	
the better hand	60-65%
the poorer hand	50-55%
- Cerebri contusion (AIS 2)	5-35%
- Instability after ligament injury (lower extremities).	5-25%
- Total loss of function of nervus medianus.	40%
- Neck strain (in separate cases higher)	5-15%
- Amputation of outer phalang of ring-finger	2%

In this study 2 384 injuries that resulted in a medical impairment, have been mapped from 1990-92 claims-settlement. All the diagnoses have also been coded according to AIS-90.

RESULTS

Table 1-3. The impairment pattern for different body regions among car occupants by age. Drivers, front seat passanger and rear seat passenger (%).

Drivers	-29 year %	30-49 year %	50- year %
Skull/Brain	6,7	3,6	5,7
Neck	57,6	63,5	52,7
Lower extr.	17,0	17,9	17,5
Upper extr.	9,3	8,9	14,4
Thoraco-lumbar	9,3	6,1	9,7
	n=590	n=641	n=402

Frontseat-passenger	-29 year %	30-49 year %	50- year %
Skull/Brain	10,7	5,4	3,8
Neck	42,0	60,1	38,6
Lower extr.	22,0	11,8	16,4
Upper extr.	12,0	12,5	22,2
Thoraco-lumbar	13,3	10,2	19,0
	n=150	n=128	n=158

Rearseat-passenger	-29 year %	30-49 year %	50- year %
Skull/Brain	12,0	7,5	2,6
Neck	41,0	42,5	26,3
Lower extr.	25,3	15,0	29,0
Upper extr.	8,4	15,0	26,3
Thoraco-lumbar	13,3	20,0	15,8
	n=83	n=40	n=38

There are only few consistent correlations between age and the relative proportions of impairment, mainly related to the skull/brain (fsp, rsp) and upper extremities. This does not indicate that there is no overall relationship between age and impairment, but merely that for most body areas, the relation is constant, except for the skull/brain and the upper extremities. The neck is the most common body area that result in a medical impairment in all age groups except the rear seat passenger 50- year.

Nygren (11) used the same method of describing the injury pattern from the claims-settlement 1976-78. A comparison between the two different impairment distributions is shown below.

Table 4. The distribution of medical impairment, 10% or more, among different body areas ≥ 10% from 1976-78 and 1990-92

Body area	1976-1978 %	1990-1992 %
Skull/ brain	11.4	11.2
Neck	19.2	46.9
Facial	5.4	0.7
Eye/ teeth	3.4	0.4
Upper extr.	14.8	9.4
Lower extr.	24.9	19.9
Chest	9.2	0.7
Abdomen	2.4	0.4
Pelvic	2.1	2.3
Thoraco-lumbar spine	7.3	8.0
	n=535	n=733

The table shows that the amount of impaired necks is much higher in the group that was settled between 1990 and 1992 primarily due to an increase of neck strain. The chest injuries seems to have decreased since the earlier settlement. This is also true for facial injuries including injuries to the teeth and the eyes.

Of all injuries settled 1990-92 that received a medical impairment of 10% or more, the body area neck represented 47% (92% of these were neck strain diagnosis), while nearly 20% was from the lower extremities and 11% from skull/ brain injuries.

Table 5. The ten most common injuries causing medical impairment 1% or more and 10% or more (n).

Medical impairment ≥ 1%	Medical impairment ≥10%
1. Neck strain (1155)	1. Neck strain (309)
2. Lumbar spine fract./ disloc.(80)	2. Lumbar spine fract/disloc. (26)
3. Lumbar strain (77)	3. Tibia fracture (24)
4. Lower Extr. contusion (75)	4.Ankle fracture (22)
	5. Cervical spine fracture (21)
5. Thoracic spine fracture/ disloc. (57)	6. Cerebr. hematoma subdural (19)
6. Upper Extr. contusion (50)	7. Hip diloc. (18)

	8. Femur shaft fracture (17)
7. Cervical spine fracture (49)	9. Thoracic spine (15)
8. Tibia fracture (47)	10.Patella fracture (14)
9. Commotio cerebri (44)	10.Malleolus fracture (14)
10.Ankle facture (42)	t
10.Femur shaft fracture (37)	

Even when one examines impairment at ≥1% or ≥10% the diagnosis neck strain is clearly the most common injury. One difference between the groups is that diagnoses rated AIS 1 disappear from the list of the ten most common medical impairments ≥10% except the neck strain injuries. Also, there are two new injuries that appear on the ≥10% list, hip dislocation and subdural hematoma.

Table 6. The relationship between injuries that received different levels of medical impairment and diagnoses rated according to AIS.

n=2 384

Med. impairm.	AIS 1	AIS 2	AIS 3	AIS 4	AIS 5
1-9%	1114	338	194	7	-
10-14%	188	61	55	2	-
15-19%	143	59	46	3	-
20-29%	25	29	32	4	1
30-99%	2	10	17	19	6
100%	-	-	6	9	14
S:a %	61.8	20.8	14.7	1.8	0.9

The table shows the injuries that receieved different levels of medical impairment and their distribution on respectivly AIS score. While the levels of medical impairment varied substantially, the AIS scores were mostly 1 to 3 (97,3%). Nearly 62% of the injuries with medical impairment were rated as AIS 1. Of all injuries that were rated AIS 1, it was 11.5% that receieved a medical impairment 15% or more. Half of the cases with the level 1-9 % and AIS 1, had a neck strain diagonosis.

Earlier studies (12,13) have shown the relationship between risk of impairment and age. Table 7 shows that there were big differences in impairment risk due to age. Not overall though, some diagnoses do not vary in the impairment risk (e.g the injury neck sprain , see table 8).

Table 7. Medical impairment pattern of hip and femur fracture, AIS 2-3.

Med. imp.	Total %	-39 year %	40- year %
-5%	40.0	51.1	27.9
6-9%	12.2	14.9	9.3
10-14%	12.2	10.6	14.0
15-19%	12.2	12.8	11.6
20- %	23.3	10.7	37.2
	n=90	n=47	n=43

Table 7 shows that the level of medical impairment concerning hip and femur fractures (AIS 2-3), is highly dependent on age. In the younger group, up to 39 years of age, over 50% had ≤ 5% medical impairment, but only 28% in the elderly group, 40 years and older. There were more people in the elderly group who had a level of impairment of ≥20% than in the younger group, 37% compared to 11%.

Table 8. Medical impairment pattern of neck sprain, AIS 1.

Medical impairment	Total %	-39 year %	40- year %
-5%	57.8	58.8	56.6
6-9%	16.1	15.0	17.4
10%	13.4	15.6	10.7
11-19%	11.4	9.4	13.6
20- %	1.4	1.2	1.7
	n=1049	n=572	n=477

In table 8 it can be seen that the age factor for a neck sprain diagnosis does not vary to any great extent. In both groups, the percentage of moderate impairments (10% or more) was more than 25%.

In the figures 1-2 below, the impairment pattern for different diagnosis is presented.

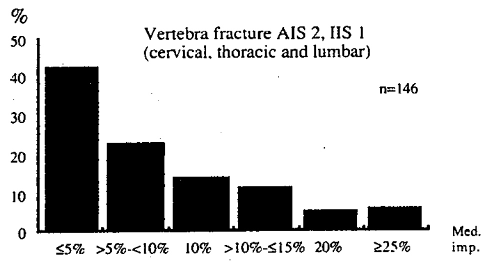

Figure 1. The medical impairment pattern for spine fracture.

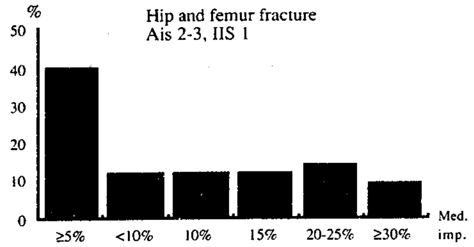

Figure 2. The medical impairment pattern for hip and femur fracture.

In figures 1-2, the impairment pattern for different injuries is shown. The level of medical impairment is very spread out.

DISCUSSION

The outcome of a traffic accident can be described in many different ways, number of fatalities, injured, costs, impaired, loss of health, etc. There are some scales that describe different diagnoses and their severity on short term basis. The most used and well documented is AIS but it is basically addressing the fatality risk. Regarding long-term consequences, there is no universally accepted way to link the diagnosis to the outcome. Some studies have attempted to use AIS to predict long-term consequences, but it has been found that this is not possible. For instance, there are some injuries that have a low AIS ranking, but often lead to impairment. Such injuries may be considered to be of less importance than other injuries, if only using AIS.

Long-term consequences togheter with fatalities can be considered to be the most important field for prevention. Therefore it must be considered to be of importance to construct and use scales that adequately describe, assess and predict long-term consequences.

The long-term consequenses can be described in many ways. They can be described as a loss of a bodily function, loss of ability to work or function in society, or as the loss of the total health, both the functional as well as the bodily fitness and medical health. It has been shown that there is a relation between an incapacitating injury and physical fitness as measured by body weight, blood pressure, plasma lipids, etc(14). These parameters are known to influence the risk of morbidity and mortality and this should be taken into consideration.

The newly developed Injury Impairment Scale (IIS) is rating individual diagnoses and their impairment risk from AIS. However, when comparing the IIS and AIS scales (9) it was found, that there was a high correlation between AIS and IIS scores, despite the fact that AIS has been considered to be a poor predictor of impairment. The IIS, as it is currently structured, does not seem adequately predict real life long-term consequences.

In this study an information from an insurance company was used. All injuries that had some long-term consequenses have been judged according to the guidelines in a national manual in which injuries are identified on a scale ranging from 1-100% of medical impairment. This material has been used for several recent studies and was also the basis for a specific scale for predicting the risk of serious consequenses from injuries (RSC) (15).

The relationship between injuries that received different levels of medical impairment and diagnoses rated according to AIS, showed that 97.3% had AIS 1-3. Of all injuries that were rated AIS 1, it was 11.5% that recieved a medical impairment 15% or more.

The impairments for different injuries are mostly spread over several outcome levels, and impairment are in some cases related to age and other cases it is not. IIS tries to summarize the levels into one score and the IIS is based on the most probable outcome for individuals of age 25-30 years.

Of all injuries in this study that received a medical impairment 10% or more, the neck strain diagnosis represented 47%. Nearly 20% was from the lower extremities and 11% from skull/ brain injuries.

From these findings, it is apparent that an impairment scale must be able to assess initial minor injuries, to have a sufficient resolution also for minor to moderate impairments, and properly take into account the age factor.

CONCLUSIONS

- The neck strain diagnosis is the injury that cause most impairment, followed by fractures from lower extremities and injuries from skull/ brain.

- The level of impairment are, even for one diagnosis, spreed over several severities and related to age.

- An impairment scale must have a sufficient resolution for minor to moderate impairments.

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How Drivers Sit in Cars

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Paper No. 94 S5 O 03

ABSTRACT

This paper presents results from a study to measure the separation of the driver's head and shoulder to various internal features of the car. Drivers were filmed whilst driving in general traffic flow, hence were unaware that they were involved in a study. The results show that certain sub-groups of the driver population are likely to be more at risk for certain impact types. Small females are considerably closer to the steering wheel than the rest of the population, and therefore prone to head strikes in frontal impacts. Large males are likely to interact with the cant rail and 'B' pillar in side impacts.

INTRODUCTION

Much design work related to crash performance is predicted on the initial sitting positions of current crash test dummies. In-depth crash reconstruction aimed at evaluating seat belts, steering wheel design and airbag performance is similarly based on assumptions about sitting position and the posture of drivers. Several studies have attempted to quantify how drivers actually sit in cars, but these have generally been laboratory based, and therefore not necessarily representative of the real-world driver population under real-world driving conditions. The data used to position dummies in the current crash tests came from a National Highway Traffic Safety Administration (NHTSA) sponsored study at The University of Michigan Transportation Research Institute (UMTRI) (Robbins et al 1983) in which the subjects were seated in a 'Standardised driving posture', with the seat back angle fixed. The subjects were asked to sit upright, with their back pressed against the seat. In a study to determine the driver's eye position, Meldrum measured subjects seated in actual vehicles, but under simulated driving conditions, placing the vehicle in front of a large street scene mural. The data from this work lead to the driver's field of vision standard Society of Automotive Engineers (SAE) J941.

Other studies have attempted to measure drivers during, or after, driving. Schneider et al (1979) compared driver anthropometry in non-driving and after-driving conditions, and found little overall differences in the two situations. This study, however, took no account of seated posture. A study at Jaguar Cars by Wankling measured the driver's eye position under actual driving conditions, using an electromagnetic sensor, but no firm conclusions were reached due to the small sample size. In a recent study, Schneider compared measured driver eye position to SAE J941, from a sample of 50 subjects and 6 vehicles <u>after</u> driving on a short test track.

This paper will present results from drivers, driving their own cars, under actual driving conditions, without the subjects being aware that they are being involved in a study.

METHODOLOGY

Drivers were filmed using a video camera equipped with a high speed shutter as they passed a white screen. Three separate locations were used, with the camera being out of sight of the drivers. The camera was pointed at right angles to the traffic flow, facing the screen, as shown in Figure 1.

Hence, the drivers were silhouetted against the background. The camera was able to capture the image of the vehicle and driver, even when the vehicle was travelling at around 30 miles per hour. The camera height was set at mid side window height for an average vehicle, and filming took place at between 15 and 20 metres from the

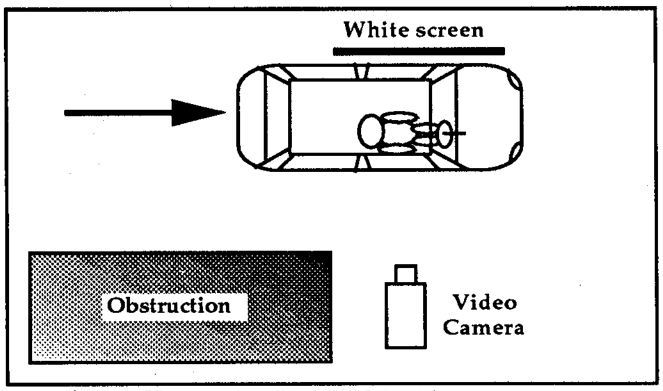

Figure 1. Unobtrusive filming of the drivers.

subjects. The angle from the camera to mid side window and top of the side window was therefore very small, and so parallax was not considered to unduly affect results. The video was played back and measurements taken from a television monitor. Figure 2 shows which measurements were taken: nasion (junction of the forehead and nose) to the steering wheel top (A-B), and to the top of the side window (A-D); the centre of the shoulder to the centre of the 'B' pillar (I-J); and front or back of the head (whichever was in view) to the centre of the head restraint (A or G-H). The 'B' pillar height was measured and used as a scaling factor for all the measurements when compared to the known height of the 'B' pillar. A correction factor was also applied, as explained later in the paper.

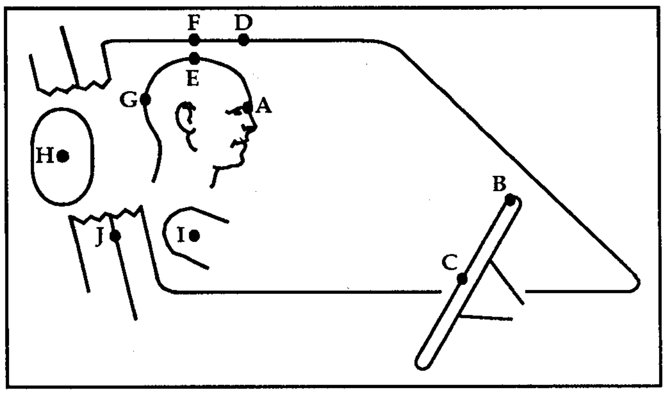

Figure 2 . Measurements taken of the driver to the vehicle.

After the measurements were scaled and corrected, they were converted to the following dimensions: nasion to steering wheel centre (horizontal, vertical and direct; A-C); top of head to top of side window (vertical; E-F); back of head to centre of head restraint (horizontal and vertical; G-H); and centre of shoulder to centre of 'B' pillar (horizontal, I-J). The measurements to the top of the side window and the centre of the head restraint required anthropometric data to shift the originally measured point on the head to the required point on the head (A-E, and A-G).

CALIBRATION

In order to calibrate the system, five subjects of varying age, sex and stature were filmed in two different car types from a number of filming distances. The driver's head was fixed in a stable position using the car's head restraint. The actual forehead to steering wheel separation was measured and then compared with measurements taken from five filming distances, both static and dynamic. In the dynamic condition, the car was driven at between 15 and 20 miles per hour. Results indicated that the on-screen measurements were all between 1 and 11% greater than the actual measurements. A correction factor of -6% was therefore applied to all subsequent measurements making them accurate to within +/- 5%.

SAMPLE

19 car models were chosen based on the most popular models from 7 manufacturers. 3 of the manufacturers had most of their range in the sample, from the smallest to the largest model (the cars sampled are shown in Table 3). The car sample was thus thought to reasonably represent the general car population in terms of size and weight. As each of the sample vehicles passed the camera in the general traffic flow, the measurements were recorded. In this way the driver population generated itself, and was completely random. 1000 readings were taken. The following tables show how the driver and vehicle population was comprised. In the age category 'Young' means the driver looked to be below 35 years old; 'Middle', the driver appeared to be aged 35-55; 'Old', the driver looked to be aged over 55.

Table 1
Vehicle population by make and model

Make and Model	Number
Citroen BX	26
Ford Fiesta MK3	49
Ford Escort MK3	94
Ford Escort MK4	58
Ford Sierra	148
Ford Granada	21
Peugeot 205	47
Peugeot 405	33
Rover Metro	38
Rover 200	69
Rover Montego	96
Rover 800	24
Vauxhall Nova	47
Vauxhall Astra	81
Vauxhall Cavalier	63
Vauxhall Carlton	17
Volvo 760	19
Volkswagen Polo	39
Volkswagen Golf	31
Total	**1000**

Table 2
Vehicle population by wheelbase and size

Wheelbase (m)	Crash3 size	Number
2.05 - 2.40	1	218
2.41 - 2.58	2	432
2.59 - 2.80	3	350
Total	-	**1000**

Table 3
Driver population by sex

Sex	Number	Percent
Male	742	75.8
Female	237	24.2
Not known	21	-
Total	1000	100.0

Table 4
Driver population by age

Age	Number	Percent
Young	315	32.9
Middle	564	58.9
Old	78	8.2
Not known	43	-
Total	1000	100.0

The majority of the driver sample was male (75%) and aged between 35 and 55 (60%).

RESULTS

The following graphs are the plotted results for each of the measurements taken. For each graph the sample is plotted as a whole, and also split by sex. Each sub-group has the following percentiles plotted: 1, 5, 25, 50, 75, 95, 99. It should be noted that each percentile plotted is the percentile within the measurements and does not necessarily represent the overall population percentile. Hence, when the paper quotes '50%ile male' it means the 50%ile measurement of the male sample, not the measurement that occurs with the 50%ile male.

Nasion to steering wheel centre

The following figures show the distance from the nasion (junction of the forehead and the bridge of the nose). Figures 3, 4, and 5 are the horizontal, vertical, and direct distances respectively.

Figure 5 shows that females are considerably closer to the steering wheel than males.

At the 50%ile level, females are 6.2cm (2.5") closer than the males. The difference between 5%ile female and 95%ile male is 21.5cm (8.5"). 15% of the female population are closer than 40cm (15.7") to the steering wheel.

We looked at whether the 'Old' driver population was closer to the steering wheel than the rest of our sample. We found that they were, but only by 1 cm. The 'Old' driver population was compared to the 'Young' plus 'Middle' population for their proximity to the steering wheel centre, horizontally, vertically, and directly, and by sex. In almost all the cases the 'Old' group at all percentile levels were approximately 1.0 cm closer than the 'Young' plus 'Middle' group. This is possibly explained by virtue of the reduced stature of the older generation, but is equally explained by the error band of the measurements of +/- 5%, and cannot, therefore, be said to be significant. The 'Old' group is defined (arbitrarily) as looking over 55 years of age, is not particularly old. The onset of increased thoracic spine curvature does not become especially marked until age 70 or so, and thus our definition was unlikely to pick out this factor clearly.

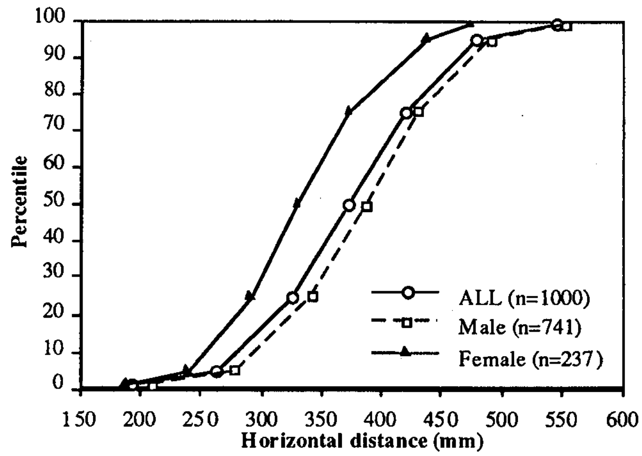

Figure 3. Nasion to steering wheel centre (horizontal).

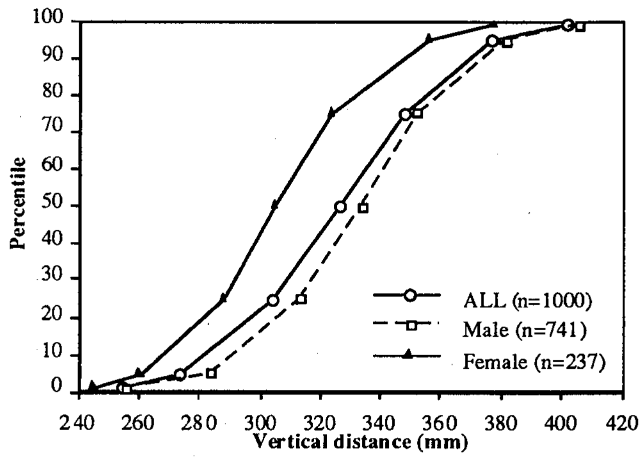

Figure 4. Nasion to steering wheel centre (vertical).

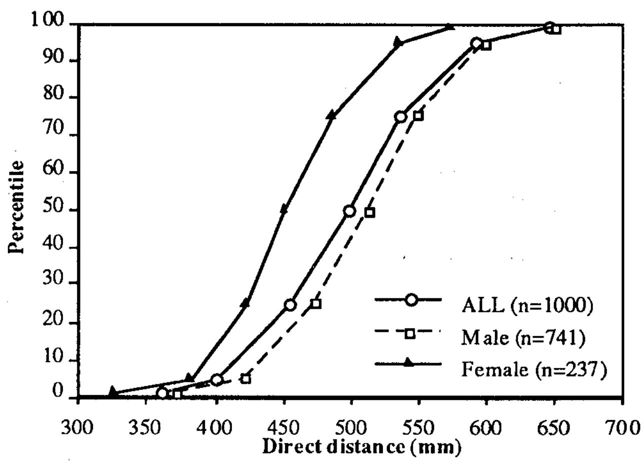

Figure 5. Nasion to steering wheel centre (direct).

Top of head to top of side window

Figure 6 shows that only a small proportion of the driver population has the top of their head level with or above the top of the side window, and hence the start of the metal structures at roof level. Males are considerably more at risk from a head strike with metal during a lateral impact than females (14.6% compared to 2.6%). More than 1/10th (11.7%) of the whole driver population is similarly exposed.

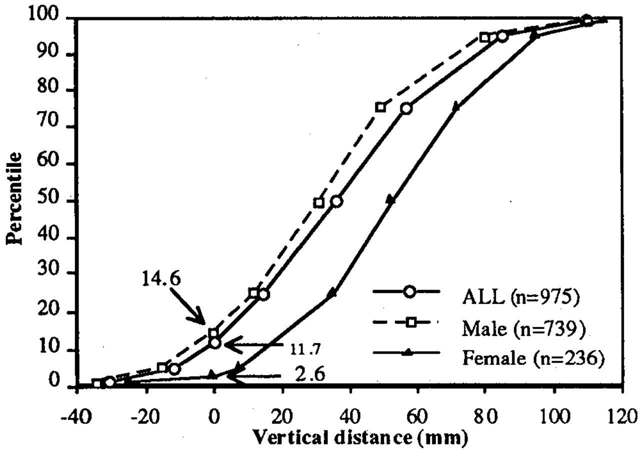

Figure 6. Top of head to start of metal structures (vertical).

Back of head to centre of head restraint

Very little difference is apparent between the horizontal separation of the back of the head to the centre of the head restraint for males and females. 50% of the population were

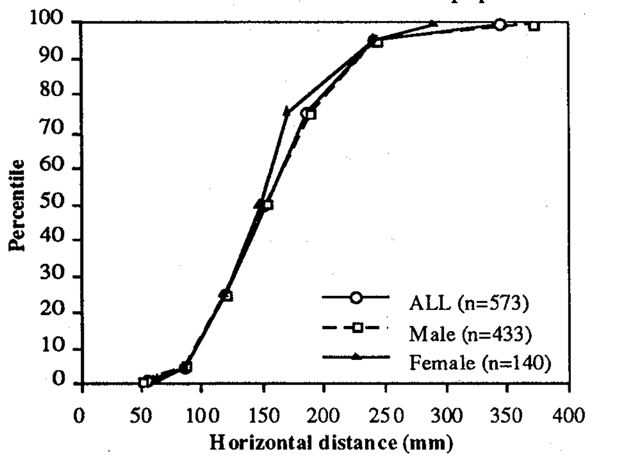

Figure 7. Back of head to centre of head restraint (horizontal).

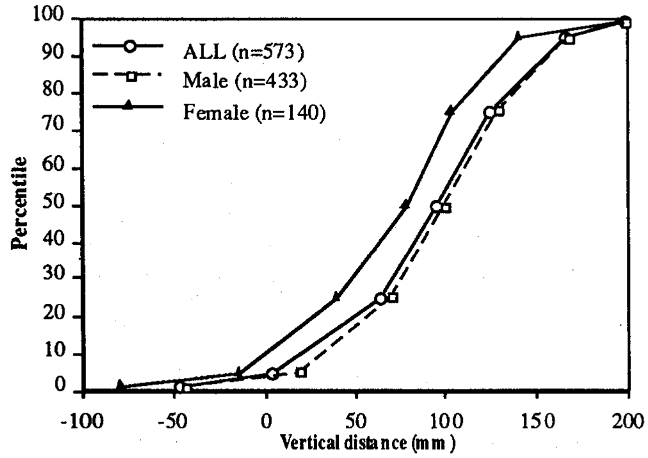

Figure 8. Back of head to centre of head restraint (vertical).

15.1cm (5.9") or more from the head restraint, horizontally.

The optimum vertical position of the head restraint is for the centre of the head restraint to be level with the centre of the back of the head. The great majority of the drivers had their head restraint set too low, with only 5% of the drivers at or above this level. Some 50% of the population had the head restraint 10cm (4") or more below the centre of the head, probably representing a particularly high risk condition for a rear end collision.

Centre of the shoulder to the centre of the 'B' pillar

Only male shoulders are likely to interact with the 'B' pillar in a purely lateral impact, as illustrated in Figure 9. Only 1% of the males had the centre of their shoulder directly in line with or behind the centre of the 'B' pillar. The number of males who had the back of their shoulder level with the leading edge of the 'B' pillar is clearly dependent on the average width of the large male shoulder, and the 'B' pillar at shoulder height. If these figures are taken to be 11cm (4.3") and 8cm (3.1") respectively, then 25% of the males will interact with the 'B' pillar in a purely lateral impact.

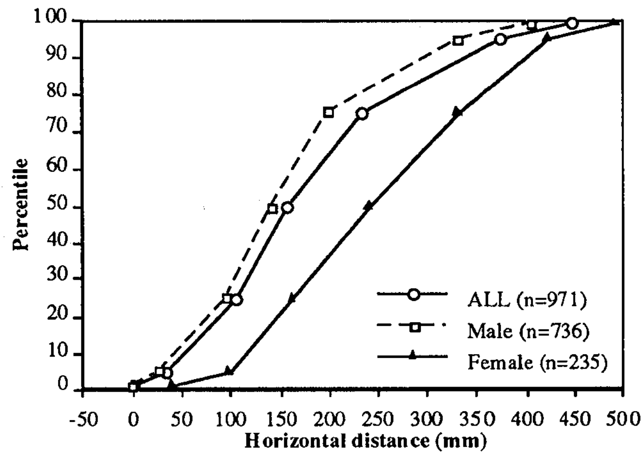

Figure 9. Centre of shoulder to centre of 'B' pillar (horizontal).

COMPARISON OF THIS STUDY'S DATA WITH CRASH TEST DUMMY POSITIONING

Figure 10 shows the 5%ile female, 50%ile and 95%ile male positions relative to the steering wheel, top of side window and centre of 'B' pillar, as illustrated earlier in the paper. The nasion (junction of forehead and nose) position of the three equivalent Hybrid III crash test dummies is included for comparison, and is shown as a dot. The data for the dummy positions was extracted from a study by Bacon (1989) in which top of head trajectories were measured for the dummies during frontal impacts in a current model car. In that study the centre position of the driver's seat was used for all the dummies. The vertical position of the nasion was scaled from a figure within the paper for each dummy, with the measurements being taken from the steering wheel centre. The horizontal position was scaled as above, using the 50%ile male dummy position, and assuming a standard fore-aft adjustment of 20cm for the driver's seat, and that the posture of all three dummies was the same, that is, the seat back angle was constant. In all three cases the dummy positioning is further from the steering wheel than the 5%ile female, 50%ile and 95%ile measurements observed in this study. The differences were greatest for the small female at

9.2cm (3.6") but were also significant for the other two dummies at 4.7cm (1.9") and 4cm (1.6") respectively. It is likely that these differences in the context of the results of crash tests would have a profound influence on assessing head injury risk to the population actually exposed.

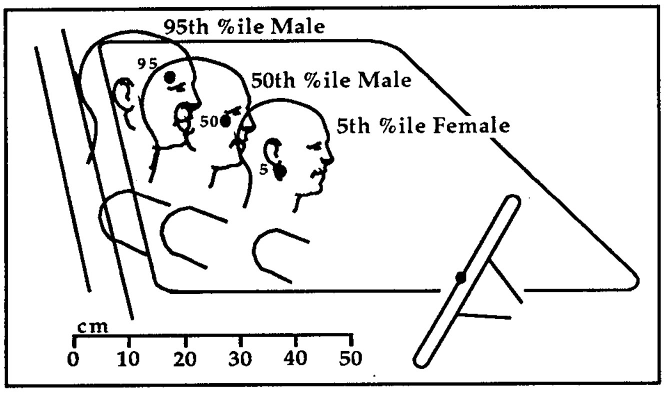

Figure 10. Crash test dummy nasion position compared to observed driver positions (black dots are the dummy nasion positions).

DISCUSSION

The main current crash performance standards are, in essence, predicted on single-point global crash tests, as specified under Federal Motor Vehicle Safety Standards (FMVSS) 208 and 214, using 50%ile male dummies. In actuality, however, the car designer is faced with the problem of optimising protection for two populations. The first population is that of the collisions, with many occurring at relatively low speeds, but having a skewed distribution, leading to a tail of collisions at higher severity (Ricci 1980). The second population is that of the actual people sitting in cars. Surprisingly little attention has been directed at the characteristics of this second population.

Many insights have been provided into variations into biomechanical response to impact forces, which reflect the population at risk, but in the context of restraint system design, side impact protection and rear end collision performance, the simple question of size, initial sitting position and posture can have a profound effect on how the car should be designed for optimum protection.

Thus, this research program. We limited our observations and analysis to the most popular, mainstream cars on European roads. We thus excluded sports cars, utility vehicles and vans, which probably have their own specific characteristics relating to driving positions. We examined literature which describes the anthropometry of the British, North American and other populations which have been surveyed adequately. Broadly speaking, these differences, with the exception of the Japanese, who tend to be shorter stature and have long torsos in relation to leg length, are not great. The North American population is slightly taller than the European, and has an incidence of obesity which is two to four times greater. With these reservations, however, it is likely that our results have general applicability.

There is also the question of how representative the 19 models of cars are of other vehicle populations. It is commonly suggested that a straight arm driving position modelled after Grand Prix cars (making it like Nuvoarli) is a fashionable posture, at least for the young male European driver. This may be an element, but our results indicate a significant proportion of drivers in fact sitting especially close to the steering wheel, particularly females. Only a quarter of our driving population was female, in North America the proportion is about one third or higher.

With airbag technology, sitting closer than the design position to the steering wheel carries risk of increased injury to the brain, neck and chest, especially with the large volume North American bag needed to meet FMVSS 208 passive requirements. The data in this study may well be useful to the designer, therefore, in optimising specific designs to minimise the conflicting requirements of the various elements within the population. It suggests that the ultimate 'smart' restraint system would be programmed for the sex and age of the occupant.

When the crash begins to occur it would monitor both the crash severity and the sitting position of the occupant, and time the airbag deployment and seat belt tension for optimum protection of that particular occupant in that particular crash.

For lateral collisions our results suggest that interior head contacts with the side roof rail are relatively uncommon, as is born out by crash investigation studies (Morris et al, 1993). The data shows, however, the obvious corollary of partial ejection through side windows and the need to review current thinking on tempered glass or other possible glazing constructions. 'B' pillar interaction will occur for some quarter of the male population and is, in fact, a particular characteristic of small, four door cars. This condition is not addressed in either the U.S. or proposed European side impact test procedures.

Head to head restraint geometry was the third aspect considered in this study. Experimental studies have illustrated the disadvantages of large separation distances between the head and the head restraint (Svensson et al 1992). Our data show that vertical adjustment is a major factor in increasing the potential for neck injury, but that also illustrate a wide range of horizontal separation distances. The small female, who is particularly susceptible to neck injury (Larder et al 1985) is the very person with the head restraint positioned inappropriately. Perhaps the inclusion of horizontal adjustment in head restraint design should be examined as a design possibility.

This study has been limited to drivers of mainstream cars on UK roads. In the future we would like to extend the work to some other populations in North America or Japan, for example. The actual data collection takes little time, and thus useful comparisons with other environments could be made easily. It would also be useful to examine the front passenger population. Drivers are naturally limited in choice of position by the very act of driving; passengers have the freedom to slouch, sit turned or indeed put their feet on the passenger side airbag module or out of the window, and do so, as any casual observation of an expressway in summer will confirm. In addition, children represent a small, but significant part of the front seat population. Quantitative data on the front seat population sitting position should be a necessary component part of the designer's knowledge if future restraint systems and other aspects of the vehicle crash protective package are to be optimised for the real world, rather than the conditions prescribed by current dummies.

CONCLUSIONS

i) 76% of the driver population was male and 58% appeared to be between 35 and 55 years old.

ii) 25% of the total population are within 45.4cm (18") of the centre of the steering wheel.

iii) Females are considerably closer than males to the steering wheel by 6.2cm (2.5") at the 50%ile level. The 5%ile female is 21.5cm (8.5") closer than the 95%ile male, at 38.5cm (15") from the centre of the steering wheel.

iv) 'Old' people, as defined in this study, are only 1cm closer to the steering wheel than the rest of the population. This can be explained by the reduced stature of the older generation, or by the error in the measurements of +/- 5%.

v) The specified positions of the Hybrid III dummies appear to be markedly different from their equivalent percentiles in the actual population, particularly for the small female, where the difference is 9.2cm (3.6").

vi) 14.6% of the male population is likely to suffer a head strike with the metal structures at roof level during a lateral impact, as compared to 2.6% of females. Overall, more than 1/10th of the driving population is similarly compromised.

vii) 50% of the driving population have the head restraint positioned greater than 15cm (6") from the back of their head, horizontally. Only 5% have the head restraint correctly positioned vertically, with the great majority having it positioned too low. 50% of the population had the head restraint positioned 10cm (4") or more below the centre of the head.

viii) Only male shoulders are likely to interact with the 'B' pillar in purely lateral impacts. Dependent on the size of a particular vehicle's 'B' pillar, this figure is likely to be approximately 25% of the male driving population.

ACKNOWLEDGEMENTS

Grateful thanks are extended to the David R. Foust Memorial Fund which partly sponsored the work for this study. The fund was established in 1988, and is administered by the Association for the Advancement of Automotive Medicine. The fund is designed to help young researchers in their research into impact biomechanics.

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Priorities of Real Car Crashes and the Agreement of Real Accidents with Results from Crash Testing

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ABSTRACT

The German Motor Insurers have continued their accident research programme with a new representative large-scale analysis "Vehicle Safety 90", which includes a data bank of 15,000 car-to-car crashes and over 1,000 single-car accidents.

The distribution of collision types of this representative accident material with personal injuries is analysed. The ranking of collision types in this new accident material based on the traffic environment of the year 1990 is demonstrated with respect to occurrence and intensity of crashes, combined with the frequency and severity of injuries.

An analysis is carried out to ascertain whether collision characteristics are influenced by different mass categories of cars. The differences which has been observed might be due to other risk exposures by the driver, utilisation criteria or safety characteristics.

1. THE ACCIDENT SITUATION IN GERMANY

The long-term comparison of traffic accidents in Germany has to take into account that reunification in 1990 resulted in a new traffic situation.

In West Germany, accidents with fatalities have shown a continous decrease since the "disastrous year" of 1970, when there were some 19,300 people killed.
In 1992 there were in the Old Federal States of Germany 7,300 traffic fatalities - the lowest level ever reached since this statistic was first recorded in 1953.
In the New Federal States since 1990 traffic accidents have exploded, but in the meantime the rate of fatalities is decreasing, too.

In 1992, 395,462 road traffic accidents with personal injury occurred in reunited Germany, 87% of them involved cars (Table 1).

Table 1
Road Traffic Accidents in Germany 1992

Accidents with personal injuries	395,462	
of these with participation of cars	343,901	87.0 %
Casualties	527,428	
of these car-occupants	320,058	60.7 %
Fatalities	10,631	
of these car-occupants	5,595	52.6 %

Source: Statistisches Bundesamt

Almost 530,000 people were injured. The largest proportion of these, about 60%, were car occupans. Car occupants accounted for over half (52.6%) of the 10,631 people killed in Germany /1/. They are thus the most prominent group in traffic accidents.

Table 2 shows the accident opponents of cars in accidents with personal injuries. The car-to-car accident, accounting for over one third of all cases, has first priority, followed by single-car accidents with 18%.

Table 2
Accident Opponents of Cars
Single-Car Accidents and Accidents with two Participants - Personal Injuries

Accident opponent	Number of cases	%
Cars	106,310	35.2
Single-car accidents	54,005	18.0
Unprotected road users	115,841	38.6
Trucks and buses	19,924	6.6
Others	4,708	1.6
Total	300,788	100

Source: Statistisches Bundesamt

In accidents with fatally injured car occupants, however, the single-car accident predominates, accounting for almost half of all car occupants killed; here the proportion of car-to-car accidents is only about half that of the single-car accidents (Table 3).

Table 3
Accident Opponents of Cars
Collisions with Fatally Injured Car-Occupants
Single-Car Accidents and Accidents with two Participants

Accident opponent	Number of fatally injured car-occupants	%
Single-car accident	3,036	47.2
Cars	1,559	24.3
Trucks	724	11.3
Buses	82	1.3
Σ	5.401	
Others*	1,030	16.0
Total	6,431	100.0

* including accidents with several participants
Source: Statistisches Bundesamt

In conclusion, the number of fatally injured car occupants has decreased due to the safety design of cars, to improved rescue service and to safety campaigns.
The optimization of energy-absorbing front structures, the belt-law and the high usage rate of belts of more than 95% on the front seats /2/ made it possible to achieve considerable improvements - especially in the case of head-on collisions.

The law of restraining children in cars, effective since 1st of April 1993, resulted in a substantial increase in the use of protection systems and in a reduction of fatally injured children in cars by 15% /3/.
Moreover, the subject of active and passive safety of cars has become a sales argument in recent years and this has additionally promoted safety elements as airbag, ALB, etc. Even if the figures of airbag-equipped cars are lower than in the USA, it is to be expected that by 1994 more than 50% of the newly registered cars in Germany are equipped with a driver airbag /4/.

Thus, for assessment of future car safety priorities it is necessary to reflect the actual accident situation and the technical safety equipment of cars and to arrive at an "integrated ranking" of impact priorities, taking into account car-to-car accidents and single-car crashes.

It is the main aim of this paper to analyse whether the development in safety influenced the ranking of collision types and to contribute to an integrated assessment of real accidents and corresponding crash testing.

2. NEW ACCIDENT RESEARCH MATERIAL OF THE GERMAN MOTOR INSURERS

In January 1990 a new large-scale analysis of traffic accidents was started by the Department of Automobile Engineering and Accident Research, Munich, continuing former retrospective studies of traffic accidents with personal injury on the basis of insurance claims.

All German insurance companies reported accidents occurring from January to December 1990 and including personal injury - in total 140,000 accidents.
From this data base, 15,000 car-to-car accidents and 1,000 single-car accidents with personal injury were randomly selected in a representative sample.

These cases were subjected to a first phase of evaluation by specially trained HUK engineers and physicians. The "basic evaluation" covered about 80 parametres of each case, concentrating on "core data" only. This procedure increased the evaluation speed and offered a broad basis for special analysis, for example, of accidents of young drivers, injuries to children in cars, crash distribution etc.

In a second evaluation phase, which started mid 93, every case with MAIS 2 and up was subjected to an in-depth analysis.

Independent of the randomly selected representative material of 15,000 car-to-car accidents and 1,000 single-car accidents, special material of serious accidents with respect to accident intensity and personal injury (AIS 2+) including about 400 items per case will be available by the end of this year.

Table 4 shows the accident material within HUK-research as of May 1994.

Table 4
Current Data Banks in the HUK-Department for Automobile Engineering and Accident Research, Munich

▪	15,000	car to car crashes	West	1990
▪	1,000	car to car crashes	East	1991
▪	1,000	single car accidents	West	1990
▪	100	single car accidents	East	1991
▪	500	motorcycle accidents	West	1990
▪	300	truck accidents	West	1990
▪	204	highway fatalities	West	1991
▪	5,600	"FS 80" (all kinds of road users)	West	1980
▪	2,200	truck accidents	West	1984
▪	1,000	accidents with light powered two-wheelers	West	1985
▪	400	children in cars	West	up to 1989
▪	1,100	children in cars	West	1989

3. FIRST RESULTS OF DATA BANK "CAR SAFETY 90"

The "selection procedure" offered the possibility to form homogeneous accident groups.
The "car-to-car" accident material covers collisions between two cars only, excluding accidents with several opponents. Thus, the real crash situation can easily be transferred to the conditions of crash testing.

3.1 Injury Severity of Car Occupants

The distribution of "injury severity" within the two materials "car-to-car accidents" and "single-car accidents" is shown in Table 5. It clearly emerges that serious and fatal injuries to the car drivers occur more frequently in the case of single-car accidents, in which approximately one-third of the drivers are seriously or fatally injured. In car-to-car collisions, this rate is about 8 %.

Table 5
Severity of Injuries to Car Drivers in Car-to-Car and Single-Car Accidents

	Car-to-car accidents	Single-car accidents
No or slight injuries	91.8 %	65.5 %
Moderate to serious injuries	6.9 %	25.5 %
Fatalities	1.3 %	9.0 %
Total	100 %	100.0 %

HUK data bank "Car safety 90"

Single-car accidents on average show increased crash intensity, as the cars often collide with fixed obstacles, which cannot absorb any of the energy, the crash speed is rather high and the rate of side impacts, due to skidding movements is increased.

3.2 Car Categories Involved

Table 6 shows that about two third of the cars involved in collisions with other cars producing personal injury are below a mass category of 1,000 kg. This corresponds well to the registration rates in Germany.

Table 6
Frequency of Mass Categories Depending on the Injury Severity

	Empty weight of vehicle	
	≤ 1000 kg	> 1000 kg
Driver or front seat passenger killed	72.9%	27.1%
Driver or front seat passenger injured	66.5%	33.5%

The increased risk in smaller cars shows up when crashes with fatally injured passengers are selected: then about 73% of all fatalities occur in cars up to 1,000 kg, the risk thus, being overrepresented. Car-to-car compatibility proves to be a problem, but optimization of "deformation zones", integrity of the passenger compartment and advanced safety systems, like airbags, are able to reduce the problems.

3.3 Collision Types

In HUK-research collision types are used, describing the relative position of the cars involved in car-to-car accidents and the type and impact area of obstacles in single-car accidents.

Figure 1 shows collision types of car-to-car accidents, figure 2 of single-car accidents.

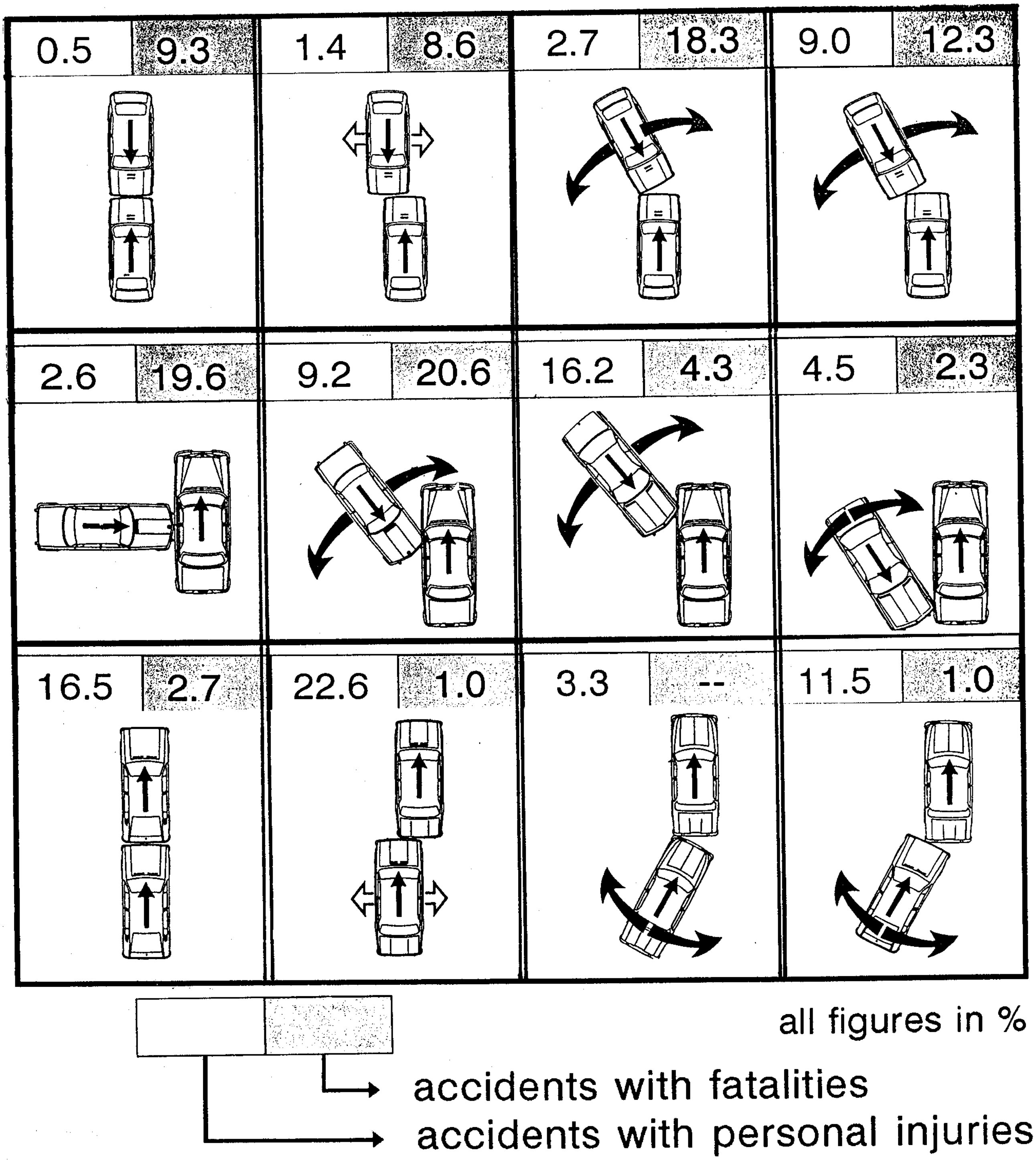
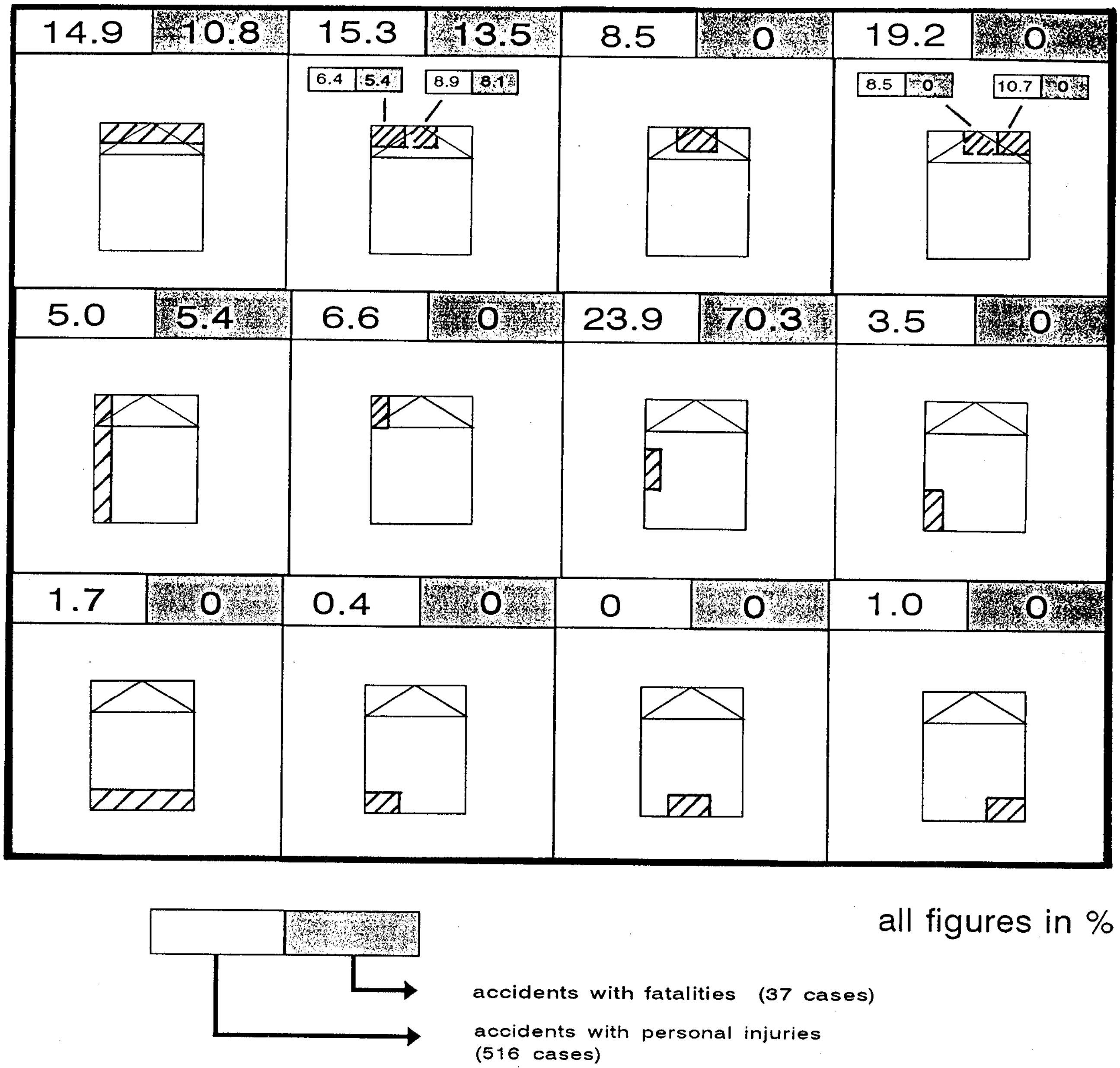


FIGURE 1: FREQUENCY OF DIFFERENT COLLISONS TYPES IN CAR-TO-CAR ACCIDENTS (N = 15,000)



Accidents without rollover (n = 553)

Rollover accidents (n = 461)

Total rollover: 185 cases (40 %) **Partial rollover: 276 cases (60 %)**

FIGURE 2: FREQUENCY OF DIFFERENT COLLISION TYPES IN SINGLE-CAR ACCIDENTS WITH AND WITHOUT ROLLOVER

In comparison with former results, based on occupants with a low seatbelt usage rate, the percentage of front-to-front collisions has dropped to about 50% in car-to-car collisions - a clear indication of the restraint safety measures introduced /5/ and their efficiency in frontal crashes.
But it is still necessary to improve the front structures and restraint effectivity, since the front of the car is still the most frequent impact area, in total about two third in car-to-car collisions, involved in the collision types front/side and front/rear too.

3.4 Areas of Impact

To assess the priorities of real accidents in comparison to safety tests it is, therefore, necessary to analyse the relative frequency of impact areas.
This "crash distribution" is strongly influenced by accident intensity and resultant injury severity. Table 7 shows the frequency of impact areas when the driver sustained MAIS 2 injuries or higher.

Table 7
Impact Areas of Cars in Car-to-Car and Single-Car Accidents, Severity of Injury to the Driver MAIS 2+

Impact area	Car- to- car accident		Single- car accident*	
Front	1,134	62.6 %	110	51.9 %
Rear	239	13.2 %	1	0.5 %
Right } side	152	8.4 %	37	17.5 %
Left } side	286	15.8 %	64	30.0 %
Total	1,811	100.0 %	212	100 %

HUK data bank "Car safety 90" *without rollover accidents

The front impact area is the most frequent, both in car-to-car and single-car accidents. This is followed by the left and right side of the car. The impact area "rear" is only of secondary importance in serious car accidents.
Single-car accidents show with 47.5% an extremely high rate of side impact, which is about double the percentage in car-to-car accidents. This fact is due to the frequent accidents with skidding. A confirmation of the current side impact test procedure onto the driver's side results from the fact that left side impacts are about twice as frequent as right side impacts in Germany.

Rollover constitutes a considerable risk of serious injuries which is often underestimated and which is not reflected in current crash testing suffcently. This seems to result from the fact that in car-to-car collisions rollover is not predominant: according to our material, about 4% of MAIS 2+ injuries to restrained drivers are caused by rollover accidents in car-to-car crashes.

But 45% of the single-car accidents investigated ended up with a rollover - partial or total - of the car. Roughly half of the car occupants killed in a single-car accident (50.5%) are killed in rollover accidents (including the car's tipping over).

3.4.1 Frontal Impact

Figure 3 summarised the results from figure 1 and 2 with respect to frontal impacts.

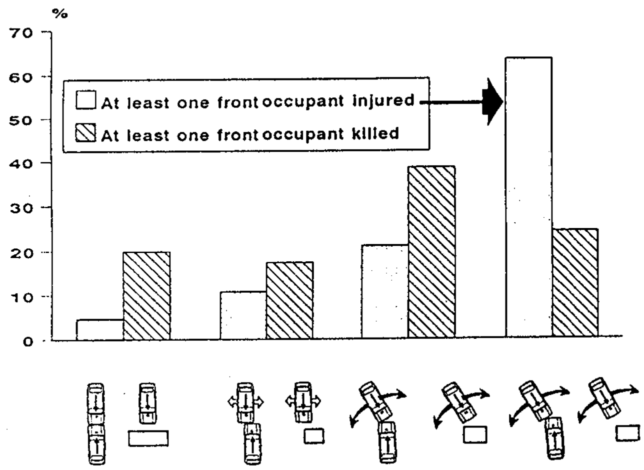


FIGURE 3: FREQUENCY OF HEAD-ON COLLISION TYPES IN CAR ACCIDENTS DEPENDING ON THE INJURY SEVERITY

It is confirmed that with increasing crash intensity and resultant occupant injuries the offset crashes have high priority - also in single-car crashes without rollover -, even if crashes with full frontal deformations cover about half of the severe frontal collisons.
This result confirms that safety crash testing of the car front should be done by two standard tests focussing especially on
- restraint effectivity (test with 100 % overlap)
and
- structural characteristics (test with 40 to 50 % overlap).

This fact, which has been stated in former research projects already /11/, is confirmed by in-depth reconstructions, described in chapter 4.2 of this report.

3.4.2 Side Impact

Figure 4 shows the special impact areas in car-to-car side collisions.
Again, the car's left side is involved twice as frequently as the right side (1.242 vs. 662 cases); only in perpendicular impacts the right/left ratio is balanced.
Angled impacts predominate. In cases of injury to the driver of MAIS 2+ the direct intrusion into the compartment rises from 37.7% to 49.6.

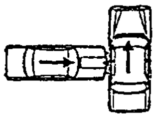
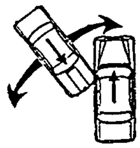
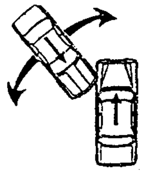
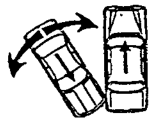
Collision types	Driver, belted, all injury severities			Driver belted, Injury severity MAIS 2+		
	Side Impact			Side Impact		
	left	right	total	left	right	total
	5.9 % n=73	11.2 % n=74	7.7 % n=147	10.4 % n=17	27.5 % n=19	15.5 % n=36
	31.4 % n=390	27.3 n=181	30.0 % n=571	35.0 % n=57	31.9 % n=22	34.1 % n=79
	50.1 % n=623	45.0 % n=298	48.4 % n=921	47.9 % n=78	29.0 % n=20	42.2 % n=98
	12.6 % n=156	16.5 % n=109	13.9 % n=265	6.7 % n=11	11.6 % n=8	8.2 % n=19
Σ	100.0 % n=1242	100.0 % n=662	100.0 % n=1904	100.0 % n=163	100.0 % n=69	100.0 % n=232

FIGURE 4: OCCURING TYPES OF COLLISION IN SIDE IMPACTS, CAR TO CAR COLLISIONS

This creates the highest relative risk, even if side impacts against the frontal side area with more than 40% have high ranking in real crashes.
Thus, safety measures have to cover perpendicular and angled crashes. This finding is especially of importance for the development of side airbags.

Intrusion is a dominant factor: over 70% of the cars where belted drivers sustained an MAIS 2+ injury are severely to extremely damaged (classification of lateral damage Appendix I, example of a serious side impact Appendix II).
43% of the cars impacted laterally are lighter than the impacting cars, about 18% have the same mass and in about 38% of the cases the laterally impacted car is heavier than the impacting car. Therefore, the mass ratio is less important than the impact conditions.

In single-car crashes the problem of intrusion (87 %) is extremly relevant too. In more than half of the cases of driver's injuries being MAIS 2+ (20 out of 36) the cars collided with narrow objects like trees, posts or masts. In one third of the crashes the car collided with side guards on the roads.

3.4.3 Rollover

Special attention was given to rollover accidents in single car crashes were the fatalities reached the high figure of 6.2% (Table 8). Therefore a study was made of 52 rollover accidents with MAIS 2+ injuries to the belted driver; typical parameters are listed in Table 9.

Table 8
Injury Severity of Car Drivers in Single-Car Accidents (Belted Drivers, n = 585)

	with rollover	without rollover
No or slight injuries	71.4 %	70.9 %
Moderate to serious injuries	22.4 %	24.8 %
Fatalities	6.2 %	4.3 %
Total	100.0 %	100.0 %

The case cars show a relatively high longitudinal speed, leaving the road and often begin, because of sloping embankments to rotate around the car's longitudinal axis in a "screw-movement" (example of a serious accident, see Appendix III).

In 40% of the cases the rollover ends with the car lying on its roof, which frequently is bent in the impact area, mostly at the A pillars. The difference in height between the road and the impact side during rollover is about 2 metres in most cases.

Table 9
Important Parameters of Single-Car Rollover/Tipover Accidents, Belted Drivers, Injury Severity MAIS 2+

Velocity at beginning of rollover	50-140km/h ∅109km/h	
Direction of rollover	left 47% right 53%	
Drop height	0.5-8m ∅ 2.8m	
Impact medium	Earth	47%
	Asphalt	10%
	Trees	10%
N.I. 31%	Others	2%
Impact area	Roof	40%
	Side	60%

n=52

For the loading of the A pillars it is remarkable that in general there is not only a lateral rotation, but a "screw movement".
It would therefore be advisable for the car's longitudinal speed at the "onset of rollover" to be of about 70 kph and the structure test should not be characterised by lateral rollover but by a "screw-type movement".

Furthermore, a high rate of occupancy (2.8 persons per car) could be observed. Therefore in tests, the car should be occupied with driver, passenger and rearseat dummies.

3.5 Integrated Ranking of Impact Area Priorities

The results above have confirmed that - due to the different conditions of collisions - different priorities exist.
Safety crash testing should be as closely related to real accidents as possible and should reflect the utmost proportion of real crashes.
It would therefore be desirable that an "integrated ranking" of the impact areas on the car should be established for all the relevant accident groups. The accident research of the German motor insurers offers initial data for crashes with different accident groups.

Basic data on the risk distribution in car-to-car and single-car crashes have been described above; data with respect to car-to-truck/bus crashes are available in /6,7,9/. Due to the relatively low risk for car occupants in accidents with unprotected road users (pedestrians, two-wheelers), this accident group has not been considered in the integrated ranking.

Starting from analysing the German National Statistics, the number of accidents with fatally injured car occupants have been broken down into the crash opponents.

By combining HUK-research data including crash and impact configurations with this statistical analysis a weighting of impact areas was possible.
Table 10 shows the result: out of 5,400 accidents, excluding accidents with several involved parties, 36.7% of the fatalities are due to frontal impacts.
A surprising fact is the high importance of side impacts with 33.6%. This is often overlooked as mostly car-to-car crashes are focused and thus the high ranking of side impacts for fatal injuries is not taken into consideration.

The same fact is true for the underestimating of rollover crashes in the "general risk assessment". Rollover cases (including partial or total rollover) account for 28.4% of all fatalities in cars. This result is well corresponding to former research work regarding fatal highway accidents in the state of Bavaria 1991 /14/.

Table 10
Integrated Ranking of Impact Areas of Cars, Fatally Injured Car-Occupants, Single-Car Accidents and Accidents with Cars, Trucks and Buses

front	1,984	36.7 %
side	1,814	33.6 %
rollover/ tipover	1,533	28.4 %
rear	70	1.3 %
Total	5,401	100.0 %

Total number of fatalities see table 3

This result shows that

- the intensive safety development in frontal crashes, both from structural and restraint aspects, was successful

- main importance has to be dedicated to side impact protection

- rollover crashes are by far more important than has been assessed up to now.

The result confirms furthermore that an integrated risk assessment is necessary to cover as many real-life accidents with safety standards as possible.

4. CRASH RISKS AND CAR CATEGORIES

Based on the HUK-large-scale material two studies have been started to analyse, if typical car categories characterised by their weight/size are subjected to special risk factors.

One pilot study dealt with the distribution of impact areas versus injury severity. This in-depth analysis of special car categories is important, as the main proportion of serious/fatal injuries is represented by cars below an empty weight of 1,000 kg (see also Table 6). As economical cars or small cars may be used specifically in urban traffic, a change in risk exposure could be supposed.

Crash testing up to now has proved that with these "eco- or urban cars" the existing safety regulations can be fulfilled but they need all systems of modern technology available to protect the occupants /15/.

The other study analysed crash configurations in 102 head-on collisions using the "Enhanced Energy Screen Method EESM" to assess the crash intensity by EES classification.

4.1 Ranking of Impact Areas

To analyse if risk exposure by car use influences the crash conditions, the accident material of 15,000 car-to-car collisions has been broken down into categories of cars being represented by the following classes of "empty weight".

Category I	600 - 799 kg
Category II	800 - 999 kg
Category III	1,000 -1,199 kg
Category IV	1,200 -1,600 kg.

The result showed that different frequencies of impact area occur, depending on the varying mass of the reference car (figure 5). But surprisingly the share of impact area "side" does not change significantly throughout the mass categories, showing in general a value of 18 % if accidents of all type of injury severity are included.

The changed risk exposure shows up in the changed values of rear-end impact frequency. About one-third of all injury-producing crashes of small cars are due to rear-end impacts, whereas this type only covers about one fourth of the crashes with higher car weight.

On the other hand heavy weight cars, category IV, have an increased share of about 60 % frontal crashes. Protection in rear-end crashes, especially with optimal seat and head restraint construction, is a major safety aspect for smaller cars.

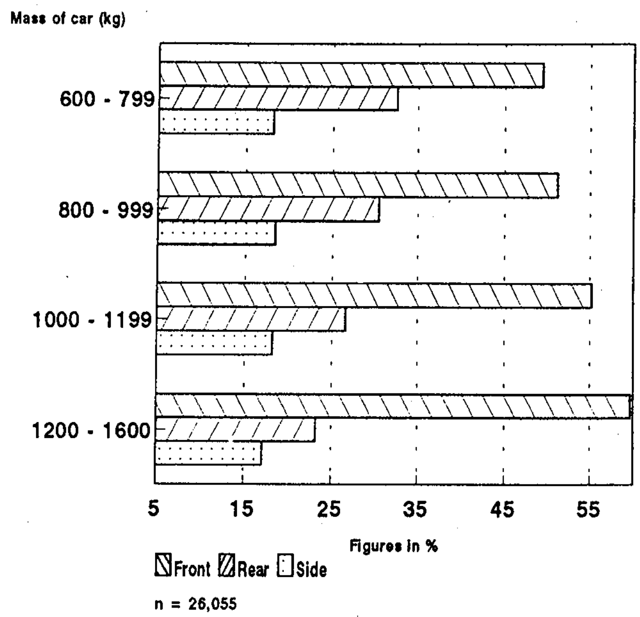


FIGURE 5: RELATIVE FREQUENCY OF IMPACT AREAS RELATED TO DIFFERENT MASS CATEGORIES, CAR-TO-CAR COLLISIONS

These typical differences are balanced as the severity of injuries, i.e. MAIS 3+ to belted drivers, increases. Then, the impact area "front" predominates in all mass categories, having a share of roughly two-thirds; side impacts arrive at about 35 % (figure 6). Thus, for safety standards, small cars have to be subjected to the same criteria as are requested of to all other categories.

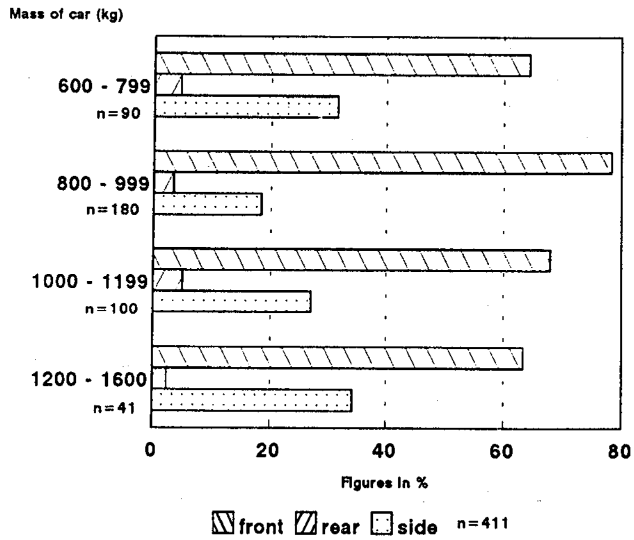


FIGURE 6: RELATIVE FREQUENCY OF IMPACT AREAS RELATED TO DIFFERENT MASS CATEGORIES, CAR-TO-CAR COLLISIONS, INJURY SEVERITY OF THE DRIVER MAIS 3+

4.2 Crash Intensity and Analysis of Offset

The frequency reported of "impact area distribution" (see chapter 4.1) relates to the involvement in injury producing collisions only and does not reflect the "crash loading and occupant risk". Differences in safety levels of small, medium and large cars can only be assessed when combining crash intensity (e.g. described by Energy Equivalent Speed) with injury severity.
In an in-depth analysis, 102 collisions were analysed by specially trained engineers, applying the "Enhanced Energy Screen Method, EESM" /8, 12/ resulting in classification of a car's frontal damage by EES (Appendix IV).
The method enables to classify frontal car deformations by mathematical calculation if there is an "Energy Screen" existing for the car type to investigate. These "Energy Screens" have to be based on crash tests.

The 102 cases were subjected to the following conditions:

- head-on collision in a car-to-car accident
- driver restraint by safety belt
- injury to driver at least MAIS 2 and up
- energy screen available for this type of car.

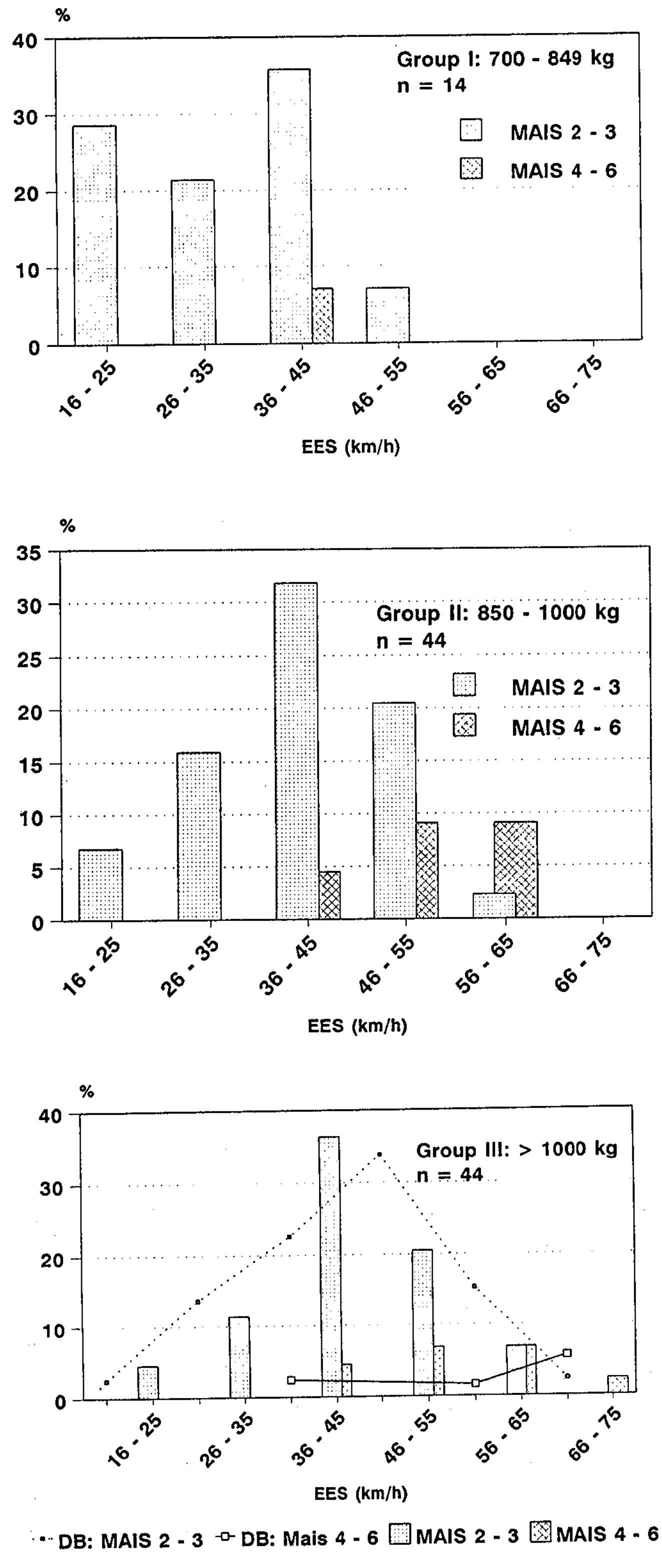
To increase the numbers in each group only three mass classes have been formed:

- Group I: 700 - 849 kg n = 14 cars
- Group II: 850 - 1,000 kg n = 44 cars
- Group III > 1,000 kg n = 44 cars.

Beeing slightly underrepresented caused by a lack of "Energy Screens" the group of small cars of the pilot material is not directly representative with the whole HUK data bank "Car Safety '90". But the general trend is clearly obvious.
Apart from these deficits of Group 1 case numbers, the EES distribution of the other groups corresponds well with results published by Zeidler /13/.

Some general trends could be observed as the EES values differed considerably between the car categories (Figure 7).
The "light-weight group 1" already showed with about 29% a high number of injuries MAIS 2/3 at an EES of 16 to 25 kph, where the heavier cars, group 2/3, still show low injury risk. MAIS 2/3 injuries of these car categories are being concentrated at EES 36-45 kph.

Figure 8 shows a case with MAIS 5 of the driver and an EES of 44 kph, favoured by a relatively slight overlap of about 30% on the driver's side.



EES-values according to Zeidler /13/

FIGURE 7: EES AND SEVERITY OF INJURY TO DRIVERS IN FRONT-TO-FRONT COLLISIONS

Photo of the damaged car

Total vehicle weight: m = 860 kg

Offset: 30 %

EES = 40 + 5 km/h

Driver: 21 years, male, belted
Injury severity: MAIS 5

Specification of injuries:

Spleen laceration AIS 4
Major pancreas laceration AIS 5
Pelvis ring fracture AIS 3
Lung contusion AIS 3

FIGURE 8: SERIOUS CAR-TO-CAR OFFSET-COLLISION INVOLVING A SUB-COMPACT CAR "GROUP I"

But at EES 36 - 45 kph even in heavier cars MAIS 4-6 injuries start to occur for belted drivers. In general with heavier cars the occurrence of serious injuries is strongly shifted to higher EES categories but even at EES of 56 to 65 kph, MAIS 2/3 injuries can still be found for belted drivers. A detailed case analysis showed that characteristics of crash, size of overlap and especially age of the drivers involved are of strong influence.

Table 11 shows the distribution of the 102 head-on collisions with respect to degree of frontal overlap. This analysis confirmed former results of the predominant occurrence of cases with overlap up to 50% in real crashes.
With regard to the mass category of cars, no substantial differences could be found. In general, left-hand frontal overlap predominates with almost two third (60%). Right-hand overlap was found in about one quarter of the cases. A full frontal overlap of both cars occurred in about one sixth of the cases (15,7 %).
In total two third (62 cases) had a frontal overlap of up to 50%; cases with overlap of about 30% are slightly more frequent than cases with overlap between 30 and 50%, showing a frequency of 25.5%.

Table 11
Horizontal Overlap in Front-to-Front Collisions
(N = 102)

Overlap of car fronts	left (driver)	right
0-30%	27.5%	7.8%
30-50%	16.7%	8.8%
50-70%	15.7%	7.8%
100%	15.7%	

The majority of these cases (typical case example in Appendix V) show a deformation of the front structure typically of a crash with a small longitudinal angle of impact.

The result of this special analysis, even when limited to 102 serious frontal cases showed that two test configurations should be taken as standard safety tests for frontal impact:

- The full frontal test with 50 kph against the wall has with about 16 % sufficient significance in real accidents; this test configuration offers good reproduction of measurements and good comparability and it leads as "reference test for restraint characteristics" to valid information for occupant safety.

- A 40% offset-barrier test corresponds to 60% of serious real-life frontal accidents. In future, this test configuration should complement the "reference test" focussing the dominant risk factors of structural loading and intrusion risk occurring in offset crashes.

These test configurations should form the European safety standards in frontal testing and should replace the 30° anti-slide test, which seems to be a mixture of structural and restraint test specifications.

The pilot study showed that in general a higher test speed than 55 kph (for offset testing) or less overlap of about 30% have not been supported by our accident material.

It seems that moving forward to more serious test conditions with higher test speeds a danger of negative consequences for overall safety could not be ruled out. Both with respect to car-to-car compatibility and to risk characteristics of unprotected road users in collision with cars as higher test speeds may result in stiffer cars.

Safety test configurations being in close relation to real crashes to the accident sample presented are shown in figure 9. Future European test regulations should take these configurations into account.
Due to the high risk evaluation of rollover cases, the standard test configurations for frontal, side and rear impacts should be complemented by a rollover test according to results in Chapter 3.4.3

5. SUMMARY

The intensive development of passive safety of cars and the high belting rate in Germany has proved to be successful. Compared with former HUK-accident samples the risk in frontal crashes was reduced, serious injuries in frontal crashes are shifted to higher crash intensity and side impact gaines more and more in importance. Nevertheless, the impact area "car front" is still predominant.

This is the major result from new large-scale accident material, established within the accident research of the German motor insurers. From a total material of 140,000 accidents with personal injury in 1990, a representative sample was selected by a random procedure covering 15,000 car-to-car crashes and 1,000 single-car accidents.

In a two-phase analysis the evaluation was split up into a "basic-evaluation" and an "in-depth-evaluation" of serious cases. With this second enquiry, expected to be finished by the end of 1994, about every fourth fatality of car occupants in the old western states of Germany is covered.

A new procedure for EES calculation by an "Enhanced Energy Screen Method, EESM" has been developed and applied to a special material of 102 serious frontal impacts.

An "integrated ranking" of the impact areas in all types of real crashes is necessary. The safety discussion of cars up to now seems to be influenced too much by the characteristics of car-to-car accidents; crash characteristics in single-car accidents are not sufficiently taken into consideration. Single-car accidents play an important role in real crashes, as more than half of all car occupant fatalities in Germany are due to single-car accidents.

Rollover constitutes a major risk in single-car accidents - causing about half of all fatalities. Furthermore, side impacts have high priority in single-car accidents due to skidding movements and crashing into trees and other narrow objects.
The distribution of collision types is given for single-car- and car-to-car-collisions.
About 60% of serious real-life car-to-car frontal crashes have a frontal overlap up to 50%, corresponding to a "40% offset barrier test".
Full frontal overlap has about 16 % share in front crashes.
Side impact has a significance of 18 % in all collisions with personal injury, this share going up to about 35 % in serious collisions. This percentage does not significantly change throughout the different mass categories of cars in car-to-car accidents. Detailed collision types are given in the paper including a comparison of EES and the injury severity of belted drivers.

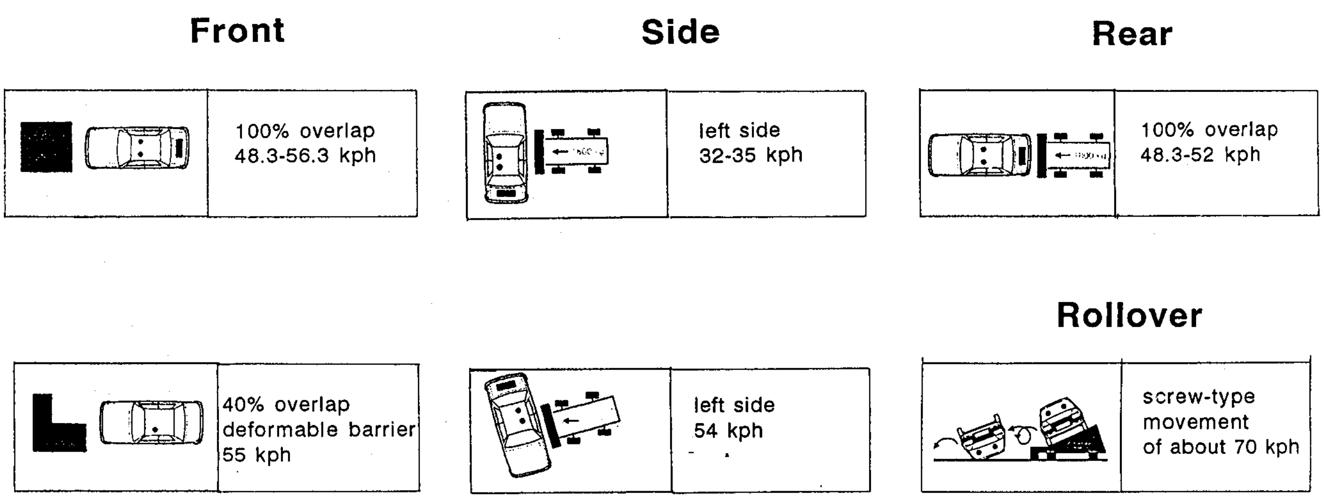


FIGURE 9: CRASH CONFIGURATIONS WITH HIGH CORRESPONDANCE TO REAL ACCIDENTS

An "integrated ranking of impact areas", based on fatal car-to-car collisions, single-car collisions, car-to-truck/bus collisions and weighted by their overall occurrence in national traffic accidents, showed that

- frontal impact has, with 37%, priority number one, but

- side impact, with about 33%, and rollover crashes (28%) have far more importance in fatal accidents than taken into account.

The European safety standards should reflect these facts. To achive a high correspondence to real accidents a standard crash testing procedure should consist of

- a full frontal crash test against a wall with 50 kph and

- a complementary 40% offset barrier test with a speed of about 55 kph using a deformable barrier.

Higher crash speeds or other frontal test configurations cannot be supported as a crash standard by the analysis of the present HUK accident material. The 40% offset barrier test reflects real crashes far better than the 30° anti-slide test which should be regarded as an intermediate solution only.

Side impact protection has high priority in car safety. Additional to reduction of intrusion, the interior impact of occupants against the side wall of the car has to be reduced.
Side airbags could be an outstanding system to do that. Due to the high frequency of angled side collisions, these safety measures have to cover both perpendicular and angled crashes.
The ususal side crash tests

- 90° flat barrier crash into compartment

- angled crab barrier impact to the compartment

show high correlation with real-life accidents. Impacts to the left side of the car have double the frequency to the right side. Side impacts should be conducted with both front seats occupied and with an impact side rear seat dummy.

The rear-end barrier test is close to reality and is supported by the high significance of 23 to 33% crash frequency in collisions with all categories of personal injuries.

Rollover crashtests should be included in the standard safety crash test program. More than one-quarter of all fatalities are due to rollover cases, especially caused by the high rate of rollover in single-car accidents. In reality, the car usually starts to rollover with a still considerable longitudinal movement; thus the tests should not be characterized by lateral rollover movement, but by a "screw-type movement" starting with a longitudinal speed of about 70 kph and the impact level should be about two metres below the level at the onset of test.
A further important demand is a "safety standard for car compatibility". Three-quarters of all fatalities in car-to-car crashes are due to low/medium weight cars up to 1,000 kg. Optimum injury reduction is only possible if there are optimum chances of survival in collisions between small and large vehicles for both parties. This aspect will increase in importance on account of the growing number of economical compact cars.
It is an important task to derive realistic conditions for "compatibility tests" from real crashes. A possible solution could be found in connection with the deformable barrier in offset tests.
The basic material, presented within the accident research of the German motor insurers, will be extended in future and should contribute to offering practical solutions for improving in passive safety, which are still neccessary and possible.

ACKNOWLEDGEMENTS

The authors owe a special debt of gratitude to the German motor insurers contributing to the HUK data bank "Car safety '90".

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Appendix

Including
Appendix I, II, III, IV, V

Appendix I

Car Damage Classification: Example of Damage to Side Area

Moderate

Large area deformation of side structure with minor intrusion of passenger compartment

Severe

Severe deformation of side structure with moderate intrusion of passenger compartment

Extreme

Severe deformation of side structure with critical intrusion of passenger compartment

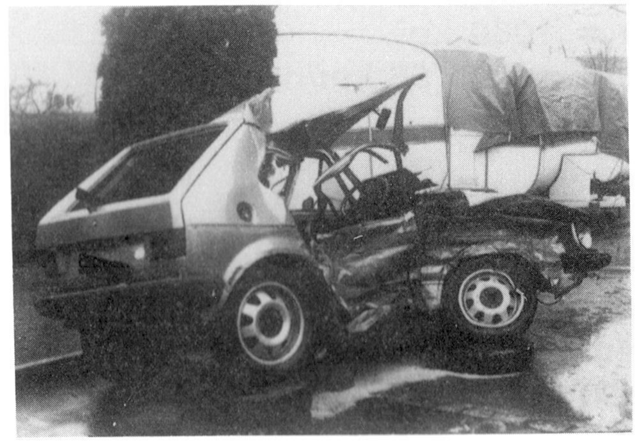
Total

Total destruction of passenger compartment

Example of a Serious Side Collision

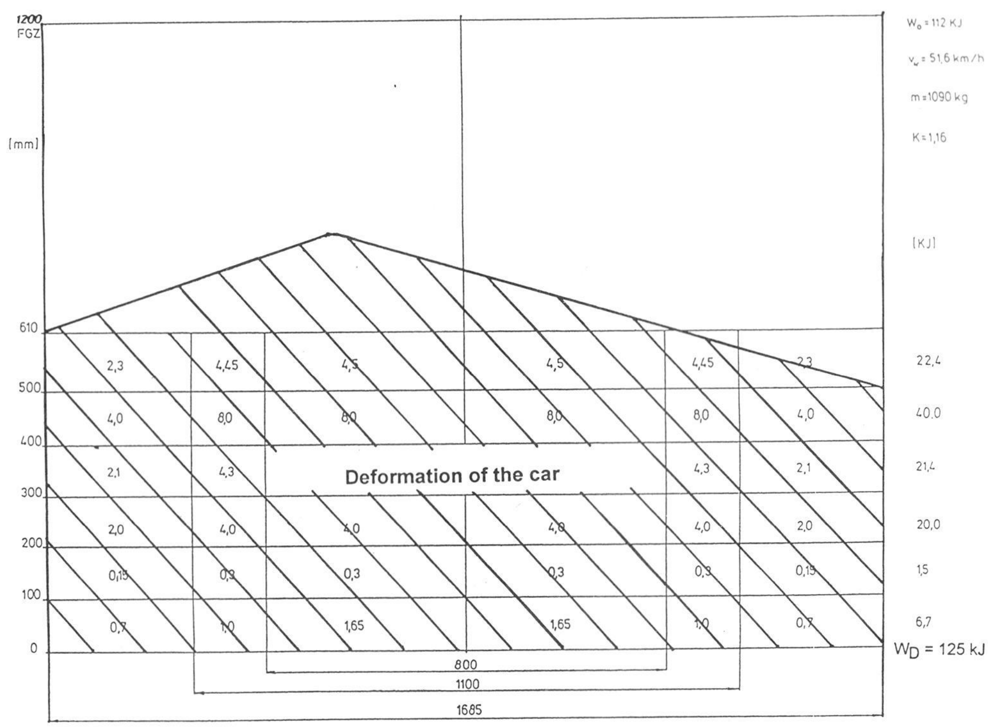
Driver as opposite side passenger

accident opponent



car incolved in side impact

Photos of the damaged cars



Energy screen of accident opponent

Appendix II

Accident opponent

Curb weight:
m = 1060 kg
EES = 50 - 55 km/h

Driver:

32 years
female
belted

Injury severity: MAIS 2

Specification of injuries:

- **Cerebral concussion AIS 2**
- **Fracture of sternum AIS 2**

Rearseat passenger, right:

8 years
male
restraint

Injury severity: MAIS 1

Specification of injuries

- **Major skull laceration AIS 1**
- **Thorax contusion AIS 1**
- **Blunt abdominal injury AIS 9**

Car involved in side impact

Curb weight:
m = 825 kg
EES = 55 - 60 km/h

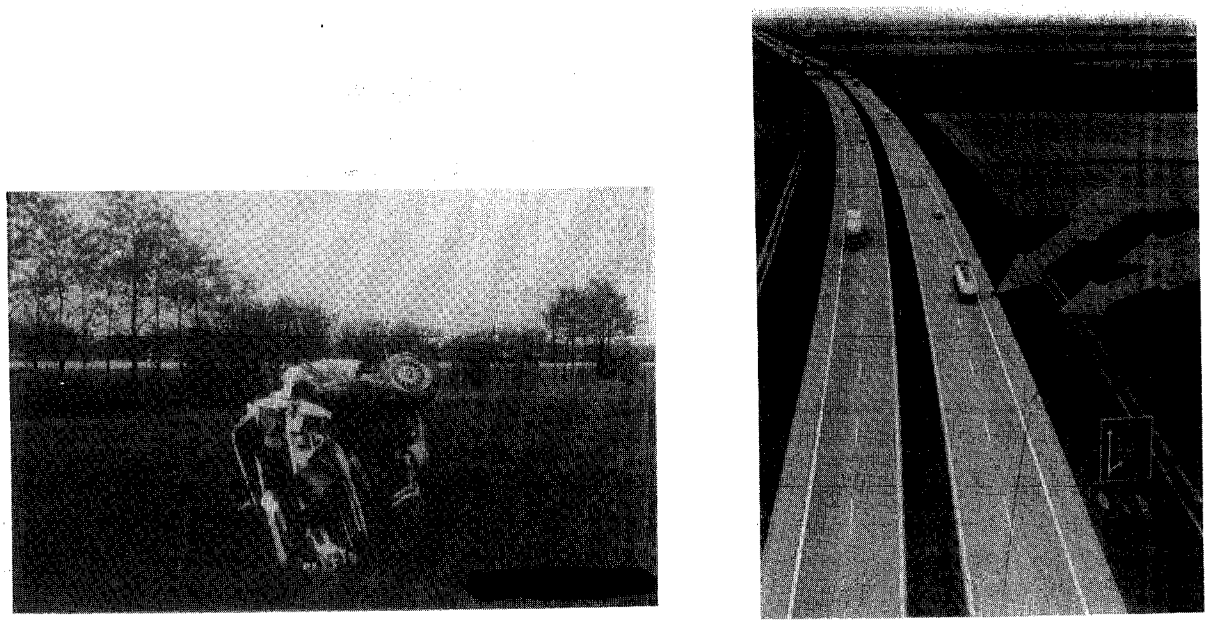
Driver:

18 years
male
belted

MAIS 5 (died 1 week later)

- **Cerebral contusion AIS 5**
- **Multiple fractures, NFS**

Example of a Serious Rollover Accident (Single-Car Accident)



Photos of the damaged car and accident scene

First contact : C-pillar

Contact media: earth

Velocity at beginning of rollover: 140 - 160 km/h

Drop height: 2 - 3 m

Direction of rollover: right

Appendix III

Driver:

22 years
male
belted

Injury severity:

MAIS 1

Specification of injuries:

- Lacerations AIS 1

Front seat passenger:

20 years
female
belted

MAIS 2

- Cerebral concussion AIS 2

Rear seat passengers:

21 years
male
belted

Injury severity:

MAIS 4

Specification of injuries:

- Cerebral contusion with epidural haematoma AIS 4
- Lung contusion AIS 3

19 years
male
belted

MAIS 5

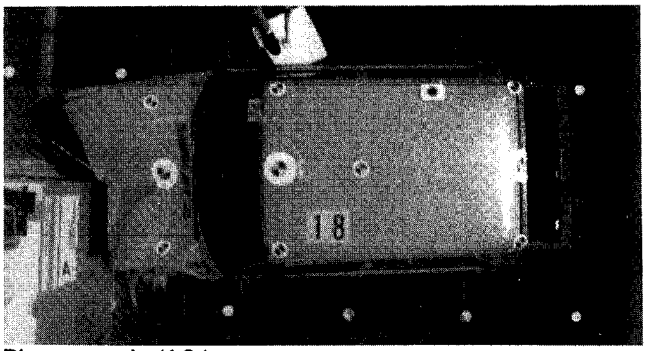
- Severe head and internal injuries, NFS
  died some hours later

Appendix IV

Calculation of the Energy Equivalent Speed by using the Enhanced Energy Screen Method (EESM)

Example VW Golf I:


Photograph /10/



Photograph /10/

Damaged VW Golf

1) Find out the real mass [m_{real}]

The "real mass" means the mass of the damaged car including the occupants.

2) Calculation of the dynamic deformation [s_{dyn}]

Find out the real deformation, especially the deformation line, usually by measuring the damage of the car or by estimating the car's deformation out of a photograph. For registering the static deformation[s_{stat}] there must be at least four characteristic points of the deformation line, multiply them with the factor of elasticity to obtain the dynamic deformation.

$$s_{dyn} = K_{ES} * s_{stat}$$

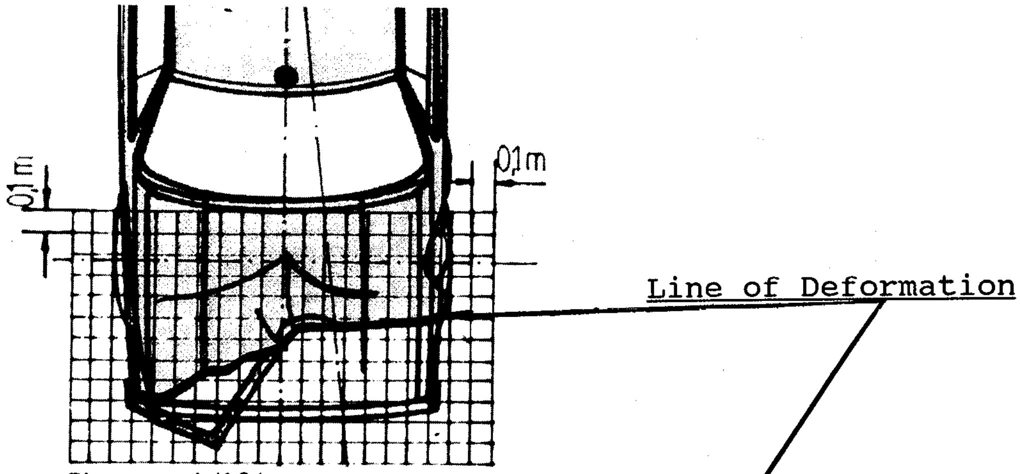
3) Transfer the deformation line into the energy screen

To transfer the deformationline into the energy screen, use the four dynamic deformation points and combine them with the energy screen.

4) Calculate the deformation energy with the help of the energy screen

The screen is classified by different energy levels written on the right hand side. Depending on the car's structure there are several sections of energies. To calculate the deformation energy[W_D], add up all sections of energy below the deformation line. In the case of this example, damaged VW Golf I, there is a deformation energy of W_D = 48 kJ.

Appendix IV



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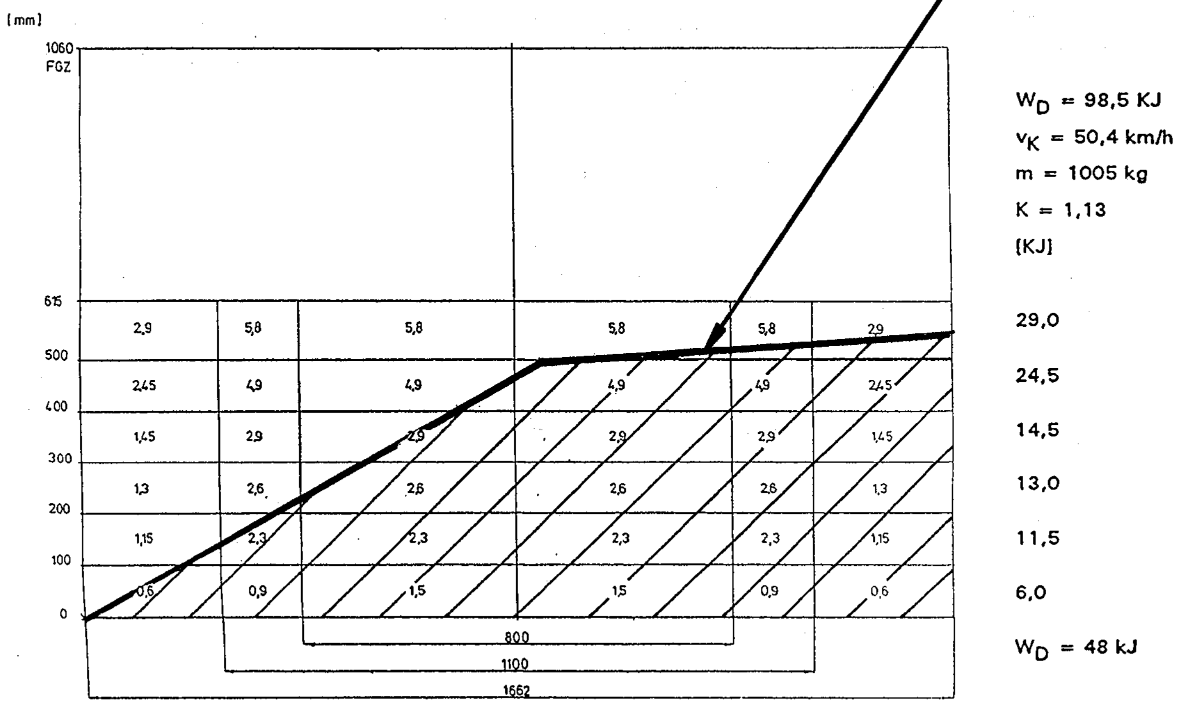


Photograph/12/

Energy Screen VW Golf I with entered damage

5) Calculate the mass correction factor [f_1]

$$f_1 = \frac{m_{ES}}{m_{real}} = \frac{1005kg}{882kg} = 1.14$$

The mass correction factor is the quotient of the mass given in the energy screen and the real mass.

6) Calculate the factor of the elasticity [f_2]

$$f_2 = \frac{K_{real}}{K_{ES}} = \frac{1.21}{1.13} = 1.07$$

The factor of elasticity is the quotient of the real factor of elasticity and the factor of elasticity given in the energy screen.

6.1) The real factor of elasticity [K_{real}]

$$K_{real} = \frac{52.3}{v_c^{1.53}} + 1 \quad \text{(collision speed)}$$

Just put the collision speed[v_c] into the formula. In this example the collision speed v_c = 37 km/h was given by a crash-test record. The normal way is to estimate v_c.

$$\text{For } v_c = 37 \text{ km/h} \Rightarrow K_{real} = 1.21$$

7) Calculate the energy equivalent speed by using the two correction factors [f_1, f_2]

By using all known parameters the EES can be calculated

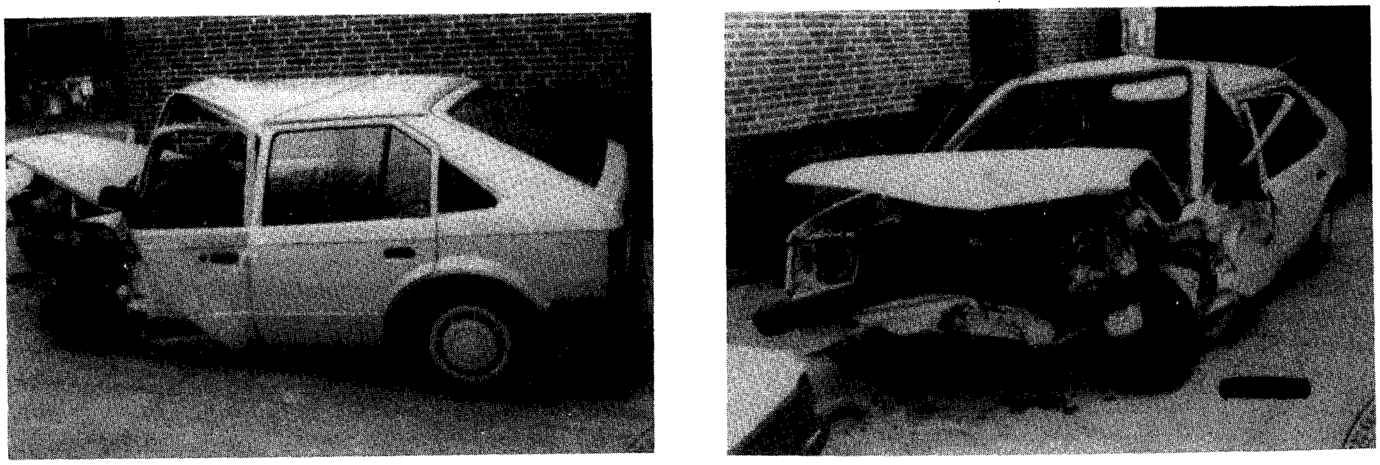
$$EES = \sqrt{f_1 * f_2 * \frac{2 * W_D}{m_{ES}}}$$

$$EES = \sqrt{1.14 * 1.07 * \frac{2 * 48 * 10^3 \text{ J}}{1{,}005 \text{ kg}}}$$

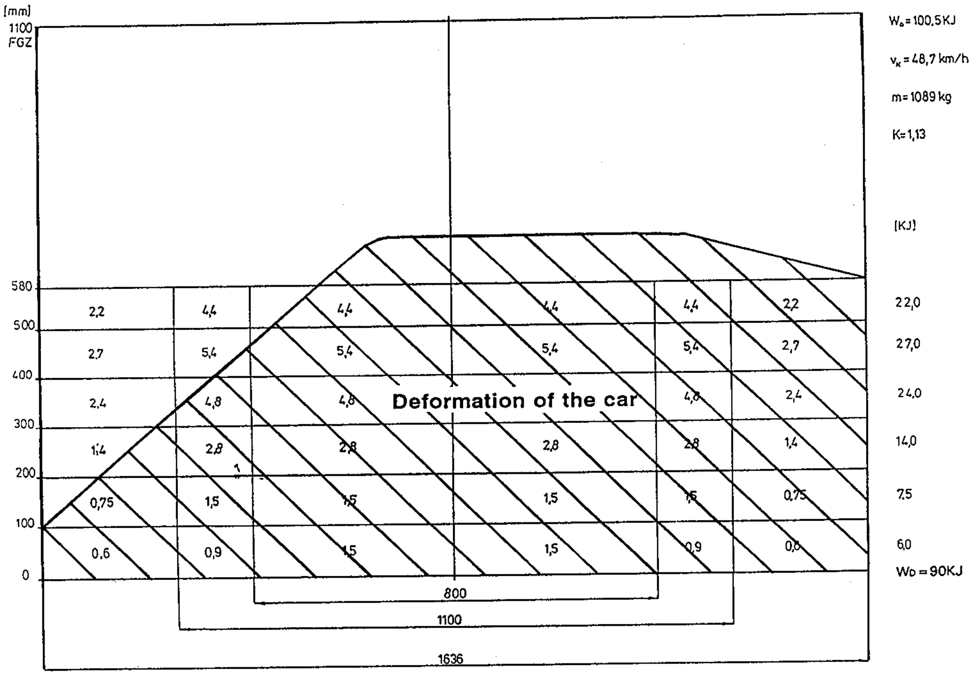
$$EES = 39 \text{ km/h}$$

Appendix V

Example of a Serious Front-to-Front Collision, Overlap 50 %



Photos of the damaged car



Energy screen

Appendix V

Car incolved in frontal impact:

Curb weight:
m = 890 kg
Offset: 50 %
EES = 50 +5 km/h

Driver:

18 years
male
belted

Injury severity: MAIS 2

Specification of injuries:

- Cerebral concussion AIS 2
- Distortion of cervical spine AIS 1
- Forehand fracture left AIS 1
- Abrasions and contusions

Accident opponent:

Curb weight:
m = 875 kg
Offset: 50 %
EES = 48 + 5 km/h

Driver:

23 years
male
belt usage uncertain

Severely injured

- NFS

Assessment of Passive Safety by Crash Tests and Accident Statistics

Wilfried Klanner
ADAC
Germany
Paper No. 94-S5-O-06

ABSTRACTS

A basic requirement for a realistic evaluation of crash-tests is suitable rating procedures. The rating procedures published up to now largely use the dummy loading values obtained from crash-tests. This paper deals with a rating procedure which gives the greatest possible consideration to all parameters having a bearing on the injury relevance and therefore considers not only dummy loading values but also to a large extent car-related data obtained by measuring and observation.

To illustrate the efficiency of the procedure presented here results of comparative head-on crash-tests with small cars and space cars are given as examples.

In order to be able to ascertain the limits of the validity of the results obtained using the rating procedure a suitable validating procedure is basically essential. Besides this, quite a large quantity of type-specific accident data must be known for a selection of car models. The basic features of a validation procedure are described which can be used to convert these data into assessment quantities in such a way that they can be directly compared with the results of the crash-test rating procedure.

INTRODUCTION, OBJECTIVES

Accident statistics mirror at least partially the safety performance of our cars. Fig 1 shows an evaluation of relevant data from the Federal German Statistical Office. From this it can be seen that although the mileage of cars steadily increased the number of fatalities steadily declined up into the mid-80s. The number of car occupants killed each year was lowest in 1985 with about 4,500. In 1993, however, some 6,000 car occupants were killed in traffic accidents. The numbers do not, it is true, mean that our cars have become less safe, but show that it is appropriate to make an effort to further improve their safety.

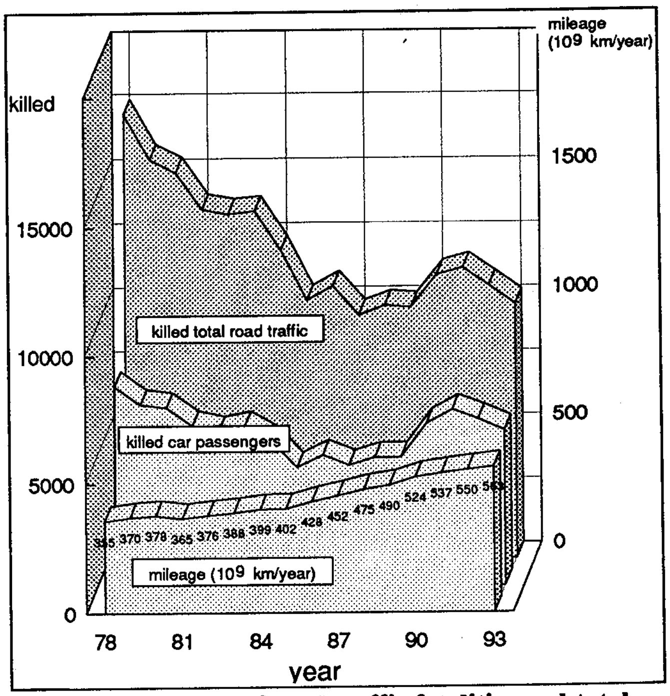


Figure 1. Number of road traffic fatalities and total car mileage per year in Germany

Experience shows that publishing information on the safety performance of cars represents an efficient incentive for work to be continued on increasing safety. For it has the effect of making the consumer sensitive to safety aspects, and the manufacturer notices from his sales figures whether positive or less positive information is available on his product. In view of the great effect of this information on the public, the question arises with regard to its quality and the limits of its validity.

There are basically two different methods of obtaining information on the passive safety of cars.

1. By means of crash-test ratings, ie performing and evaluating suitable crash-tests. This method is used in particular by automobile clubs and consumer magazines [1,2,7,8,9,14,15].

2. By evaluating accident statistics. In contrast to crash-test ratings, in this case as a rule only generally valid but not car-specific information is published [3,4]. Exceptions to this are Folksam and Focus, which also publish model-specific findings [5,6].

methode		accident data		crash test data	assessment variation				
data source vehicle	constr. year	FOLKSAM REPORT insurance data	FOCUS REPORT police data	ADAC	++	+	o	-	--
Opel Corsa	(88)	-	o	--					
Nissan Micra	(88)	--	+	o/-					
Ford Escort	(89)	o	o	--					
VW Golf	(89)	o	-	+/o					
Audi 80	(90)	+	-	+/o					
Ford Sierra	(90)	+	-	-					
ˈercedes 190	(90)	o	o	+					

Figure 2. Car assessment variation

Fig 2 compares model-specific findings, which are obtained, on the one hand, using the crash-test rating method and, on the other, using the method of evaluating accident statistics. It emerges from the comparison that the results for a single model deviate considerably from each other. In addition, the accident statistics, by their very nature, only supply data on car models which have already been on the road for quite some time. This means that to obtain the information which provides help in buying a new car only the crash-test rating method is suitable.

The crash-test rating procedures published up to now are based mainly on the dummy loading values [10,14]. It is suspected that the validity of information obtained in this way remains very closely related to the crash-test configuration selected. The main features of a procedure which takes into account not only the dummy loading values but also the behaviour of all the assembly groups relevant to injuries and thus probably produces a greater general validity of the results are presented below.

It is always desirable to validate a crash-test rating procedure. Validate means here to provide evidence of the usability and the limits of the validity of the procedure in the light of representative data from real-life accidents. Up to now a validation of this kind has not been carried out for any rating procedure. In view of this state of affairs an attempt is undertaken below to derive, at least as a starting point, the principal features of an appropriate validating procedure.

On account of the enormous diversity in real-life accidents crash-test rating and validating are extremely complex problems. It would therefore appear to be a good idea to first reduce this complexity by applying specific restrictions. The restrictions that suggest themselves are

1. Limiting consideration to head-on collision, as this is still the most frequent kind of accident and

2. limiting the procedure to the driver's seat, as it is the seat that is used most frequently.

If validating is successful with these restrictions, an expanded procedure according to the same principles would appear to be relatively unproblematical.

CRASH-TESTS AND ASSESSMENT PROCEDURES

In view of the restrictions made, it is here essentially a question of obtaining quantitative information on the injury risk to the driver in a head-on collision. The information should be as practical as possible, have a wide validity and, at the same time, require as little expenditure as possible for the crash-test.

Crash-tests

In [11] there is a report on the efficiency of various head-on crash-test procedures. Each procedure has its specific advantages and disadvantages. In agreement with [12] it is noted here that the 50km/h offset impact with 40% overlap constitutes a particularly representative test procedure for simulating the offset car/car front collision. This car/car front collision is again the type of accident that occurs most frequently in practice. If for reasons of costs only one test for each car model is envisaged, then it should be based on this procedure.

The accident opponent has so far been a rigid wall, but as soon as possible it should be replaced by the more realistic deformable barrier [13].

Crash-test results

To ensure the reliability of a rating procedure the validation should generally be carried out for different car

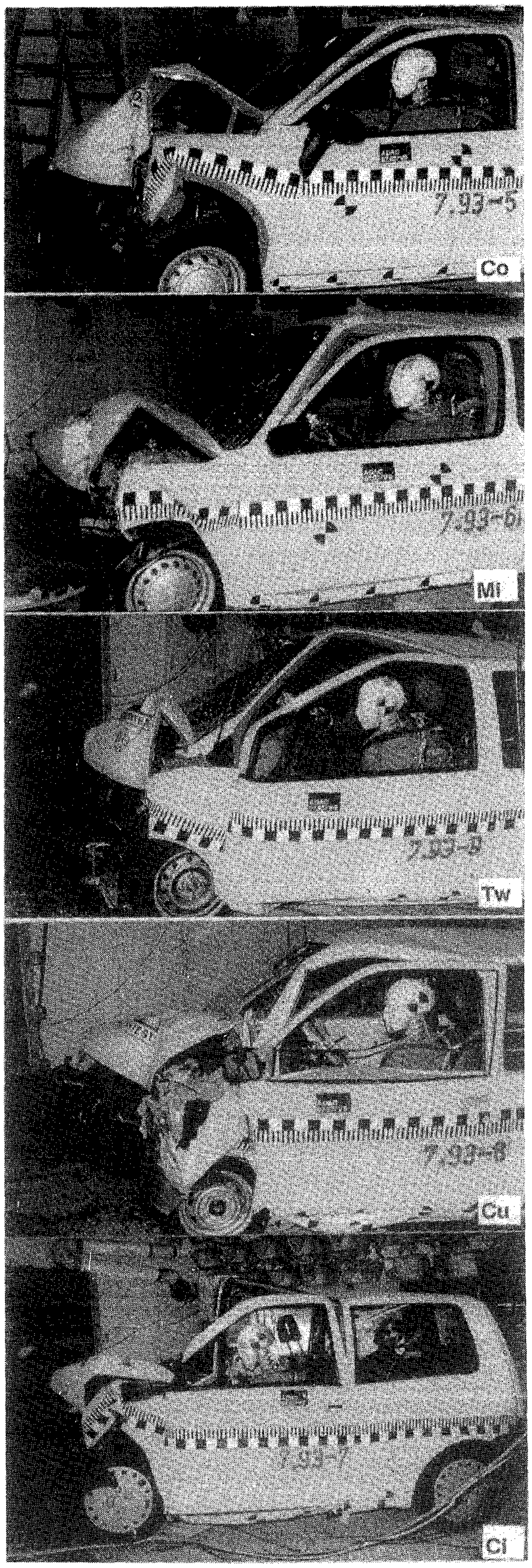


Figure 3. Small car crash behaviour, 50km/h impact with 40% overlap

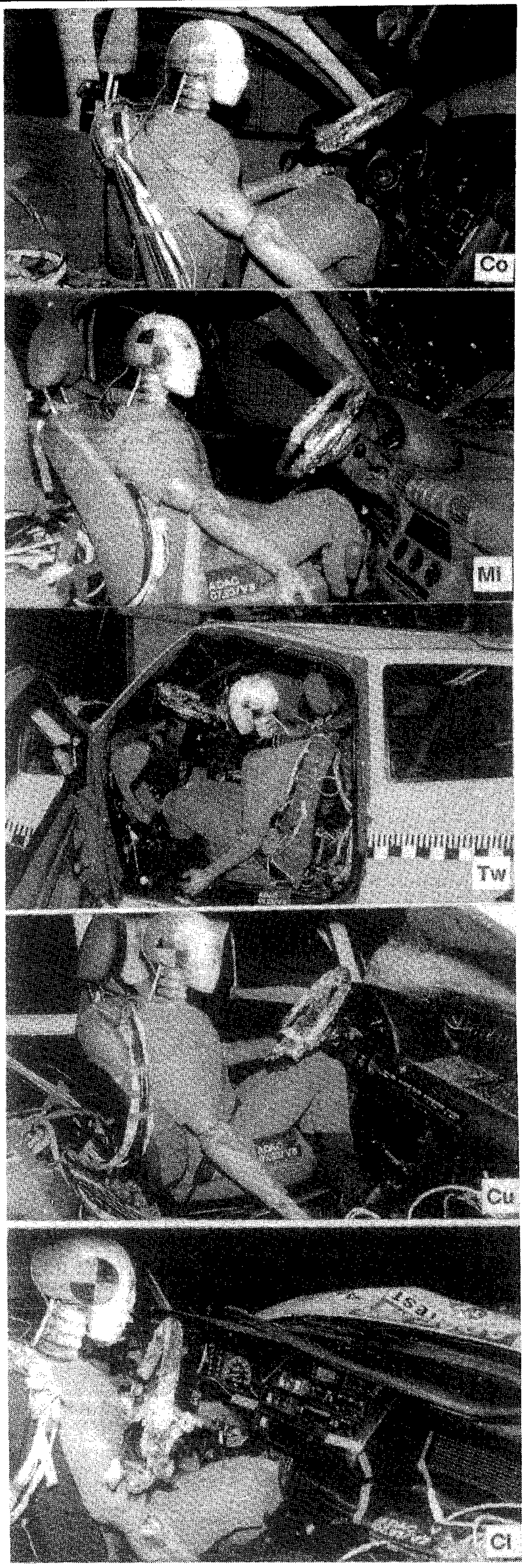


Figure 4. Small car steering wheel and panel behaviour

size-classes and also for various car models within these classes. As examples of this, the results of two car classes will be given below, namely the small car class (5 models: Co, Mi, Tw, Cu, Ci) and the space car class (2 models: Es, Vo).

Fig 3 shows the deformations to the fronts and the passenger cells of the five small cars. In two cars the energy absorption occurs largely in the crumple zone, and that means they have a rigid passenger cell. Unlike these, in the case of the other three cars considerable energy absorption occurs in the cell, with the result that the survival space for the occupants is reduced accordingly and there is far less safety.

To further illustrate the results, Fig 4 shows the individual drivers' sitting positions after the crash. One of the things that shows up clearly here is that with some cars quite considerable steering wheel intrusion can occur.

Crash-test rating procedures

Each crash-test produces a large number of measurements (eg decelerating at the tunnel, Fig 5, or dynamic car deformation, Fig 6, both essential features for the behaviour of the car body) and also observed data.

assembly groups that cause the injuries. These are the steering wheel area, the dashboard area, the foot space and the driver's seat including the belt. In addition the parameters influencing the rescuing of the driver are also taken into consideration.

This list does not contain the assembly groups front windscreen and A pillar regions because in the crash-tests carried out so far nothing conspicuous has been noticed. It is known from real-life accidents that these assembly groups can also have a considerable influence on a driver's injuries. That is why, when the rating procedure has been further developed in the future, they, too, should be taken into account.

The further evaluation calls for the test results to be converted into assessment grades. This is done using suitable rating scales, which are based, on the one hand, on state-of-the-art engineering and, on the other, on the generally recognised threshold values.

An example of a rating scale of this kind is shown in Fig 8. There the horizontal and vertical steering wheel intrusions are entered for the different cars tested. It is known from [4] that as the steering wheel intrusion

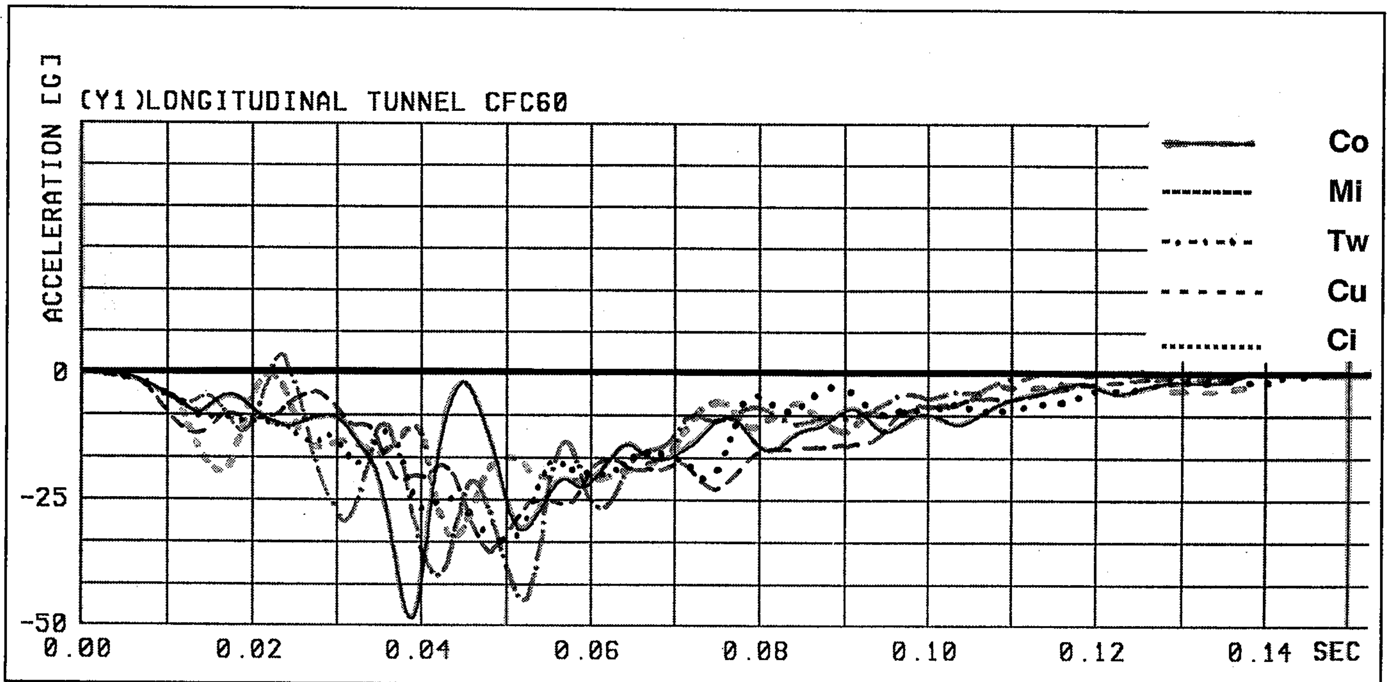


Figure 5. Vehicle decelerations

increases in both a horizontal and a vertical direction the injury risk to the driver rises steeply. The threshold value for the steering wheel intrusion is 127 mm according to the ECE Standard. All these factors were important for allocating the intrusion figures to the appropriate assessment grade, as can be seen from this figure.

In order to achieve the aim of obtaining the broadest possible band of information, the evaluation must not be restricted to measurements, let alone just dummy measurements. On the contrary, the aim must be to take into account if possible all the parameters affecting injuries. Fig 7 shows the result of an analysis of the parameters for the driver's injuries related to the cars'

The test results show that in practice considerable differences occur:

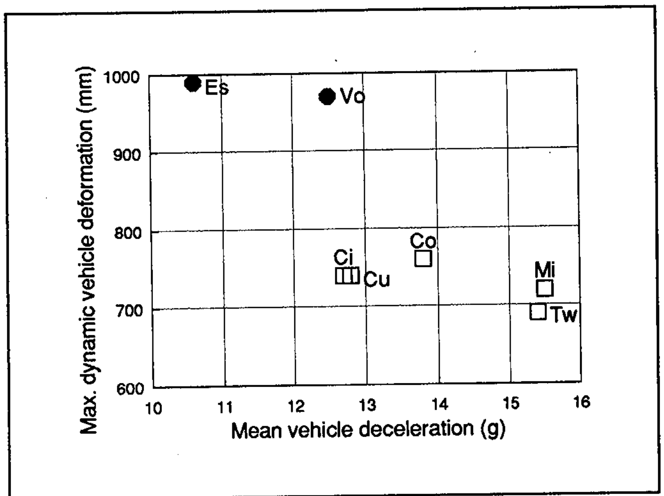


Figure 6. Max. dynamic vehicle deformation and mean vehicle deceleration

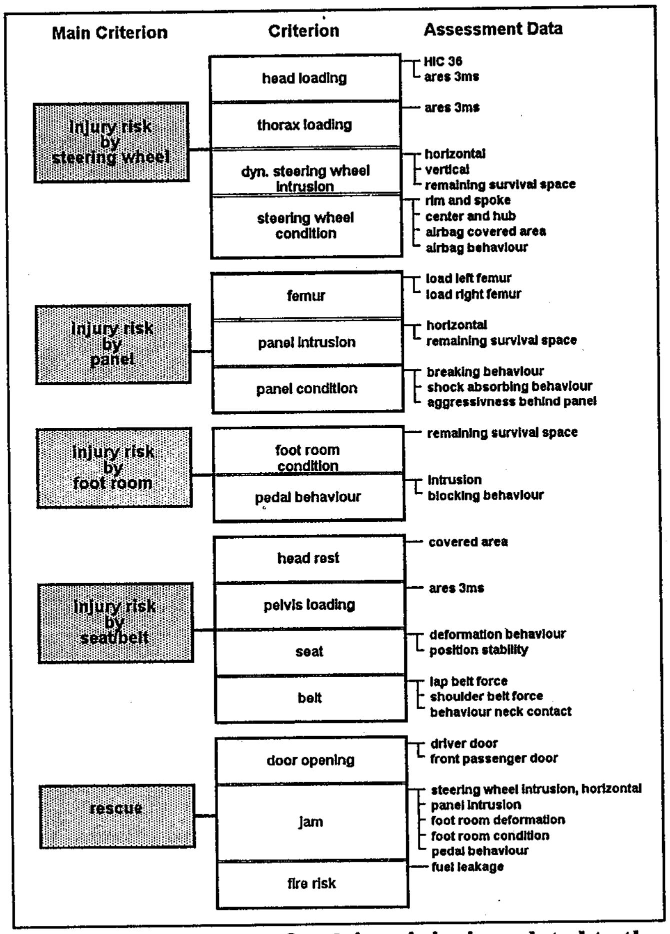


Figure 7. Parameters for driver injuries related to the vehicle areas

thus the small car Ni, for example, exhibits steering wheel intrusion of under 50 mm and is therefore given the assessment grade 2. In contrast to that, the small car Tw and the space car Es shows steering wheel intrusions of around 200 mm, the standard value is greatly exceeded

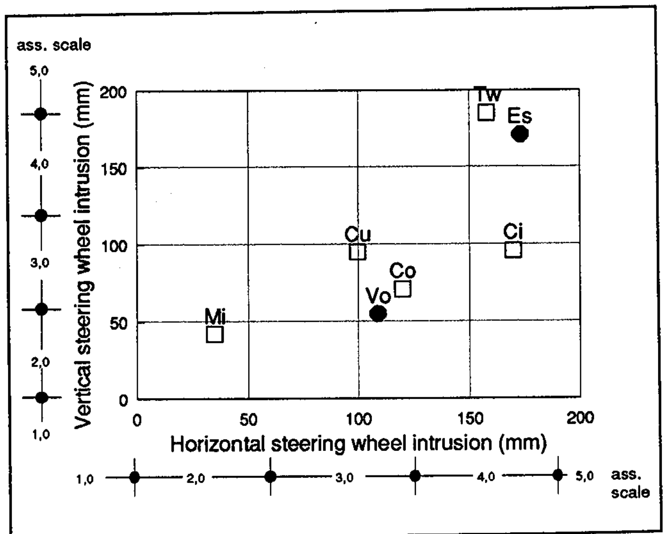


Figure 8. Horizontal and vertical steering wheel intrusions

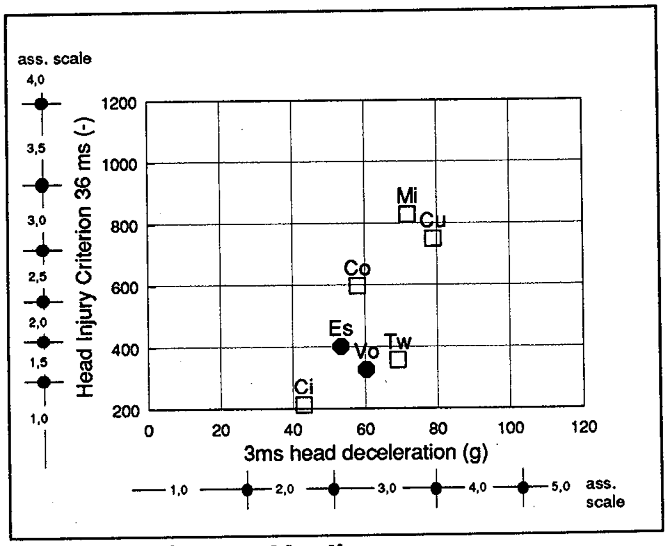


Figure 9. Driver head loading

and the assessment of 4 and 5 respectively is correspondingly negative.

The results for the head loading figures have been entered in Fig 9. It can be seen that, although there were serious steering wheel intrusions in all the vehicles tested, the head loading figures are well below the existing threshold values. One reason for this is that in the offset crash-test with 40% overlap the driver dummy does not usually strike the hub of the steering wheel directly, which as we know from experience produces greater head loading than the spoke or steering wheel rim. In real-life accidents this may well be different. Only considering the head loading figures, ie ignoring the intrusion results, would lead to misinterpretations here.

Further examples of allocating values from measurements/observations and assessment grades are to

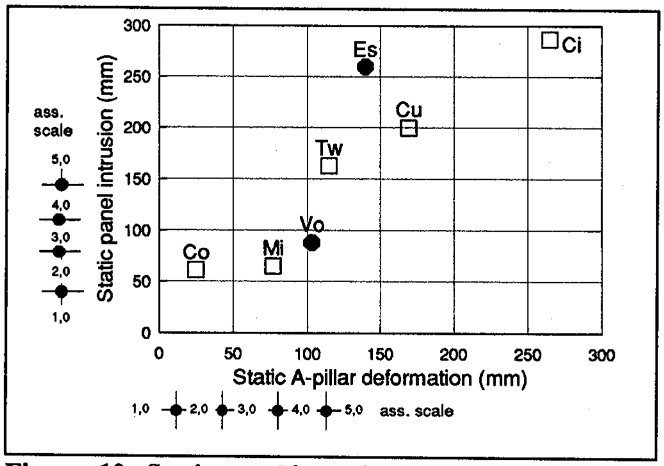


Figure 10. Static panel intrusion and A-pillar deformation

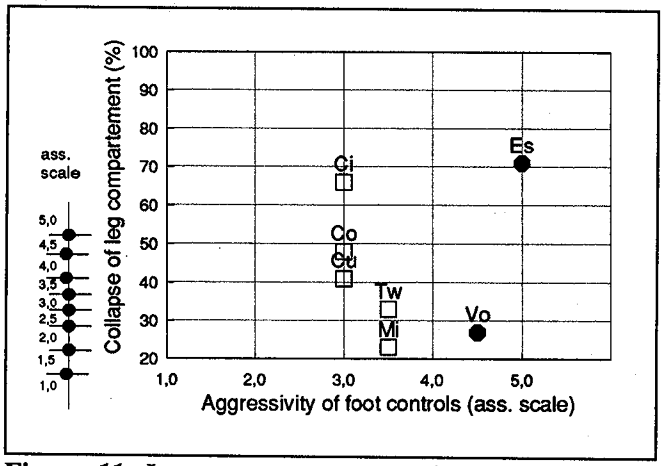


Figure 11. Leg compartment behaviour

be found in Figs 10 and 11: it can be generally noted that there are very great differences between the various cars. Thus the deep dashboard intrusion and the severe foot room deformation in the small car Ci is especially noticeable. Behaviour of this kind certainly means that there is a considerable risk of injury to the driver's legs.

To make the information intelligible to the consumer further condensation is necessary. So the results of the separate criteria on weightings in the grades to assess the injury risks of the individual assembly groups are combined. The results show that this injury risk can vary considerably from car to car, Fig 12.

This method of presentation already allows a certain ranking of the car models: thus the car Co, for example, offers the smallest risk of injury to the driver and the small car Ci the highest. Presenting the results in this way makes it easy for the consumer to understand them. But it is also very informative for the development engineer, since it becomes absolutely clear which assembly groups should be given priority when improvements are made.

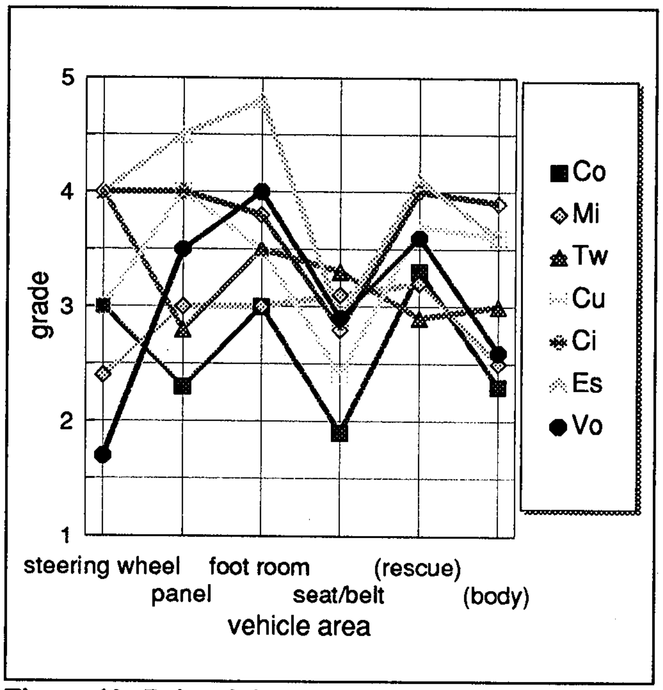


Figure 12. Driver injury risk of the individual assembly groups

It is important that the assessment grades at first only within the individual car classes can be compared. In making a comparison of the individual car classes the fact that as a rule small cars are exposed to a greater accident loading than larger ones has to be taken into account.

CONSIDERATIONS ON DEVELOPING A VALIDATION PROCEDURE

Validation means ascertaining the correlation between the crash-test rating results and results from real-life accidents on the basis of selected car models. In contrast to crash-tests, which supply information about the behaviour of different assembly groups as well as occupant loading values, real-life accidents in the first place only provide data on injuries to the occupants. To make a comparison possible, the crash-test rating results, which at first are available related to car assembly groups (injury caused by the steering wheel etc), have to be converted into injury risks to the different parts of the body.
Two possible methods are conceivable for this conversion:

1. Ascertaining a formal connection between the injury risk of the individual assembly groups (vehicle area grades) and the injury risk to the individual parts of the body (body area grades). This connection can be derived from the accident statistics [3]. Fig 13 shows this derivation of a formal connection as well as the corresponding figures for carrying out the conversion. This

$$grade_{body\ area} = \sum_{vehicle\ area = steering\ wheel}^{foot\ room} (weighting_{body\ area,\ vehicle\ area} * grade_{vehicle\ area})$$

$grade_{vehicle\ area}$ =... out from crash test results

$$weighting_{body\ area,\ vehicle\ area} = \frac{injury\ frequency_{body\ area,\ vehicle\ area}}{\sum_{vehicle\ area = steering\ wheel}^{foot\ room} (injury\ frequency_{body\ area,\ vehicle\ area})}$$

Table for *wheighting* $_{body\ area,\ vehicle\ area}$ calculated with the above formula (data for *injury frequency*$_{body\ area,\ vehicle\ area}$ from accident statistics[3]):

body area / vehicle area	head	neck	thorax	arms	abdomen	pelvis	legs
steering wheel	0,91	0	0,44	0,1	0,66	0,16	0
panel	0,09	0,34	0	0,9	0	0,05	0,64
foot room	0	0	0	0	0	0	0,36
belt/seat	0	0,66	0,56	0	0,34	0,79	0

Figure 13. Formal connection between injury risk of individual assembly groups and injury risk to individual parts of the body

should be qualified by saying that there are certainly car type-specific differences which are concealed by this conversion. Thus a high horizontal steering wheel intrusion may result in abdominal injuries in the average car. This is taken into account in the conversion procedure. But if at the same time a high vertical steering wheel intrusion occurs abdominal injuries are improbable. This effect is not taken into account by the conversion procedure.

2. In view of these restrictions another way of proceeding is being considered. It would be based on an influence analysis, analogous to the procedure described in Fig 7, in which the parts of the occupants' body are considered instead of the car assembly groups. The result of an analysis of this kind is presented in Fig 14. It is supposed that by combining both procedures realistic results can be achieved.

Fig 15 shows the result of an attempt to apply such a combination of both procedures to the results of the small cars and the space car crash-tests. This allows the injury risk to the different parts of the occupants' body, limited here to the driver, to be ascertained for each car model: again significant differences arise between the individual cars. Thus the small cars Co and Mi have a low injury risk to the driver's head and the cars Tw and Ci a high one.

For the comparison between the real-life accident and the crash-test rating results the accident statistics data must also be assessed. The crucial measure for this assessment is the frequency of the injury severities occurring in real life. For the cars on which the validation procedure is based a type-specific evaluation would first have to be

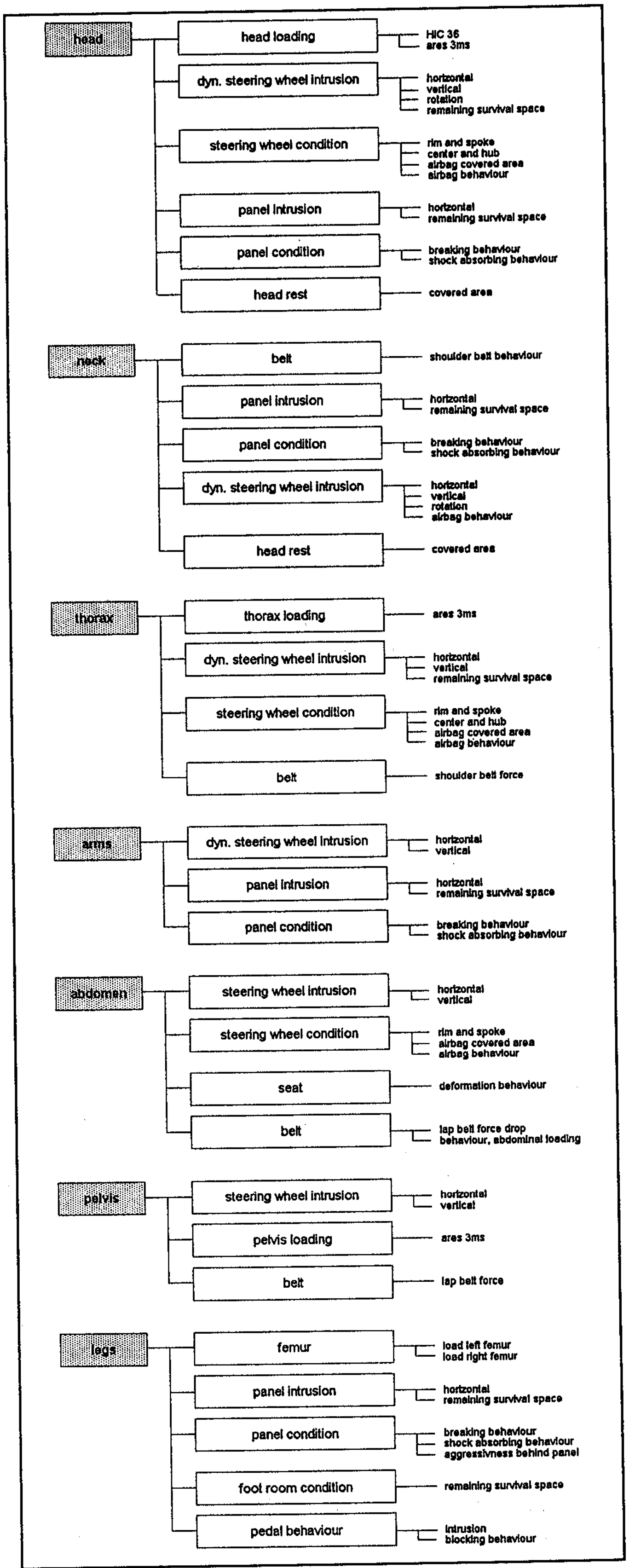


Figure 14. Parameters for driver injuries related to the body areas

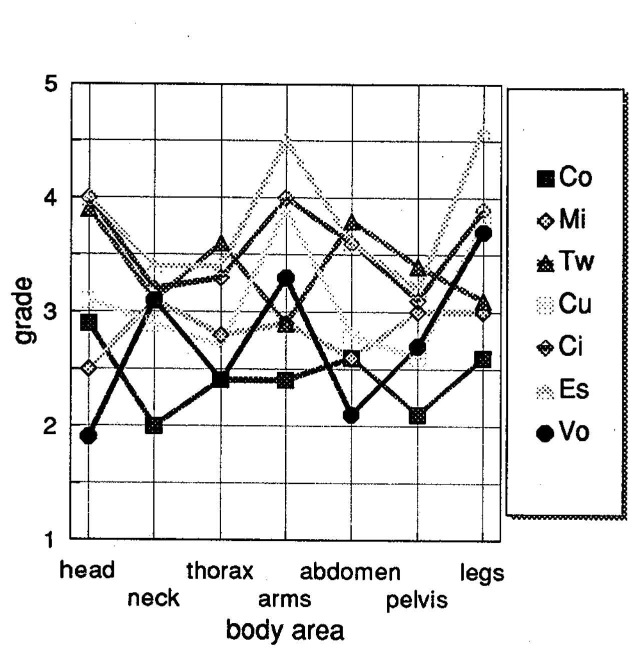


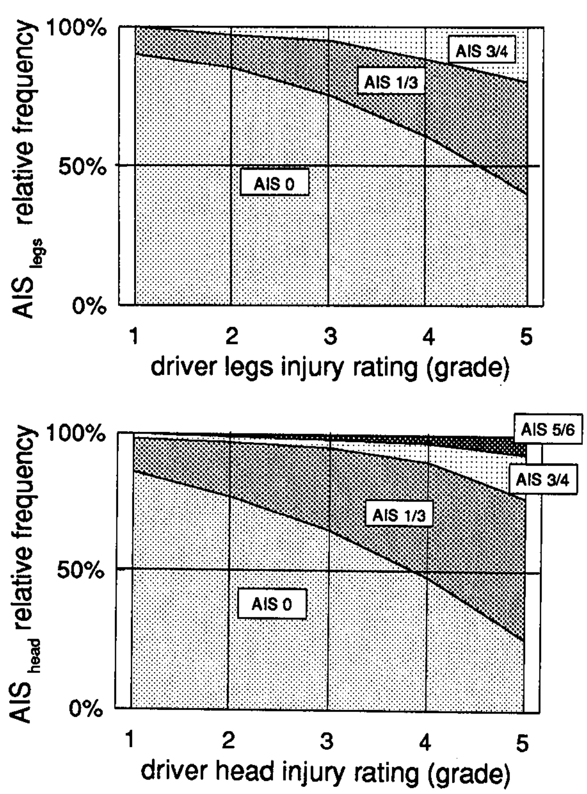
Figure 15. Driver injury risk of the individual body areas

made from an appropriate representative selection of all head-on collisions. This evaluation is broken down in each case into the different accident severity grades (Energy Equivalent Speed EES). This will result in frequencies, and namely for each combination

Injury severity grade (AIS 0 to AIS 5/6)
Part of the body (head to leg)
EES level (0/30 to > 70 km/h)

The results of the individual EES levels must be combined on the basis of the same accident frequencies (in the individual EES levels) [12]. The formula presented in Fig 16 produces type-specific AIS distributions representative of all the details of the accident, ie the shares of AIS 0, AIS 1/2... up to AIS 5/6, and broken down into the individual parts of the body. These type-specific results obtained from the real-life accident now have to be assessed.

To find the rating scale the same procedure has to be adopted as in the case of the type-specific evaluation, in which the accident of all important cars, ie the average accident, and not the type-specific results, has to be applied. This results in an average AIS distribution (the shares of AIS 0...AIS 5/6). If the average grade 3 (average, satisfactory) is allocated to this average result, it becomes evident that cars with a better AIS distribution than the average should be allocated the grades 1 or 2, and cars with a worse AIS distribution than the average should be allocated the grades 4 or 5. The first suggestions for rating scales of this kind are presented in Fig 16, and namely for both the driver's head and the driver's legs.



$$AIS\ i_{body\ area}(grade3) = \sum_{EES\ 0-30}^{EES>70} (AIS\ i_{body\ area,\ EES} * rel.\ accident\ frequency_{EES})$$

$AIS\ i_{body\ area,\ EES}$ =... out from accident data analysis [3]

relative accident frequency$_{EES}$ = ... out from accident data analysis [12]

Figure 16. Rating scales for evaluation of typ specific accident data and formula for calculation of AIS distributions

A comparison of the assessment results obtained in this way with the crash-test results related to the parts of the body makes it possible to judge the quality and the limitations to the validity of the crash rating procedure.

CONCLUSIONS

The rating procedure described produces results which can be easily understood by the consumer and thus important information to help him decide which car to buy. The manufacturer can, on the basis of the strengths and weaknesses that have been discovered, take specific decisions on improving the safety of his models.

The question remains open as to where the limits of the rating procedure are that has been described. It would thus be of significance whether or not there are important aspects which are given too little consideration or none at all. To answer these questions the fundamentals of a validation procedure are being developed. This will point out in particular how not only type-specific accident data but also crash-test results can be converted into assessment grades for the injury risk to the various parts of the car occupants' body (restricted here to the driver and head-on collision). Using the method described it will be possible to validate the rating procedure that has been presented if type-specific accident data are available for only a few models.

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The Effect of Countermeasures To Reduce the Incidence of Unintended Acceleration Accidents

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Paper No. 94 S5 O 07

ABSTRACT

This paper provides a description of "Unintended Acceleration" (*UA*) in passenger cars, presents data pertaining to the scope of the problem as defined by the number of accidents and injuries reported annually to NHTSA that are alleged to be associated with *UA*, discusses the causes of *UA* and countermeasures to reduce the incidence of *UA*, and provides analysis to assess the reductions in reported *UA*-related accident rates which have resulted from the use of automatic shift locks.

UA reports are defined as incidents of high-powered unwanted vehicle acceleration from a stationary position or very slow speed, accompanied by reportedly ineffective brakes. Previous studies and investigations conducted by the National Highway Traffic Safety Administration (NHTSA), and by Canadian and Japanese government agencies have concluded that the major cause of such incidents has been drivers unknowingly depressing the accelerator instead of the brake pedal on automatic transmission-equipped cars.

Based on data obtained from NHTSA's computerized consumer complaint file system, and information obtained in the course of agency defect investigations, the paper concludes that the best known countermeasure to *UA* has been factory installation of automatic shift lock systems which prevent the driver from shifting the transmission out of Park unless the brake pedal is simultaneously applied . A comparison of reported *UA* accident rates (accidents per vehicles produced) for automatic transmission-equipped cars indicates that vehicles equipped with shift locks have experienced approximately a 60 percent reduction in *UA*-related accidents compared to similar cars without shiftlocks. Also, the effect on *UA* of retrofitting shift locks on one particular make/model is assessed.

INTRODUCTION

What is "Unintended Acceleration" (*UA*)

The National Highway Traffic Safety Administration (NHTSA) frequently receives letters and telephone calls from drivers who report incidents involving vehicles which seemed to suddenly accelerate very rapidly from a stationary position until they crashed. Typically, the driver reports that pushing on the brake pedal had no effect whatsoever and that the vehicle only stopped when it crashed. The driver usually reports that the vehicle began to accelerate as rapidly as possible immediately after he or she shifted the automatic transmission into Drive or Reverse. Evidence of high engine power output is frequently found, consisting of acceleration skid marks (the wheels spun) which begin where the vehicle had been parked, and crash damage which indicates that the vehicle had accelerated at its maximum rate. The term "Unintended Acceleration" (*UA*) has been applied to describe such types of complaints, which involve all of the following three elements:

1. High-powered unwanted vehicle acceleration;
2. Initiated from a stationary position or very slow speed (parking lot, driveway speed); and,
3. Accompanied by apparently ineffective brakes.

Less severe types of unwanted engine power problems, such as an abnormally fast idle or throttle sticking which can be controlled with the brakes, are not considered to be *UA*, even though such problems can be safety related.

Two Examples of *UA*

Washington Square Park in New York City was crowded with people enjoying the sunshine on one of the first pleasant warm afternoons in April 1992 when, outside the park, the driver of a parked car shifted the transmission into Drive. To her horror, the wheels suddenly spun and the car lurched forward toward the park at the end of the street, almost 120 m straight ahead. "Knowing" her foot was on the brake, she pushed on the pedal as hard as she could, but the car continued to accelerate, crossed two intersections, and hit the curb at the edge of the park at over 80 km/h. The impact with the curb blew out a tire and deflected the car upwards through the air before it obliterated a concrete drinking fountain in the center of a walkway and came back down. People tried to get out of the way, but many were hit, and several people were thrown through the air as the car continued to move along the walkway, hitting occupied benches, first on the right, and then on the left side of the walkway. Finally, after traveling more than 60 m inside the park, it stopped with one person on the hood and several people underneath the car. The driver said she had been pushing on the brake pedal, and there was something wrong with the car.

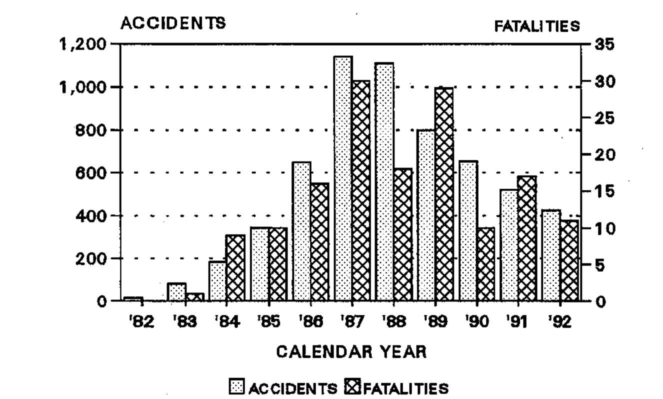
Five people died and 26 people, between the ages of 1 and 84, were injured. The police collected enough shoes scattered at the scene to fill a large plastic trash bag. A comprehensive vehicle inspection was conducted after the accident, but no vehicle defect which could have caused the car to accelerate so rapidly was found. Witnesses reported that the vehicle's brake lights were not illuminated at any time during the *UA* incident, even though they were found to function normally after the accident.

Another exceptionally serious *UA* accident occurred in a small town in Illinois in June of 1990, at a church-sponsored picnic in a local park. When the driver of a van shifted the transmission from Park to Reverse in an unpaved parking area, it suddenly accelerated much more rapidly than the driver intended. The startled driver reacted by shifting from Reverse to Drive, but the wheels spun in the opposite direction, and the vehicle began to accelerate forward toward a pavilion filled with men, women, and children, most of whom were friends or relatives. The vehicle shot forward and struck several people. An alert woman quickly moved two children out of the way, but she did not have time to move a 17-month old child in a stroller before the vehicle struck her and the child. The vehicle's forward progress was stopped only when it hit a building attached to the pavilion, with the woman and child pinned between the vehicle and the wall, as the engine was still racing. Other people screamed at the driver to turn the engine off, but she was too horrified to respond, and the passenger turned the ignition key off. After the driver moved out of the driver's seat, a half dozen people were able to push the vehicle backwards away from the wall against which the woman and child had been pinned, but both died shortly thereafter. Nine other people were injured.

The vehicle was impounded by the police and thoroughly inspected by several parties, including NHTSA, but no relevant defect was found. The cruise control system was tested, brake fluid was analyzed, and the electronic engine control computer was removed for testing in an identical vehicle. The engine control unit was subjected to a strong magnetic field, and high voltage sparks were applied to its metal housing. No malfunctions of the engine or braking system were found, and none could be induced.

Magnitude of The Problem

NHTSA's Office of Defects Investigation maintains a consumer complaint data system. This system includes all reports regarding safety problems provided by consumers. This system is used to determine if certain real world safety problems exist which warrant a defect investigation. Figure 1 presents the number of *UA* accidents which have been entered into NHTSA's computerized consumer complaint data system for each calendar year (based on the date of accident). This file does not fully indicate the magnitude of the *UA* problem because it only contains reports of incidents which were submitted voluntarily, and does not include information obtained directly from manufacturers during specific investigations or from other sources. However, the file is useful for making comparisons among different groups of vehicles, and for identifying time-related trends.



BASED ON COMPLAINTS IN THE NHTSA CONSUMER COMPLAINT DATA SYSTEM. ACCIDENT DATA REDUCED BY 16% (THE AVERAGE DUPLICATE COMPLAINT RATE). DUPLICATE FATALITIES DELETED MANUALLY.

Figure 1. Reported *UA* Accidents Per Calendar Year. All Model Years of Passenger Cars.

Figure 1 shows that a total of 151 fatalities allegedly involving *UA* were reported for calendar years 1982 through 1992. During this 11 year period, a total of 485,000 traffic fatalities occurred in the U.S. Thus fatalities associated with reported *UA* incidents represent 0.03 percent of fatalities. The percentages may be higher since not all *UA* accidents are reported for inclusion into NHTSA's computerized consumer complaint data system. Under-reporting before approximately the middle of 1986 is probably the major reason for the low number of accident reports shown in Figure 1 for 1982 through 1986. In 1986, the NHTSA investigation of *UA* (at that time called "Sudden Acceleration") in Audi 5000 vehicles, as well as *UA* in general, received extensive publicity on television and other media, and this had the effect of greatly increasing the number of *UA* accidents which were reported (fewer unreported accidents).* Therefore, the reported number of fatalities allegedly associated with *UA* could be close to the actual number during the peak reporting year of 1987. At this level, reported *UA* incidents could involve 0.07 percent of total fatalities.

Balancing the above discussion of underreporting of *UA* incidents, the number of *UA* accidents which are not reported is less than for most other types of accidents because the involved drivers usually believe that they were the victim of a serious vehicle defect for which they blame the vehicle's manufacturer. Also, publicity may have influenced some driver's interpretations of what happened during the rapid, unexpected chain of events associated with *UA*, with the results that some accidents were incorrectly attributed to *UA*. For example, after widespread publicity pertaining to *UA* in Audi 5000 vehicles, one driver turned off the ignition key while idling at a traffic light, refused to drive the car, and reported *UA*, when she heard a sound produced when the cooling fan suddenly started. Several other Audi drivers reported *UA* in the forward direction when they shifted from Park to Reverse, even though the transmission linkage was not subsequently found misaligned. In those instances, the engine had probably been started in Neutral and was then shifted one detent position, into Drive. The startled and disoriented drivers subsequently thought *UA* had occurred because they had been led to believe that Audi vehicles were prone to suddenly accelerate uncontrollably. This demonstrates that some inaccurate reports, which probably compensated for under-reporting to some extent, are included in the data. Taking all of these factors into consideration, it is postulated that *UA* is associated with between 0.03 and 0.07 percent of all traffic fatalities.

* Reinhart, W. 1989. Investigative Report, ODI Case No. C86-001 (1978-1986 Audi 5000 Passenger Cars) NHTSA. 32-33.

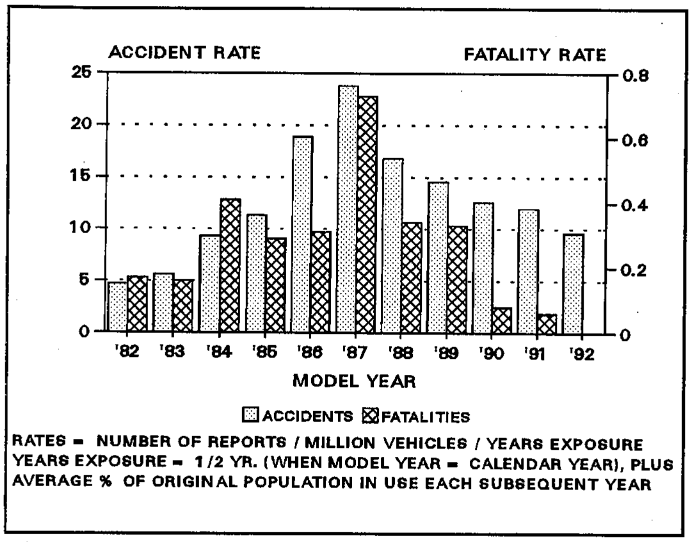


Figure 2. Reported *UA* Accidents And Fatalities Per Million Vehicle Years For Each Model Year.

Figure 2 shows the reported *UA* accident and fatality rates for each model year, in terms of reports per million vehicle years of exposure. Vehicle exposure is based on the assumption that exposure (in vehicle years) during the calendar year which is equal to the model year is 1/2 times the total number of vehicles sold; and that for each subsequent calendar year, exposure equals one times the percentage of the original population which remains in use each year, applicable to each specific vehicle model year. All vehicles of the same model year are assumed to have experienced the same rate of attrition.

Figures 1 and 2 indicate that the *UA* accident and fatality rates have been declining, beginning with both calendar and model year 1988. Additional data is presented later in this report, which explains how vehicle design changes have resulted in a substantial reduction in the *UA* accident rate for 1988 and newer vehicles. The relevant design changes made to some 1988 models do not involve a sufficiently large proportion of all of the passenger cars in use during calendar year 1988 to explain the magnitude of the reduction in reported *UA* accident rates. However, the two models of older vehicles which had accounted for a substantially disproportionate number of *UA* accident reports before 1988* had automatic shift locks installed during recall campaigns begun in 1987, and those changes resulted in a great reduction in *UA* reports beginning with 1988. This is discussed further in the "Countermeasures" section presented later in this report.

Although *UA* is involved in only a small portion of traffic accidents and fatalities, such events can have devastating consequences, as demonstrated by the two previously cited examples. These anecdotes show how anyone can become a victim, since each person injured or killed during those two accidents had been relaxing in a park away from traffic, and the involved drivers had not engaged in any illegal, reckless, or unusual activities before they suddenly lost control of their vehicles. Perhaps more significant is that drivers perceive *UA* incidents as occurring regardless of human actions, and unresponsive to human intervention. This perceived lack of human control over the machine has made it necessary to determine the root causes of *UA*, and to convince drivers that they are not likely to become helpless victims of an uncontrollable machine.

Importance of Accident Data

Figures 1 and 2 are based on reports which allege that an accident occurred, and which were entered in the NHTSA consumer complaint file under a fault code for "Engine Runaway/Sudden Acceleration or Surge." Only reports coded as accidents, rather than all incident reports, were considered for this analysis, because some of the reports of "Engine Runaway" or "Surge" contained in the file involve incidents which do not meet the criteria for *UA*. For example, an engine surging incident, in which the driver was able to control the vehicle sufficiently to avoid an accident, probably did not involve the high engine power and allegedly ineffective brakes characteristics reported in *UA* incidents. However, the unexpected high-powered acceleration of *UA*, accompanied by an apparent loss of braking effectiveness, almost always results in a crash.

Another reason for limiting this analysis to accident involvement is that it provides a more objective measure for comparing *UA* rates among different vehicles, by removing the subjectivity involved in deciding which reports, involving a wide range of unwanted engine power incidents ranging from minor fast idle conditions to allegations of powerful unexpected engine surging,

* 1978 through 1986 Audi 5000, and 1979 through early production 1987 Nissan 280/300 ZX passenger cars.

should be classified as *UA*. For example, it is not always possible to determine if an incident involving a low speed collision with a parked vehicle or a wall in a confined area should be classified as *UA* (high powered acceleration accompanied by apparently ineffective brakes), or simply as an engine surging incident, because it is not always clear whether or not the driver had sufficient time to make effective use of the brakes before the collision stopped the vehicle. Such an incident is more likely to involve *UA* if the vehicle accelerated for an amount of time and distance sufficient to reach an impact speed which results in property damage or injury (an accident), than if the available space and time for the vehicle to accelerate was so limited that it was stopped by a benign collision (not an accident).

CAUSES OF UNINTENDED ACCELERATION

Pedal Misapplications

Most drivers who experienced a *UA* accident claim that the vehicle must have malfunctioned in some mysterious way, even though in the vast majority of cases, no vehicle defects which would explain the vehicle's apparent behavior are ever found. A *UA* involved vehicle manufacturer generally explains the events by stating that the driver stepped on the accelerator pedal instead of the brake pedal. However, the driver often does not believe that explanation, since he or she has correctly applied a brake pedal without error on thousands of previous occasions.

A pedal misapplication by the driver just before shifting out of Park provides a logical explanation for those *UA* incidents which began as soon as the driver shifted out of Park, since this would cause a vehicle to accelerate abruptly as soon as the transmission engages in a moving gear.* A driver who believes that his/her right foot is on the brake pedal could be expected to react to sudden unexpected acceleration by pushing more forcefully on that pedal, since increasing brake pedal application force normally reduces vehicle speed. As a result, if the wrong pedal were being depressed, the accelerator pedal would be depressed as far as possible, causing it to then feel firm like a brake pedal. Under these conditions, the throttle would be held in the fully open, maximum engine power position, no braking action would be produced, and no relevant vehicle defects would be found afterwards.

That explanation is consistent with the following facts and observations:

- Most *UA* incidents began when the driver shifted an automatic transmission out of Park, or into or out of Reverse.

  Pedal misapplications are more likely to occur when the driver attempts to make the first brake application after entering the car or when the upper body is rotated to look behind the vehicle.

- Although reports of engine performance problems such as excessive idle speed, surging, throttle linkage sticking, and cruise control system malfunctions are received for almost all car models, reports involving all of the characteristics of *UA* are not received for cars with manual transmissions.

  A car with a manual transmission cannot be put in motion unless a driver places one foot on the clutch and the other on the accelerator pedal.

- Reports of *UA* have been received for all common makes, models, and model years of cars with automatic transmissions sold in substantial quantities during the last 20 years.

  Many different engine and braking system design features have been utilized, and many changes in vehicle design have been made during the last 20 years, while the basic characteristics of humans pertaining to perception, neuro-muscular control and feedback, panic reactions, etc., have not changed.

- A disproportionally large number of *UA* accidents have been reported for elderly drivers, based on the number of licensed drivers and the average miles driven. For certain domestic cars, the mileage based reported *UA* accident rate for drivers over the

* 70% of *UA* accidents for vehicles without shift locks were reportedly triggered by shifting out of Park. See Table 1, Infra.

age of 70 was approximately 5 times above average.*

The fact that drivers over the age of 70 have experienced a substantially higher accident rate for other types of accidents, suggests that elderly drivers are more likely to make driving errors than younger drivers.** This suggests that the occurrence of *UA* is related primarily to human factors.

- Drivers of borrowed or newly obtained cars have experienced a disproportionately large number of *UA* accidents.***

  Drivers are most likely to make pedal misapplications when driving vehicles with which they have had little experience, even if they have had extensive driving experience in general.

- The average height of drivers who experienced *UA* is less than the average height for all drivers.****

  The ergonomic relationship between a driver and the control pedals is affected by the physical dimensions of the driver. For example, short drivers normally position the seat further forward than tall drivers to be closer to the control pedals. As a result, shorter drivers have to move their right legs through a larger angle to the left of the accelerator pedal to apply the brake pedal.

UA symptoms can also result if the driver's foot contacts both the brake and the accelerator pedal at the same time. The visible wear found on the rubber brake pedal pads of high mileage passenger cars indicates that most drivers step on the right side, rather than in the middle of the brake pedal. Applying the brake in this manner causes a portion of the driver's shoe to project beyond the right edge of the brake pedal. This creates no problems as long as the lateral distance between the brake and accelerator pedals is sufficient to prevent both pedals from being depressed simultaneously. However, dual pedal application can be a problem on vehicles with limited lateral pedal separation if, due to braking system characteristics and the design of the control pedal system, the brake pedal must be pushed below the height of the accelerator pedal (closer to the floor), before substantial braking action is produced. Some braking action is obtained in such cases, but the vehicle can accelerate to a moderate speed if the power output exceeds braking action at certain levels of pedal force.* Dual pedal application can also occur in vehicles with normally sufficient vertical pedal offset, if the driver's foot is angled so that the right side of the shoe is lower, as may occur if the driver's body is twisted to look backwards.

One situation which does not actually constitute a pedal misapplication, but which involves *UA* resulting from driver action, can occur when a vehicle is stopped parallel to a curb. If the front wheels are turned into the curb and the driver does not recognize that fact, the vehicle will not move forward after the transmission has been shifted into Drive and the driver releases the brake, because the vehicle is restrained by the curb. If the driver then increases power gradually, the vehicle still will not move until engine power output is sufficient to suddenly cause the front tire to climb up and over the curb. The driver then has to hastily apply the brake because power output is excessive once the curb no longer restrains the car. A *UA* accident can result if the driver makes a pedal misapplication as he or she tries to hastily apply the brake while being jostled physically as each wheel goes over the curb, or if the driver is not able to apply the brake during the short distance which may be available to stop on the sidewalk.

Vehicle Defects

An important aspect of *UA* is the fact that drivers allege that pushing on the brake pedal did not noticeably affect the unwanted acceleration.

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* Reinhart, W. 1986. Engineering Analysis Action Report EA78-110 (1973-1986 GM passenger cars). NHTSA.

** Williams, A. and Carsten, O. 1989. Insurance Institute of Highway Safety Status Report Vol. 24, No. 5.

*** The median experience driving an Audi 5000 passenger car which experienced an *UA* accident was 6 months. Reinhart W. 1989. Investigative Report, ODI Case C86-001. NHTSA.

**** Reinhart, W. 1989. Investigative Report, ODI Case No. C86-001 NHTSA.

* 1978 through 1983 Audi 5000 vehicles were recalled (Recall Campaign 83V-095) voluntarily by the manufacturer to address *UA*, by attaching a spacer plate to raise the brake pedal surface.

This means that, in addition to the vehicle having a defect which produces unwanted engine power, the braking system also would have had to fail simultaneously. Tests conducted with numerous vehicles demonstrated that pushing on the brake pedal with reasonable force decelerates and stops any passenger car with normal brakes,* even if the accelerator pedal is held in the maximum power position.**

No single defect, involving failure of the two vehicle systems which must occur simultaneously to produce *UA*, has ever been found in a group of vehicles. However, safety-related defects which produced unwanted engine power have produced *UA* in rare, exceptional cases involving individual vehicles which also had a coincidental braking system abnormality. However, in such rare instances, the braking system malfunction was repeatable and detectable. For example, such a chain of events could begin if the driver fully depressed the accelerator pedal before starting the engine. If the accelerator pedal or throttle linkage then became stuck in the open position, the engine, when started would produce very little vacuum for a vacuum power-assisted brake system. In addition, if the power brake booster check valve was also coincidentally defective and failed to retain stored vacuum, then the driver would be confronted with unexpected engine power and a weak braking system as soon as the transmission was shifted out of Park. Under such a scenario, *UA* could result.

Examples of safety recall campaigns which have been conducted to correct vehicle defects that could in a small number of instances be associated with a *UA* event include:

- Recall 71V-235: If the left engine mount failed in 1965 through 1971 full-size and intermediate passenger cars produced by General Motors Corporation, the engine torque reaction could rotate the engine slightly, causing the throttle to be pulled fully open. Such engine rotation could also pull the check valve out of the power brake booster, if the vacuum hose between the engine and the power brake booster was too short, resulting in a loss of power braking assist.

- Recall 79V-111: The accelerator pedal could become stuck, but only after the driver fully depressed it, in certain 1977 and 1978 Cadillac vehicles. Drivers who depressed the accelerator pedal to the maximum extent before starting the engine could experience *UA* when they shifted out of Park, if the stored vacuum in the power brake booster had leaked out while the vehicle was parked, due to coincidental check valve malfunction.

- Recall 82V-037: The accelerator pedal could become stuck due to interference with a floor mat, but only after the driver fully depressed the pedal, in 1978 through 1983 Audi 5000 vehicles. Drivers who depressed the accelerator pedal to the maximum extent before starting the engine could experience *UA* when they shifted out of Park if the stored vacuum in the power brake booster had leaked out while the vehicle was parked.

It should be noted, however, that these scenarios did not occur during the vast majority of reported *UA* incidents. Post-accident investigations of cars which experienced *UA* almost always indicated that the power brake booster stored adequate vacuum for normal power braking action.

Numerous recall campaigns have been conducted involving throttle linkage, cruise control system, engine idle speed control system, and other problems which could result in unwanted engine power. If the braking system has a mechanical weakness, such as an abraded hydraulic brake pipe or hose, or a deteriorated seal, then it may fail when the brake is being applied with exceptional force to overcome the unwanted engine power. Thus almost any problem involving unwanted engine power may conceivably result in *UA* in a very small number of isolated incidents involving coincidental braking system failures. However, this has not occurred during most of the reported *UA* accidents. Post-accident investigations in most cases produced no evidence of braking system failures, even though such evidence would have

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* Pollard, J. 1989. An Examination of Sudden Acceleration. Transportation Systems Center. Report No. DOT-HS-807-367

** Some exceptionally powerful cars with rear wheel drive and good rear tire traction may slow to walking speed, rather than come to a complete stop, as the rear wheels push the car and the front tires slide with locked front brakes.

been easily detectable, since the brakes would not have functioned normally until repairs were made.

A list of NHTSA investigations relating directly and indirectly to *UA* is provided in Appendix A.

CONTRIBUTING FACTORS IN UNINTENDED ACCELERATION

Human Factors and Ergonomics

Driver-related factors pertaining to *UA*, which were discussed in a previous section of this report concerning pedal misapplications, include advanced driver age, short height, and unfamiliarity with the vehicle. However, whether or not pedal misapplications occur also depends greatly on the interactions between drivers and vehicles.

Several studies have been performed which attempted to correlate vehicle control pedal designs with the *UA* accident rate, since it was suspected that certain pedal design features would influence the frequency of pedal misapplications. One study, performed in 1982 as part of a NHTSA defect investigation, failed to establish a relationship between control pedal dimensions and *UA* events on 84 different 1973 through 1981 model year domestic passenger cars.* Two additional studies, one involving 24 different 1976 through 1982 model year domestic cars,** and the other involving 10 different 1976 through 1982 imported cars,*** were performed in 1984. These studies, which included measuring pedal dimensions, and pedal force/displacement characteristics, did not identify a relationship between vehicle factors and the potential for pedal misapplications.

It is intuitively obvious that separating the brake and accelerator pedals with a large distance in both the lateral and vertical directions would reduce the potential for pedal misapplications. However, possible pedal locations are limited by the space available in the vehicle, as well as comfort considerations for a wide range of drivers of different sizes. Also, increasing vertical offset increases the time required for a driver to quickly release the accelerator pedal and lift his or her foot up and over the brake pedal to make an emergency brake application.

During a study performed at Virginia Polytechnic Institute, using a laboratory simulator on which the pedals were adjusted to duplicate the dimensions of four different actual cars, the largest number of pedal errors occurred with a vehicle with a relatively large vertical pedal offset, but which had experienced a below average *UA* accident rate in the real world.* The observed pedal errors involved drivers scuffing their feet underneath the brake pedal, an action which would not have caused *UA*, but which would have lengthened the effective stopping distance of the vehicle. Thus, although providing a large vertical offset might help prevent *UA* incidents for a few drivers, such a design could also produce negative safety consequences in the form of longer braking reaction time for all drivers.

However, the pedals should not be so close together that dual pedal misapplications are likely to occur. The 1978 through 1983 Audi 5000 vehicles were recalled to raise the height of the upper brake pedal surface, after NHTSA test results indicated dual pedal misapplications were more likely to occur with 1978 through 1983 Audi 5000 vehicles than with any of the other cars tested.**

A study performed by the Texas Transportation Institute, based on both real-world and laboratory observations of drivers, found no single location where all drivers would expect to find the brake pedal.*** The study produced general guidelines for control pedal design, but no pedal design was found which would prevent all pedal misapplications without producing other negative consequences.

The Transportation Systems Center in Cambridge, MA (TSC) attempted to combine several control pedal-related factors in one single variable, which TSC called "Critical Vertical

* General Adjustment Bureau. 1982. Control Pedal Evaluation. Engineering Analysis E78-110. NHTSA

** Vehicle Research and Test Center. 1984. Control Pedal Performance Evaluation - Domestic Vehicles. NHTSA

*** Vehicle Research and Test Center. 1984. Control Pedal Performance Evaluation - Imported Vehicles. NHTSA

* Rogers, S.B. and Weirwille, W.W. 1988. The Occurrence of Accelerator And Brake Pedal Actuation Errors During Simulated Driving. Human Factors, 30.

** NHTSA Recall No. 83V-095. (1978-1983 Audi 5000 Passenger Cars)

*** Brackett, Pezoldt, Sherrod, and Roush. 1989. Human Factors Analysis of Automotive Foot Pedals. Texas Transportation Institute. DOT Report DOT HS 807 512.

Offset" (CVO).* The value of CVO for any given vehicle is determined by clamping onto the surface of the brake pedal a flat plate which also extends over the accelerator pedal. This plate itself does not touch the accelerator pedal, but a threaded rod which passes down through the plate can be adjusted to contact the accelerator pedal (which is normally at a lower height than the brake pedal). The driver can depress the brake pedal with a repeatable force by stepping on a brake pedal force transducer which is attached to the upper surface of the plate above the brake pedal. The length of the rod below the plate is then adjusted until depressing the brake pedal with a specific force causes the rod to depress the accelerator pedal sufficiently to cause engine power (transmission in Drive) to just balance brake torque (the vehicle is on the threshold of moving). The measured length of the rod below the lower surface of the plate (which is at the same height as the surface of the brake pedal) constitutes the CVO value for that vehicle.

Rather than simply measuring the positions of the brake and accelerator pedals when they are not in use, this method takes into account the slack in both linkages, and the force/displacement characteristics of each pedal near the point where significant braking torque and engine power begin to be generated. It was thought that this method might be useful because a driver not only has to make a pedal misapplication to experience a *UA* accident due to pedal misapplication, but also must not be aware of the situation, since he or she would otherwise reposition the foot correctly. For example, a driver of a vehicle which has a very firm brake pedal but weak throttle return springs might be more likely to notice if the wrong pedal is being applied than the driver of a vehicle whose brake and accelerator pedals had nearly identical force-displacement characteristics.

TSC theorized that a low CVO value primarily would be a problem on vehicles which also had a small lateral separation. At first, it appeared that a combination of a low CVO value and limited lateral separation (e.g a CVO of less than 1.5 mm with less than 8 cm lateral separation) would be a predictor of substantial *UA* over-involvement. However, certain exceptions were noticed. Specifically, mid-1980s model year Honda Civic vehicles were found to have low values for CVO and lateral separation, even though they have not produced a disproportionately large number of *UA* accident reports. Substantial lateral separation and only slightly low CVO were measured for the 1984 Mercury Marquis, yet those vehicles had produced an above average number of *UA* accident reports.

One possible explanation is that the Civic enables more engine noise to be heard in the driver/passenger compartment, making it more likely that a driver making a pedal misapplication would hear abnormal engine noise before shifting the Civic out of Park. Also, Honda Civic drivers tend to be younger, and Mercury Marquis drivers tend to be older than the average driver, and older drivers have been over-involved in *UA*.

Vehicle Defects As Contributing Factors

The most common type of vehicle defect which can not by itself cause *UA*, but which can be a significant contributing factor, is any defect which results in unwanted engine power in stationary or slow moving vehicles. The primary reason why unwanted engine power can result in *UA*, even though a reasonably firm application of the brake would have stopped the vehicle, is that some drivers react by making a pedal misapplication when they are surprised by unwanted engine power. For example, if the engine is idling abnormally fast before the transmission is shifted out of Park, a short duration power surge can be felt by the driver as the rotating parts of the engine, which have considerable rotational momentum, are coupled to the drive train.* This could startle a driver into making a pedal misapplication. This was demonstrated during a test performed by NHTSA, when one test subject, driving a specially prepared Audi 5000 vehicle, responded to a sudden unexpected engine idle speed increase by stepping on the accelerator, instead of the brake pedal.**

Incidents involving unwanted engine power caused by vehicle defects are sometimes described as *UA* (even though they do not completely meet

* Pollard, J. 1989. An Examination of Sudden Acceleration. Transportation Systems Center. Report No. DOT-HS-807-367

* Vehicle Research and Test Center 1987. Inspection and Testing of a 1984 Audi 5000S For Surprise Acceleration. Investigative Case C86-001, Exhibit E15.15 NHTSA.

** Vehicle Research and Test Center 1987. Driver Reaction To Unexpected Fast Engine Speed And Sudden Acceleration. Investigative Case C86-001, Exhibit E15.16 NHTSA.

the definition of *UA*), if the driver does not have sufficient time to make effective use of the brake before an impact with a nearby object stops the vehicle. Such incidents tend to result in less serious accidents than *UA* involving pedal misapplications, because the vehicle cannot accelerate to high speed in the short distance available. However, they may have a significant effect on the number of *UA* incidents which are reported.

Accelerator pedal or throttle linkage sticking can result in high engine power output, since drivers may depress the accelerator pedal before or while starting the engine, or to obtain momentary acceleration from a slow speed. This may contribute to *UA* resulting from pedal misapplication, if the driver is startled when the transmission is shifted out of Park, or when the driver releases his or her foot from the accelerator pedal but the engine speed does not decrease as expected.

Cruise control system malfunctions could, in extremely rare instances, involving two or more defects, open the throttle and produce near maximum power output. It should be noted that this is not a major contributing factor for *UA* since the majority of the vehicles which experienced *UA* were not equipped with a cruise control system. Also, cruise control systems installed by vehicle manufacturers have a low-speed cut-off circuit which must fail before the system can operate at the stationary or low speeds associated with *UA*. Furthermore, many cruise control systems utilize a brake pedal controlled "vacuum dump" switch which releases the vacuum used to power the cruise control servo when the brake pedal is applied, thereby mechanically depriving the cruise control system of the force needed to hold the throttle open in opposition to the force of the throttle return springs. Such brake pedal cruise control system vacuum switches are designed so that a spring opens the valve whenever the brake pedal is not in the rest position. Thus, misadjustment of the switch or failure of its support bracket would result in a safe failure mode (inoperative cruise control).

Electronic engine idle speed control system malfunction can cause excessive engine idle speed, which can become a contributing factor with respect to *UA*, if the driver is suddenly surprised by unwanted engine power. Most such systems employ an electronically-controlled valve which permits air to bypass the throttle valve, while some others rotate the throttle valve a limited amount. However, such systems cannot produce the high power output which is exhibited during *UA* accidents, because they only move the throttle a limited amount, or control a valve which permits air to bypass the throttle through an idle air passage. The size of the idle air bypass passages is only large enough to permit sufficient airflow, even if the idle air valve is completely open, to produce a fraction (less than 20 percent) of the power which the engine could produce with a fully open throttle.

Alleged Intermittent Vehicle Defects

Drivers who report *UA* usually reject the pedal misapplication explanation, based primarily on their own perceptions and the fact that they had never applied the wrong pedal on any previous occasion. Drivers who continued to push on the same pedal until the vehicle crashed are not easily convinced to change their belief that they had been pushing on the brake pedal. Such drivers may suspect that something was overlooked during the vehicle examination, especially if the vehicle was equipped with electronic components, which may be suspected of having experienced intermittent malfunctions, even if no problem was found in a post-incident inspection.

Some drivers involved in *UA* accidents who were certain that they had not stepped on the wrong pedal hired someone to find a vehicle defect. Unable to find a verifiable vehicle defect, yet not willing to disbelieve their client's assertion about applying the brakes, some individuals developed theories about vehicle defects which could have caused intermittent malfunctions. Theories about intermittent malfunctions are not convincingly disproved merely because the malfunction is not observed after the accident.

Systems which have been suspected of intermittent malfunctions include electronic engine idle speed control, fuel injection, and cruise control systems. Suspected causes of such alleged malfunctions include cracked soldered electrical connections, malfunctions of electronic components, malfunctions of sensors, or improper programming of micro-processor logic. Electromagnetic interference (EMI) produced by surges of electrical power within the vehicle's electrical system, as well as radio frequency interference (RFI), allegedly produced by sources such as television transmitters or airport radar, have been mentioned as possible causes for intermittent idle speed control, cruise control, or fuel injection system malfunctions which were not repeatable.

However, all major vehicle manufacturers design their vehicles to be unaffected by EMI or RFI, and perform appropriate tests to verify the adequacy of their designs. Also, micro-processors have normally been programmed to return the engine idle to a predetermined slow speed, and to turn off the cruise control system, if a malfunction or abnormality is detected. To date, no instances have been found where *UA* or unwanted engine power resulted from EMI or RFI in motor vehicles.

Electronic fuel injection system malfunctions can not increase engine power substantially, because power output on all modern gasoline engines is controlled by the amount of air which flows past the throttle valve into the combustion chambers of the engine. Fuel cannot be combusted, and power cannot be created, unless the fuel is mixed with air in the proper proportion. Fuel injection systems (and carburetors) are designed to provide the proper amount of gasoline for any given airflow, and only a slight power increase can be obtained by increasing the amount of fuel above the ratio which provides best fuel economy and emissions performance.* The magnitude of engine power exhibited during *UA* accidents can not be produced by any type of malfunction of the electronic fuel injection system, because adding too much fuel actually reduces power, and in extreme cases, causes the engine to stop running.

Most *UA* accidents which have been reported in the United States involve passenger cars with braking systems which are completely independent of the electrical system (most did not have ABS braking), so that braking system failure could only have occurred if a hydraulic or mechanical component had failed. The fact that braking systems were found to operate normally (or had only crash damage) after almost all of the *UA* accidents which were investigated is significant. Such braking system failures would not be intermittent, since broken parts or ruptured hydraulic lines, hoses, or seals remain permanently damaged, and must be replaced to restore normal braking system performance.

Another fact which contradicts theories claiming that malfunction of electronic components or other engine-related components have caused *UA* incidents is that *UA* has been reported for all major make, model, and model year vehicles, including vehicles with one, two, three, or four venturi carburetors, all types of fuel injection systems, and Diesel engines. Not only does this group of vehicles include a great diversity of electronic components, but many of the older vehicles which experienced *UA* did not utilize any electronic components.

The fact that many investigators, assessing different *UA* accidents in different countries, have not found defects which could have produced maximum engine power and simultaneous brake failure, serves as extremely strong evidence that such intermittent defects did not exist. It is unlikely that engine control and braking system defects would suddenly occur at the same time and then correct themselves after an accident.

COUNTERMEASURES

Automatic Shift Locks

Automatic shift lock systems were designed to address *UA* events by preventing the driver from shifting an automatic transmission out of Park unless the brake pedal is being depressed. This is usually accomplished by use of a mechanism which prevents the gear selector linkage from being moved out of the Park position except when an electric solenoid is energized by the brake light switch. Some other vehicles utilize a cable, having one end connected to the brake pedal linkage, and the other end connected to the transmission linkage such that it prevents shifting out of Park except when the brake pedal is depressed.

Shift locks do not make pedal misapplications completely impossible. However, they greatly reduce the risk of *UA* resulting from pedal misapplications, since *UA* cannot occur if the driver makes a pedal misapplication when the transmission is in Park. Further, a driver is less likely to

* The Transportation Systems Center calculated that power on certain Audi engines could be increased by a maximum of 5 percent by changing the air-fuel ratio to maximize power. Pollard and Sussman 1989. An Examination of Sudden Acceleration. TSC. Appendix H.

depress the wrong pedal after having correctly applied the brake pedal while shifting out of Park.

The 1987 model year Audi passenger cars were the first cars which were sold in the United States equipped with factory-installed shift locks. Nissan also began to install shift locks in 1987 Nissan 300ZX cars,* and the Japan Automobile Manufacturers Association agreed in December 1987 that its members would begin to phase in shift locks until all cars with automatic transmissions produced in Japan for sale in Japan would have shift locks. The first Toyotas sold in the U.S. equipped with shift locks were 1988 Corollas. Honda, Mazda, and Nissan began to phase-in shift locks beginning with several 1989 models. Ford Motor Company began to install shift locks in some 1990 Ford models, and General Motors Corporation began to install them in some 1991 models. Appendix B identifies all 1988 through 1992 passenger car models equipped with shift locks which were sold in the United States. Figure 3 presents the percentages of automatic transmission equipped passenger cars of each model year which were equipped with shift locks.

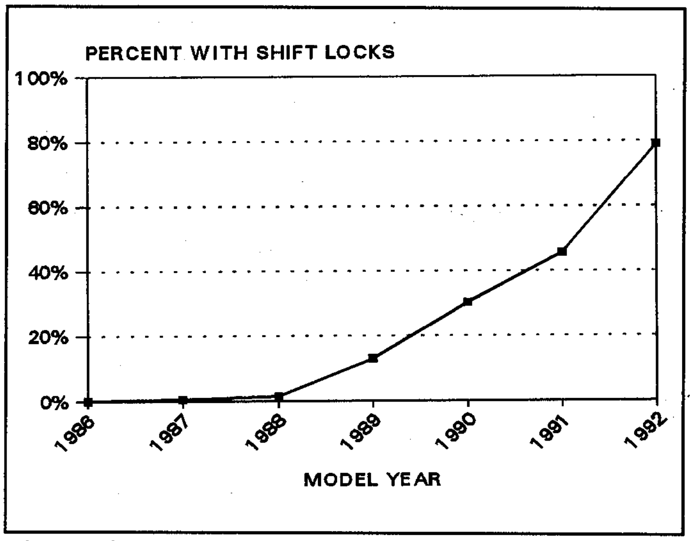

Figure 3. Percent of automatic transmission passenger cars sold in the U.S. equipped with shift locks.

The reports contained in the NHTSA consumer complaint file for 1991 and 1992 models were reviewed to determine the shifting sequence which preceded each reported *UA* accident. Table 1 shows the shift sequence reportedly performed just before the *UA* began.

Table 1
Reported Shift Sequence Immediately Prior to *UA* Accidents Reported for 1991 and 1992 Model Year Passenger Cars

Shift * Sequence	Cars Without Shift Locks		Cars With Shift Locks	
	Reports	Percent	Reports	Percent
P/R	23	25%	5	12.5%
P/N	1	1%	0	0%
P/D	40	44%	3	7.5%
Total From Park	64	70%	8	20%
P/P	9	10%	1	2.5%
R/R	3	3%	2	5%
N/N	0	0%	2	5%
D/D	11	12%	23	57.5%
Total No Shift	23	25%	28	70%
N/D	0	0%	1	2.5%
R/D	3	3%	2	5%
D/P	1	1%	1	2.5%
Total Other	4	4%	4	10%
Total Reviewed	91		40	

* Shift Sequence: From/To. Based on those 1991 and 1992 model year reports which described shift sequence.

P = Park, R = Reverse, N = Neutral, D = Drive.
N/N or P/P = *UA* Allegedly triggered by starting engine.
UA not triggered by shifting transmission if both are the same.

The shift sequences in Table 1 are based primarily on the recollection of the drivers pertaining to the transmission shift which triggered the *UA*. Shifting performed after the *UA* had reportedly begun and shifts made shortly, but not immediately, before the *UA* reportedly began are not considered to have triggered *UA*. For example, if *UA* began when the driver reportedly applied the brake one or two seconds after having completed shifting out of Park into Drive, then the incident would be coded as D/D for Table 1. Also, in some

* Shift locks were retrofitted to 1979 through early production 1987 models during a recall campaign (NHTSA No. 87V-098).

instances the actual shift sequence may have been different than what the driver remembers. For example, several reports indicate that the vehicle accelerated in Park, even though the car should not move in Park. Possible explanations include a misadjusted gear selector linkage which caused the transmission to be in Reverse gear (the position adjacent to Park) in some instances, or inaccurate reporting.

It can be seen from Table 1 that the largest category of the reported *UA* accidents for cars without shift locks occurred when the driver shifted out of Park (64 reports; 70%). This category only constitutes eight reports (20%) of the reported *UA* accidents for cars equipped with shift locks. The conclusion that pedal misapplications made just before or while shifting out of Park have been the major cause of reported *UA* is supported by this data, which (in conjunction with data presented in Table II) indicates that avoidance of that specific type of accident has enabled shift lock equipped cars to experience a substantially lower reported *UA* accident rate than cars without shift locks.

One unexpected result is that 20 percent of the reported *UA* accidents for cars with shift locks allegedly occurred when the transmission was shifted out of Park, even though the shift lock system should not have permitted shifting out of park if the driver was stepping on the wrong pedal. One possible explanation is that the *UA* may have begun shortly, but not immediately, after the driver shifted out of Park. For example, if a driver is startled by an abnormally fast idle condition which was not noticed until the driver released the brake immediately after shifting out of Park, the driver may hastily attempt to re-apply the brake but make a pedal misapplication. Also, in confined areas, an accident can result even if a driver, surprised by a fast idle speed, correctly steps on the brake pedal, because it may be too late to stop the vehicle within the small distance available. Such incidents may then incorrectly be described as *UA*. In general, many drivers who experienced a *UA* accident (with or without shift locks) became confused and disoriented by the rapid, frightening events occurring during the incident, to the extent that their best recollection of the precise details surrounding the events which occurred may be faulty.

Effectiveness of Retrofitted Shift Locks In Audi 5000 Passenger Cars

In August 1986, the first automatic shift lock systems began to be to retrofitted in the 1984 through 1986 Audi 5000 vehicles which were the subject of a NHTSA defect investigation based on reports of *UA*.* This recall provides data for another assessment of the effectiveness of shift locks, since the change in the reported *UA* accident rate resulting from installation of the shift locks could be observed. A reduction in the number of *UA* accidents which reportedly occurred each month began to be noticeable by the end of December 1986, when approximately 35 % of all Audi 5000 vehicles in use in the U.S. had been equipped with shift locks during a service campaign which proceeded the formal safety recall campaign. Figure 4 indicates a continuing decline in the number of *UA* accidents which reportedly occurred each month until the number stabilized by approximately October 1987, when the percentage of 1978 through 1986 Audi 5000 vehicles equipped with shift locks had reached approximately 70 percent. Shift locks continued to be installed after October 1987, but at a relatively slow rate. As is common for all recalls, a 100 percent completion rate was not possible because some vehicles had been scrapped, some vehicle owners could not be located, and some owners chose not to participate in the recall campaign.

The analysis of shift lock system effectiveness is complicated slightly by the fact that the Audi 5000 vehicles also were found to have problems involving erratic engine idle speeds,** which were corrected during recall campaigns begun in February and October of 1987. These recalls also relate to *UA* because an unexpected fast engine idle condition can startle drivers, thereby increasing the likelihood that a pedal misapplication may occur. However, Figure 4 shows that the number of *UA* accidents reported for each month had already declined significantly by February 1987, when

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* Investigative Case C86-001. Sudden Unwanted Acceleration in 1978 through 1986 Audi 5000 passenger cars equipped with automatic transmissions.

** NHTSA Recall Campaigns 87V-008 (all 1978 through 1986 models), 87V-009 (1985 and 1986 models without turbo-chargers), and 87V-170 (All 1984 models and turbocharged 1985 models).

approximately 40 percent of the Audi 5000 vehicles had been equipped with shift locks, but the idle speed control recalls had just been initiated. Further, the fast idle speed control recall (begun in October 1987) did not appear to have a substantial effect on reported *UA*, based on the data presented in Figure 4.

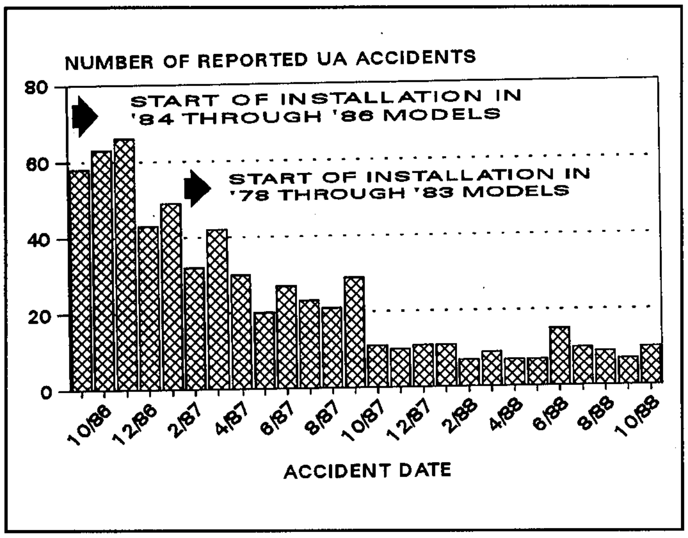

Figure 4. Effect of retrofitting shift locks on the number of *UA* accidents reported for each month for 1978 through 1986 Audi 5000 passenger cars.

In December 1987, after shift locks had been retrofitted in most of the Audi 5000 vehicles, NHTSA mailed a questionnaire to approximately 100,000 Audi 5000 owners to find out if they had experienced any problems related to *UA*. The vehicle manufacturer provided specific information for each vehicle whose owner had reported a relevant problem, including whether or not a shift lock system was installed, and the date it was installed. This provided an opportunity to evaluate the effectiveness of shift locks, since most of the vehicles had been operated for a substantial period without, and then with, shift locks. It was found that cars without shift locks had experienced an average of 2.8 times the reported *UA* accident rate of cars equipped with shift locks. Thus, the Audi experience indicated a shift lock effectiveness in reducing *UA* of 64 percent.

Effectiveness of Shift Locks

A comparison of the *UA* accident rates reported to NHTSA for passenger cars with and without shift locks was made, utilizing NHTSA's computerized consumer complaint data system. Table 2 compares the reported *UA* accident rates for cars with and without shift locks for each specific model year since 1988 (the first year when a substantial number of vehicles were equipped with shift locks).

Table 2
Reported *UA* Accident Rates
Vehicles With And Without Shift Locks *

Model Year	1988	1989	1990	1991	1992
Automatic Transmission Cars Without Shift Locks					
Reported Accidents	772	442	272	164	49
Vehicles Sold (thousands)	8,550	6,543	5,254	3,994	1,496
Accident Rate (per 100,000)	9.03	6.76	5.18	4.11	3.28
Years Exposure **	5.35	4.40	3.45	2.47	1.49
Acc./Million Vehicle Yrs.***	16.9	15.4	15.0	16.6	22.0
Cars With Shift Locks					
Reported Accidents	8	42	54	53	64
Vehicles Sold (thousands)	121	975	2,289	3,351	5,730
Accident Rate (per 100,000)	6.61	4.31	2.36	1.58	1.12
Years Exposure **	5.35	4.40	3.45	2.47	1.49
Acc./Million Vehicle Yrs.***	12.4	9.8	6.8	6.4	7.5
All Cars With Automatic Transmissions					
Percent With Shift Locks	1.4%	13%	30%	46%	79%
UA Accidents Avoided By Shift Locks ****	27%	36%	54%	61%	66%

* Based on cumulative data up to February 9, 1994.

** Years exposure = 1/2 year (when model year = calendar year), plus average percent of original population in use each subsequent year.

*** Accidents/million vehicle years = number of reports in Appendix A / million vehicles originally sold/ years exposure.

**** *UA* accidents avoided = 1 - (accident rate for cars with shift locks/accident rate for cars without shift locks).

Table 2 and Figure 5 provide a strong indication that the use of shift locks has resulted in a substantial reduction in *UA* accident rates. The effectiveness of shift locks provides evidence that pedal misapplications have been the major cause of *UA*, since shift locks do not correct any engine or braking system defects, but only influence driver behavior.

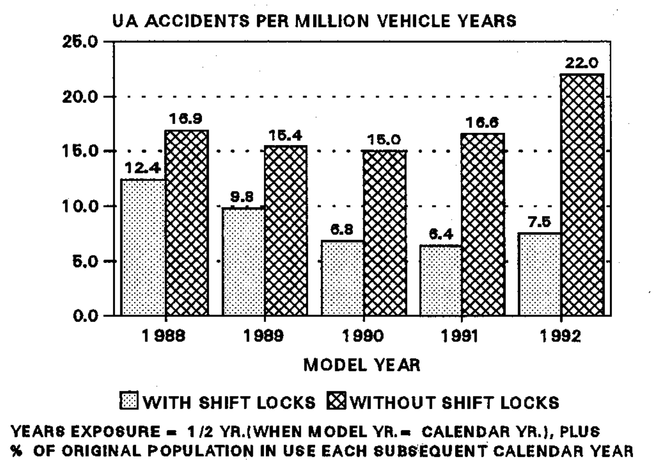

Figure 5. Reported *UA* accident rates for passenger cars with and without shift locks.

The higher reported average annual *UA* accident rates shown in Figure 5 for 1992 model year vehicles without shift locks, compared to earlier model years, are probably due to the fact that, historically, the highest annual *UA* accident rate is reported during the first year of a vehicle's existence, when every one is operated by a driver who only recently obtained it. This supports the theory that driver unfamiliarity with a specific vehicle is a factor which contributes to pedal misapplications. As the 1992 models experience a few more years of exposure, their average annual reported *UA* accident rate is expected to decline.

It is noticeable that the calculated shift lock effectiveness shown in Table 2 for 1988 models is substantially less than for the newer model years, even though shift lock effectiveness was compared for the same model year vehicles, with and without shift locks, which have had the same exposure. The best explanation for this is based on the fact that shift locks were installed in only a small number of 1988 model year cars (less than 2 percent), which had in prior model years experienced extremely high rates of reported *UA* accidents,* compared to other vehicles of the same model year, and which had been the subjects of publicized NHTSA investigations for which consumer complaints were actively solicited. The extent to which publicity, or vehicle design factors, such as control pedal dimensions, or driver characteristics, or other factors such as driver/purchaser profiles were involved in producing the 1988 model year statistics is not known. In any event, the effectiveness of shift locks can best be determined by analyzing data from 1992 and newer model years, when typical passenger cars, rather than only a few selected models, are equipped with shift locks.

Figure 5 shows that the difference between reported average annual *UA* accident rates for vehicles with and without shift locks is the least for 1988 models. The *UA* rate for the 1988 model year vehicles with shift locks is, nevertheless, lower than for vehicles without shift locks of any model year.

Safety Defect Recall Campaigns

On numerous occasions, NHTSA has been asked by vehicle owners and other parties to investigate complaints of *UA*, in order to identify possible vehicle defects which could then be corrected during recall campaigns performed by the manufacturers. During numerous investigations which were conducted by NHTSA, or of which NHTSA otherwise became aware, throughout the last 20 years, vehicle design or quality control defects which, by themselves, resulted in full power acceleration accompanied by complete brake failure have never been found.

However, numerous recall campaigns have been conducted to correct defects which were related to *UA* because they produced unwanted engine power. The relationship between unwanted engine power and *UA* was discussed in an earlier section of this report titled "Vehicle Defects As Contributing Factors."

It is noteworthy that after the 1978 through 1983 Audi 5000 vehicles were recalled to prevent accelerator pedals from getting stuck in the fully depressed position, those vehicles continued to

* The 1978 through 1987 Audi 5000 cars had produced a combined reported *UA* accident rate of 586 reports per 100,000 cars.

generate a disproportionate number of new reports of *UA* until an additional recall was performed to install shift locks. The accelerator pedal defect apparently was less of a problem than pedal misapplications, probably because only a small percentage of the accelerator pedals actually became stuck.

Control Pedal Design

The relationship between control pedal design and *UA* was discussed in the previous section of this report titled "Human Factors And Ergonomics." As stated in that section, and as evidenced by a wide range of reported *UA* accident rates for different models of passenger cars, vehicle design appears to have a substantial effect on the rate of *UA* involvement resulting from pedal misapplications. However, even though three relevant studies have been performed by NHTSA, and studies were also performed by the Transportation Systems Center, and by the Texas Transportation Institute (TTI), no specific pedal location has been identified which would be effective in preventing *UA* without producing other undesirable effects. For example, a high brake pedal position would appear to be desirable, but this also increases the time the driver requires to move the right foot from the accelerator to the upper surface of the brake pedal, and in some instances causes drivers to temporarily trap the right foot underneath the brake pedal. A large horizontal pedal separation also would appear to be desirable, but many vehicle chassis designs make this impractical, especially in vehicles with four wheel drive systems which require space for the transmission or transfer case. A firm brake pedal which can only be pushed a very short distance, contrasted to a "soft" accelerator pedal, might help drivers know when the wrong pedal is being applied, but this might negatively affect the ability of drivers to modulate braking system output.

Furthermore, as suggested by the human factors analysis of automotive foot pedals performed by TTI, it may not be possible to completely prevent pedal misapplications, since the behavior of human beings cannot always be predicted. For these reasons, it appears that issuance of relevant government regulations at this time would not be appropriate.

Driver Education

Many of the reported *UA* accidents could have been avoided if the drivers had simply turned off the ignition key as soon as the vehicle began to accelerate uncontrollably. Some drivers have experienced panic reactions which caused them to "freeze" and prevented them from steering the car or taking any action other than continuing to push on what they believed was the brake pedal. Another common reaction is for drivers to concentrate on steering, while continuing to push on what they believed was the brake pedal. In some instances, drivers have attempted to shift the automatic transmission into Neutral or Park. That course of action can be helpful, but in many instances the drivers were unable to select the desired gear (probably because they were occupied with steering the car), and this sometimes resulted in the vehicle changing direction but crashing nevertheless. In general, it appears that most of the drivers who experienced *UA* did not respond in the most appropriate way, probably because they were confronted with an unexpected, stressful situation for which they had never been prepared, and which occurred too fast to enable them to take any action other than acting on conditioned reflexes.

It would be useful if drivers were prepared to interpret *UA* as a signal that they might not be pushing on the brake pedal, and responded by applying the brake with the left foot and lifting the right foot. However, training drivers not to panic, and how to cope with *UA* once it has begun, has severe practical limitations. In the U.S., most drivers receive training as a prerequisite to obtaining their driver's licences, with no additional training being provided afterwards. In general, this has not been a problem for most drivers because they continued to utilize the acquired skills and knowledge during their routine driving. However, the majority of drivers who experienced *UA* had obtained their drivers' training many years before the *UA* accident occurred, and would probably have had no occasion to utilize training applicable to *UA* during the intervening years, since *UA* events are quite rare. Thus it is doubtfull that drivers who make a pedal misapplication for the first time in their lives after many years of driving would remember the relevant instructions, if such instructions had been provided during driver training many years earlier.

A more practical approach involves educating new drivers in good procedures which should always be followed. The primary procedure applicable to preventing *UA* involves being sure that the brake pedal is being applied before shifting the transmission out of Park. When one manufacturer filmed the feet of drivers without their knowledge, it was found that many drivers who said (and believed) that they had applied the brake before shifting out of Park had actually begun to move the transmission gear selector before they completed moving the right foot onto the brake pedal.* If an aiming error occurred and the foot went on the wrong pedal, such a driver would receive no indication of a problem until the vehicle suddenly accelerated and the driver was confronted with an immediate emergency situation.

When the foot movements and shifting habits of 216 drivers in their own cars were observed during TTI's human factors study, it was found that 35 percent of the drivers did not have a foot on the brake pedal when they shifted out of Park. Apparently, some drivers allow the engine to idle in Park until they are ready to move, at which time they shift into Drive without any pedal being depressed. If the engine idle speed is abnormally fast, or if, due to traffic or other reasons, the vehicle's acceleration has to be slowed, the first brake application after the driver enters the car may have to be made in haste. A driver who already has a foot on the brake pedal is in a much better position to respond to unexpected events which may not become apparent until the transmission is shifted out of Park.

Educating drivers always to be certain the brake is being applied before shifting out of Park has some merit, but shift lock systems provide a more reliable method of achieving the desired result. With a shift lock system, the driver must apply the brake before the vehicle can be moved, so that the driver's foot will be positioned on the brake pedal at the time when the engine can begin to move the car. Furthermore, driving a shift lock-equipped vehicle helps those drivers who had not previously done so develop the habit of always depressing the brake before shifting out of Park.

* Reinhart, W. 1986. Engineering Action Report EA78-110. NHTSA

SUMMARY

o Pedal misapplications by drivers who inadvertently and unknowingly stepped on the accelerator instead of the brake pedal have constituted the most common cause of *UA*.

o Vehicle defects which by themselves caused all of the symptoms of *UA*, including high powered acceleration from a stationary position accompanied by total braking system failure, have never been found in any group of vehicles sold in the United States.

o In rare instances, solitary vehicles have experienced failure of a deteriorated braking system component (e.g., a chafed brake tube or hose), when the driver applied the brake with exceptional force in response to unwanted engine power.

o Vehicle defects which produce unwanted engine power, even though the brakes remain capable of stopping the car, can be contributory factors relating to *UA* for two reasons: drivers may not be able to react fast enough to use the brake to stop in certain confined parking areas, and drivers who are startled at inopportune times are more likely to make a pedal misapplication.

o Shift lock systems which prevent the driver from shifting an automatic transmission out of the Park position unless the brake pedal is being applied simultaneously constitute the most effective known countermeasure for preventing *UA* accidents.

o Consumer complaint data received by NHTSA indicates that automatic transmission-equipped passenger cars with shift locks experience a reported *UA* accident frequency approximately 60 percent less than comparable cars without shift locks.

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ACTION_NO	MFR	VEHICLES	SUBJECT	DATE OPENED	DATE CLOSED	RECALL	UNINTENDED ACCEL *
IR008	FORD	ALL 1967	LINKAGE CAUSES GAS PEDAL TO STICK	31-Oct-67	18-Dec-67		N
IR050	GM	ALL 1968	VEH. W/6 CYL., THROTTLE CLIP	06-Sep-68	11-Oct-68	68V-085	N
IR059	FORD	THUNDERBIRD 1967	THROTTLE/FLOOR MAT INTERFERENCE	22-Oct-68	21-Jan-69		N
IR074	CHRYSLER	ALL 1968	THROTTLE CABLE STICKING	20-Dec-68	24-Jun-71		N
IR078	FORD	THUNDERBIRD 1967	THROTTLE PREVENTED FROM CLOSING	14-Jan-69	13-Mar-69		N
IR162	GM	CHEVROLET CAPRICE 1968	ENG. ROTATES IF MOUNT FAILS	20-Oct-69	23-Jun-70		Y
IR196	GM	BUICK SKYLARK 1969-1970	CABLE STICKS	09-Jan-70	20-Feb-70	70V-010	N
IR213	HONDA	CB 750 1969-1970 MOTORCYCLES	THROTTLE STICKING	07-Apr-70	01-Jul-70	71V-147	N
IR228	VOLVO	140,164,1800 MODELS, 1969	ACCELERATOR STICKAGE	14-May-70	20-Jun-72		N
IR258	GM	CHEVROLET 1965-1970	ACCELERATOR/ENGINE MOUNTS	28-Oct-70	01-Feb-72	71V-235	Y
IR258.5	GM	1965-1967 BUICK, 1970 CADILLAC	ACCELERATOR/ENGINE MOUNTS	28-Oct-70	01-Dec-76	76V-120	Y
IR268	TOYOTA	CORONA 1970	LINKAGE MAY BIND	30-Dec-70	08-Feb-72	71V-084	N
C72-022	WHITE MOTOR	ALL	903 V8 TRACTOR. ACCEL.SPRING FAIL.	27-Sep-71	10-Mar-72		N
IR258.6	FORD	ALL 1965-72	ACCELERATOR/ENGINE MOUNTS	19-Nov-71	06-Apr-72		Y
IR258.7	CHRYSLER	ALL 1965	ACCELERATOR/ENGINE MOUNTS	19-Nov-71	06-Apr-72		Y
IR258.8	AMC	ALL 1965-71	ACCELERATOR/ENGINE MOUNTS	27-Nov-71	06-Apr-72		Y
IR258.9	CHECKER	ALL 1965-70	ACCELERATOR/ENGINE MOUNTS	27-Nov-71	06-Apr-72		Y
C72-034	TOYOTA	CELICA 1972	CARB. ACCEL.PUMP LINKAGE HANGUP	22-Dec-71	25-Feb-72		N
C72-035	GM	CHEVROLET VEGA 1971	THROTTLE SOLENOID BRACKET	04-Jan-72	22-May-72	72V-112	N
EA72-007	TOYOTA	TOYOTA	THROTTLE LINKAGE	10-Jul-72	03-Aug-72		N
EA72-025	GM	CHEVY NOVA 1971	ACCELERATOR STICKING	20-Sep-72	14-Nov-72		N
EA72-049	FORD	MERCURY MONTEREY, 1971	ACCELERATOR CABLE	09-Nov-72	16-Feb-73		N
EA72-051	TOYOTA	TOYOTA/MARK II, 1971	ACCELERATOR LINKAGE	15-Nov-72	16-Feb-73		N
EA72-054	GM	VEGA WITH 2300 ENG., 1972	BINDING/STICKING ACCEL	15-Nov-72	22-Mar-73		N
EA72-050	CHRYSLER	PLYMOUTH CRICKET, 1971-1972	ACCELERATOR LINKAGE	29-Nov-72	16-Feb-73		N
EA73-019	FORD	STATION WAGON 1969	ACCELERATOR CABLE	09-Feb-73	03-May-73		N
EA73-049	HONDA	CIVIC	ACCELERATOR LINKAGE	18-Apr-73	03-May-73		N
EA73-055	GM	CHEVY PICKUP 1972	THROTTLE CONTROL	11-May-73	18-Oct-73		N
C73-042	FORD	F-500 TRUCK 1967-1972	THROTTLE BINDING	12-Jun-73	06-Oct-76		N
EA73-071	FORD	MERCURY 1972	SPEED CONTROL	21-Jun-73	13-Sep-73		N
EA74-022	FORD	PINTO 1971-1972	THROTTLE SOLENOID	08-Aug-73	18-Oct-73		N
EA74-023	VOLVO	VOLVO 1971-1972	THROTTLE RETURN SPRING	08-Aug-73	18-Oct-73		N
EA74-026	AMC	MATADOR 1973	ACCEL. PEDAL INTERFERENCE	15-Aug-73	18-Oct-73		N
C74-018	FORD	FORD 1965-1970	ACCELERATOR/ENGINE MOUNTS	13-Sep-73	23-Nov-82		Y
EA74-045	MACK	MACK TRUCK 1972	WHEELS AND ACCEL.	15-Oct-73	10-Dec-73		N
EA74-047	GM	CHEVROLET 1969-1974	ACCELERATOR/ENGINE MOUNTS	16-Oct-73	05-Jul-74		Y
EA74-048	GM	VARIOUS 1968-1973	ACCELERATOR LINKAGE	16-Oct-73	05-Jul-74		N
C74-029	FORD	ALL 1967-1974	NON-METALIC FAST IDLE CAM	13-Dec-73	07-Apr-79		N
C74-053	GM	CHEVROLET CHEVELLE, 1965-1969	ACCELERATOR/ENGINE MOUNTS	24-Apr-74	07-Nov-79		Y
C75-008	TOYOTA	COROLLA 1971-1973	THROTTLE STICKS. 1600 CC ENG.	18-Oct-74	10-May-79		N
EA76-002	NISSAN	DATSUN 240 Z	ACCEL. LINKAGE	31-Jul-75	31-Dec-75		N
EA76-015	NISSAN	DATSUN TRUCK 1971	ACCELERATOR CABLE	13-Jan-76	03-May-76		N

ACTION_NO	MFR	VEHICLES	SUBJECT	DATE OPENED	DATE CLOSED	RECALL	UNINTENDED ACCEL *
EA77-012	JRT	AUSTIN MARINA 1974	BRAKES/ACCEL CABLE	01-Dec-76	02-Nov-78	78V-016	Y
C77-014	VW	RABBIT,DASHER,SCIROCCO, 1973-1976	ALLEGED THROTTLE CONTROL STICKS	11-Apr-77	26-Apr-79	77V-245	N
EA77-042	JRT	TRIUMPH 1974-1976	IGNITION & ACCEL. CABLE	25-May-77	18-Jun-77		N
EA77-044	VOLVO	VOLVO 1974-1975	ACCELERATOR STICKS	26-May-77	10-May-78	77V-219	N
EA77-051	FORD	TRUCK, C600/C700, 1977	THROTTLE PLATE HANGS UP	15-Jun-77	08-Dec-77		N
C77-032	JAGUAR ROVER	TRIUMPH TR7, 1975-1977	THROTTLE CABLE FAILURE-ACC STICKS	18-Jul-77	17-Jul-79	77V-143	N
EA77-069	JRT	AUSTIN MARINA, 1974-1975 & 1970-1977 TRIUMPH	ENGINE SURGE	27-Jul-77	27-Jul-78		N
EA77-082	FIAT	FIAT 1975-1977	THROTTLE RETURN SPRING	27-Sep-77	19-Jan-78	78V-010	N
C77-040	JAGUAR ROVER	MG MIDGET 1970-1974	THROTTLE CABLE MAY STICK	28-Sep-77	28-Aug-79		N
EA78-034D	AMC	CARS 1977	CAR STUMBLE AND SURGE	12-Jan-78	26-Apr-78		N
EA78-038	VOLVO	1970-1978	THROTTLE MALFUNCTION	09-Feb-78	10-May-78		N
EA78-039	GM	F/S CHEV/PONTIAC 1975-1978	ACCEL. PEDAL JAMS	09-Feb-78	09-May-78		N
EA78-041	FORD	FORD 1977	CRUISE CONTROL	14-Feb-78	30-Apr-78		N
EA78-061	ANNUNCIONICS	PACESETTER CRUISE CONTROL	CRUISE CONTROL JAMS THROTTLE	16-May-78	20-Nov-78		N
EA78-034Q	GM	CUTLASS 1978, PONTIAC 1977	HESITATION/ENGINE SURGE	17-May-78	23-Jun-78		N
EA78-034Z	CHRYSLER	TRANSMISSION	MID-SPEED SURGE COLD DRIVE	18-May-78	25-Jun-78		N
EA78-066B	FORD	LIGHT TRUCKS WITH 302 CID ENG., 1977	ENGINE SURGE	22-May-78	08-Jun-78		N
EA78-066V	VW	RABBIT 1978	THROTTLE KICKER W A/C	16-Aug-78	15-Nov-78		N
EA78-110	GM	AUTOMATIC TRANSMISSION MODELS, 1973-1986	SUDDEN ACCELERATION	30-Aug-78	05-Aug-86		Y
EA78-117E	MACK	R,RD,U AND R FIRE TRUCKS	ACCEL. RTN. SPRING BREAKAGE	22-Sep-78	24-Oct-78		N
EA79-016	SUBARU	ALL MODELS 1974-1978	COLD WEATHER THROTTLE STICK	07-Nov-78	16-Nov-78	79V-016	N
EA79-004J	FORD	FIESTA 1978	CARB. HOT SOAK SURGE, HESITATION	08-Nov-78	14-Dec-78		N
EA79-044	GM	CADILLACS 1977-1978	SUD ACCEL WHEN 1ST IN GEAR	22-Jan-79	02-May-79	79V-111	Y
EA79-080	CHRYSLER	OMNI/HORIZON, 1978-1979	ALLEGED THROTTLE STICKING	22-May-79	10-Sep-81		N
EA79-068P	FORD	CARS AND TRUCKS 1977-1978	SECONDARY THROTTLE PLATES	23-May-79	18-Apr-80		N
EA79-068V	FORD	3200 MOD. CARB. 1974-1978	THROTTLE SHAFT ICING	08-Aug-79	03-Nov-79		N
EA79-068Y	SAAB	900	ELECTRONIC SPEED CONTROL	17-Sep-79	20-Dec-79		N
C80-004	VW	DIESEL RABBIT 1977-1980	ENGINE RUNAWAY	22-Jan-80	23-Jul-82		N
EA80-050	TOYOTA	MODEL RT 134	ACCELERATOR LINKAGE	12-Feb-80	27-Apr-80		N
EA80-052	NISSAN	DATSUN 1974-1983	SUDDEN ACCELERATION	29-Feb-80	30-Apr-85		Y
EA80-074	TOYOTA	CELICA,COROLLA,CORONA 1975-1978	ACCELERATOR PEDAL STICKING	17-Apr-80	29-Sep-83		N
EA80-097	A.R.A. MFG	AFTERMARKET CRUISE CONTROL	CRUISE CONTROL SYSTEM	02-Jul-80	22-Dec-80		N
EA80-109	GM	CHEVETTE 1979	THROTTLE STICKING	14-Aug-80	15-Nov-83		N
EA81-005	FIAT	STRADA 1979	THROTTLE STICKING	01-Oct-80	05-Jul-84		N
EA81-006	JRT	TRIUMPH TR-7, 1977	THROTTLE STICKING	05-Nov-80	15-Jul-81		N
C81-002	VW	RABBIT,FOX,DASHER,SCIROCCO, 1975-1980	ALLEGED THROTTLE STICKING-CABLE	09-Jan-81	27-Sep-82	81V-012	N
EA81-010J	EAGLE	VARIOUS BUSES	THROTTLE LINKAGE	19-Jun-81	28-Jul-81		N
EA82-002	VW	AUDI 5000 1978-1981	SUDDEN ACCELERATION	31-Oct-81	10-May-82	82V-037 (a)	Y
IR82-009	SEARS	AFTERMARKET CRUISE CONTROL	CRUISE CONTROL	27-Nov-81	14-Jan-82		N
EA82-045	GM	CAMARO/FIREBIRD 1982	THROTTLE STICKING	28-Sep-82	06-Aug-84		N
IR83-041	GM	X-BODY CARS, 1981	VACUUM HOSE/THROTTLE HANGUP	07-Mar-83	15-Jul-83		N
IR83-044	BENDIX	CRUISE CONTROL SYSTEM	THROTTLE PROBLEMS	22-Mar-83	14-Jul-83		N
IR83-076	IHC	SCHOOLBUS 1983	THROTTLE STICKING	29-Jun-83	09-Jul-83		N
IR83-087	DEUTZ	VARIOUS TRUCK VANS	THROTTLE CABLE FAILURES	23-Aug-83	28-Aug-84		N
EA83-020	TOYOTA	CORONA/CELICA/CRESSIDA, 1979-1982	SUDDEN ACCELERATION	20-Sep-83	26-Nov-84		Y
EA84-001A	BLUEBIRD	WANDERLODGE 1983-1984	CRUISE CONTROL MOD	19-Oct-83	28-Dec-83		N

ACTION_NO	MFR	VEHICLES	SUBJECT	DATE OPENED	DATE CLOSED	RECALL	UNINTENDED ACCEL *
IR84-017	HONDA	HONDA 1981-1982	SUDDEN ACCELERATION	28-Oct-83	04-Feb-85		N
IR84-020	VW	QUANTUM 1982	ACCELERATOR PEDAL STICKS	08-Nov-83	21-Jul-84		Y
EA84-003	MERCEDES	MERCEDES 1978-1982	SUDDEN ACCELERATION	09-Nov-83	23-Jan-84	84V-007	Y
IR84-054	IHC	SCHOOL BUS 1983	THROTTLE STICKS	22-May-84	07-Sep-84	84V-091	N
IR84-061	RADATRON	AFTERMARKET CRUISE CONTROL UNIT	THROTTLE HELD OPEN	26-Jun-84	16-Nov-84		N
PE85-030	GM	J BODY CARS, 1982-1985	ENGINE SURGE	14-Feb-85	04-Feb-86		N
EA85-029	NISSAN	280Z/300Z 1979-1987	SUDDEN ACCELERATION	09-May-85	11-Jul-89	87V-098	Y
PE85-051	GM	CHEVETTE 1979-1982	THROTTLE STICKING	01-Jul-85	08-Nov-85		N
PE85-056	MAZDA	GLC 1981-1982	THROTTLE STICKS	08-Aug-85	23-Oct-85	85V-136	N
EA85-043	AMC	ALLIANCE/ENCORE 1983-1984	UNWANTED VEHICLE ACCELERATION	21-Aug-85	21-Jul-87		N
EA85-045	TOYOTA	CRESSIDA 1981-1984	SUDDEN ACCELERATION	30-Aug-85	18-Feb-88	86V-132	Y
PE85-065	FORD	FULL / MIDSIZE CARS 1983-1985	SUDDEN ACCEL AND SURGING	06-Sep-85	05-Aug-86		N
PE86-050	VOLVO	ALL MODELS 1980-1986	SUDDEN ACCELERATION	28-Apr-86	01-Oct-86	86V-129	N
EA86-013	GM	CAMARO 1984	CRUISE CONTROL	08-May-86	28-Sep-87		N
C86-001	VW	AUDI 5000, 1978-1986	SUDDEN ACCELERATION	05-Aug-86	11-Jul-89	87V-008 (b)	Y
PE87-001	MERCEDES	300E, 1986	SUDDEN ACCELERATION	02-Oct-86	14-Jan-87		Y
EA87-007	GM	J BODY CARS 1982-1985	SUDDEN ACCELERATION	16-Dec-86	07-Aug-87		N
PE87-018	CHRYSLER	COLT 1985-1986	SUDDEN ACCELERATION	03-Feb-87	06-Jul-87		Y
EA87-012	HONDA	ACCORD, 1986-1987	SUDDEN ACCELERATION	06-Mar-87	10-Sep-87		Y
EA87-021	FORD	FUEL INJECTED 3.8L & 5.0L ENGINES, 1983-1986	ENGINE SURGE	29-Jun-87	16-Mar-89		N
PE87-061	ALFA ROMEO	SPIDER 1985	THROTTLE STICKING	30-Sep-87	30-Nov-87		N
EA88-003	MERCEDES	MERCEDES 300E 1986-1987	SUDDEN ACCELERATION	29-Oct-87	29-Oct-87		Y
EA88-010	GM	H BODY CARS, 1986-1987	THROTTLE CONTROL	30-Nov-87	30-Nov-87	88V-080	Y
EA88-023	GM	CARS WITH 5L. ENG., 1984-1985	CRUISE CONTROL	12-Feb-88	23-Mar-89	89V-102	N
PE88-029	CHRYSLER	JEEP 1987-1988	THROTTLE CONTROL	23-Feb-88	19-Sep-88		N
EA88-026	HONDA	ACURA,STERLING 1986-1988	SUDDEN ACCELERATION	08-Mar-88	10-Jan-91		Y
PE88-033	GM	FIERO 1984	THROTTLE CABLE	10-Mar-88	06-May-88		N
EA88-031	GM	C BODY CARS, 1985-1987	SUDDEN ACCELERATION	22-Apr-88	23-Oct-89	88V-080	Y
EA88-034	MERCEDES	ALL MODELS EXCEPT 300E 1986-1988	SUDDEN ACCELERATION	15-Jul-88	31-Jul-90		Y
PE88-082	NAVISTAR	MODEL S SCHOOL BUS 1985-1988	SUDDEN ACCELERATION	18-Jul-88	03-Nov-88		Y
PE88-090	GM	G SERIES VANS WITH 6.2L DIESEL ENG., 1988	CRUISE CONTROL	08-Aug-88	28-Oct-88		N
PE88-097	FORD	T-BIRD,COUGAR 1987-1988	FLOORMAT/ACCEL.PEDAL INTERF.	31-Aug-88	02-Dec-88		N
EA89-001	CHRYSLER	PLYMOUTH SUNDANCE 1987 & 1988	CONTROL LOGIC MALFUNCTION	05-Oct-88	17-Nov-89		N
PE89-019	FORD	TRUCKS/SCHOOL BUSES 1987	THROTTLE STICKING	01-Dec-88	05-Mar-89		N
PE89-095	CHRYSLER	JEEP CHEROKEE 1987	CRUISE CONTROL	01-Mar-89	28-Jun-89		N
PE89-097	GM	TRUCKS WITH 5.7 & 7.4 L ENG., 1988	CRUISE CONTROL	06-Mar-89	05-Jun-89		N
EA89-037	FORD	MUSTANG,CAPRI,TEMPO,TOPAZ, 1986-1987	CRUISE CONTROL	19-Apr-89	06-Sep-89		N
PE89-149	YAMAHA	FZR400, FZR600 MOTORCYCLES, 1989	THROTTLE STICKING	03-Aug-89	28-Sep-89		N
EA89-035	WILLIAMS	ELECTRICAL ACCELERATOR PEDAL, 1985-1988	ELECTRONIC ACCELERATOR PEDAL	29-Aug-89	16-Nov-90	90E-010	N
PE89-163	L.A.G.	BUS THROTTLE CABLE, 1986-1987	THROTTLE CABLE	11-Sep-89	07-Nov-89	89V-201	N
PE90-003	ARA MFR.	CRUISE CONTROL	CRUISE CONTROL	10-Oct-89	05-Feb-90		N
PE90-014	GM	REGAL, CUTLASS SUPREME, 1985-88	CRUISE CONTROL LINKAGE	31-Oct-89	28-Feb-90		N
PE91-031	VW	JETTA 1985 & 1986	ENGINE MOUNT FAILURE	31-Oct-89	29-Apr-91		N
PE90-019	FORD	TAURUS, SABLE 1986-1988	CRUISE CONTROL	27-Nov-89	27-Mar-90		N
PE90-026	GM	SUBURBAN 1984-1988	CRUISE CONTROL	02-Dec-89	09-Apr-90		Y
EA90-009	FORD	COUGAR, THUNDERBIRD, 1988-1989	THROTTLE STICKING	08-Feb-90	28-Feb-91		N

APPENDIX A - ALL INVESTIGATIONS SINCE 1967 RELATED TO UNINTENDED ACCELERATION

ACTION_NO	MFR	VEHICLES	SUBJECT	DATE OPENED	DATE CLOSED	RECALL	UNINTENDED ACCEL *
PE90-051	FORD	PICKUP & VANS WITH EFI 1985-1990	IDLE SPEED	05-Mar-90	05-May-90		N
PE90-058	GM	LUMINA 1990	CRUISE CONTROL	15-Mar-90	20-Jun-90		N
PE90-081	CHRYSLER	RENAULT MEDALLION 1988-1989	THROTTLE LINKAGE	11-May-90	14-Aug-90	90V-138	N
EA90-042	FORD	TAURUS, SABLE 1986-1989	THROTTLE STICKING	31-Aug-90	31-Dec-91		N
PE91-001	BMW	3,6,&7 SERIES CARS WITH MOTRONIC EFI	MOTRONIC IDLE SPEED CONTROL	03-Oct-90	28-Jan-91		N
PE91-029	GM	CAD. DEVILLE & FLEETWOOD 1990	THROTTLE LINKAGE INTERFERENCE	07-Jan-91	16-Apr-91		N
PE91-080	CHRYSLER	SPIRIT, ACCLAIM WITH 2.5L ENG., 1991	ENG SPEED FLUCTUATIONS	30-May-91	30-Sep-91		N
PE91-088	MAZDA	MPV, MX6, 626, 929, 1989-1991	THROTTLE STICKING	18-Jun-91	21-Oct-91		N
PE91-089	FORD	MUSTANG WITH 5.0L ENG.,1990	THROTTLE STICKS, HIGH IDLE	19-Jun-91	26-Nov-91		N
EA91-032	HONDA	ACURA INTEGRA 1991	SPEED CONTROL FAILURE	12-Jul-91	13-Jul-92		N
EA91-034	FORD	EXPLORER 1991	THROTTLE RELEASE FAILURE	17-Jul-91	10-Apr-92		N
EA91-005	CATERPILLAR	3304,3306,3006B,3406,3406B ENG.	GOVERNOR PIN, THROTTLE	26-Nov-91	24-Feb-92	92E-005	N
EA92-015	GM	S10,BLAZER,JIMMY WITH 4.3L TBI ENG.,'89-'91	HIGH IDLE SPEED FLARE	07-Jan-92	28-May-93		N
EA92-005	GM	CAMARO,F.BIRD,CORV. W. 5&5.7L TBI ENG.'85-'88	THROTTLE STICKING	30-Jan-92	29-Jan-93		N
PE92-014	FORD	TAURUS,SABLE,CONT. W. 3.0L &3.8L ENGS.'88-'90	ENGINE MOUNTS	04-Feb-92	25-Jun-92		N
EA92-024	GM	GM A, J, L, & W BODIES W. 2.8L ENG. '87-'91	THROTTLE STICKING	26-Jun-92			N
EA92-044	TOYOTA	CAMRY & CELICA W. 2.0L ENG. '87-'89	THROTTLE STICKING	18-Dec-92			N
EA93-003	FORD	EXPLORER, 1991	FLOOR MAT/ACCEL PEDAL INTERFERENCE	15-Jan-93	06-Jan-94		N
EA93-004	FORD	EXPLORER & NAVAJO. 1992	TRANS. GEAR INDICATOR MISALIGNMENT	29-Jan-93	06-Jan-94		N
PE93-011	FORD	MUSTANG, 1986 -1988	CRUISE CONTROL	02-Mar-93	19-Jul-93		N
PE93-014	DAMON	CHALLENGER MOTORHOMES, 1992	THROTTLE LINKAGE INTERFERENCE	08-Mar-93	18-Jul-93	93V-097	N
EA93-012	GM	CAPRICE W. 4.3L. V-6 ENG.	THROTTLE STICKING	12-May-93			N
PE93-056	CHRYSLER	CHRYSLER, DODGE, & PLYMOUTH MINI-VANS, 1991	THROTTLE CABLE MELTING	09-Jun-93	14-Sep-93		N
PE93-069	FORD	L-SERIES TRUCKS, 1993	THROTTLE RETURN SPRING FAILURES	27-Jul-93	30-Sep-93		N
EA93-022	FORD	'91 TAURUS/SABLE & '91 & '92 LIGHT TRUCKS	IDLE AIR SPEED CONTROL VALVE	30-Jul-93			N
EA93-033	FORD	THUNDERBIRD COUGAR W. 3.8L. ENG.,'89-'92	THROTTLE VALVE INSULATOR BUSHING	30-Dec-93			N

ACTION NUMBERS BEGINING WITH:
"PE" OR "IR" ARE PRELIMINARY EVALUATIONS
"EA" ARE ENGINEERING ANALYSIS
"C" ARE INVESTIGATIVE CASES

ADDITIONAL RECALLS:

AUDI AUDIT (A83-02)	(a)	83V-095	Y
AUDI CASE (C860-01)	(b)-1	87V-009	Y
AUDI CASE (C860-01)	(b)-2	87V-170	Y

* UNINTENDED ACCELERATION IS DEFINED AS HIGH-POWERED, UNWANTED ACCELERATION FROM SLOW OR STATIONARY SPEED COMBINED WITH INEFFECTIVE BRAKES.

"PEs" OR "IRs" MAY BE UPGRADED TO "EAs." "EAs" MAY BE UPGRADED TO INVESTIGATIVE CASES ("C")
EACH INVESTIGATION ("PE," "EA," ETC.) IS COUNTED ONLY ONCE ("PE" IS NOT COUNTED IF UPRADED TO "EA," ETC.)

INVESTIGATIONS ARE CLASSIFIED AS UNINTENDED ACCELERATION BASED ON INCIDENT DESCRIPTIONS BY DRIVERS OR OTHER INTERESTED PARTIES, REGARDLESS OF TECHNICAL CONSIDERATIONS.

INVESTIGATIONS PERTAINING TO UNWANTED ENGINE POWER AT SLOW OR STATIONARY SPEED ARE CONSIDERED TO BE RELATED INVESTIGATIONS BECAUSE, ALTHOUGH SUCH PROBLEMS CANNOT BY THEMSELVES CAUSE UNINTENDED ACCELERATION, THEY CAN IN SOME SITUATIONS STARTLE DRIVERS AND CONTRIBUTE TO INADVERTANT APPLICATION OF THE ACCELERATOR INSTEAD OF THE BRAKE PEDAL (THE MOST COMMON CAUSE OF UNINTENDED ACCELERATION).

BRAKING SYSTEM INVESTIGATIONS WHICH DO NOT INVOLVE UNWANTED ENGINE POWER ARE NOT SHOWN.

MAKE	MODEL	1988 MODELS VEHICLES SOLD	1988 REPORTED ACC.	1988 RATE*	1989 MODELS VEHICLES SOLD	1989 REPORTED ACC.	1989 RATE*	1990 MODELS VEHICLES SOLD	1990 REPORTED ACC.	1990 RATE*	1991 MODELS VEHICLES SOLD	1991 REPORTED ACC.	1991 RATE*	1992 MODELS VEHICLES SOLD	1992 REPORTED ACC.	1992 RATE*	NOTES
ACURA	ALL ACURA							88,386	5	5.7	85,513	4	4.7	90,094	4	4.4	
ACURA	LEGEND				57,061	3	5.3	Y			Y			Y			
AUDI	ALL AUDI	11,866	2	16.9	11,781	2	17.0	17,099	0	0.0	9,381	0	0.0	9,421	0		(1)
BMW	ALL BMW													45,000	2	4.4	(2)
BUICK	SKYLARK													60,647	1		
BUICK	LESABRE										90,756	2	2.2	171,551	1		
BUICK	PARK AVENUE										109,482	0	0.0	68,942	0		
BUICK	RIVIERA													5,200	0		(3)
BUICK	ROADMASTER													85,532	3	3.5	
CADILLAC	DEVILLE/FLEETWOOD										147,910	1	0.7	142,328	0		
CADILLAC	ELDORADO													31,151	0		
CADILLAC	SEVILLE													43,954	0		
CHEVROLET	CAPRICE													116,781	2	1.7	
CHEVROLET	CAVALIER													187,952	1		
DODGE/PLYMOUTH	COLT							8,514	1	11.7	13,528	2	14.8	9,000	0		
DODGE	STEALTH										6,932	0	0.0	0	0		
EAGLE	SUMMIT							6,517	0	0.0	15,018	1	6.7	5,469	0		
EAGLE	TALON							6,800	0	0.0	12,104	0	0.0	10,479	0		(4)
FORD	CROWN VICTORIA													86,000	1		(5)
FORD	ESCORT										199,203	3	1.5	70,314	1	1.4	
FORD	FESTIVA							15,659	0	0.0	8,273	0	0.0	7,278	0		
FORD	MUSTANG										61,711	3	4.9	46,555	1		
FORD	PROBE							69,675	0	0.0	53,216	1	1.9	24,826	1		
FORD	TAURUS													334,248	6	1.8	
FORD	TEMPO													194,485	0		
FORD	THUNDERBIRD										80,909	1	1.2	72,636	1		
GEO (GM)	ALL GEO							155,538	2	1.3	74,926	0	0.0	220,107	1	0.5	
HONDA	ALL HONDA							680,989	11	1.6	901,582	8	0.9	755,747	9	1.2	
HONDA	ACCORD				237,729	10	4.2	Y			Y			Y			
HYUNDAI	ALL HYUNDAI										65,000	2	3.1	62,025	0		(6)
INFINITI	ALL INFINITI							18,469	0	0.0	34,025	0	0.0	24,756	1		
ISUZU	ALL ISUZU										5,302	0	0.0	673	0		
ISUZU	IMPULSE							1,634	1	61.2				Y			

* RATE = REPORTED ACCIDENTS PER 100,000 VEHS. "Y" = EQUIPPED WITH SHIFT LOCKS, NUMBER SOLD INCLUDED IN TOTAL FOR VEH. MAKE. BLANK SPACE = NONE SOLD WITH SHIFT LOCKS.

		1988 MODELS			1989 MODELS			1990 MODELS			1991 MODELS			1992 MODELS			
MAKE	MODEL	VEHICLES SOLD	REPORTED ACC.	RATE*	VEHICLES SOLD	REPORTED ACC.	RATE*	VEHICLES SOLD	REPORTED ACC.	RATE*	VEHICLES SOLD	REPORTED ACC.	RATE*	VEHICLES SOLD	REPORTED ACC.	RATE*	NOTES
ISUZU	STYLUS													Y			
LEXUS	ALL LEXUS							60,225	1	1.7	58,978	0	0.0	84,945	1	1.2	
LINCOLN	CONTINENTAL													40,822	0		
LINCOLN	TOWN CAR													71,000	1	1.4	(7)
MAZDA	ALL MAZDA							109,996	5	4.5	119,840	7	5.8	130,500	4	3.1	
MAZDA	RX-7				8,900	0	0.0	Y			Y			Y			(8)
MERCEDES	ALL MERCEDES							54,795	4	7.3	63,813	0	0.0	63,165	0		
MERCEDES	300E				14,200	1	7.0	Y			Y			Y			(9)
MERCURY	CAPRI													2,807	0		
MERCURY	COUGAR										63,701	1	1.6	49,254	1	2.0	
MERCURY	GRAND MARQUIS													102,000	1	1.0	(5)
MERCURY	SABLE													127,530	2	1.6	
MERCURY	TOPAZ													90,796	0		
MERCURY	TRACER										53,729	0	0.0	21,617	0		
MITSUBISHI	ALL MITSUBISHI													119,062	2	1.7	
MITSUBISHI	3000GT										2,761	0	0.0	Y			
MITSUBISHI	ECLIPSE							25,900	0	0.0	24,849	0	0.0	Y			(10)
MITSUBISHI	GALANT							29,828	1	3.4	29,277	0	0.0	Y			
MITSUBISHI	MIRAGE							41,151	0	0.0	52,982	0	0.0	Y			
NISSAN	ALL NISSAN							185,094	6	3.2	260,387	5	1.9	271,058	5	1.8	
NISSAN	240SX				33,117	0	0.0	Y			Y			Y			
NISSAN	300ZX	8,378	2	23.9	11,481	0	0.0	Y			Y			Y			
NISSAN	MAXIMA				85,845	2	2.3	Y			Y			Y			
OLDSMOBILE	88/BROUGHAM/ROYALE										50,429	0	0.0	115,324	0		
OLDSMOBILE	98/REGENCY										54,905	1	1.8	47,584	0		
OLDSMOBILE	ACHIEVA													72,809	0		
OLDSMOBILE	CUSTOM CRUISER													4,347	0		
OLDSMOBILE	TORONADO/TROFEO													2,000	0		(11)
PLYMOUTH	COLT VISTA													3,000	0		(12)
PLYMOUTH	LASER							23,816	1	4.2	10,715	0	0.0	10,994	0		
PONTIAC	BONNEVILLE										42,797	0	0.0	116,002	0		
PONTIAC	GRAND AM													176,713	4	2.3	
PONTIAC	SUNBIRD													67,099	0		
SATURN (GM)	ALL SATURN (GM "Z")										34,039	1	2.9	119,000	1	0.8	(13)

* RATE = REPORTED ACCIDENTS PER 100,000 VEHS. "Y" = EQUIPPED WITH SHIFT LOCKS, NUMBER SOLD INCLUDED IN TOTAL FOR VEH. MAKE. BLANK SPACE = NONE SOLD WITH SHIFT LOCKS.

MAKE	MODEL	1988 MODELS VEHICLES SOLD	1988 REPORTED ACC.	1988 RATE*	1989 MODELS VEHICLES SOLD	1989 REPORTED ACC.	1989 RATE*	1990 MODELS VEHICLES SOLD	1990 REPORTED ACC.	1990 RATE*	1991 MODELS VEHICLES SOLD	1991 REPORTED ACC.	1991 RATE*	1992 MODELS VEHICLES SOLD	1992 REPORTED ACC.	1992 RATE*	NOTES
SUBARU	ALL SUBARU				39,500	3	7.6	81,689	5	6.1	99,548	1	1.0	119,325	2		(14)
TOYOTA	ALL TOYOTA							566,059	10	1.8	266,292	8	3.0	630,765	4	0.6	
TOYOTA	CAMRY				233,675	11	4.7	Y			Y			Y			
TOYOTA	CELICA							Y			Y			Y			
TOYOTA	COROLLA	100,422	4	4.0	147,794	3	2.0	Y			Y			Y			
TOYOTA	CRESSIDA				27,787	4	14.4	Y			Y			Y			
TOYOTA	PREVIA													Y			
TOYOTA	SUPRA				8,689	1	11.5	Y			Y			Y			
TOYOTA	TERCEL				57,866	2	3.5	Y			Y			Y			
VOLKSWAGEN	CABRIOLET							2,460	0					1,000	0		(15)
VOLKSWAGEN	ALL VW EXCEPT CABRI							38,848	1	2.6	34,677	1	2.9	19,295	0		
VOLVO	ALL VOLVO										52,056	0	0.0	66,585	0		
Total Cars With Shift Locks		120,700	8	6.6	975,400	42	4.3	2,289,000	54	2.4	3,351,000	53	1.6	5,730,000	64	1.1	

REPORTED UNWANTED ACCELERATION ACCIDENTS FOR AUTOMATIC TRANSMISSION EQUIPPED CARS WITHOUT SHIFT LOCKS

	1988 MODELS		1989 MODELS		1990 MODELS		1991 MODELS		1992 MODELS	
ACURA	--	83	--	6	--	NA	--	NA	--	NA
ALFA ROMEO	--	0	--	0	--	0	--	1	--	1
BMW	--	7	--	10	--	4	--	6	--	NA
BUICK	--	48	--	20	--	22	--	12	--	7
CADILLAC	--	25	--	12	--	11	--	5	--	1
CHEVROLET	--	59	--	43	--	27	--	45	--	5
CHRYSLER	--	6	--	3	--	2	--	6	--	2
DODGE	--	3	--	8	--	5	--	4	--	0
EAGLE	--	0	--	12	--	1	--	2	--	0
FORD	--	71	--	104	--	61	--	23	--	7
GEO	--	0	--	1	--	NA	--	NA	--	NA
HONDA	--	111	--	15	--	NA	--	NA	--	NA
HYUNDAI	--	9	--	5	--	3	--	NA	--	NA
ISUZU	--	1	--	0	--	0	--	NA	--	NA
JAGUAR	--	2	--	2	--	13	--	1	--	1
LINCOLN	--	27	--	24	--	27	--	18	--	5
MAZDA	--	21	--	11	--	NA	--	NA	--	NA
MERCEDES	--	21	--	17	--	NA	--	NA	--	NA

* RATE = REPORTED ACCIDENTS PER 100,000 VEHS. "Y" = EQUIPPED WITH SHIFT LOCKS, NUMBER SOLD INCLUDED IN TOTAL FOR VEH. MAKE. BLANK SPACE = NONE SOLD WITH SHIFT LOCKS.

MAKE MODEL	1988 MODELS VEHICLES SOLD	1988 REPORTED ACC.	1988 RATE*	1989 MODELS VEHICLES SOLD	1989 REPORTED ACC.	1989 RATE*	1990 MODELS VEHICLES SOLD	1990 REPORTED ACC.	1990 RATE*	1991 MODELS VEHICLES SOLD	1991 REPORTED ACC.	1991 RATE*	1992 MODELS VEHICLES SOLD	1992 REPORTED ACC.	1992 RATE*	NOTES
REPORTED UNWANTED ACCELERATION ACCIDENTS FOR AUTOMATIC TRANSMISSION EQUIPPED CARS WITHOUT SHIFT LOCKS																
MERCURY	--	44		--	50		--	29		--	13		--	11		
MERCUR	--	5		--	1		--	NA		--	NA		--	NA		
MITSUBISHI	--	6		--	1		--	0		--	0		--	NA		
NISSAN	--	16		--	8		--	NA		--	NA		--	NA		
OLDSMOBILE	--	58		--	28		--	24		--	8		--	6		
PEUGOT	--	1		--	0		--	0		--	1		--	0		
PLYMOUTH	--	8		--	2		--	4		--	4		--	2		
PONTIAC	--	53		--	24		--	14		--	14		--	1		
RENAULT	--	12		--	1		--	0		--	0		--	0		
SAAB	--	2		--	3		--	0		--	1		--	0		
STERLING	--	1		--	0		--	0		--	0		--	0		
SUBARU	--	10		--	5		--	NA		--	NA		--	NA		
TOYOTA	--	35		--	3		--	NA		--	NA		--	NA		
VOLKSWAGEN	--	9		--	1		--	1		--	0		--	0		
VOLVO	--	18		--	22		--	24		--	NA		--	NA		
Total Automatic Trans. Cars Without Shift Locks	8,555,000	772	9.0	6,543,000	442	6.8	5,254,000	272	5.2	3,994,000	164	4.1	1,496,000	49	3.3	
Total Cars With Shift Locks	120,700	8	6.6	975,400	42	4.3	2,289,000	54	2.4	3,351,000	53	1.6	5,730,000	64	1.1	
Percent Reduction Due to Shift Locks (1-[Rate With/Rate Without])	27%			36%			54%			61%			66%			

NOTES: SALES DATA FROM "AUTOMOTIVE NEWS" UNLESS OTHERWISE INDICATED
POPULATIONS ESTIMATED WHERE NOTES INDICATE ONLY A PORTION OF THE MODEL, MODEL YEAR PRODUCTION WAS EQUIPPED WITH SHIFT LOCKS.

(1) POPULATION DATA FROM MFR.
(2) ALL EXCEPT CONVERTIBLE SINCE 9/91
(3) ONLY AFTER 2/92
(4) EXCEPT VERY EARLY MYR. '90 PROD.
(5) ONLY AFTER 11/26/91
(6) '91 POPULATION ESTIMATED
(7) ONLY AFTER 11/14/91 PRODUCTION
(8) MYR. '89 POPULATION ESTIMATED
(9) ONLY AFTER JAN. '89 PRODUCTION
(10) EXCEPT EARLY MYR. '90
(11) TORONADO W. CONSOLE SHIFT ONLY AFTER 2/92
(12) SEE PLYMOUTH FOR COMBINED DODGE/PLYM. COLT DATA
(13) DATA FROM WARD'S AUTOMOTIVE REPORTS
(14) EXCEPT '89 L-SERIES HATCHBACKS
(15) EXCEPT BETWEEN EARLY '90 & LATE '92 MODELS

* RATE = REPORTED ACCIDENTS PER 100,000 VEHS. "Y" = EQUIPPED WITH SHIFT LOCKS, NUMBER SOLD INCLUDED IN TOTAL FOR VEH. MAKE. BLANK SPACE = NONE SOLD WITH SHIFT LOCKS.

Fatality Reduction by Automatic Occupant Protection in the United States

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ABSTRACT

Automatic occupant protection, state belt laws, and greater voluntary belt use amount to a 'winning combination' that saves lives. Federal Motor Vehicle Safety Standard 208, as amended on July 17, 1984, combined a nationwide effort to increase belt use through state belt laws, enforcement and education, and a requirement that automatic occupant protection, such as air bags or automatic belts, be phased into passenger cars and light trucks. The effectiveness of automatic occupant protection is measured by statistical analysis of fatal crashes involving model year 1985-93 passenger cars, based on FARS data from 1986 through mid-1993.

Fatality risk of occupants in cars equipped with air bags plus manual belts (at 1993 use rates) is 23 percent lower than in "baseline" cars with manual belts at 1983 use rates. In similar comparisons, the fatality reductions for the four types of automatic belts range from 11 to 19 percent. All reductions are statistically significant. In the 1993 model-year mix of cars with air bags or automatic belts, at 1993 belt use rates, the average fatality risk is 20 percent lower than for baseline, manual-belt cars at 1983 use rates.

INTRODUCTION

Federal Motor Vehicle Safety Standard 208 ("Occupant Crash Protection"), as amended on July 17, 1984, defined the National Highway Traffic Safety Administration's (NHTSA) occupant protection program.[1] It consisted of two components: an immediate, nationwide effort to increase belt use, through encouragement of State buckle-up laws, enforcement and public education, and a rule requiring that automatic occupant protection, such as air bags or automatic belts, be phased into passenger cars during 1987-90. Based on fatal accident data collected between January 1986 and June 1993, this paper estimates the fatality reduction associated with increased manual belt use, driver air bags, and four generic types of automatic belts for front-seat occupants of passenger cars in the United States.

OVERVIEW OF THE OCCUPANT PROTECTION PROGRAM

Manual safety belts are highly effective in reducing fatalities and serious injuries in crashes, but only if occupants take the time to buckle them. Numerous research studies indicate that, when used, manual lap and shoulder belts reduce the risk of fatal injury to front-seat passenger-car occupants by 45 percent.[2] In 1983, the year before FMVSS 208 was promulgated, manual safety belts were used by 14 percent of the general driver population.[3] NHTSA's occupant protection program attacks the problem of low belt use from two directions. Buckle-up laws, enforcement and public education directly address the deficiency of belt use. Automatic occupant protection, such as air bags or automatic belts, provides a level of safety in crashes even without any buckling-up action by the occupants. (Some types of automatic protection, such as air bags and motorized belts, are accompanied by a manual belt; NHTSA strongly recommends buckling the manual belts and using them in combination with the automatic system.)

The two components of NHTSA's occupant protection program always have reinforced one another. The FMVSS 208 regulation, by offering a choice between automatic protection and belt laws, was the catalyst that broke the logjam on belt laws in the States. No States had buckle-up laws in 1983; as of September 1993, 45 States plus the District of Columbia and Puerto Rico have enacted them. In the United States, public consciousness of health and safety issues generally increased during the 1980's. Buckle-up laws and educational programs nurtured the public's awareness of auto safety issues. By 1989, the public did not want to choose between belt laws and automatic protection: they wanted both, and they were willing to pay extra for the best protection. Although the FMVSS 208 provisions relating to belt use laws expired on April 1, 1989, the nationwide effort to encourage State buckle-up laws and to increase belt use has continued.

Belt use by the driving population increased to 62 percent in late 1992 and reached 66 percent in 1993.[4] The agency estimates that safety belts saved about 5,226 lives in 1992 in passenger cars and light trucks.[5] The increase in belt use enables the combination of air bags and manual belts to approach its full life-saving potential, and it has made air bags, plus manual belts, the first choice of consumers. Conversely, as motorists have acquired the motivation and habit of buckling up, the "automatic" feature of automatic belt systems became relatively less important, and those systems lost market share to air bags.

FMVSS 208's phase-in requirement for automatic occupant protection was 10 percent of passenger cars in model year 1987, 25 percent in model year 1988, 40 percent in model year 1989, and all cars manufactured after September 1, 1989 (model year 1990). To encourage the installation of air bags (which initially evolved for drivers only and later for passengers), FMVSS 208 exempted the right-front passenger position from automatic protection until September 1, 1993, if an air bag (or other non-belt technology) is installed for the driver; thereafter, automatic protection is required at both positions in all cars.

In 1991, NHTSA extended the automatic occupant protection requirements to light trucks and vans, on a phased-in basis: 20 percent in model year 1995, 50 percent in model year 1996, 90 percent in model year 1997 and all light trucks and vans manufactured after September 1, 1997 (model year 1998).

The Intermodal Surface Transportation Efficiency Act of 1991 requires all passenger cars manufactured after September 1, 1997 and all light trucks and vans manufactured after September 1, 1998 to have driver and passenger air bags, plus lap and shoulder belts.

The 1987-90 phase-in of automatic occupant protection was completed on schedule. Manufacturers met or exceeded the yearly production targets and sold the cars. Six distinct types of automatic protection have been offered, including two configurations using air bags and four types of automatic belts:

(1) Driver air bag plus manual 3 point (lap/shoulder) belts for the driver and the right-front passenger. Mercedes, in late 1985, was the first to make driver air bags standard; Chrysler was the first to make them standard on all domestic cars (1988-90). A rapid market shift from automatic belts to air bags followed: by 1991, driver air bags were the automatic system with the highest market share.

(2) Driver and right-front passenger air bags with manual 3 point belts. Initially in Porsche and Lincoln, passenger air bags were still produced in small quantities through 1991, the last model year in this study. It is anticipated, however, that this will become the dominant type of occupant protection after September 1, 1993, when the passenger seat will no longer be exempted from automatic protection in cars with driver air bags.

(3) Motorized 2 point (torso) belts without disconnect, plus manual lap belts - the motors automatically move the torso belts into place when the ignition is turned on; the belts can be loosened but not disconnected in emergency egress situations. Motorized belts without disconnect were first installed in the 1981 Toyota Cressida, and subsequently were installed on certain Fords, Toyotas, and other cars.

(4) Motorized 2 point belts with disconnect, plus manual lap belts - they resemble the preceding type, but they can be disconnected rather than just loosened (Nissan, Mazda, Subaru et al.)

(5) Nonmotorized 3 point (lap/shoulder) belts with disconnect - the door-mounted belts automatically move into place when the doors close; they can be disconnected (GM, Honda, et al.)

(6) Nonmotorized 2 point belts - the door-mounted belts automatically move into place when the doors close (VW, Hyundai, some Toyotas, et al.). Most can be disconnected. Beginning in 1990, all of them included manual lap belts, but some 1987-89 systems had knee bolsters instead of lap belts.

EVALUATION GOALS

NHTSA periodically evaluates the effectiveness of the occupant protection program in accordance with a plan published in 1990[6] and in response to Executive Order 12866 [7] and the Intermodal Surface Transportation Efficiency Act of 1991. NHTSA issued an Interim Evaluation Report in June 1992, based on information available at that time.[8] The Insurance Institute for Highway Safety published an analysis of the fatality reduction for driver air bags in October 1991.[9] These studies showed that the occupant protection program, as a whole, was significantly reducing fatality risk in passenger cars in 1991, and that cars with air bags plus manual belts had significantly lower fatality risk than cars with manual belts alone.

There are two separate measures of the effectiveness of the overall occupant protection program or of any specific type of occupant protection system in reducing fatalities or injuries: the actual and the potential effectiveness. In some studies, these measures have been called "effectiveness as used" and "effectiveness when used."

The actual effectiveness of an automatic protection system is the difference in fatality or injury risk with this system, at current (1993) belt use rates, and the baseline fatality or injury risk of cars with manual belts at 1983 use rates (before FMVSS 208). It measures the net total benefit of the occupant protection program: improvements in occupant protection technology plus increases in the use of the systems. For example, the fatality risk for all drivers of cars with air bags (some of whom currently use the manual belts provided in air bag cars, some of whom do not) is compared to the risk for all drivers of similar cars with manual belts only, at 1983 use rates. As belt use rises, actual effectiveness increases.

NHTSA is also interested in the potential effectiveness of an occupant protection system, which is the difference in fatality or injury risk of a person who fully and properly uses this system and the fatality risk of a completely unrestrained person. For example, the injury risk of a belted driver of an air bag car is compared to the risk of an unrestrained driver of a similar car without air bags.

This paper, however, does not address the potential effectiveness of occupant protection. Its goal is to produce six estimates of actual fatality reduction:

1) **Manual** belts at 1993 use rates vs. manual belts at 1983 use rates
2) Driver **air bags** plus manual belts at 1993 use rates vs. manual belts at 1983 use rates
3) **Motorized** 2-point belts **without** disconnect plus manual lap belts at 1993 use rates vs. manual belts at 1983 use rates
4) **Motorized** 2-point belts **with** disconnect plus manual lap belts at 1993 use rates vs. manual belts at 1983 use rates
5) **Nonmotorized 3-point** automatic belts at 1993 use rates vs. manual belts at 1983 use rates
6) **Nonmotorized 2-point** automatic belts at 1993 use rates vs. manual belts at 1983 use rates

As of mid-1993, there was insufficient accident xperience with dual air bags for estimating the fatality eduction for the right-front passenger. The other types of utomatic protection differ widely in sales and exposure; as a onsequence, the estimates of fatality reduction vary in their recision and statistical significance. Assessments of tatistical precision or significance are an integral part of the esults and the effectiveness estimates could be misleading vithout them.

DATA SOURCES AND ANALYSIS OVERVIEW

The Fatal Accident Reporting System (FARS) provides census of fatalities in the United States, including drivers nd right-front passengers of cars with air bags or automatic elts.[10] As of March 1994, the FARS file is essentially omplete through the first half of 1993. The study is based on FARS records of model year 1985-93 passenger cars involved n fatal crashes between January 1986 and June 1993. Make-nodels were identified by analyzing the Vehicle Identification Number and the type of occupant protection was identified rom the VIN, based on various sources in the literature.[11] Whereas the FARS file reports "occupant belt use," this data lement is not needed for the analyses of actual effectiveness.

Beginning with model year 1987, R. L. Polk has urnished NHTSA with monthly car registration counts by nake-model, subseries, body style and type of occupant rotection. Registration data for model years 1985-86 are btained from Polk's annual National Vehicle Population Profile. These new-car registration data, in combination with vehicle survival probabilities,[12] are used to calculate the xposure, in vehicle years, for cars of a given make-model nd model year in a given calendar year - e.g., 1989 Ford Mustang in 1992. FARS and Polk data are merged to allow computation of fatality rates per million vehicle exposure years, by calendar year, make-model, model year, body style nd type of occupant protection.

The evaluation of the actual effectiveness of manual belts (as currently used) is carried out in a single step. NHTSA has already developed a method for estimating the ives saved by safety belts and belt use laws since 1983 - based on the trend of the actual, observed belt use in the driving population (19 city survey) and certain assumptions about manual belt effectiveness and belt use in fatal crashes vs. the general driving population.[13] As will be described below, this method is applied to 1983 and 1993 manual-belt cars, to obtain an estimate of actual manual belt effectiveness.

The evaluation of the actual effectiveness of air bags or automatic belts is carried out in two analysis steps. First, the effectiveness of an automatic system, at current belt use rates, is estimated relative to a manual belt system, at current use rates. Next, this incremental fatality reduction is added to the benefits of 1983-93 increases in manual belt use, to estimate the benefits of automatic systems, as currently used, relative to the baseline of manual-belt cars at 1983 belt use rates. The two-step approach is necessitated by the data and analysis methods used in the evaluation.

FATALITY REDUCTION FOR 1983-91 INCREASE IN MANUAL BELT USE

The agency has developed a general method for estimating the number of lives saved by safety belts.[13] This method does not rely on belt use reporting in FARS (whose accuracy in some States with belt use laws has been a matter of debate), but is based on an empirical relationship between U1, the belt use of the general driver and right-front passenger population, which can be accurately observed in NHTSA's 19 City Survey[3] or a State belt use survey, and U2, the belt use of fatally injured drivers and right-front passengers. U2 is much lower than U1 for two reasons: (1) the types of people who get involved in severe crashes (e.g., drunk drivers) are less likely to buckle up than the general population; (2) belts save lives, so an even smaller percentage of the fatalities than the survivors of severe crashes are belted.

U2, belt use of fatally injured occupants, although perhaps inaccurately reported on FARS in States with belt use laws, was always considered accurate prior to belt use laws. Before belt use laws, the empirical relationship between U1, general belt use, and U2, fatality belt use was

$$U2 = .43\ U1 - .019$$

In 1983, the baseline year, belt use on the road was 14 percent in the 19 city study[3] and 4 percent among fatally injured persons. In 1993, overall belt use on the road was estimated to be 66 percent in the United States.[4] However, this overall figure includes cars with automatic belts, which have higher use rates than cars with manual belts and which, by mid-1993, constituted approximately 18 percent of the passenger cars on the road. It is estimated that use of manual belts during 1993 was 63 percent.[14] Based on the above empirical formula, 63 percent manual belt use on the road corresponds to 25.2 percent belt use among fatally injured persons in cars equipped with manual belts.

The fatality reduction attributable to the increase in manual belt use can be inferred from the increase in belt use among fatally injured occupants. Since the fatality risk of an occupant protected by manual belts is 45 percent lower than the fatality risk of an unrestrained occupant[2], every 55 belted fatalities imply the existence of an additional 45 belted persons, involved in potentially fatal crashes (i.e., fatal for an unrestrained occupant), but saved by the belt. It is possible to define U3, the <u>manual belt use rate in "potentially fatal" crashes</u>, from U2, as follows:

$$U3 = [U2 + (.45/.55)\ U2] \ / \ [1 + (.45/.55)\ U2]$$

U3 was 7.25 percent in 1983 and would have reached 38.0 percent in 1993 if all cars had manual belts. Since the fatality risk of a person using manual belts is 45 percent lower than the risk for an unrestrained person, the fatality reduction attributable to the increase in manual belt use during 1983-93 is

$$1 - [(1 - U3_{1993} + .55\ U3_{1993}) \ / \ (1 - U3_{1983} + .55\ U3_{1983})]$$

$$= 1 - [(1 - .38 + .55 \times .38) \ / \ (1 - .0725 + .55 \times .0725)]$$

$$= \textbf{14.3 percent}$$

FATALITY REDUCTION FOR DRIVER AIR BAGS

As of March 1994, the Fatal Accident Reporting System (FARS) contained records of 2107 occupant fatalities in model year 1985-93 passenger cars at seating positions equipped with air bags (2069 drivers and 38 right-front passengers). That is almost three times as many fatal cases as were on file two years ago, consistent with the large increases in the sales of cars equipped with air bags. There are enough accident cases for meaningful statistical analyses.

At first, air bags were not installed in make-models with high sales volumes. Many of the early installations were in luxury cars such as Mercedes and BMW. Chrysler made them standard on all domestic cars in 1988-90. At that time, also, air bags became standard equipment on sporty cars such as Daytona, Mustang, Camaro, Miata, etc. In 1990-93, they began to appear on typical "family" cars such as Taurus, Corsica, Accord and Camry. By the end of model year 1993, air bags were common in all market classes of cars.

A principal task in the analyses of fatality reduction for air bags is identifying groups of crashes or occupants that will be helped by air bags as well as control groups of crashes or occupants that are unlikely to be helped by air bags. One factor in the phase-in process for FMVSS 208 had an unexpected benefit that aided the analysis. The regulation exempted the right-front passenger position from automatic protection until September 1, 1993 in cars with driver air bags. Through mid-1993, over 90 percent of the crash-involved cars equipped with air bags had them only for the driver. In cars with driver-only air bags, the right-front passengers are a "control group": they are unlikely to be helped by the [driver] bags.

The ratio of driver to right-front passenger fatalities in cars with driver air bags (<u>where both seats are occupied</u>) is compared to the corresponding ratio in earlier cars of the <u>same makes and models</u>, equipped only with manual belts at both positions. The effectiveness of air bags is estimated by the difference in the ratios. The only real disadvantage of this method is that the analysis has to be limited to cars where both seats are occupied (about 1/3 of the fatality data sample).

Table 1 lists make-models that switched from manual

Table 1

Make-Models that Switched from Manual Belts to Air Bags Plus Belts: Model Years Included in the Effectiveness Analyses

Make-Model		Model Years with Manual Belts	Model Years with Air Bags
Chrysler	LeBaron	1987-89	1988-93
	New Yorker C	1989	1990-93
Dodge	Diplomat	1988	1988-89
	Omni	1989	1990
	Daytona	1985-88	1988-93
	Shadow	1987-89	1990-93
	Dynasty	1988-89	1990-93
	Spirit	1989	1990-91
Plymouth	Gran Fury	1988	1989
	Horizon	1989	1990
	Sundance	1987-89	1990-93
	Acclaim	1989	1990-91
Ford	Mustang	1988-89	1990-93
	Crown Victoria	1988-89	1990-93**
	Taurus	1988-89	1990-93**
Lincoln	Town Car*	1987-89	1990-93**
	Mark 7/Mark 8	1988-89	1990-93**
	Continental	1985-88	1989-93**
Mercury	Grand Marquis	1988-89	1990-93**
	Sable	1988-89	1990-93**
Buick	Electra*	1988	1991-93
	Riviera*	1988-89	1990-93
	Reatta	1989	1990-91
Cadillac	DeVille*/Fleetwood*	1988-89	1989-93**
	Eldorado*	1988-89	1990-93**
	Seville*	1987-89	1990-93**
Chevrolet	Caprice*	1989	1991-93
	Corvette	1987-89	1990-93
	Camaro	1988-89	1990-93**
	Spectrum, Storm	1987-89	1990-93
Oldsmobile	Toronado*	1987-89	1990-92
Pontiac	Firebird	1989	1990-93**
Audi	100*/200*	1989	1989-93
BMW	300	1988-89	1990-93
	500	1987-89	1989-93
	600	1986-87	1988-89
	700	1985-87	1987-93**
Nissan	300ZX*	1988-89	1991-93
	Pulsar*, NX*	1989	1990-93
Honda	Accord	1989	1991-93**
Acura	Legend*	1986-88	1987-93**
Jaguar	XJ-S*	1985-89	1990-93
Mazda	929	1988-89	1992-93***
Mercedes	basic sedan*	1985	1986
	190	1985	1986
Porsche	944	1986-89	1987-91***
Saab	900*	1987-89	1990-93
Toyota	Celica	1987-89	1990-93
	Supra	1989	1990-93
	MR-2*	1987-89	1991-93
Volvo	240	1989	1990-93
	740*/760*/940*/960*	1986-89	1987-93**

* Make-model equipped with Antilock Brake Systems at about the same time as air bags: **excluded from the analysis of frontal vs. nonfrontal fatalities**

** Some of the cars have dual air bags; these cars are **excluded from the analysis of driver vs. right front passenger fatalities**

*** All of the cars have dual air bags; make-model is **excluded from the analysis of driver vs. right front passenger fatalities**

belts only to air bags plus belts at some time during 1986-93, showing the ranges of model years used in the analysis. These ranges are chosen to assure that each make-model has an accident sample of manual-belt cars as close as possible to **double** its air-bag equipped sample: a uniform ratio of manual-belt to air-bag cars, by make-model, assures that the manual-belt and air-bag samples have a similar make-model mix. In this particular data set, a ratio of **two** manual-belt cars to one air-bag equipped car minimizes sampling error. Cars with dual air bags or automatic belts are not included in this analysis.

Table 2

Effectiveness of Driver Air Bags Based on Reduction of Driver Fatalities Relative to Right Front Passenger Fatalities

(both seats occupied; make-models that switched from manual belts to driver air bags)

	Driver Fatalities	Right Front Fatalities	Risk Ratio	Percent Reduction
IN PURELY FRONTAL CRASHES (12:00 principal impact; most harmful event is not a rollover)				
Cars w. manual belts only	327	356	.919	
Cars w. driver air bags	105	177	.593	35
(statistically significant difference: chi-square = 9.14)				
IN ALL FRONTAL OR PARTIALLY FRONTAL CRASHES (10:00-2:00 principal and/or initial impact)				
Cars w. manual belts only	668	728	.918	
Cars w. driver air bags	263	337	.780	15
(not a statistically significant difference: chi-square = 2.72)				
IN ALL CRASHES				
Cars w. manual belts only	1081	1205	.897	
Cars w. driver air bags	503	609	.826	8
(not a statistically significant difference: chi-square = 1.27)				

Fatality reduction for air bag cars at current belt use rates relative to manual-belt cars at 1983 use rates: 21 percent

Table 2 computes the effectiveness of cars with driver air bags, relative to cars with manual belts only at current use rates, for three groups of crashes. The first section of Table 2 addresses "purely frontal" crashes, where air bags are expected to be most effective: the principal impact location, as defined in FARS, is 12:00, and the most harmful event is a collision with a vehicle or object (i.e., not a rollover). There were 327 driver fatalities and 356 right-front passenger fatalities in the manual-belt cars, a risk ratio of .919. But in the air-bag cars, there were only 105 driver fatalities (with air bags) as opposed to 177 right-front passenger fatalities (without air bags), a risk ratio of .593. That is a 35 percent fatality reduction for driver air bags relative to manual belts at current use rates in "purely frontal" crashes and it is statistically significant at the .01 level: Chi-square (χ^2) for the 2 x 2 table is 9.14.[15]

In the middle section of Table 2, the accident sample is extended to include all frontal or partially frontal crashes, where either the principal or the initial impact, as defined in FARS, is between 10:00 and 2:00. These included most of the crashes in which air bags are likely to have some effect.[16] The risk ratio in the manual-belt cars is .918, almost the same as before, but the risk ratio in the air-bag cars is up to .780. Effectiveness drops off substantially from the preceding case: the fatality reduction for driver air bags relative to manual belts at current use rates is 15 percent and it is not statistically significant ($\chi^2 = 2.72$).[15]

The lower section of Table 2 extends the analysis to all crashes, including both frontals and nonfrontals. In the cars with driver air bags, there are 503 driver and 609 right-front passenger fatalities. The driver-to-right-front risk ratio is .897 in the manual-belt cars and .826 in the air-bag cars. Thus, the fatality reduction for driver air bags relative to manual belts at current use rates is 8 percent and it is not statistically significant ($\chi^2 = 1.27$).[15] However, the ultimate goal of the analysis is to compare air-bag equipped cars at current belt use rates to manual-belt cars at baseline, 1983 use rates. It was shown above that the fatality reduction for manual belts as currently used relative to manual belts at 1983 baseline use is 14.3 percent. As a result, the **fatality reduction for driver air bags relative to the baseline of manual belts at 1983 use rates** is

$$1 - [(1 - .143)(1 - .08)] = \textbf{21 percent}$$

Another distinctive characteristic of air bags, which leads to a second method for estimating effectiveness, is that they are primarily designed for action in frontal crashes. With an inclusive definition of "frontal and partially frontal" crashes (initial or principal impact location between 10:00 and 2:00 on FARS), it can be assumed that air bags have little effect, relative to manual-belt cars at current use rates, in the remaining "nonfrontal" crashes. These nonfrontal fatalities are a control group. The ratio of frontal to nonfrontal driver fatalities in cars with driver air bags is compared to the corresponding ratio in earlier cars of the same makes and models, equipped only with manual belts.[16] The effectiveness of air bags in frontal crashes is estimated by the difference in the ratios. This analysis has the disadvantage of relying on the unproven assumption of zero effectiveness in nonfrontal crashes, but allows a larger sample size than the preceding method (since it is not limited to cases where the right-front seat was occupied).

Table 1 lists make-models that switched from manual belts only to air bags plus belts at some time during 1986-93. However, not all of them are appropriate for the current analysis. Make-models that received Antilock Brake Systems (ABS) on all or most of the cars, simultaneous with or close to the switch to air bags must be excluded. That is because ABS, which improves a driver's control during braking and can reduce stopping distances in certain situations, may also be causing a shift from frontal to nonfrontal impacts. Drivers of cars with ABS may be able to avoid frontally striking other vehicles; a higher proportion of their crash involvements would be as the "struck" vehicle in the collision (nonfrontal damage). The effect of ABS (reduced involvements in frontal relative to nonfrontal crashes) would be mistakenly attributed to air bags (reduced fatality risk in frontal relative to nonfrontal crashes). The analysis has to be limited to make-models that received ABS well before (e.g, Chevrolet Corvette) or well after air bags (e.g., Chevrolet Camaro). Table 1 shows which make-models are excluded and what ranges of model years for the other models are used in the analysis.

Table 3

Effectiveness of Driver Air Bags Based on Reduction of Frontal Fatalities Relative to Nonfrontal Fatalities

(make-models that switched from manual belts to air bags; make-models that got ABS with air bags are excluded)

	Cars with Manual Belts	Cars with Driver Air Bags	Frontal Fat. Red. for Air Bags (%)
PURELY FRONTAL CRASHES (12:00 principal impact; most harmful event is not a rollover)			
Nonfrontal fatalities	911	498	
Purely frontal fatalities	924	362	28
(statistically significant difference: chi-square = 16.02)			
OTHER FRONTAL OR PARTIALLY FRONTAL CRASHES (10:00-2:00 principal and/or initial impact, excluding purely frontal crashes)			
Nonfrontal fatalities	911	498	
Other frontal fatalities	802	411	6
(not a statistically significant difference: chi-square = 0.61)			
ALL FRONTAL OR PARTIALLY FRONTAL CRASHES (10:00-2:00 principal and/or initial impact)			
Nonfrontal fatalities	911	498	
Frontal fatalities	1726	773	18
(statistically significant difference: chi-square = 7.99)			

Overall fatality reduction for air bag cars at current belt use rates relative to manual-belt cars at current use rates: 12 percent

Overall fatality reduction for air bag cars at current belt use rates relative to manual-belt cars at 1983 use rates: 24 percent

The lower section of Table 3 presents the data needed to calculate the effectiveness of air bags in frontal crashes, and overall. There were 1726 frontal driver fatalities and 911 nonfrontal driver fatalities in the manual-belt cars. But in cars with air bags, there were only 773 frontal driver fatalities as opposed to 498 nonfrontal driver fatalities. The reduction of frontal fatalities for air bags, relative to manual-belt cars at current use rates, is

1 - [(773/498) / (1726/911)] = **18 percent**

and it is statistically significant (χ^2 = 7.99).[15] The overall fatality reduction for air bags, relative to manual-belt cars at current use rates, is

{1 - [(773/498) / (1726/911)]} [1726 / (1726+911)]

= **11.8 percent**

Thus, the **fatality reduction for driver air bags relative to the baseline of manual belts at 1983 use rates** is

1 - [(1 - .143)(1 - .118)] = **24.4 percent**

The two upper sections of Table 3 compute the fatality reduction for air bags, relative to manual-belt cars at current use rates, for two mutually exclusive subgroups of frontal crashes. The top section compares fatalities in "purely frontal" crashes (principal impact 12:00 and most harmful event a collision) to fatalities in purely nonfrontal crashes. The reduction for air bags is

1 - [(362/498) / (924/911)] = **28 percent**

and it is statistically significant (χ^2 = 16.02).[15] The middle section of Table 3 considers all other types of frontal and partially frontal crashes: where the principal impact is angle-frontal (10, 11, 1 or 2:00 - i.e., 15 to 75 degrees away from straight-ahead), or where a frontal impact is merely the initial crash event and it is followed by a more severe, nonfrontal event, such as a side impact, rollover or fire. In these partially frontal crashes, where the principal forces are not straight-ahead, the fatality reduction for air bags is only 6 percent, and it is not statistically significant (χ^2 = 0.61).[15]

In summary, two rather different methods for computing the actual fatality reduction for driver air bags (relative to the baseline of manual-belt cars at 1983 use rates), yielded quite similar results: 21 and 24.4 percent. In both analyses, the reduction of "purely frontal" fatalities was statistically significant at the .01 level, and in the second analysis, the reduction of all frontal or partially frontal fatalities was also significant at the .01 level, relative to manual-belt cars at current use rates.

FATALITY REDUCTION FOR AUTOMATIC BELTS

Three methods are used to estimate fatality reductions for each of the major types of automatic belts at current use

Each method is based on front-seat occupant fatality rates per million vehicle exposure years, derived from FARS and R. L. Polk data. These reductions are added to the benefits of 1983-93 increases in manual belt use, to obtain effectiveness estimates for automatic belts, as currently used, relative to the baseline of manual belts at 1983 use rates. Fatality and exposure data are available for model years 1985-90, by calendar year, for the period extending from January 1986 to June 1993. The goal is to average the three estimates, each of which may have its own sampling errors and biases, to obtain a single "best" estimate for each type of automatic protection.

In the first method, five actual front-outboard occupant fatality rates per million vehicle exposure years are computed, using data for all model year 1985-90 cars: the rate for cars with manual belts and the rates for the four types of automatic belts. Right-front passenger as well as driver fatalities are included in the rates, since automatic belts are installed at both positions. The actual fatality rates are compared to the rates that would have been expected if the cars did not have automatic belts, but only had manual belts, at current use rates. The expected rates are derived from an aggregate, log-linear regression model, calibrated from data on 1985-89 manual-belt cars. The model predicts front-seat fatalities per million years as a function of a car's mass, market class (2 door vs. 4 door; luxury, sporty or neither), vehicle age, manufacturer-nameplate (9 domestic and 7 import groups), driver age and sex (percent of fatals who are males under 30 years) and calendar year.[17]

Table 4

Actual vs. Expected* Fatality Rates for Automatic Belts

(cars of model years 1985-90 on the road during 1/86-6/93)

Type of Belts	Fatalities	Exposure (10^6 Car Years)	Fatality Rate: Actual	Fatality Rate: Expected*	Fatality Reduction (%) Rel. to Manual Belts: At Current Use	Fatality Reduction (%) Rel. to Manual Belts: At 1983 Use
Manual, at current use rates	43497	261.71	166.20	166.21	-	14
Motorized 2 point without disconnect	2469	16.54	149.30	156.19	4	18
Motorized 2 point with disconnect	1232	8.49	145.15	145.80	none	15
Nonmotorized 3 point	3666	24.55	149.31	153.53	2	17
Nonmotorized 2 point	752	4.10	183.64	181.53	- 1	13

*Expected for comparable manual-belt cars at current belt use rates

Table 4 shows that cars with manual belts, at current use rates, had actual and expected front seat fatality rates of 166 per million car years. Cars with motorized 2 point belts (without disconnect) had a lower actual fatality rate of 149.30. However, these cars, even without the automatic belts, would have been expected to perform slightly better than the average manual belt car: their expected fatality rate is 156.19. Thus, the actual fatality rate is

$$1 - (149.30/156.19) = 4 \text{ percent}$$

lower than would be expected for comparable manual belt cars at current use rates. The actual fatality rate is

$$1 - \{[1 - .143][1 - (149.30/156.19)]\} = \mathbf{18\ percent}$$

lower than would be expected for comparable manual-belt cars at 1983 use rates. Motorized 2 point belts (with disconnect) have a fatality rate 15 percent lower than the expected baseline rate. Nonmotorized 3 point belts have 17 percent lower than baseline fatalities; nonmotorized 2 point systems, 13 percent lower.

The second method for estimating effectiveness is based only on actual fatality rates. The actual fatality rate for cars with a particular type of automatic belt is compared to the actual rate for cars of the same makes and models with manual belts. The analysis is facilitated by another unique characteristic of the implementation process for FMVSS 208: automatic protection was gradually phased in during 1987-90 and coexisted with manual belts until as late as 1989. Cars with a particular type of automatic belt have counterparts of the same makes and models, with manual belts, that are about the same age.

The approach is to identify groups of make-models which began the transition from manual belts to a specific type of automatic belt some time during 1987-90. For example, the group that got motorized 2 point belts (without disconnect) includes Escort, Lynx, Tempo, Topaz, Thunderbird, Cougar, Isuzu Impulse and Toyota Camry. Models which had such belts before 1987 (Toyota Cressida) are excluded. Within each group of make-models, the actual fatality rates of the 1987-90 cars with automatic belts are compared to the actual rates of the 1985-89 cars without automatic belts. However, to keep the sample sizes "balanced" between manual and automatic-belt cars, only the 1987-88 manual-belt cars are used in the comparison with models that got automatic belts in 1989, and only the 1989 manual belt cars are used in the comparison with models that got automatic belts in 1990.[18]

Table 5 shows that the group of make-models which switched from manual to motorized 2 point belts (without disconnect) had a fatality rate of 179.79 with the manual belts and 153.18 with the automatic belts. That is a 15 percent reduction for motorized 2 point belts (without disconnect) relative to manual-belt cars at current use rates, corresponding to a **27 percent fatality reduction relative to manual-belt cars at 1983 use rates.** The other three automatic belt systems had effectiveness estimates ranging from 10 to 22 percent.

Table 5

Actual Fatality Rates for Groups of Make-Models that Switched from Manual to Automatic Belts in 1987-90

(cars of model years 1985-90 on the road during 1/86-6/93)

Make-models Switching from Manual to	Belt Type	Fatalities	Exposure (10^6 Car Years)	Actual Fatality Rate	Fatality Reduction (%) Rel. to Manual Belts: At Current Use	At 1983 Use
Motorized 2 point without disconnect	manual	3427	19.06	179.79		
	auto	2381	15.54	153.18	15	**27**
Motorized 2 point with disconnect	manual	1349	8.37	161.12		
	auto	674	4.61	146.30	9	**22**
Nonmotorized 3 point	manual	3980	26.96	147.60		
	auto	2834	18.48	153.35	- 4	**11**
Nonmotorized 2 point	manual	1885	10.71	176.04		
	auto	651	3.53	184.29	- 5	**10**

Table 6

Actual vs. Expected Fatality Rates for Groups of Make-Models that Switched from Manual to Automatic belts in 1987-90

(cars of model years 1985-90 on the road during 1/86-6/93)

Make-models Switching from Manual to	Belt Type	Fatality Rates At Current Use: Actual	Expected	Fatality Reduction (%): Actual Rel. to Expected	Relative to 1983 Baseline
Motorized 2 point without disconnect	manual	179.79	183.93		
	auto	153.18	160.77	3	**16**
Motorized 2 point with disconnect	manual	161.12	175.73		
	auto	146.30	146.38	- 9	**7**
Nonmotorized 3 point	manual	147.60	150.56		
	auto	153.35	155.26	- 1	**14**
Nonmotorized 2 point	manual	176.04	183.14		
	auto	184.29	182.36	- 5	**10**

The third procedure for estimating effectiveness is a synthesis of the two preceding methods. In the groups of make-models which switched from manual belts to a specific type of automatic protection during 1987-90, the difference in actual fatality rates of the 1987-90 cars with automatic protection and the 1985-89 cars with manual belts is measured relative to the difference in expected rates, as derived from the regression equation. Table 6 carries out the estimation for each type of automatic belt. For example, the group of make-models which switched from manual to motorized 2 point belts (without disconnect) had an actual fatality rate of 179.79 with the manual belts and 153.18 with the automatic belts. But the expected fatality rate also decreased, from 183.93 to 160.77, since the mix of cars with automatic belts included a larger proportion of the make-models with historically low fatality rates. The reduction in the actual relative to the expected is

$$1 - [(153.18/179.79) / (160.77/183.93)] = 3 \text{ percent}$$

which corresponds to a **16 percent fatality reduction relative to manual-belt cars at 1983 use rates.** By this method, the fatality reductions for the other three types of automatic belts range from 7 to 14 percent, relative to manual-belt cars at 1983 use rates.

In summary, three rather interrelated estimates of fatality reduction are computed for each type of automatic belt. The three estimates for motorized 2 point belts (without disconnect), 16, 18 and 27 percent are evidence that this type of automatic belt is saving many lives, relative to the baseline of manual-belt cars at 1983 use rates. The nine estimates for the other three types of automatic belts are all positive, and eight of them are 10 percent or more.

"BEST" ESTIMATES OF EFFECTIVENESS

The individual estimates of actual fatality reduction (Tables 2 and 3 for air bags, Tables 4-6 for automatic belts) are averaged[19] to derive current "best" estimates, with approximate confidence bounds[20], for five types of automatic occupant protection, relative to cars with manual belts at 1983 use rates. The results are shown in Table 7. For example, the two estimates of fatality reduction for driver air bags (21 and 24.4 percent) average out to 23 percent.

Also, the overall effectiveness of the occupant protection program for model year 1993 cars is estimated by taking a weighted average of the five individual estimates, based on the distribution of FARS of model year 1993 cars through June 1993 (which was 59 percent air bags, 13 percent motorized 2 point belts without disconnect, 4 percent motorized 2 point belts with disconnect, 19 percent nonmotorized 3 point belts and 5 percent nonmotorized 2 point belts). The weighted average represents the difference between the actual fatality rate in model year 1993 cars, at 1993 belt use, and the fatality rate that would occur in those cars if they were equipped only with manual belts, at 1983 use rates.

Table 7

Best Estimates of Fatality Reduction (%)
Relative to Manual Belts at 1983 Use Rates

Cars Equipped with	Best Estimate	Approx. Confidence Bounds Lower	Upper
Manual belts only (at 1993 use rates)	14	-	-
Driver air bags with manual 3 point belts	23	16	30
Motorized 2 point belts (without disconnect)	19	13	25
Motorized 2 point belts (with disconnect)	13	5	21
Nonmotorized 3 point belts (with disconnect)	14	9	19
Nonmotorized 2 point belts	11	1	21
MY 1993 WEIGHTED AVERAGE	20	15	25

It is clear that the occupant protection program - the automatic protection requirement of FMVSS 208, in combination with a nationwide effort to increase belt use - has reduced fatality risk. The average fatality reduction for model year 1993 cars at 1993 belt use rates is 20 percent relative to the baseline of manual-belt cars at 1983 use rates, with confidence bounds of 15 to 25 percent. Furthermore, the average fatality reduction has improved since 1991, when it was 16 percent.[21] A market shift from automatic belts to cars with air bags and manual belts, and increased use of these belts, are contributing to the improvement.

Each of the five individual types of automatic protection has a positive and statistically significant "best estimate" of fatality reduction relative to the baseline, as evidenced by the positive lower confidence bounds. It is too early for a definitive rank-ordering of the systems. Air bags and motorized 2 point belts (without disconnect) have the highest "best estimates," but the overlap in the confidence bounds for the various types is still substantial.

As stated above, all of the estimates represent actual effectiveness of automatic systems, as currently used. Continued increases in the use of 3-point belts supplied with air bags, as well as other manual or automatic belt systems would boost "actual" effectiveness. As the market share for air bags increases toward 100 percent, the weighted average will rise and approach the estimate for air bags.

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14) Assuming 80 percent belt use in the cars with automatic belts, as reported in *Evaluation of the Effectiveness of Occupant Protection, Federal Motor Vehicle Safety Standard 208, Interim Report*, op. cit., p. 37, footnote 6.

15) χ^2 has to be at least 3.84 for statistical significance at the .05 level and at least 6.64 for statistical significance at the .01 level.

16) The procedures of using the initial as well as the principal impact to define "frontal" crashes, and of limiting the manual-belt comparison cars to the same make-models as the air bag cars emulate Zador, op. cit.

17) The regression model is the same as the one described in *Evaluation of the Effectiveness of Occupant Protection, Federal Motor Vehicle Safety Standard 208, Interim Report*, op. cit., pp. 39-41, except for the following modifications: the data are extended from June 1991 to June 1993, the exposure data have been modified to show scrappage of older vehicles, and the "percent male $\leq$ 30 drivers" variable is based on all the drivers in FARS, not just the fatalities, and has 5

rather than 4 class intervals.

18) The groups of make-models switching from manual to the various types of automatic belts during 1987-90 are listed in Ibid., p. 41.

19) Each average effectiveness estimate is a harmonic average (see Ibid., pp. 41-42). The two air bag effectiveness measurements (Tables 2 and 3) are given equal weight. The automatic belt results in Table 6 are given twice the weight of those in Tables 4 and 5, because they are considered least prone to bias.

20) The confidence bounds are only approximate rather than rigorous and are intentionally wide to allow for biases as well as sampling error (see Ibid., p. 42). They are derived as follows: the analyses for air bags are based on 1271 actual fatalities (in Table 3), but given that air bags reduce fatalities by 23 percent, the "expected" number of fatalities is 1651; the standard deviation of a Poisson variate with mean 1651 is 41 and $\pm$ three standard deviations are close to 7 percent of the mean. The actual fatalities for the four types of automatic belts are 2469, 1232, 3666 and 752, respectively, as shown in Table 4. The confidence bounds for the weighted average are obtained by treating it as a weighted sum of five normal, independent variates (i.e., the estimates for the five individual types of automatic protection).

21) Ibid., p. 35.

The Use of Crash Recorders in Studying Real Life Accidents

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94-S5-O-10

ABSTRACT

The estimation of crash severity, such as the change of velocity (ΔV), is a fundamental measurement of the exposure to car occupants in crashes. Such estimates are mainly based on reconstructions related to the energy dissipated in the crash, as measured by vehicle deformations. The reliability of such estimates are known to be fairly low, in the region of 20 % accuracy, leading to a possibility in i e evaluating crash protection systems.

A low cost crash recorder for frontal impacts, based on a mass spring system has been developed and mounted in a population of 30.000 cars. In this paper, the experience of the crash recorder is shown in terms of crashes and outcome in real life. The pulses of several crashes are presented as well as the change of velocity. Some typical crashes where a traditional reconstruction would have led to poor estimates are also presented.

BACKGROUND

In accident reconstruction accident severity is often calculated or estimated by measurements of the deformation of a vehicle. Equivalent barrier speed (EBS), energy equivalent speed (EES), equivalent test speed (ETS) or change of velocity (ΔV) are often parameters used for accident severity. Several studies has been made concerning the accuracy of such methods. One major problem when calculating ΔV is that deformations and other parameters as stiffness of both vehicles must be known. When calculating for example EBS it is only related to the studied vehicle. The random errors when calculating ΔV are in general beween 11 and 20 % according to ref (2, 12, 13, 14, 16, 17, 19). In most cases the random error of the accident severity is higher than the changes in safety levels that was supposed to be detected. One problem which is often neglected is that data with low accuracy can not be replaced by more data, but will only lead to an answer that is wrong, but with a better precision (5). The reliability and validity is of great importance when making accident data collection (9).

In all accident recontructions and accident data analysis accident severity is represented as one measurement, ΔV, EBS etc. The relation between injuries and the shape of the pulse in real life accidents has never been studied. Studies has been made concerning the relation between the shape of the pulse and dummy measurements in laboratory crashes (10,11).

This paper shows acceleration measurements from real life accidents measured with a low cost one dimensional accelerometer called Crash Pulse Recorder (CPR) (1,7). The CPR is mounted in over 30.000 cars on the Swedish market and over 100 of them has been exposed to real life accidents with a repaircost over 6000 USD. In this paper 8 interesting cases are picked out and the results from those accidents are presented.

A very interesting parameter in accident reconstruction is also the initial angle of force. It is also possible to detect from the registration in the CPR and included in the results.

One interesting item to study is how different acceleration time histories with the same change of velocity varies in its shape. Presented are pulses from almost full frontal accidents and impacts with very small overlap (15%).

MATERIAL AND METHODS

General description

The presented accelerometer, called Crash Pulse Recorder (CPR) see fig 1, is based on a spring mass system where the movements of the mass in a collision is measured. It includes mechanical, electronical and optical features. The quote spring coefficient over the mass, is choosen in a way that the displacement of the mass covers the time for a normal crash. It means that around 120 ms will be registered depending of the shape of the crash pulse.

The displacement of the mass is registered on a photographic film, fig 2, where light emitting diods (LED) registers its location. The LED is driven by a crystal oscillator circuit which gives a modified square pulse with a frequency of 1000 Hz. The circuit has its own power cell and does not need an external power unit. The circuit is activated via a micro switch when the mass starts to move in a crash. The trigger level is choosen to be approximately 1 g to avoid registration of manouvre decelleration as breaking.

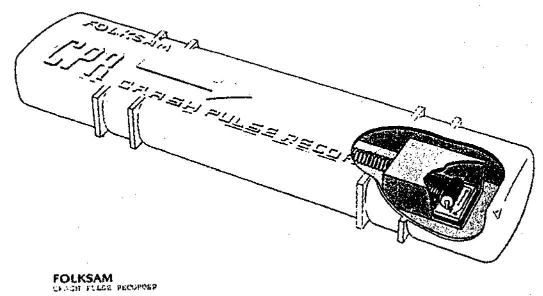

Fig 1, CPR

Analysis of the registration

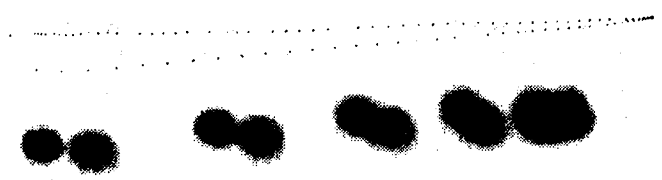

Fig 2. Displacement registration of the CPR on a photographic film (upper), zoom in of the area where the mass turns (lower).

After an impact the registrations on the photographic film, fig 2, is scanned into a computer as a digital image. The computer finds the greylevel center of gravity for each mark. From these measurements it is possible to get the displacement of the mass as a function of time. With all characteristic parameters for the CPR measured and with the displacement time history, the acceleration time history can be calculated with the mathematics presented below.

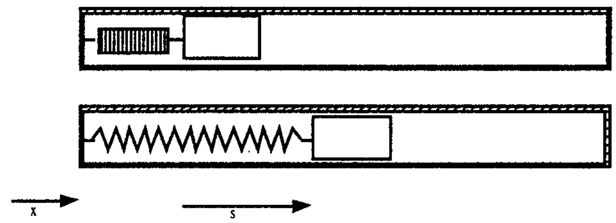

Fig 3, schematic picture of coordinate system for the mathematic model of the CPR

x = displacement of the tube relatively a fixed point
s = relative displacement of the mass
m = $m_{mass} + m_{spring}/2$ = equivalent mass for the system
c = damping coefficient for the system
k = constant for the spring
F_o = prestress force of the spring
F_μ = frictional drag

The coordinate system choosen for the calculations is described in fig 3 where x and s are described above. The relation between the force of inertia and the external forces acting on the mass is shown in equation 1. Included are terms for spring force, viscous damping, prestress force and frictional drag.

$$m(s''+x'') = -cs' - ks - F_o - F_\mu \qquad \text{eq 1}$$

$$x'' = -s'' - c/m\, s' - k/m\, s - (F_o - F_\mu)/m \qquad \text{eq 2}$$

$$s' = ds/dt \qquad \text{eq 3}$$

$$s'' = ds'/dt = d^2s/dt^2 \qquad \text{eq 4}$$

x" is the acceleration pulse for the tube and by that the acceleration pulse for the car if the tube is fixed to the car.

The initial conditions in this case are

$$x(0) = s(0) = 0,\ x'(0) = s'(0) = \Delta V$$

Large fleet field experience

After several tests both with sled and in full scale crash tests (1,7) a large field experience study was made to detect accident severity in terms of acceleration time history from real life accidents. In total over 30.000 CPRs have been installed in cars on the swedish market.
The first ones were installed in July 1992. The CPRs is most of the times mounted under the driver seat, fix to the seat rails.
The results from 8 interesting real life accidents was picked out from the material of over 100 real life accidents. Included are 2 frontal collisions with very small overlap, 15 %, one frontal collision with very high ΔV, two normal frontal collisions with ΔV around 32 km/h, one crash with a pole between the front members into the engine, one sideimpact with the CPR in the hitting car and one accident with two impacts, one pole and one road side rail.
A very interesting parameter in accident reconstruction is also the initial angle of force. It is included in the registration from the CPR.

RESULTS

The results from the CPR in the different crashes are presented as plots concerning the decelleration measurements and as a table concerning the initial angle of force. In the following plots both acceleration and change of velocity as a function of time is presented. Table 1 shows the presented collisions.

1 Frontal impact, car to car, ΔV 39 km/h, 15% overlap, 355 degrees angle
2 Frontal impact, car to car, ΔV 28 km/h, 15% overlap, 0 degrees angle
3 Frontal impact, car to car, ΔV 89 km/h, 70% overlap, 0 degrees angle
4 Frontal impact, car to car, ΔV 31 km/h, 65 % overlap, 0 degrees angle
5 Frontal impact, car to car, ΔV 33 km/h, 100% overlap, 350 degrees angle
6 Frontal impact, pole, ΔV 35 km/h, 0 degrees angle
7 Frontal impact into side of opposite vehicle, ΔV 65 km/h, 0 degrees angle
8 Frontal impact, 2 impacts, pole and side rail, ΔV 18 and 35 km/h, 0 and 45 degrees angle

Table 1

Fig 4 and 5 shows the results from the two car to car collisions with 15 % overlap, collision 1 and 2.

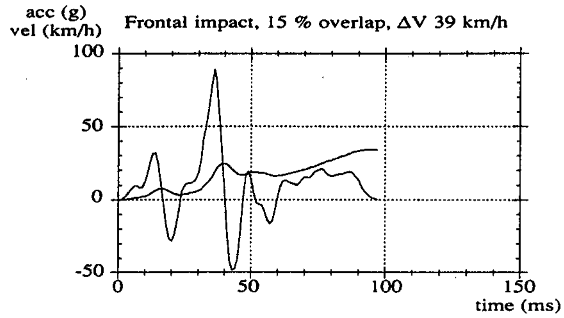

Fig 4, the pulse from crash 1

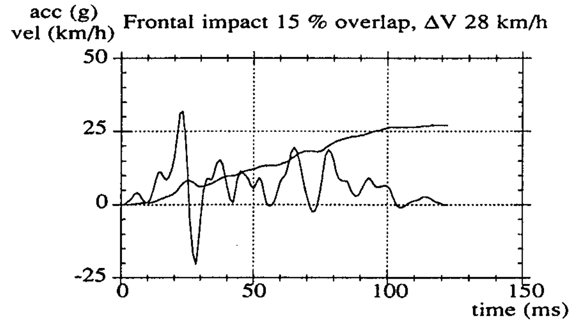

Fig 5, the pulse from crash 2

Fig 6 shows the measurements from the CPR in a very severe accident with a ΔV of 89 km/h.

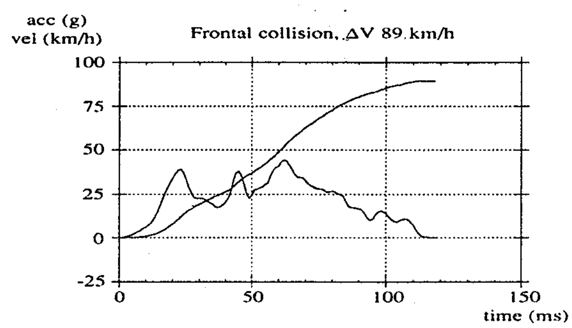

Fig 6, the pulse from crash 3

Fig 7 and 8 shows the results from the CPR in two frontal collisions with ΔV around 32 km/h but with different overlaps, 65 % and 100 % respectively.

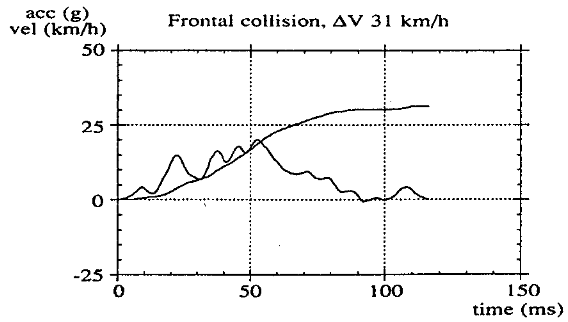

Fig 7, the pulse from crash 4

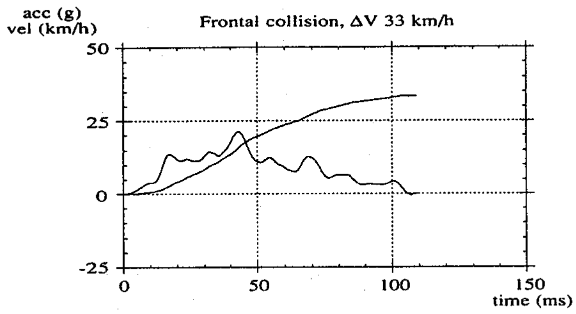

Fig 8, the pulse from crash 5

In fig 9 an impact into a pole with ΔV of 35 km/h is presented. The car hit the pole at the centre of the nose.

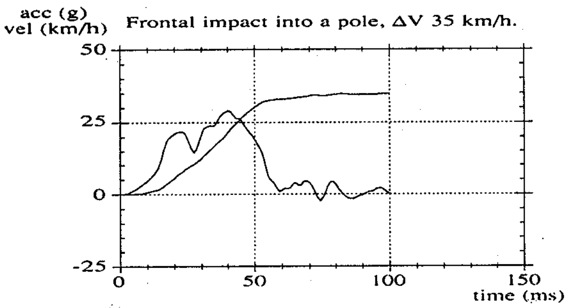

Fig 9, the pulse from crash 6

Fig 10 shows the measurements from the CPR in a severe side impact. The CPR was mounted in the hitting car. The hitted car was hitted at the centre of the side.

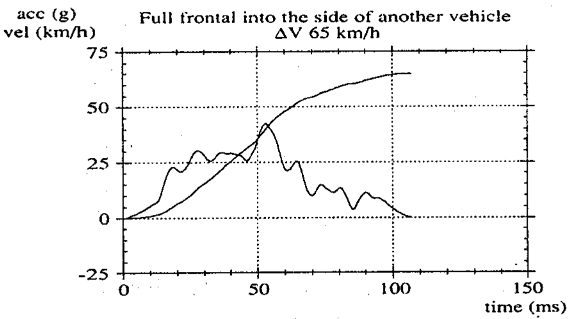

Fig 10, the pulse from crash 7

In fig 11 and 12 the two measurements in the double impact collision is presented. The first one was into a pole with ΔV of 17.5 km/h and the second into a side rail with ΔV of 35 km/h.

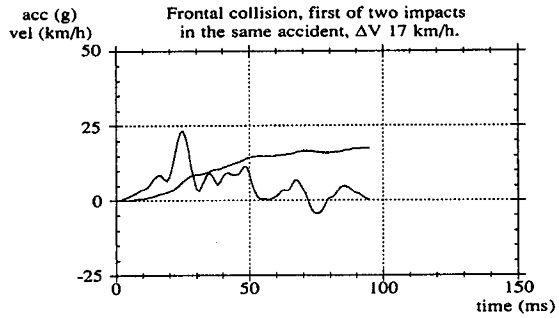

Fig 11, the first pulse in crash 8

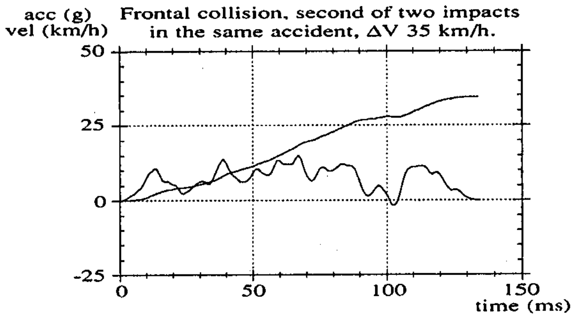

Fig 12, the second pulse in crash 8

Crash	ΔV_{total} (km/h)	a_{mean} (g)	length (ms)	$\Delta V_{0\text{-}40}$ (km/h)	$\Delta V_{40\text{-}80}$ (km/h)	$\Delta V_{80\text{-}120}$ (km/h)
1	39.1	10.6	104	25.0	2.5	11.6
2	27.1	6.3	122	9.8	11.4	5.9
3	89.1	22.3	113	26.3	46.5	16.3
4	31.4	7.7	116	11.1	18.0	2.3
5	33.4	8.9	106	13.6	16.3	3.5
6	34.9	16.5	60	21.6	13.0	0.3
7	64.8	17.1	107	25.3	33.6	5.8
8a	17.5	5.2	95	11.1	5.0	1.4
8b	34.4	7.3	134	8.7	14.2	10.2

Table 2

Table 2 shows ΔV and mean acceleration for different segments of the crash pulse. Also the length of each crash pulse are presented.

There are 5 pulses with ΔV between 31 and 39 km/h. The mean acceleration in these crashes varies between 7.3 g and 16.5 g, and the shape of the pulses varies substantially.

DISCUSSION

When making accident reconstruction the knowledge of the severity of an accident is fundamental. Accident severity is often expressed in terms of equivalent barrier speed (EBS), energy equivalent speed (EES), equivalent test speed (ETS) or some other vehicle related measurement. Such measurements are poor as a severity measurement when making relations to the injury outcome. That is because the deformation of a vehicle does not nessesarily express the severity of an accident. A better severity measurement is the change of velocity (ΔV) and even better is of course the acceleration time history. To be able to calculate or estimate ΔV the deformation of both vehicles in a car to car collision must be known. Also the angle of both vehicles and its weights must be known. That means that the accuracy of a ΔV estimation will be reduced dramatically compared to an EBS estimation. Ref (2, 12, 13, 14, 16, 17, 19) all shows the accuracy in such calculations and estimations. In general all studies shows errors in ΔV calculations of between 11 and 20 %. Smith and Noga (16) made the conclusion that 70 % of the error in ΔV estimation was due to measurement errors in the principal direction of force and 28 % of errors in the deformation measurements. Deformation measurement errors can be reduced if photogrammetrical technique is used (8). That would reduce the errors of ΔV estimation but not enough to be able to make accident data analysis, the problem with the principal direction of force will still remain. To increase the accuracy of a &V measurement to an acceptable level crash recorder technique is nessesary.

The relationship between injury outcome and shape of the pulse has never been studied before, although attemps has been made to calculate the mean decelleration with help of the deformation and the reconstructed change of velocity by Peugeot-SA/ Renault (15). Studies has been made concerning the relation between dummy measurements and the shape of the crash pulse in laboratory crashes. Kurimoto et al (10) have made comparisons of dummy resonses with crash pulses built up by approximated trapetzoids, where two different accelerations levels was used, and original pulses. The differences were very small. It is also analysed how small variations in g level and deformation in each trapetzoid results in big variations in dummy measurements as HIC and chest g. Furthermore the study shows that it is not enough to only have the change of velocity to relate to the injury outcome. Kurimoto et al also made the conclusion that it is enough to differentiate the pulse in a few different acceleration levels to be able to discriminate between pulses. Lundell (11) concludes in a study that variations of the pulse has a large influence on the occupant response. An important parameter is the time when a variation in a pulse is introduced. Lundell also concludes that the most important parameter when considering the effect of variations in the crash pulse on occupant response is the velocity amplitude of the variation.

One parameter which affects the injury outcome to a large extent is intrusion. It is showed by Hartemann et al (3). The study also showes that to measure only &V or other parameters as mean acceleration is not enough to relate to injury and fatality rates. A study made by Hobbs (4) also shows that intrusion affects the injury risk very much.

The presented crash recorder, called Crash Pulse Recorder (CPR), is a one dimensional low cost measurment device which measures the acceleration time history of an impact. The accuracy and precision are tested in previous studies (1,7). When making &V measurements the accuracy is under five percent (1,7). Large efforts has been made to minimize the cost per unit. Each CPR can be calibrated in retrospect after an accident, and all parameters necessary for the analysis can be measured. The prize per unit can therefore be reduced dramatically. The production cost per unit is at the present around 5 USD. The presented crash recorder compared to other proposed crash recorders (6,18) only measures parameters that are fairly insensitive to the driver. Most of the times legal purposes are dominating in crash recorder projects.

So far over 30.000 CPR units are installed in cars on the Swedish market. The first ones were installed in July 1992. Over 100 of them have been involved in accidents with a repair cost over 6000 USD. Most of them are low &V impacts, but some are very severe accidents. Only one with fatal outcome has ocurred. The accident with highest &V had a &V of 89 km/h.

The material from the CPR in combination with deformation measurements made with photogrammetry (8) gives possibilities to study the relation between shape of the pulse, exterior and interior deformations and the injury outcome. The variation of the shape of the pulse in real life accidents will be very big. The pulses in fig 4, 7, 8, 9 and 11 all have a &V around 35 km/h. The variation both in g levels and length can also be studied in table 2. The mean acceleration for the total crash pulse varies a lot between pulses with almost the same &V. In the five pulses with &V around 35 km/h the mean acceleration varies from 7.3 to 16.5 g. The length varies from 60 ms to 116 ms. The accidents with the most severe accidents, crash 1 and 2, were both small overlap accidents with moderate &V but very large intrusion. The shape of the crash pulse were in variations in g levels and very high peak accelerations. In crash 1 the position of the CPR were in a slightly deformed part of the vehicle. The very high g levels can partly be explained by that fact. These types of accidents with very small overlap with a following side swipe will be very hard to reconstruct.

When looking at the injury outcome it is interesting to see that the accidents with highest ΔV is not the ones with the most severe injuries. The most severe injuries were the ones with small overlap but with moderate change of velocity. In those accidents the intrusion was quite large, and the velocity of the intruding parts were probably very high. The study shows that large interior deformation is more injury producing than high change of velocity.

The CPR project will continue with around 30.000 units mounted for frontal impacts per year. The next step will be rear end collisions in autumn 1994 for three differents car models and later on side impacts.

CONCLUSIONS

- In vehicles with the same change of velocity the shape of the crash pulse varies a lot, both in g levels and length.

- Large intrusion is probably more injury producing than high change of velocity.

- ΔV is not sufficient to relate to injury and fatality rates.

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Opportunities for Casualty Reduction in Rollover Crashes

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Paper No. 94-S5-O-11

ABSTRACT

Each year, in the United States, about 220,000 passenger vehicles are involved in rollover crashes. The number of occupants in these vehicles is about 355,000 per year. Of these, about 224,000 are injured or killed; 9,800 fatalities, 14,100 seriously to critically injured, and 200,400 moderately or lightly injured survivors. The injured occupants incur about 789,000 injuries, aproximately 3.5 injuries per occupant. The comprehensive cost of these injuries is about $ 40 billion annually. As a class, rollover crashes constitute about 2.4% of the crashes but cause 33% of the injury costs.

This paper applies on-the-road crash data and computer modeling to clarify opportunities for reducing rollover crash casualties. Countermeasures to reduce rollover casualties include increased belt use, and technoloogical interventions to prevent ejection and reduce the severity of body contacts with the vehicle interior.

The vehicle speed immediately prior to the rollover is a pivotal predictor of rollover crash severity. The number of vehicle quarter turns, the vehicle damage, and the roll rate are also predictors, and are strongly related to the initial vehicle speed. Computer simulations described in this paper suggest that the severity of the tripping acceleration may also have a strong influence on occupant ejections and injuries.

PAST RESEARCH

Earlier papers have provided a summary of related research [Digges 91a and b; and Malliaris 91]. This research dealt with pre-crash factors which influenced the severity of occupant injuries. It was found that vehicle pre-roll speed and potential for lateral slide were two predictors of injury risk. Computer modeling of the vehicle and occupant during rollover indicated that the vehicle angular velocity and displacement during rollover were related to the vehicle's pre-rollover speed. These variables also produced conditions to increase the likelihood of complete or partial ejection. Ejection or partial ejection were found to be extremely harmful intermediate outcomes. An examination of FARS data suggested that occupant containment within the vehicle reduced fatality risk by a factor of 5 or more [Malliaris 87].

DISTRIBUTION OF INJURIES AND INJURY SOURCES IN ROLLOVERS

The National Accident Sampling System, specifically the Crashworthiness Data System [NASS/CDS 1988-91] is the primary source of data. This data system is a nationally representative sample of Police reported towaway crashes. NASS is supplemented by the Fatal Accident Reporting System [FARS 1988-1991] which is a census of all fatal crashes on U.S. roads. The General Estimates System of NASS [NASS/GES 1988-90] covering Police reported accidents is a basis for nationally representative estimates.

In order to compare injuries of different types and severities, the AIS and HARM scales are used. AIS injury coding is a method of partitioning injuries in six categories, according to threat to life. The coding scale is maintained by the Association for the Advancement of Automotive Medicine. The HARM scale [Malliaris 82] applies a weighing factor to each injured survivor according to the severity of the injuries. The weighing factors are based on the cost and injury outcome schedules appearing in the work of Miller conducted for the Department of Transportation [Miller 91]. The total HARM in the NASS file can be calculated by summing all the injured people, each weighted in proportion to the severity of injury in monetary consequences, irrespective of fatal outcome. The total HARM can then be subdivided according to crash mode, injured body region, injury cause, etc. The resulting fractions of the total HARM in the NASS file should be representitive of the fraction of HARM which is occurring in Police reported crashes on the U.S. roads. These HARM fractions provide a basis for estimating the magnitude of the opportunities for interventions.

In the work of Miller, all the costs of multiple injuries received by an occupant were assigned to the most serious injury. The application of the HARM weighing factors in the analysis to follow is based on the same procedure. Miller uses two levels of costs. Monetary costs are the direct costs and lost wages associated with the injury. Comprehensive costs include monetary costs plus nonmonetary costs, such as loss of functional capacity and quality of life. Comprehensive costs are roughly four times monetary costs. For the analysis to follow, comprehensive costs are used for the weighing factors.

The distribution of HARM in rollover crashes by Injuring Source is shown in Table I. Ground and vehicle exterior contacts account for 35% of the HARM, confirming the serious consequence of partial or complete ejection. Within the vehicle, the roof, pillars and headers, and upper interior are the major sources of HARM, accounting for about 33%.

TABLE I
SOURCES OF INJURIES IN ROLLOVER CRASHES
HARM FROM MOST SERIOUS INJURY

INJURY SOURCE	PERCENT HARM
EXTERIOR	35.6
UPPER INTERIOR	21.1
ROOF	14.1
STEERING ASSY.	5.7
LOWER SIDE INT.	5.7
WINDSHIELD	4.8
DASHBOARD	4.0
SEAT BACK	2.8
FLYING OBJECTS	2.6
SEAT BELTS	1.3
OTHER	2.1

The distribution of HARM by Injuring Source and Body Region is shown for both restrained and unrestrained occupants in Table II. This table shows that significant portions of the HARM are associated with head/brain and spinal injuries are from contacts with the roof and upper interior structure. The difference in HARM distribution for restrained and unrestrained occupants is also shown. Exterior contacts comprise about 35% of the HARM for unrestrained occupants compared with 12% for the restrained. Injuries from pillars and windshields also comprise a lower percentage of HARM for restrained occupants. Conversely, the HARM percentage for roof and rail/header contacts is higher for the restrained than for the unrestrained. The relative distribution of HARM in the 1988-91 NASS rollover file is 84% unrestrained and 16% restrained.

TABLE II
INJURIES AND SOURCES OF HARM
FROM MOST SERIOUS INJURY

INJURY SOURCE	BODY REGION	UNRESTRAINED % HARM	RESTRAINED % HARM
EXTERIOR	ALL	34.2	11.9
ROOF	HEAD/SPINE	11.8	19.8
PILLARS	HEAD	8.6	2.3
RAIL/HEADER	HEAD/SPINE	5.6	10.8
WIND. EDGE	HEAD/SPINE	3.3	2.3
WINDSHIELD	HEAD	4.8	0.0
LOW SIDE	CHEST/ABD	3.9	10.4
SEAT BACK	PELVIS/EXT	3.4	1.1
STEER ASSY	CHEST/EXT	2.5	3.8
FLY OBJ.	HEAD/EXT	1.4	5.8
DASH	EXTREMITY	1.0	3.7
SEAT BELTS	CHEST/ABD	0.0	2.2
NONCONTACT	ALL	0.0	2.5
OTHER	ALL	19.5	23.4

In rollover crashes, complete and partial ejections comprise less than 10% of the events but contribute about than 55% of the HARM. A further examination of NASS provides insight into the ejection paths of occupants of light vehicles. The relative frequency and HARM associated with partial and complete ejections was discussed in an earlier paper [Malliaris 91] and has been updated to include 1991 NASS/CDS data for this paper. The distribution of ejectees according to ejection path is shown in Table III. In this Table, both partial and complete ejections are included. Ejections through closed glazings are the most frequent path for both restrained and unrestrained occupants in rollover crashes.

TABLE III
EJECTION PATHS IN ROLLOVER CRASHES
ALL LIGHT VEHICLE OCCUPANTS

EJECTION PATH	ALL EJECTEES	RESTRAINED EJECTEES
CLOSED GLAZING	43.7	43.8
OPEN GLAZING	14.7	31.4
WINDSHIELD	6.8	9.0
DOOR/GATE	11.9	0.3
SUNROOF	11.9	12.0
OTHER/UNK.	10.9	3.5

OPPORTUNITIES FOR INJURY REDUCTION IN ROLLOVERS

Reductions in the severity of contacts which produce injury can be achieved by reducing the relative displacement between the occupant and the surface contacted, and by providing a yielding "friendly" surface. The former suggests improved safety belts and/or reduced vehicle intrusion. The latter suggests air bags, padded surfaces, etc.

Ejection is a particularly harmful outcome. Earlier analysis suggests that occupant containment within the vehicle provides major benefit in rollovers, even for unrestrained occupants. The risk of fatality in a rollover crash is reduced by factors of 5 to 8 based on paired comparison analyses of FARS data [Malliaris 87]. Vehicle design improvements to reduce occupant ejections are worthy of further examination.

Tables I, II and III provide a basis for examining the magnitude HARM which could be influenced by various safety countermeasures. For the purpose of this study, three classes of countermeasures will be considered. These three are: (1) Belt Use and Technology; (3) Interior Protection; (3) Ejection Prevention. The contacts which could be addressed by each countermeasure are shown in Table IV.

TABLE IV
OPPORTUNITIES FOR INJURY REDUCTION
HARM FROM MOST SERIOUS INJURY

INJURY SOURCE	TOTAL HARM	BELT UPGRADE	FRIENDLY INTERIOR
EXTERIOR	35.6	35.6	
UPPER SIDE INT.	21.1	21.1	21.1
ROOF	14.1	14.1	14.1
STEERING ASSY.	5.8	5.8	5.8
LOWER SIDE INT.	5.7		5.7
WINDSHIELD	4.8	4.8	
DASHBOARD	4.0	4.0	4.0
SEAT BACK	2.8		
FLYING OBJECTS	2.6		
SEAT BELTS	1.3	1.3	
OTHER	2.2		
TOTAL	100.0	86.7	50.7

Increased belt usage and improved restraint technology provides very large opportunities for HARM reduction in rollovers. Restraints could mitigate injury producing impacts from the following contacts: Exterior; Upper Side Interior; Roof; Steering Assembly; Windshield; Dashboard; and Seat Belts. These combined contacts contribute 86.7% of the HARM.

For the population restrained by safety belts, there remain opportunities for contact injury mitigation through restraint improvements. The HARM distribution for restrained occupants is shown in Table II. Improvements in restraint system might address the following contacts: Exterior; Roof; Pillars; Rail/Header; Windshield Edge/ Steering Assembly; Dashboard; Seat Belts; and part of the "Other" contacts. The identified contacts comprise 56.8% of the HARM to restrained occupants. The other miscellaneous contacts account for another 23.4%. Technological countermeasures for safety belts include belt pretensioning and improved belt geometry for rollover protection.

Interior protection countermeasures include the use of "friendly" interior surfaces, air bags which deploy for rollover protection, and intrusion control to reduce the severity of the contact. Interior protection countermeasures could apply to the following contacts: Upper Interior; Roof; Steering Assembly; Lower Side Interior; and Dashboard. These combined contacts account for 50.7% of the HARM.

Opportunities for controlling occupant ejection paths can be examined using Figure 1. Closed Glazings are the ejection path which accounts for 50% of the HARM to ejected occupants. The Roof path also accounts for a disproportionate number of ejections and HARM. This distribution suggests significant opportunities for reducing harmful ejections through interventions which could be applied to the following ejection paths: closed glazings (including windshield) - 59%; the roof - 8%; and doors -21%. The finding that most ejectees pass through windows which were closed prior to the rollover offers a new opportunity for intervention through ejection resistant glazings.

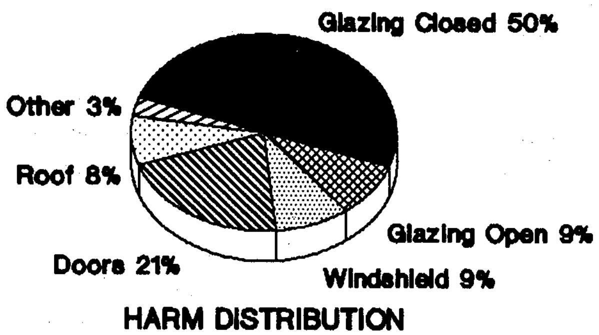

Figure 1. Ejection Paths in Rollovers

Earlier work found that at least one window disintegrated in about 65% of the rollover events involving passenger cars [Malliaris 91]. The glazing disintegration was found to occur frequently in low speed events, as well as high speed events. For car travel speeds less than 40 mph prior to rollover, 40% of the vehicles experienced glazing disintegration, thereby providing an ejection path. For speeds greater than 40 mph, the glazing disintegration occurred in around 80% of the events. By contrast, door openings occur in less than 8% of the rollovers, primarily at speeds above 60 mph [Malliaris 1991].

CHARACTERIZATION OF ROLLOVERS

Earlier studies [Terhune 1988, Malliaris 1991] suggest that the most common type of rollover involves a vehicle slipping sideways and incurring tripping acceleration, which induces the rollover. Terhune found that 70% of the cars, and 91% of the vans and pickups had tripping induced rollovers. Malliaris reported that precrash events which can induce lateral slide are predictors of rollover incidence, and that vehicle angular motion about the roll axis is recorded in more than 95% of the rollover cases.

Analysis of NASS rollovers shows that two thirds of all vehicles in rollovers undergo less than one complete revolution (three or less quarter turns). This group of rollovers accounts for 46.6% of the harm to occupants. The remaining 54.4% of the harm occurs in vehicles which undergo one or more revolutions. The mean precrash speed for rollovers is 50 mph, compared to 28 mph for all other crashes. For rollovers in which a fatality is involved, the mean speed is 63.4 mph, compared with 45.3 mph for all other fatal crashes [Malliaris 1991].

Estimates of the roll rate were made by analyzing the trajectory of vehicles from 140 cases reported in NASS. The cases were selected from the 900 rollovers in 1989-90 NASS on the basis of extent of damage. All cases in the file with severe damage (Collision Damage Classification of 4 or more) were included in the study. The mean precrash speed for these cases was 56 mph, and the mean roll rate was between 1 and 2 rev/sec. In 89% of the cases, the rollover was the most harmful event. The tripping force was the most harmful event in most of the remaining cases. The roll direction was 43% clockwise, 46% counterclockwise, and 11% unknown.

SIMULATION OF OCCUPANTS IN ROLLOVERS

Testing of countermeasures in rollover has been extremely limited to date. Laboratory testing is limited by the lack of facilities which can subject a dummy to the rollover crash environment. There is no rollover equivalent to the crash test sled which is used for developing safety systems for planar impact environments. A great deal of useful information has been gained from rollover testing of complete vehicles. During the past ten years, rollover tests conducted by the Department of Transportation have been of two types.

The first type of rollover is induced by a median barrier designed to redirect vehicles back into the roadway. However, as the angle and speed of engagement with the barrier are increased, a rollover may result. The roll rate observed when a midsize vehicle traveling at 60 mph engages the median barrier is about 1 rev/sec.

The second type of test is a staged rollover induced by ejecting the vehicle from a moving a test cart. The test cart contains platform which is hinged perpendicular to the direction of travel. The vehicle is placed on the platform at an angle (usually 45 degrees or 90 degrees) relative to the direction of travel. The cart and vehicle are towed to speed (30 mph or less) and the vehicle is ejected by rapid rotation of the platform and sudden deceleration of the cart to obtain the rollover. The roll rate is generally less than 1 rev/sec.

Computer modeling of rollover crashes permits precise and repeatable control of the rollover environment, and permits the study of a wide range of rollover conditions at low cost. Computer simulations of vehicles and occupants in rollover crashes have been developed under sponsorship of NHTSA and published in the literature [Obergefell 1986, Smith 1993]. These papers describe models which have been validated for the two kinds of tests described above. However, in both of these rollover test types, the tripping acceleration which induced the rollover is relatively low. The simulations described in this paper introduce tripping acceleration into the validated models developed for NHTSA.

Based on an analysis of the predominate rollover environments, scenarios for rollover simulations have been developed. The initial goal of the simulation is to explore occupant motion during the initial phase of the rollover. This phase begins at the pre-roll conditions including skidding, tripping and launching accelerations. It includes the subsequent linear and angular motion of the vehicle, ending just before the first impact with the ground. For the simulations reported in this paper, the vehicle is initially sliding sideways. It trips, and then rolls about the vehicle roll axis. The magnitude of the tripping acceleration is specified by delta V. It is applied in conjunction with angular acceleration over a period of 120 ms.

DISCUSSION OF BELT IMPROVEMENTS

Computer simulations of rollovers were undertaken to explore the benefits which might be obtained by two belt improvements currently under development and/or in limited production. These improvements are belts with pretensioning, and belts integrated into the seat.

Several manufacturers offer belts which are pretensioned in frontal collisions. Mercedes Benz offers a convertible which senses rollover and deploys additional occupant protection, including a roll bar. The use of pretensioning belts in rollover crashes is an alternative countermeasure which appears feasible using current technology.

Another development underway in industry which may be beneficial to rollover protection is the integrated seat [Haberl 1989; Cole 1993]. The integrated seat provides the shoulder belt anchorage location on the seat back. As a consequence, the configuration provides the possibility of anchoring the entire upper torso to the seat back during a rollover crash. Reduced chest and head excursion should result.

The characteristics of the pretensioned belt and the integrated seat were simulated during the initial 270 degrees of a simplified rollover. The occupant was a 50% male Hybrid III dummy seated in the driver position. For these simulations, the events included a 5 mph delta-V trip, followed by roll at a constant rate of 1 rev/sec clockwise (passenger side first) about the roll axis. The simulation examined only the dynamics of the tripping and subsequent roll. It did not include the acceleration from ground impacts. The vehicle geometry was selected to simulate a typical compact car. Belt slack was set at 6 cm. for the baseline cases, and 0 for the pretensioned cases. Typical results of the simulations are shown in Table V.

In these simulations, the conventional shoulder belt geometry permitted the driver to slip out of the belt during a clockwise roll. As a result, the lap belt provided the principal restraint. Slack in the lap belt permitted the dummy head to contact the roof. The resulting in neck compressive loads were greater than the injury tolerance. Pretensioning the lap belt reduced the neck loads, but still permitted the head to contact the roof.

The seat mounted shoulder belt provided greater upper body restraint during the rollover. In the cases with 6 cm. of belt slack, the head did not contact the roof. Higher shoulder belt forces were developed by the seat mounted belts. These forces acted to restrain the occupant. Performance was further improved by pretensioning this belt configuration.

TABLE V
PRELIMINARY ROLLOVER ANALYSIS
PRETENSIONED AND SEAT MOUNTED BELTS

	CONFIGURATION	STD.	STD.	SEAT	SEAT
	BELT SLACK	6 cm	PRET.	6 cm	PRET.
HEAD DISPLACEMENT	ROOF CONTACT ?	YES	YES	NO	NO
NECK COMPRESSION	% OF ALLOWABLE	1.9	0.7	0.0	0.0
SHOULDER BELT	FORCE RATIO	2.0	1.0	34.	30.

These simulations are useful in providing insights into the potential benefits of improved belt systems. However, due to the complexities of rollover events, additional data analysis, simulation and testing are required to accurately assess the benefits of pretensioning and belts integrated into the seat.

DISCUSSION OF INTERIOR PROTECTION

Interior Protection includes providing friendly interiors, and controlling occupant compartment intrusion.

A development which offers promise in interior protection is the proposed rulemaking underway at the National Highway Traffic Safety Administration to specify minimum head impact protection standards for the vehicle upper interior, including pillars, headers and roof rails. The benefits of this standard are principally oriented toward planar crashes. However, the benefits should extend to rollovers. A detailed analysis of the benefits of this protection has been published by NHTSA [NHTSA 1993]. The results of the analysis predict that improved padding for the upper interior structure will reduce fatalities in the U.S. by 1,365 to 1,614 and AIS 2-5 injuries by 841 to 1,478.

The benefits of intrusion reduction are currently under study and the results will be published when the analysis is completed.

DISCUSSION OF EJECTION CONTROL

Increased restraint use is a readily available opportunity for reducing ejections. In addition, earlier analysis suggests that occupant containment within the vehicle provides major benefit in rollovers, even for unrestrained occupants [Malliaris 87]. Based on the ejection paths shown in Table III, countermeasures to reduce ejections through closed side windows offer large opportunities for intervention. Other opportunities include the sun roof, and the windshield.

The simulation selected to examine the side window ejection opportunity was the tripped rollover described earlier. Variation of two variables were investigated: the severity of the tripping event (specified by delta V), and the roll rate. The occupant was a 50% male Hybrid III dummy in the driver position. The roll motion was counterclockwise and the simulation encompasses roll motion of 270 degrees. Post rollover ground contact was not included. Representative results are shown in Table VI.

TABLE VI
EJECTION THROUGH SIDE WINDOW
VARIATIONS IN TRIPPING DELTA V AND ROLL RATE

TRIPPING dV MPH	ROLL RATE REV/SEC	EJECTION EXTENT
1	0.5	NONE
1	1.0	NONE
5	0.5	HEAD
5	1.0	TOTAL

In these simulations the side windows were initially open. Ejections were not produced during rollovers at 0.5 and 1.0 rev/sec when the tripping delta was only 1 mph. However, as the tripping severity increased to 5 mph, ejection of the head resulted at 0.5 rev/sec, and complete ejection resulted at 1.0 rev/sec. At higher tripping severities, complete ejection was produced at both roll rates.

Figure 2 shows the head ejection which resulted from the simulation of 5 rev/sec and 5 mph tripping velocity.

A repeat of the simulations with ejection resistant glazing in the side window were made. The glazing characteristics similar to those exhibited in laminated windshields were assumed. The glazing prevented ejection in all cases. The maximum forces exerted on the glazing by the dummy were well below the strength of currently used windshield interlayers.

NHTSA has reported successful testing of ejection resistant side windows and windshields [Clark 89]. This research evaluated the penetration resistance of the glazing by laboratory tests and the rollover performance by crash testing in actual vehicles. The stated design goals for ejection resistant glazings included resisting a 40 lb ball impact at 20 mph, and maintaining integrity during a rollover. Rollover tests of eight vehicles with experimental ejection resistant side windows have been reported. The integrity of the side glazing was maintained in all tests. In the eight tests reported, the number of quarter turns ranged from 1 to 8, and the vehicle deformation at the right A-pillar ranged from .4 to 9.1 inches.

Additional research and analysis are now needed to assess the range of crashes which could be accommodated by advanced glazing technology and to estimate the benefits which might be achieved.

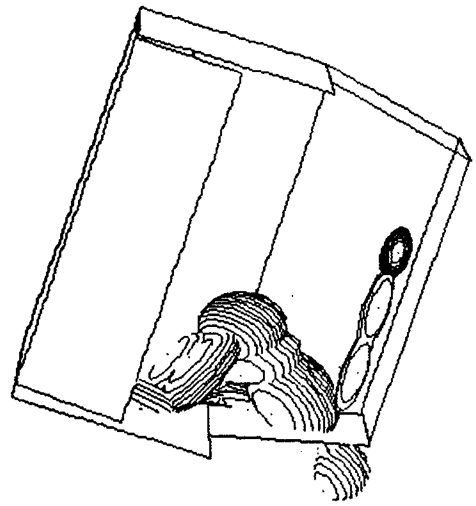

Figure 2. Rollover Model, Head Ejection 0.5 Rev/Sec; 5 MPH Tripping Delta-V

CONCLUSIONS

Significant opportunities for reducing rollover casualties have been identified and quantified. These opportunities include reduction in the severity of occupant impacts with the vehicle interior and the prevention of partial and total ejection. Technological interventions to reduce impact severity include improved restraint systems, interior energy absorbing surfaces, and reduced structural intrusion. Ejection reduction can be achieved by increased safety belt use and technology to improve restraints and reduce ejection paths.

The population of rollover HARM which could be addressed by selected approaches is as follows: Belt use and technology - 87%; Interior protection - 51%; Ejection resistant glazing - 24%; Ejection resistant doors - 7%. For the restrained population in rollovers, the countermeasure opportunities are as follows: Restraint technology - 57%; Interior protection - 53%; Ejection resistant glazing - 8%.

With regard to reducing ejection, further increases in the use of occupant restraints are highly beneficial. However, even restrained occupants continue to suffer injuries from partial ejection.

Analysis of rollover data in the NASS file suggests that in a large fraction (over 70%) of rollovers the vehicle is tripped prior to the roll. A vehicle sliding sideways prior to the trip is a common circumstance. Very little vehicle test data is available for this type of rollover. Computer simulations have been used to explore occupant motion, and countermeasure performance in tripped rollovers. These simulations of tripped rollovers show that tripping acceleration is a critical parameter which acts to induce occupant ejection through side windows early in the crash event. For the range of crashes simulated, forces exerted by the occupant on the side window could be sustained by glazings of existing strength, provided other forces and deformations do not cause its disintegration. However, analysis of NASS suggests that glazing disintegration occurs in 65% of all rollovers. It occurs more than one third of the time in the lowest severity rollover crashes - rollovers at speeds less than 40 mph, and rollovers which involve only one quarter turn.

The majority of ejections are through window openings that were closed when the rollover event began. Around 50% of the rollover harm due to ejection can be addressed by technology to reduce ejections through closed windows. Promising technologies include ejection resistant glazing designs of the type reported by NHTSA research [Clark 1989].

Other opportunities exist for reducing ejections through door and gate openings. Past improvements in the design and strength of door latches and hinges may have contributed to reducing this path from about 45% in the 1970's to the present 12%.

Belt improvements include pretensioning of the belt and improved shoulder belt geometry. Preliminary simulations of these features show reductions in head excursion during rollover, and reductions in neck loadings from roof contact.

Improvements in the safety performance of surfaces which come in contact with the head offer significant opportunities for casualty reduction. The pillars, headers, and roof rails together are responsible for about 20% of the HARM. In addition, the roof contributes to 14% of the HARM. NHTSA has initiated rulemaking to encourage improvements in the head protection of the vehicle upper interior for all crash modes. The resulting improvements could reduce fatalities by 1,614 and AIS 2-5 injuries by 1,478.

Additional research is required to quantify the benefits of other countermeasures. Research is continuing under this project.

ACKNOWLEDGEMENT

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Crash Outcome Data Evaluation System--
Data Linkage of Medical Patient Records with Highway Crash Data

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Paper No. 94 S5 W 14

ABSTRACT

Highway crashes result in tens of thousands of fatalities, millions of injuries, and billions of dollars in health care costs each year. Efforts to control these huge societal costs need data that contain details on the medical and financial consequences of these crashes.

The Crash Outcome Data Evaluation System (CODES) project has funded seven states to generate linked statewide data bases to evaluate the benefits of safety belts and motorcycle helmets on injury costs and morbidity outcomes. Using probabilistic linkage techniques, data describing the characteristics of the crash, vehicle, and occupant from the crash report will be linked to medical descriptions of the type of injury, body region injured, severity, dispositions, and total charges from the occupant's medical records.

The paper will discuss early findings on the usefulness of these linked data for examining highway safety issues as well as their shortcomings from the standpoint of data quality, completeness, and ability to be linked. Advantages of using statewide, population-based data will also be discussed.

INTRODUCTION

In the United States, crash fatalities have declined beyond what anyone anticipated during the past 25 years of organized highway safety and emergency medical services programs. The National Highway Traffic Safety Administration (NHTSA) reports that fewer than 40,000 motor vehicle crash related fatalities occurred in 1992, the fewest in more than a quarter of a century. About 5 million people were injured. Motor vehicle crashes cost our economy more than $137 billion each year. The associated medical costs account for 2.5 percent of the total national health care bill. Thirty percent of the medical costs incurred during the first year after the crash are paid by tax dollars. Non-elderly occupants fatally injured in motor vehicle crashes are deprived of more than 1,300,000 years of productive life and remain the leading cause of death for citizens ages 5-34. A large number of people become "medically indigent" as a result of not being able to afford the large medical costs resulting from serious injury.

<u>NHTSA Goals:</u> The National Highway Traffic Safety Administration (NHTSA) is charged with reducing death and injury on our highways. The Secretary of DOT has assigned priority to increasing the use of occupant restraints to 75 percent, reducing the proportion of traffic fatalities that are alcohol related to 43 percent, achieving state-of-the-art crash and braking safety in new cars and light trucks, and facilitating the introduction of the first Intelligent Vehicle Highway Systems (IVHS) collision avoidance technology in new motor vehicles for sale to the public. NHTSA calculates that achieving these goals can reduce health care costs by $1

billion each year. Reducing the percentage of alcohol-related fatalities to 43 percent of total fatalities, and related injuries by a proportionate amount, would spare the American taxpayer $282 million in health care costs and $208 million in income taxes and public assistance. Increasing safety belt usage to 75 percent from 62 percent in passenger cars alone would reduce health care costs by $684 million and another $328 million would be saved in income taxes and public assistance.

<u>NCSA Responsibilities:</u> The National Center for Statistics and Analysis (NCSA) at NHTSA is responsible for collecting and analyzing crash data to support highway safety initiatives. The Center also monitors highway safety trends. NCSA needs access to comprehensive injury information to continue the rate of highway safety improvement experienced during the past 25 years.

Knowledge of the types of injuries, their severity, the body region injured related to specific crash, vehicle, and occupant behavior characteristics is imperative for NHTSA to effectively direct its resources. These data will enable NHTSA to:

- Relate motor vehicle and crash characteristics to injury propensity and severity.
- Evaluate the benefits of roadside safety enhancements and other highway improvements.
- Monitor and describe the public and private costs of motor vehicle crash related injuries.
- Provide information to emergency physicians to assist them in developing protocols for anticipating non-obvious injuries resulting from motor vehicle crashes.
- Evaluate the benefits of motor vehicle, highway safety, and injury prevention programs in both medical and financial terms.
- Ascertain and monitor the long term health consequences of motor vehicle crashes.

INJURY INFORMATION NEEDS

Many types of injuries previously considered life threatening are now survivable, but often with greatly diminished physical and intellectual capacity. About 50,000 people sustaining serious head/neck injuries survive as a result of improvements in highway safety and emergency medical care. The cost of treating and rehabilitating these victims is substantial and part of the cost of motor vehicle crashes. It is important to understand who is at risk, the etiology of disabling injuries, and how they can be prevented. The importance of capturing information for all motor vehicle occupants involved is demonstrated by the distribution of injuries. As can be seen in Figure 1, the vast majority of occupants involved in motor vehicle crashes are uninjured. Less than 2 percent of <u>all occupants</u> involved in motor vehicle crashes require admission to a hospital.

< .5 Percent
Fatalities

< 2 Percent
Hospitalized

---

5 Percent
Transported by ambulance
to emergency department
but not hospitalized

---

17 Percent
Injured But Not Transported
by EMS or Hospitalized

---

76 Percent
Uninjured People in Crash Population

Figure 1

Analysis of any one of these subgroups without consideration of the total occupants involved skews the results. The effect of most highway safety countermeasures is to cause a downward shift in the distribution of injury severity, moving from severe to moderate, minor or none, and a subsequent change in the probability of injury or fatality. The ability to detect this effect is lost if analyses are performed only within subgroups of injured people. Thus, it is important that the evaluation of highway safety countermeasures include the total population of people involved in motor vehicle crashes.

In order to understand the nature of injuries related to highway safety, NHTSA needs to know the:

- Specific body regions injured, types of injuries sustained, and the expected severity for specific types of crash characteristics.
- Medical status of the victim in terms of physiological measures.
- The benefits of police and emergency medical services responses to motor vehicle crashes.
- Total charges and pay sources for outpatient, inpatient, and rehabilitative medical care for crash related injuries.
- Level of disability as a consequence of different types of crash related injuries.

Medical information about injuries caused by motor vehicle crashes is collected by medically trained personnel such as emergency medical services personnel at the scene and enroute, nurses and physicians at the emergency department and in the hospital, medical personnel responsible for rehabilitation and long term care, and by non-medical personnel responsible for billing and reimbursement. Unlike the police crash reports, statewide injury data systems include medical information about the patient's symptoms, treatment, and disposition. This information is generated from patient records completed at the scene, enroute, in the hospital, after discharge and/or upon death. Most medical data systems, including injury data, have been designed without consideration of linkage to non-medical data such as the police crash data.

Injury information includes data describing the level of severity. Severity may be described in functional, physiological, or anatomic terms. Functional severity refers to the apparent mobility or need for assistance by the crash victim at the scene and, except for occupants killed instantaneously, does not correlate well with survival or other medically defined measures of injury severity. Severity defined in physiological terms is based on a patient's vital signs which may be used in conjunction with other variables to predict survival. Anatomic severity is based on body region injured as defined by a narrative description of the injury or by the International Classification of Diseases, 9th Revision, Clinical Modification (ICD-9-CM) hospital discharge diagnosis codes. The different measures of severity are useful for different purposes. The functional measure provides a pointer to the next level of medical care. The anatomic measure is useful for classifying injuries into similar severity levels for highway safety study. The physiological measure is useful for monitoring the efficacy of medical treatments. A description of the available severity data will be included later in the discussion of each data source.

<u>Current Highway Safety Injury Data Sources</u>: Detailed injury data are currently available from NASS-CDS that generates accident reconstruction information and relates it to injury information on a nationally-representative sample of 5,000 crashes annually. Information on these crashes is obtained from police reports, hospital records, vehicle and scene inspections. Prior to 1993, the Occupant Injury Classification scheme was used to measure severity. Since then, detailed injury data have been collected and coded into the Abbreviated Injury Scale format, currently AIS 90. The AIS 90 is a consensus derived, anatomically-based system that ranks the severity of individual injuries in each body region on a scale of 1 (minor) to 6 (life threatening). These data support agency actions in crashworthiness and crash avoidance research and rulemaking, in performing problem identification, and in evaluating the benefits of countermeasures to reduce occupant injury.

Additional injury information is generated by the Fatal Accident Reporting System (FARS) and the General Estimates System (GES), both of which are national data bases created by NHTSA that rely heavily on police crash reports. Severity is measured by the KABCO scale in which K represents the fatal injury, A the incapacitating injury, B the non-incapacitating injury, C the possible injury, and O no injury. This scale is being replaced by an equivalent numeric identifier in which 4 represents the fatal injury, 3 the incapacitating injury, etc. to zero for no injury. Implemented by police at the scene, this scale is a non-medical indicator suggesting a victim's need for medical assistance at the scene. KABCO correlates with the probability of transport by EMS and admission to a hospital. It does not predict survivability, or provide the detailed injury information about the body systems injured and the physiological state of the injured person generated by NASS-CDS.

CRASH OUTCOME DATA EVALUATION SYSTEM (CODES)

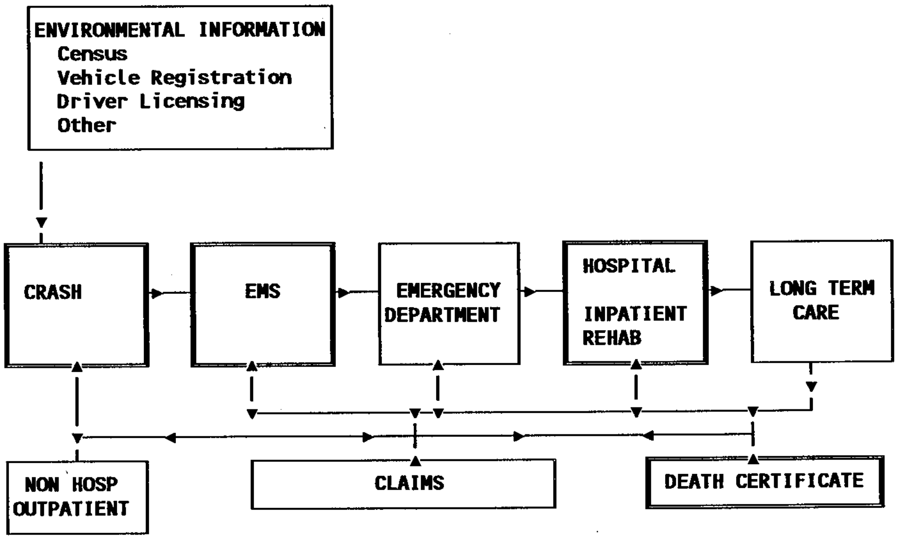
The Intermodal Surface Transportation Efficiency Act of 1991 provides funds to study the impact of safety belt and motorcycle helmet use on medical outcome and treatment charges. Effective October 1, 1992, NHTSA funded seven states--Hawaii, Maine, Missouri, New York, Pennsylvania, Utah, and Wisconsin--to generate Crash Outcome Data Evaluation Systems (CODES). Each state is using probabilistic techniques to link statewide, computerized crash data with occupant-specific medical and financial data collected at the scene, emergency department, hospital, rehabilitation, and long term care centers. The linked data will be used to determine the benefits of safety belts and helmets on severity, inpatient costs, morbidity, and mortality caused by motor vehicle crashes. The results will be included in a report to be delivered to Congress during February, 1996.

The CODES project promotes collaboration between the highway safety and medical communities. This includes collaboration at the federal level between NHTSA and CDC to promote data linkage. At the state level, the project relies on an advisory committee to build a network among the owners and users of the state crash and injury data. As a consequence of these activities, state traffic records system capabilities expand, data quality improves, and a very large volume of comprehensive, longitudinal, population-based information is generated routinely at reasonable cost.

Injury Data Systems to be Linked as Part of CODES

Occupant specific and environmental information describing the various components of a crash and its location are useful for highway safety purposes. When linked, these data enable occupants of crashes to be followed from the scene through the medical care system to final disposition. The various characteristics of the crash, vehicle, and occupant behavior then may be related to the medical and financial consequences of the injuries. Each of the data sources involved in the linkage are displayed in Figure 2. Boxes with double lines represent data systems that are usually computerized, statewide. Boxes with a single line represent data systems that are usually facility based and not merged and computerized statewide.

Figure 2
LINKED CRASH INJURY DATA SYSTEM



CRASH OCCUPANT SPECIFIC INFORMATION

__Police Accident Report (PAR):__ The crash report documents vehicle and occupant information for a specific crash. When this data base includes information about both uninjured and injured occupants, and after consideration of potential over- and under-reporting of belt and alcohol utilization respectively, police data become a potential source of information describing the success stories (such as those occupants who are not injured or who suffer less serious injuries because they were wearing safety belts). Police data also document the time of the crash and thus the time of onset for the crash-related injury.

Although population based data are needed by NHTSA for analytical purposes, the police crash report alone cannot provide the detailed medical, financial, long term disability, and EMS system performance information necessary to comprehensively address many highway safety problems. Police do not have the time, training, or diagnostic skills to collect medical information at the scene or to obtain other medical data generated enroute or at the hospital. The KABCO characterization of injuries most frequently employed by police provides no more than a gross indication of a person's functional capacity upon the officer's arrival at the scene. While adequate for describing the overall severity of the crash in terms of its injury consequences, this scale is incapable of describing the body systems injured, the physiological state of the injured person, or the victim's probability of survival. Linkage makes police data more useful by adding information to corroborate belt and alcohol police data, by providing medical descriptive data to support strategies for adjusting belt use, and by providing detailed vehicle damage claims data to estimate crash severity.

__Emergency Medical Services System:__ The Emergency Medical Services (EMS) data base, when mandated and standardized, includes information about victims who are treated and transported to a hospital by EMS. A separate report is completed to record the status, treatment, and disposition of the victim by each EMS service which responds (first responder, basic life support, advanced life support, air transport). EMS reports are the first medical records completed for people injured in motor vehicle crashes. Severity is described in physiological terms based on the patient's first set of vital signs at the scene, and also measures of eye opening, motor, and verbal responses to stimuli which are combined with the systolic blood pressure and respiration rate to generate the Champion's Trauma Score. The EMS data base is the only source of routinely collected medical information indicating the treatment provided at the scene and enroute to the hospital. Utilization of occupant protection devices and alcohol/substances recorded in the EMS data may be used to corroborate similar information on the crash report. None of the records include information about crash victims not transported by EMS.

__Emergency Department:__ The victim's arrival at the emergency department is first recorded in the emergency department log and then subsequently in notes completed by the triage nurse, the attending physician and nurse, and the medical and mental health consultants who provide treatment. In addition, billing information is collected. The emergency department is the only source of information about the treatment and disposition of crash victims who are not transported by EMS but who obtain outpatient medical treatment at a hospital. It also provides information about the additional treatment and disposition for those crash victims who were transported by EMS. Only a few states have tried to computerize this information statewide, although more and more hospitals are expanding their emergency department computerized billing systems to include patient care and disposition data items. Injury severity information includes the patient's vital signs, the Glasgow Coma Score data, plus detailed diagnostic test data.

Hospital Inpatient and Rehabilitative Records--Once admitted as an inpatient for acute and later for rehabilitative care, a medical record is completed during the victim's length of stay. At the time of discharge, the record is abstracted for many purposes including reimbursement and also merged by most states into a statewide data base to monitor hospital utilization. This data base is the only source of routinely collected financial information describing hospital total charges and, in some states, hospital-based physician charges for victims injured in crashes. It also lists the final medical diagnoses describing the victim's injuries in the ICD-9-CM format from which both the abbreviated injury score (AIS) and the injury severity score (ISS) can be generated. However, hospital records do not computerize information about the utilization of occupant protection devices, and alcohol related information may be restricted from public access.

Long-Term Health Care Information: More-seriously-injured crash victims may require long-term medical care. Long-term care data when routinely collected provide information about the nursing home charges and the permanent functional status of the crash victim. Although several states are participating in a pilot test to create statewide long term care data bases, most of this information is accessible only directly from the facilities where the crash victims are treated. Severity is described according to level of impairment related to level of functioning and also in physical terms based on vital signs. Computerization of this information varies by facility.

Death Certificate: The death certificate data base includes medical causes, time, location, and mechanisms of injury for all injury deaths, including those caused by motor vehicle crashes. The death certificate also records the time and location for the onset of an injury which can be used to corroborate information on the crash report. Unfortunately this latter information sometimes is not computerized.

Other Injury Data Systems: Medical status, treatment, and disposition information for injured victims of crashes may be obtained from other injury data systems generated by hospitals, health maintenance organizations, and government agencies. These data systems include trauma registries, primary care data systems, FARS, etc. Trauma registry data are usually generated by designated trauma centers and, thus, are considered a subset of the EMS and hospital data for those patients with the most serious injuries. Primary care data systems include data collected when outpatient care is provided. FARS data are generated by NHTSA from police and EMS data and include all victims of crashes who die within 30 days of the crash or who suffer non-fatal injuries in fatal crashes.

Claims: Claims data bases generated for reimbursement purposes provide limited medical and treatment information about specific groups of motor vehicle victims. Medical treatment and payment data describing injured crash victims over 65 years of age may be obtained from Medicare, for victims on welfare from Medicaid, for victims of occupational injuries from Worker's Compensation, and from specific insurance groups such as Blue Cross/Blue Shield, ALL STATE, etc. for victims whose care is paid by these sources. The advantage of claims data is that they may include both outpatient and inpatient medical and reimbursement information. The disadvantage is that the data included in these systems reflect requirements for reimbursement and may not provide the detailed medical information, including injury severity, required to evaluate patient outcome.

Social Support: Victims of motor vehicle crashes may also incur non-medical expenses. Disability and supplemental income benefits for victims under 65 years of age are recorded in databases generated by Supplemental Security Income (SSI), In-Home Support Services (IHSS), Homemaker Chore, etc.

ENVIRONMENTAL DESCRIPTIVE INFORMATION

Linkage to the environmental descriptive information provides access to details about the vehicle, driver, and crash location that are not related to the specific crash event. These data bases include census, vehicle registration, driver licensing and other files.

Census: Census data provide access to population estimates for geographic areas, usually towns and counties. These data can be linked to square mile estimates to standardize for inter-state comparisons the population density (population per square mile) of crash locations such as metro, urban, suburban, rural or wilderness.

Vehicle Registration Data: Vehicle registration data provide access to detailed vehicle specifications not normally recorded on the crash report but which may be useful for evaluating the consequences of particular types of crashes. When linked to census and injury data, vehicle registration data can be used to identify urban and rural variations in patterns of injuries caused by crashes involving specific types of vehicles.

Driver Licensing File: The driver file includes information about the driver's history of convictions and crashes. When driver's crash data are combined with medical cost information, this information is useful to assess the societal costs caused by repeat offenders.

Other: Other data related to bridges, pavements, motor carriers, and roadside inventories are useful for data linkage to support implementation of the Safety Management System.

Data Linkage

File Preparation: All files must be prepared for linkage regardless of the linkage methodology, and this step may take months if the state data are not routinely edited to support local decision making.

The CODES project is using probabilistic linkage software, AUTOMATCH, which requires ASCII data files with fixed record length and fixed variable locations. Non-medical data files, such as crash records, must be converted

Figure 3

Examples of Variables Useful for Blocking or Linking	
Variables to discriminate among events	location times provider and provider service area type of event hospital destination unique record number for the event
Variables to discriminate among people	Age/date of birth gender description of injury name/initials phonetic name unique patient ID number

to person specific records in order to link to person specific injury records. Linkage efficiency is facilitated when only one record exists for each person in each file.

Field Preparation: Codes used to represent categorical data must be the same for both files. Thus males designated as "1" in file A must be so designated in file B. County/town code designations in the crash files must match the county/town designations in the injury files. Provider identification codes for ambulance services and hospitals must match on both files. Missing values must be distinguishable from zero values; codes for unknown age must be distinguishable from those for newborns. Person names, if available, must be standardized using an algorithm such as SOUNDEX. Dates should be in year-month-day order and times should be military time represented as hour-minute.

Whenever possible, data errors should be eliminated prior to linkage. Out-of sequence times on the crash and EMS records should be corrected so that the time of the crash does not occur after the time of police arrival at the scene and the time of the call to EMS does not occur after EMS arrival at the scene. Age and date of birth should be compared when both are available. If the data are entered by different data collectors, it may be difficult to decide which is correct when variances occur. Date of birth entered as occupant information for the driver should be compared to the date of birth entered as driver information. Crash location codes should be consistent with the services areas for the police or EMS agencies that respond. Hospital provider codes must be consistent with the designated crash location or EMS provider. A service area code, generated to represent the locations of the crash and hospital, facilitates linkage in the absence of EMS information to point the way. All provider codes should be matched against a reference file to determine validity.

Information that is not uniform is potentially useful when standardized for linkage. For example, type and area of injury information are described in detail in the medical records but must be recoded to match the non-medical descriptions in the crash report. To illustrate, a head injury represents a check in the box labeled "head" on the crash report. The injury record codes each type of head injury with a specific ICD-9-CM code or describes the patient status as "unconscious." Type of injury coded as "broken bones" on the crash report must be matched to "splinting" on the EMS record and the comparable discharge code on the hospital record.

Data Reliability: Record linkage is feasible only when the information in the data file is sufficiently reliable to discriminate among events and people and when it is available for linkage in both files being linked. Figure 3 provides examples of variables which are useful for blocking or linking the data files. Data that are event specific focus on the location and provider including the geographic location, times, type of event, hospital destination, provider service area, and unique event record number. Data that are person specific focus on individual characteristics including age/date of birth, gender, description of injury, name, phonetic name, initials, and unique patient ID number.

Data files that include a large volume of records from areas with high population densities must be reviewed to ensure that the identifier information has sufficient power to discriminate. In some instances it may be necessary to perform ancillary linkages to other files in order to add name and date of birth to the files being linked. For example, linkage of the crash report to a head and spinal registry may provide access to names for some of the injured passengers.

Person specific crash data files including records for both the injured and uninjured are larger and thus more time consuming to link than smaller files which include only injured occupants. We expect a higher percentage of the more severe (fatal, incapacitating) injuries to link to an injury record. But we know that about 10 percent of the crash reports designating no injuries also will match at least one injury record and this total may be almost as many cases as the total fatal, incapacitating, and non-incapacitating injured occupants combined. Included in this group are people who appear uninjured at the scene but who later suffer delayed symptoms, hours or the day, after the crash, such as for whiplash.

Methodologies: The purpose of data linkage is to identify records for the same person that are located in different data files. If the data files are small, it might be efficient to manually match the records in file A with those in file B after reading all the available information in both files. When the data files are large and computerized, manual matching is not efficient. Ad hoc linkage methods are effective when data are accurate and complete. Records are usually matched in a hierarchical fashion beginning with those most likely to match. However, this method may not be the most efficient since only exact matches are accepted during each linkage pass. Thus, many passes through the data are necessary to complete the linkage. Probabilistic linkage techniques are more efficient under conditions of uncertainty when case volume is large, data quality is imperfect, and cause of injury is unknown.

Probabilistic Linkage: Unlike the ad hoc methods, probabilistic linkage effectively identifies matched pairs without requiring the linkage variables to match exactly. This process also quantifies the level of probability indicating if a matched pair is "probably" a match.

Probabilistic linkage generates all possible record pairs from the two files being linked and then classifies them as matched or not matched. For example, two files of 1000 records each create a million possible record pairs but only 1000 possible matches assuming that the files have been constructed so that every record in file A has one match in file B.

Blocking variables: The process of classification is simplified by first sorting the files into blocks. All of the records within the block match on a set of blocking variables. Blocking variables are indirect identifiers that are universally available in every record in the file and have reliably recorded values. These variables should consist of permanent data, such as date of birth, instead of non-permanent data, such as address. Blocking variables are used to sort the data file into blocks of about 10-20 records each. Multiple passes are required to ensure that records not included among the blocks in the first pass will be included within the blocks of the second pass. Weights are not assigned to the blocking variables.

Linkage variables: Linkage is then limited to the records within each block. Variables not chosen for blocking are eligible to be chosen for linkage. Both direct (unique person identifiers) and combinations of indirect (date of birth, gender, town code, time, etc.) variables are useful for linkage. The combination of blocking and linkage variables must have sufficient power to discriminate among events and among people involved in a specific event. Although efficiency may decrease as the number of blocking and linkage variables increases, linkage is more effective when all reliable direct and indirect identifiers are used together to compensate for the inevitable errors located in each.

Likelihood of matching (frequency analysis): The likelihood of matching is quantified by assigning a weight based on the frequency of each attribute for each linkage variable. Rare occurrences will have a higher value than more frequent occurrences. One weight is assigned based on the likelihood of matching among valid matched pairs. The other weight is assigned based on the likelihood of matching among unmatched pairs. This is called the disagreement weight and is expressed as the probability of chance agreement. When two attributes match, the value is expressed as a logarithm to the base two of the ratio of the agreement (match) weight and the disagreement (chance agreement) weight. When two attributes do not match, the value is calculated as the logarithm to the base two of the ratio of one minus the agreement (match) weight and one minus the disagreement (chance agreement) weight.

Matching Parameters: When two attributes are compared, exact matches receive the full weight. When they do not match exactly, adjustments to the weights are made according to pre-determined match parameters. These parameters allow weights to be prorated within an acceptable range or percentage, or to be adjusted when a character varies, a match occurs within an array of choices, etc. Thus, the process is able to take advantage of even imperfect data to identify valid matches.

Relative value (composite weights): Once the weights have been assigned for each linkage attribute, the weights are totaled and a composite weight is assigned to the record pair. Composite weights will be positive for the matches and negative for the non-matches. The unsure matches include the low positive weights, duplicates, and record pairs which do not match on critical attributes. False positive and false negatives are minimized according to how the cut-off weights for the clerical review (unsure) and non-matches are defined.

Clerical review: During the clerical review process, unsure, unusual, and duplicate matches are manually reviewed and reclassified as a match or non-match.

Validation: Validation is important to identify records that should have matched but did not and records which matched but should not have. It is also important to evaluate the case-mix of linked and unlinked records for potential systematic biases that will affect use of the linked data analytically.

Crash reports are sampled and manually linked to actual injury records to identify crash reports that linked to the wrong injury record or that should have linked but did not. Actual injury records indicating cause of injury as a motor vehicle crash are sampled to identify injury records that linked to the wrong crash report or that did not link and should have.

Systematic bias should be investigated in the case selection. Reporting thresholds and variations in submission rates by police agency, provider, or geographic service area are important to determine if specific population groups, types of services, etc. are under- or over-reported in the study population defined for analytical purposes.

Systematic bias should be investigated in the case-mix of linked and unlinked records. Of particular interest is the potential for variations in data quality to result in under- or over-representation of a particular group or unit of measure. For example, clerical review decisions for outlier cases must be reviewed to ensure that valid record pairs representing gross exceptions to the rule are not over classified as mismatches.

Systematic bias may vary with the linkage phase; thus, all phases of the linkage must be investigated for bias. This is particularly important when access to ancillary sources of data provides additional identifiers for linkage. Records receiving the additional information may have a higher probability for matching and may also increase the probability of more complete information describing the medical and financial outcomes. Thus, not all linked state data files are or will be equal. Documentation is necessary to ensure that results are based on comparable linked data.

<u>Obstacles To Obtaining Information for Linkage</u>: The potential analytical value of injury data contrasts with the legal/institutional barriers limiting its access. NHTSA's interests must be directed toward ensuring that injury data systems are accessible and compatible with highway safety interests. In doing so, a number of issues must be addressed.

While police crash reports are most often considered public records for the purposes of access, patient medical records are considered confidential and thus access to these data systems is restricted. The advent of new computer technology will make it possible to provide data security and protect patient confidentiality while still providing needed access to the patient identifiers for linkage.

Missing, inaccurate, and non-uniform data jeopardize the potential success of the linkage process. All data owners and users must appreciate the importance of, and support, good data for efficient and effective linkage.

Linkage may also be delayed when different storage media or non-computerized variables prevent access to important identifiers.

Successful linkage requires collaboration between the highway safety and medical communities. State crash and injury data have been used by different groups for different purposes without awareness of their overlapping interests. Physicians have been interested in knowing what types of injuries occur as the result of specific types of motor vehicle crashes. Highway departments have traditionally been interested in crash and injury data to reduce the occurrence of injuries without worrying about the types of injuries or costs of care. Under health care reform the medical community needs to know precisely which crash and vehicle characteristics have the potential to cause the most disabling and expensive injuries so they can anticipate the need for early intervention. The highway departments need to know which roadside improvements will have the most impact on also reducing health care costs.

Inter-agency politics may prevent collaboration among the different disciplines and multiple organizations required for successful linkage. This collaboration is necessary to resolve issues related to data access, patient confidentiality, data security, and management of the linked data.

Preliminary Results at the CODES Sites

<u>Linkage Results</u>: The CODES sites successfully used probabilistic linkage techniques to link statewide, computerized crash data with occupant-specific medical and financial data collected at the scene, emergency department, hospital, rehabilitation, long term care centers and for reimbursement purposes. The sites varied in their ability to access claims and emergency department information.

Preliminary results indicate that about 10 percent of all occupants involved in a crash were linked to an EMS record and slightly more than 1 percent were linked to a hospital record. States with statewide health or automobile claims data were able to link 30-56 percent of the total occupants to at least one injury or claim record. For those motor vehicle occupants designated as injured (KABC) on the crash report, about 40 percent were linked to EMS data and at least 50 percent were linked to at least one injury or claim record. These preliminary linkage results may change after states complete their linkages to the claims data. Linkage rates for motorcyclists were higher because most cyclists involved in police reported crashes are injured. More than half linked to an EMS record and more than 60 percent linked to at least one injury record. Sites which achieved lower than average linkage rates for either motor vehicles or motorcycles excluded passengers from their data file, or had limited, or no, access to EMS and outpatient claims data.

As expected, the linkage rates varied by the police designated severity level. Linkage rates for occupants who were fatally injured at the scene varied according to whether EMS was responsible for transporting deaths at the scene. About 70-80 percent of the occupants with incapacitating injuries successfully linked to at least one injury or claims record. Linkage rates then decreased as severity decreased. Only 20-40 percent of the occupants with possible injuries and 5-10 percent of occupants for whom no injuries were designated were linked to at least one injury or claim record.

DISCUSSION

Injury Consequences and Financial Outcome Related Applications

Data from the CODES linkage project provide unique insights into the public health costs of highway crashes. Data from the police accident reports provide information about the crash environment and driver/occupants, data from the EMS reports and hospital discharge data provide information about injury type, and hospital discharge data, and insurance claim information provide information about health costs. Taken together, these linked data have much greater value to the analyst then when considered alone. Linked crash injury state data systems include information on all occupants involved in motor vehicle crashes, whether or not they are injured. Data for all vehicle occupants indicate that fatal and serious injuries represent only a fraction of the occupants involved in crashes. Thus, the benefits of restraints is misunderstood if only restrained and unrestrained injured occupants are evaluated, since the uninjured also include restrained and unrestrained occupants. The benefits of restraint use can only be ascertained by contrasting the rates of occurrence in the "use" and "non use" populations. To calculate these rates, one must know who was restrained or unrestrained among both the injured and non-injured.

Vehicle Related Applications

Statewide linked data provide vehicle related information on hundreds of thousands of police reported crashes each year. This volume of cases increases the statistical power to discriminate among specific vehicle attribute issues. NHTSA has used police accident reports to study crashworthiness and crash avoidance issues at the make and model level.

Future analysis of CODES information will allow us to examine:

- differing injury outcome patterns by specific design features, such as restraint type, crash configuration, and vehicles involved, while at the same time controlling for non-vehicle related factors such as alcohol involvement, age, and sex of the drivers;

- problem identification efforts; and

- regulatory impact where cost benefit analyses are used to evaluate the form and stringency of vehicle safety performance standards.

Analysis of injury outcomes using PARs is limited to the functional measure of severity (KABCO), as discussed earlier. Although more medical details are added after linkage to the injury records, CODES data describing the characteristics of the vehicle and crash will be less detailed than that obtained through NASS-CDS in-depth investigations. Unfortunately, it is not feasible to inspect all vehicles involved in crashes in order to obtain from the linked state data the same level of detail about the location of injury impact within the vehicle, the immediate characteristics of the surroundings in which the crash occurred, the crash type and severity that are now generated by NASS-CDS.

As linkage capabilities and data quality improve, some of the detailed vehicle damage information may be obtained statewide from access to the national automobile claims clearinghouses

Highway Safety Applications

Traffic crashes are not accidents. They are preventable tragedies. Injury severity and economic costs could be reduced significantly with voluntary, common sense actions by motorists, including for example, not drinking and driving, using safety belts or child safety seats, helmets for motorcyclists, not speeding, and driving courteously and responsibly with respect for other motorists. To work with states to control driver behavior, NHTSA often examines state data to evaluate the benefits of specific highway safety legislation, such as per se levels of drunk driving or age 21 drinking laws. These benefits are typically measured in terms of crash and injury reductions (either a reduced number of fatalities or gross summary injury information). CODES data will allow the agency to examine not only a more accurate description of injury consequences, but also the public health cost savings associated with these highway safety initiatives. Since a high percentage of these costs are assumed by citizens through increased taxes to cover the expenses of uninsured and underinsured crash victims, documentation of these costs will have a large effect on public and legislative support for stricter laws and support for enforcement actions. Linkage generates state-specific data which are more credible to local decision makers. A cost-benefit analysis based on linked statewide crash injury data has already been used by the legislators of one state to justify continuation of its helmet law. Examples of CODES supported analysis include:

- Evaluation of head injuries to motorcycle occupants related to helmet use. The increased costs associated with head injuries for unhelmeted riders is indicative of the increased injury severity. This information is invaluable for supporting passage of mandatory helmet use laws as well as supporting police enforcement of such laws. Insurance data also will show who is paying for this treatment.

- Assignment of health care costs for specific vehicle, crash, and behaviors (e.g. alcohol involvement, unsafe driving actions), which can then be used to set program priorities, support safety legislation, and support enforcement and education activities.

- Disaggregation of statewide costs to smaller governmental units, e.g. county or city, to justify increased highway safety program efforts to local political and community leaders.

- Evaluation of roadside safety improvements for cost benefits.

- Identification of target populations regarding highway crash experience and associated medical expenses and payor source.

Medical Care-Related Applications

An important concern of the public health community relates to the availability of medical services and related morbidity outcome. Linked injury crash information assists the medical community to monitor and prevent unnecessary mortality and morbidity resulting from motor vehicle crashes. Medical personnel in many parts of the country are experimenting with crash data to develop physician practice guidelines for "predicting" the organ systems injured. Emergency department physicians and trauma surgeons use these data to streamline the triage process by "anticipating" what types of injuries to expect. This inter-disciplinary approach to solving highway safety problems encourages a collaborative relationship between the highway safety and medical communities. CODES linked data can provide detailed information on:

- How long it takes for the emergency medical system to respond as well as the association between treatment procedures and subsequent morbidity and mortality outcomes. This information can help determine the need for improved EMS services in rural areas or improved medical treatment at the scene, in the emergency room, or in the hospital. Costs and benefits for these options can be evaluated to determine the most effective public policies for providing these services, and

- Information about injuries, treatment, costs and outcome for injury surveillance and health planning, e.g., data on the incidence of head/spinal injuries per 1,000 motor vehicle occupants related to crash, restraint type, and driver characteristics.

Photogrammetry Used for Measurement in Field Accident Studies - Development of a New Simple System

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ABSTRACT

The measurement of interior and exterior deformations of cars involved in crashes is an important piece of information for evaluation of the crash protection of vehicles as well as injury sources. Such measurements are normally conducted on manual basis leading to poor precision and questionable definition of points that have been measured. The possibility to measure, not only on the object but also some time after the car has been dismantled or otherwise hard to find again, is also limited.

A photogrammetrical system has been developed and used for a couple of years on large number of cases. In this paper, further development of the system is presented, where the time used on the field as well as in the measurement phase has been reduced. It is also shown how measured points are stored in the photographs, enabling a follow up of earlier measurements.

As a complement to the measurement photographs video films from the field can be used for measurement. The video film can also be used for analysis of restraint use and documentation of contact points between the vehicle and the occupant.

BACKGROUND

Car crash safety is an important health factor in modern society. The difference in crash safety between different car models and safety systems are considerable. High quality real life data about crash behaviour and injury outcome is an important complement to laboratory data, in order to further monitor and develop crash protection.

During a period of time Folksam has used photogrammetry as a documentation and measurement method in a accident data collecting project in Sweden(5). The technique has been based on the use of small format (24x36mm) calibrated "metric" camera images for data capture. The measurements have been performed in a mono comparator style system without stereoscopic viewing. The images have been measured using enlargements on a digitizing tablet connected to a personal computer (6).

In total nearly 500 cases have been measured covering some 15 car models. The measurement data has been collected together with accident information, a close inspection of the cars and injury information. Since the summer 1992 some 30, 000 vehicles have been instrumented with crash pulse recorders for measurement of real life crash pulses and change of velocity(7).

The accident data retrieval system is designed to allow non specialist data collection in the field. The evaluation and analysis of the field material is performed by a small group working close together assuring consistent methods and results. Photogrammetry is well suited for this kind of collection set-up since it has substantial documentational value and the analysis/measurement procedure is clearly divided in a collection and an analysis phase which are possible to divide in time and space.

PHOTOGRAMMETRY

Photogrammetry uses photographic images as the base for three dimensional measurements. Pairs of photographs, taken from different positions, are used to do a reconstruction of the arrays of light captured on the film. The spatial location of a point, being seen in two photographs, can be reconstructed in an optical, mechanical or mathematical way. By orientation and scaling procedures the result of the measurements are x, y and z-coordinates in a defined coordinate system.

Photogrammetry has undergone rapid development during the last decade, mainly because the development of sophisticated mathematical reconstruction models running on line in personal computers. These numerical models uses image coordinates, measured in two or more images, to calculate real life three dimensional coordinates. There are some different ways to solve the mathematical calculations. This paper is based on the use of calibrated cameras, interior, relative, and absolute orientation. The details of the photogrammetrical calculations and software are not discussed in detail in this paper. For the theoretical and mathematical background see standard works in the field. (1, 3 and 4)

FIELDWORK

Photogrammetrical work i clearly divided in the data capture phase and the analysis phase. In the accident data collections system standard routines are used for every case. A reference car of the models studied has been measured and the coordinates for a standard set of points located on the car are known. The standard points used are sharp corners and edges on the car body together with some stickers placed in specific areas where no other distinct points are visible.

In the field, photographs are taken around the vehicle. In total eleven image pairs are taken around the vehicle, into the interior and in the motor compartment. The photographing positions are only approximate allowing hand held cameras. All the images are taken in every case, no matter the amount and location of the deformations. A complete set of images is important, since both deformed and undeformed areas are measured.

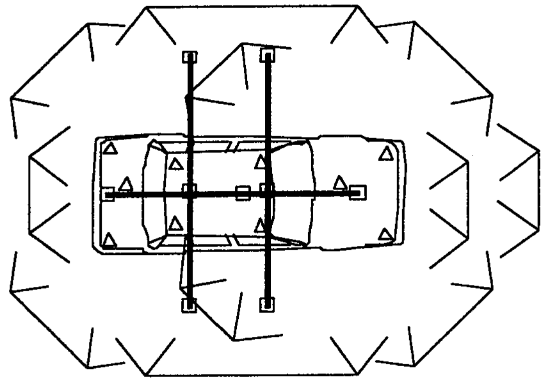

Figure 1. The standard photographing positions

MEASUREMENT WORK

In the measurement procedure the aim is to calculate deformation vectors for the standard points. First an undeformed area of the car body is measured, to establish a coordinate system equal, in scale, origin and directions, to the one used on the reference vehicle. By connection points, visible in all images, all further measurements later can be performed in the standard coordinate system. The deformation vectors are thereafter calculated as the difference between the reference coordinate and the coordinate of the deformed point.

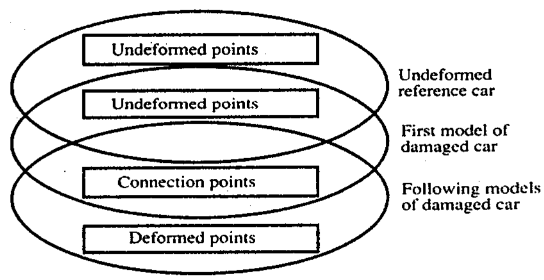

Figure 2. The relation between the reference car and the deformations

DIGITAL IMAGES

A major development in the digital image field has made new measurement methods possible. The possibility to work with high resolution digital images is closely related to the development of fast and capable personal computers. The digital images can be captured into the computer environment in many different ways. The most straight forward solution is perhaps to scan paper prints in a desk-top scanner. This will, however, in the long run cause storage problems, if the images on which the measurements are based, is to be stored. Instead the scanning and storing service offered by the Kodak PhotoCD system have been used. The PhotoCD is a CD-ROM disk (Compact Disk Read Only Memory ≈650MB of storage capacity) of standard format that can be read from CD-ROM readers integrated into modern computers. Standard 35mm, small format film, is sent to a laboratory that scans the film and stores the image information on the CD-ROM in several different spatial and colour resolutions. The maximum standard size of an image is ≈3000x2000 pixels. The low resolution images (192x128) are well suited for image data base storage on a hard disk for use as markers with reference to the PhotoCD.

There are also possibilities to get digital images from video signals using frame grabber devices. To some extent digital cameras have found a market but the products available today are either aimed at the professionals, with relatively high resolution and high cost, or to the amateur market, with too low resolution for photogrammetric work. The traditional camera with traditional film is a very resolution/information and cost effective device (>18MB per frame at < 1USD each).

THE MEASUREMENT SYSTEM

In the new photogrammetrical measurement system the previously used digitizing tablet, on which paper prints were fastened and measured by a cursor, has been substituted by computer screen measurements. The images are seen on the computer screen, and a mouse is used to place a cursor on the points of interest. An Apple Macintosh computer (LC475) is used and programmed to send out image coordinates over the serial line, as if it was a digitizing tablet. The images are read from a CD-ROM player connected to the computer. The digitizing tablet emulation solution makes it possible to use the same photogrammetrical software as before. The calculations are performed in a second computer.

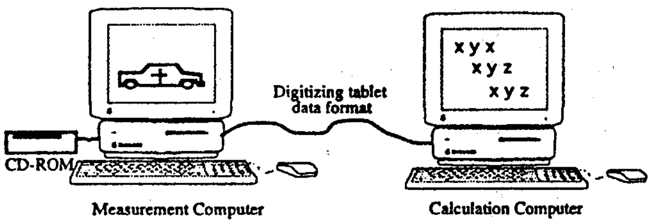

Figure 3. The measurement equipment set-up

In the photogrammetrical system the image size 1500x1000 pixel is used. The resolution is a compromise between the measurement accuracy and the capability of the computer. The 1500x1000 pixel resolution corresponds to a pixel size of ≈0, 025mm. Since the screen measurements can be performed with at least a precision better than one pixel, the resolution corresponds to the precision achieved when a digitizing table was used (0, 015-0, 030mm). The use of the highest resolution would be possible but the need of computer RAM memory would increase fourfold from ≈10MB to 40MB. To keep the speed up only the grey scale information in the images is used for measurement work.

The measuring sequence, when measuring an image pair, is divided into five steps. First the point number is chosen from a menu. Secondly a rough measurement of the point is done in an overview of the left photograph. The rough measurement is used to define a "zoom in" area that will be shown enlarged on the screen. The final measurement is then performed in the enlarged part. The rough and final measurement is repeated for the right photograph. As the measurements are proceeding, crosses are painted over the points that are measured. The point numbers are also written on to the photographs. The processed image including the crosses and point numbers can be printed on a standard printer with acceptable results.The crosses and point numbers can also be stored on a separate image file with minimum storage space requirements (≈15kB).

ACCURACY

The accuracy in a photogrammetrical measurement system is depending on a large set of parameters and is not easily calculated. To get an idea of the real life accuracy in this system indirect observations are used. There is a large difference between the measurement accuracy on distinct points in one pair of photographs and the final accuracy in the measurement project. The error propagation from the "undeformed" reference points to the final deformation calculations contains many uncertain errors.

Earlier tests of the actual accuracy have been performed when a digitizing table was used as measuring device. The test was based on points on the car that can be estimated to be unaffected by deformations but still measured in many cases. Stickers behind the door openings were used. These stickers are put in approximate position but on a relatively flat surface. Only the lateral deformation could be used for this reason. In a sample of 80 arbitrary chosen cases the "deformation" had and average value of approximately 15mm.

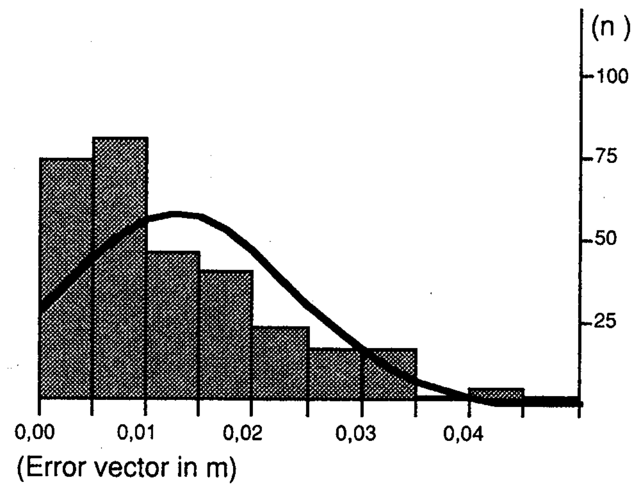

Table 1. Error distribution for digitizing tablet measurements

Another measurement precision indicator is the residual error in the images after bundle adjustment. The residual error, in this case considerably larger than the camera calibration residual error, is an estimate of the measurement accuracy in the images. In the test above based on digitizing tablet measurements these errors varied in the region 0, 015 to 0, 030mm. When computer screen measurements in digital images, size 1500x1000 pixels, have been performed the same residual errors have been reduced to around half of the numbers above. This should indicate an accuracy of around 8mm on the car body in a measurement project. Measurements of undeformed car bodies, for reference measurement purpose, shows somewhat better values when analysing the locations of symmetrically placed points. The actual accuracy in the digital system is, however, yet to be validated.

LIMITATIONS

The photogrammetrical system is generally best suited for exterior deformation measurements since there is a close connection between the possibility to take good photographs and the measurement possibility. The measurement of clearly defined points on a car body with limited deformations can be performed with relatively high precision (8). If the vehicle have small undeformed areas to define the orientation of the standard coordinate system, the orientation process will be more weak and even if the measuring accuracy is high then deformation vector calculations will be of less reliability since the coordinate system would not be parallel.

Measuring interior deformations, with the introduction of connection chains, will also cause more complications. For this reason the photogrammetrical system used by Folksam is primarily designed for measuring exterior deformations. In many cases the relation between the outer skin deformation of the vehicle and the interior deformations are evident, especially if the structure of the vehicle is known. In the procedures used today only a few points inside the passenger compartment are measured, the steering wheel and the dashboard. These interior points are photographed from outside the vehicle. No long and weak connection chains, in which error are introduced, will occur with this set-up.

More detailed information about the size of interior deformations, e. g. foot well intrusion, would need a more detailed interior documentation and more complex connection systems resulting in locally lower accuracy. The photographing of the interior also introduces photographical exposure problems since the light conditions are more differentiated and very low light areas can be foreseen.

VIDEO TECHNIQUE

As a complement to the traditional photographing, video camcorders have been used in the field. The video cameras are used as dictaphones during inspection. The person inspecting the car is also instructed to document in images the contact points, seat belt use and other important findings. The video film has become an important part of the material analysed by the central group.

For the fieldwork Sharp VL-MX7S video cameras have been used. This specific double lens camera has been chosen since it has a good wide angle lens as a complement to the standard zoom lens. The wide angle lens is well suited for interior documentation of the vehicle. Since the wide angle lens is of fixfocus type it is suited for photogrammetrical measurements. As a complement to the standard photogrammetrical images some preliminary tests have been performed to evaluate the use of video images for measurements. The aim is to be able to use video images in the interior areas, hard to depicture with the standard camera due to intricate photographing conditions and low light. For precise exterior measurements the standard photographs have a superior resolution assuring good accuracy and interpretation capabilities. The resolution in the video images do no allow measurements of many of the standard points such as sharp corners and rifts in the car body.

The quality of video images vary a lot depending on whether the camera is connected directly to the computer frame grabber or if video tape is used running or still. Considerable image deformations can bee seen when video tape is used. In this project only images stored on video tape can come into consideration.

In a test one video camera has been calibrated and some preliminary measurements have been performed. In the test the video signal was taken from running tape into a computer via a frame grabbing card. The images had the size 768x512 pixels in 256 shades of grey. The residual error in the camera was ≈1. 5 pixels after calibration. The same magnitude of residual error has been found when calibrating other video cameras. Using a simplified formula for error estimation (4) the measurement accuracy can be calculated to ≈10mm in a photographing distance of 2m. This value corresponds to the one achieved in practical test. When testing major errors occurred in some cases due to the noise introduced when storing the video images on video tape. The stochastic occurrence of gross errors indicates reliability problems making video images useful as a complement and back-up system but not an alternative to traditional images. To enhance the reliability the photographing methods can be changed in a way that long stable film sequences are taken using a tripod.

FURTHER DEVELOPMENT

Two main areas are important to develop further. The measurement program can be made more efficient, by introducing semi automatic or automatic measurement of points. The automatic procedures may also increase the accuracy. Semiautomatic measurements of stickers with a well defined shape can relatively easily be implemented, pattern recognition, relational automatic measurements will however need more competent computers and considerable development.

The development in the field of digital images will result in more consumer product digital cameras with a higher resolution. These camera may be well suited for photogrammetrical measurements. Whether the cost effectiveness and precision will challenge the capacity in traditional film and PhotoCD scanning is, however, doubtful. In some cases, especially in laboratory environment, the directness of digital camera can be valuable.

CONCLUSIONS

The following conclusions can be drawn from this study: (i) Vehicle deformations are important information sources for the car safety evaluation; (ii) photogrammetry is a useful technique for the field documentation and measurement of deformations; (iii) non specialists can perform the photogrammetric fieldwork; (iv) accuracy levels better than 10mm can be achieved with relatively simple equipment; (v) digital images increases the accuracy compared to paper prints; and (vi) in photographs taken with video camera accuracies around 10mm can be achieve in the interior of the vehicle.

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Comparison of Road Users' Injury Typology at Ten Year Intervals (First Part)

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ABSTRACT :

This paper is the first part of a study on trends in lesion typology of highway traffic users. Two accidentology investigations at ten year intervals, each lasting two years, are taking place in Nîmes, a middle town situated in South West of France and well known for its corridas.

The first phase occurred between 1981 and 1983 making it possible to achieve a lesion typology characteristic of highway traffic users, a priori defined. It concerned pedestrians, cyclists and drivers or passengers of mopeds, motor bikes, light vehicles vans and lorries.

Ten years later, in 1993, the second investigation phase was started and will be completed end 1994, using the same operating conditions and the same reception centre as in the first investigation, namely the Nîmes Emergency Service (SAMU). The compilation comprises a tie on label of the injured person, his detailed lesion evaluation and the accident circumstances.

The objective is to evaluate the trend of specific lesions linked to each user type, from the comparative study of the two investigations. In other words, it is a question of verifying if there has or has not been a development in the type and severity of lesions received by highway traffic users. This can also provide evaluation elements of the efforts made in recent years to improve both the active and passive safety of users as well as the general traffic conditions.

The second objective is to evaluate the relative risks associated with each user category as a function of the usual lesion severity criteria in accidentology. A.I.S. is an International classification of traumatic lesions which gives a severity or death risk score to each lesion. Recently, another score has been associated with it, namely the I.I.S. (Injury Impairment Scale) which defines a handicap risk scale. We will discuss the advantages and limitations of these scales for a more precise definition of the seriously injured, in the second part.

I. INTRODUCTION:

The first investigation phase lasted about two and a half years, between 1981 and 1983. The second phase started in 1993 and will last two years. For the second phase this study is based on one year of data compilation, which explains the difference in size of the two phases. We can only therefore give partial results in this study. Also for this reason, the detailed study of trends in lesion typology can only be carried out when the second investigation phase is completed.

PREAMBLE:

Having said this, the Public Authorities have changed the way in which SAMU (emergency services) intervenes during road accidents. In fact SAMU doctors are no longer automatically sought after during a corporal accident except when children are involved. This signifies that a part of the lightly or superficially injured is not taken into account in the second compilation.

II. ROAD USER TRENDS

In this first part, we will attempt to pin point the main changes in the distribution of the injured per user type, sex and age group. These modifications can be explained by changes in behaviour and habits but also in the displacement means chosen by the population.

Table 1 : Distribution of the Injured by Road User Type

Road Users	First survey		Second survey	
Pedestrian	299	8.3%	84	7.6%
Bicycle	169	4.7%	42	3.8%
Moped	656	18.2%	123	11.1%
Motorcycle	338	9.4%	82	7.4%
Car	2016	56.0%	731	66.0%
Van	68	1.9%	30	2.7%
Lorry	54	1.5%	15	1.4%
All users	3600	100%	1107	100%

We noted an increase in the injury rate of light vehicle users, primarily due to an increase in the number of light vehicles and a reduction in other user categories, especially mopedists.

II.1. Distribution by Sex

Table 2: Distribution of Injured by User Type and by Sex.

	1° Investigation		2° Investigation	
Road User	Men	Women	Men	Women
Pedestrian	156 53%	137 47%	53 63%	31 37%
Cyclist	127 75%	42 25%	34 81%	8 19%
Motocycle	765 77%	223 23%	179 87%	26 13%
Four-wheeler	1278 60%	840 40%	471 61%	303 39%
All users	2326 65.2%	1242 34.2%	737 66.7%	368 33.3%

We noted a slight reduction in the percentage of injured females, and this in all forms of locomotion and especially amongst motorcyclists, mopedists, cyclists and pedestrians.

II.2 Distribution by Age Group

During the first investigation, we noted a preponderance of young people in the 15 to 24 age group in all accident types and primarily in motorcycle accidents which represented 65% of the victims. More precisely, 15 to 17 years old adolescents in particular were injured in moped accidents in more than 60% of the cases. This high moped accident frequency mainly involving adolescents could be explained by the drivers' lack of experience, the fact that a driving licence or wearing a crash helmet is was not obligatory.

Young adults in the age group 18 and 24 constitute 30% of road accident victims, represent 55% of large motorbike accidents and 30% of car accident victims.

Table 3: Distribution of Accident Victims by Age and by User Type - First Investigation

Road Users	under 15yrs	15-24 years	25-34 years	35-54 years	over 54y	Total
Pedestrian	58	54	34	52	110	298
Bicycle	40	36	15	40	37	168
Moped	38	414	65	84	52	653
Motor cycle	2	225	77	26	8	338
Car	148	675	434	474	277	2008
Van	2	22	21	15	8	68
Lorry	0	11	16	17	10	54
All users	288 8%	1427 40%	662 18%	706 20%	502 14%	3587 100%

From the comparison between tables 3 and 4, we noted significant trends, in the 1993 investigation :
- an increase in the rate of 25 to 34 year old casualties from 18% to 22.8%,
- a reduction in the number of 15 to 24 year old accident victims (40% to 32.1%), this is a direct consequence of the virtual abandon of the lightweight motorcycle, especially by adolescents. The obligation to wear a crash helmet for all motorcycles also contributed to this improvement in youngsters safety.

Table 4: Distribution of Accident Victims by Age and User Type: - Second Investigation.

Road Users	under 15	15-24 years	25-34 years	35-54 years	over 54	Total
Pedestrian	26	13	11	10	22	84
Bicycle	7	5	9	9	12	42
Moped	2	78	9	20	12	123
Motor cycle	1	38	31	11	-	82
Car	52	216	176	166	107	731
Van	3	4	10	5	8	30
Lorry	-	1	6	8	-	15
All users	91 8.2%	355 32.1%	252 22.8%	229 20.7%	161 14.5%	1107 100%

We noticed a general reduction in the number of injured in all road user categories in relation to the referenced category which here is the users of light vehicles. On this subject, data from National sources show a regular increase in the number of "four-wheelers" vehicles and motorbikes, whereas the number of mopeds continues to reduce. The increase in the number of bicycles is difficult to assess, and even more so as it includes a large number of unused vehicles.

III. TRENDS IN ACCIDENT SEVERITY

Comment 1: The A.I.S. records the number of deaths occurring in the 24 hours after the accident. This threshold underestimates the real number of deaths, as the convention in France says that road accident victims are to be accounted amongst ordinary deaths if they die at the end of 6 days after the accident date.

On the contrary, for counting the number of severely injured we will use a criteria defined from the A.I.S., being an OAIS more than or equal to 3. In France, the rule is that a victim's injury is considered serious if the victim has to be hospitalised for more than 6 days. This is a debatable definition, because it does not necessarily reflect the severity of the lesions. Further this criteria is often poorly informed by doctors.

In consequence a victim injury will be considered light if his OAIS is less than or equal to 2.

Comment 2: We recall the likely data compilation bias between the two investigations. The absence of a certain part of the superficially injured in the second investigation artificially inflates the percentage of victims severely injured or killed.

Concerning the percentage of killed, it is possible as in the first investigation to underestimate the real percentage of victims killed. It seems to us that the number of deaths at 6 days recorded in the first investigation did not include everything. We know the problem of counting the victims killed: immediately killed, 24 hours later, 3 days or 6 days later.

III.1. Severity by User Type:

In the first investigation, we noted that although moped accidents were relatively frequent, but in terms of severity, it was especially accidents involving lorries which gave the most serious injuries, followed by pedestrians. For the second investigation, the data so far is too limited to draw any conclusions for each category, but globally speaking, if we keep to the traditional criteria of the percentage killed over injured, road accident severity would have increased. Although in terms of severely injured percentages, the situation seems to have improved.

Table 5: Percentage of Killed and Severely Injured per 100 Accident Victims by Road User Type

Road Users Severity	*First Survey*		*Second Survey*	
	Killed	*Severely Injured*	*Killed*	*Severely Injured*
Pedestrian	6.0%	28.45%	6.0%	20.24%
Bicycle	3.0%	14.75%	7.2%	11.90%
Moped	2.6%	14.01%	1.6%	13.01%
Motorcycle	3.3%	23.33%	7.3%	19.51%
Car	4.6%	15.10%	6.4%	13.54%
Vans	3.0%	20.50%	6.7%	30.00%
Lorry	14.8%	13.80%	13.3%	6.67%
% All users	4.25%	16.83%	6.1%	14.91%
Kill./Injured	21.08%		20.96%	

Mopedists : Moped users are the only ones for which all indications concord to indicate a reduction in the severity of their accidents. A fact which illustrates the full justification of the generalised obligation to wear a crash helmet which came into force in the interim period. We would also point out the general abandoning of this means of transport including adolescents.

Pedestrians : The severity of pedestrian accidents seems stationary in terms of percentage killed, but there seems to be a significant reduction in the percentage of seriously injured. Pedestrians killed represented 11.76% of accident victims in the first investigation and 7.46% in the current investigation.

Cyclists : We are much more concerned about the situation of the Nîmes cyclists. This category has registered one of the highest scores in terms of victims killed even if the percentage of severely injured is the lowest of all road user categories and is reducing compared to the previous investigation.

Motorcyclists : For motorcyclists, the seriousness of their accident seems to be linked partly to speed and partly to user rejuvenation. In the 1993 compilation, all the motorbike riders were under 55 years of age.

Car users : For light vehicle users, we only noted a slight reduction in the severely injured percentage.
But this must be weighted by the fact that the number of users had considerably increased.

Other users : In the second investigation the number of van and lorry user accidents was very small, thus no valid conclusions could be drawn.

III.2 Severity Trends by Age Group :

In severity terms, we noted a positive trend in the under 18 age group whereas for the 18 to 24 age group, as well as the next one, there was a clear severity increase.

The percentage killed per age group was on the increase for all the other age groups. However, taking into consideration our reservations given above, we do not feel this criteria is reliable. However, all age groups showed a reduction in their severely injured percentages, even elderly age group.

Table 6: Severity Distribution as a Function of Age Groups

1° Investig. / 2° Investig.	Severity by group age: Slight	Serious	Killed	Marge
under 15	83.0	13.9	3.1	100%
	86.8	11.0	2.2	100%
15-17y	83.4	14.2	2.4	100%
	87.8	11.0	1.2	100%
18-24y	81.1	14.5	4.4	100%
	78.0	14.3	7.7	100%
25-34y	79.3	16.9	3.8	100%
	78.2	15.9	6.0	100%
35-54y	78.1	17.7	4.2	100%
	80.3	14.0	5.7	100%
over 54	69.9	23.9	6.2	100%
	71.9	18.8	9.4	100%
All	78.9	16.8	4.3	100%
	79.1	14.7	6.2	100%

III.3 Severity Trends by Sex

The distribution of females by age group was relatively constant for both investigations. Two age group categories could be distinguished: the first group, aged 15 to 54, comprised less than 30% women whereas the second, which regrouped young people under 15 and old people over 55 comprised on average, more than 40% female.

Table 7: Severity Distribution in Relation to Sex in the Two Investigations

Road Users	*First Survey*		*Second Survey*	
Severity	*Men*	*Women*	*Men*	*Women*
Slight	76.93	82.94	77.6	82.0
Serious	18.57	13.60	15.7	13.1
killed	4.50	3.45	6.6	4.9
Sum	100%	100%	100%	100%
All	64.60%	34.50%	66.8%	33.2%

Females represented about one third of the injured in the 1993 investigation. Generally speaking, they were represented in the same proportions as in 1982-83, with even a slight reduction (34.5% against 33.2%).We did not see any difference in severity trends by sex: in both investigations we noted that the percentage of seriously injured males was slightly higher than for females. This difference between the sexes is however more significant for the percentage killed.

IV. LESION TYPOLOGY TRENDS

Lesion distribution within different road user categories is generally the same in the two compilations. However very contrasting trends were revealed (see table 8 in annex).

We are not going to deal with van or lorry road users, as their number is very low, particularly in the 1993 investigation. We compiled 30 injured involving vans and 15 involving lorries. These vehicle categories have diverse and poorly defined characteristics and there are many parameters to be taken into account. It is therefore pointless to try to draw conclusions from such data. In the same way, we will not discuss external or non specified lesions. It is a miscellaneous class. They are badly specified and very diverse.

Head: For various reasons the number of head lesions in the total number of lesions has dropped for all road accident categories (14% to 9.3%, excluding cranial traumatism and loss of consciousness). For pedestrians this seems to be a result of improvement to the fronts of light vehicles, since in 85% of cases it is their main obstacle. For motorcyclists, especially mopedists, the explanation is obvious: the crash helmet, although we recorded many cases of helmets worn but not fastened or even "unfindable" helmets following the accident. For light vehicles the explanation is also simple: wearing seat belts.

Face: For facial lesions, it is difficult to both pinpoint precise tendencies and to explain them. Although wearing seat belts had reduced head lesion frequency for front seat car passengers, facial lesion however seem to have increased because cars are becoming smaller and smaller. Another possible explanation is a much greater interest by doctors in facial lesions and also by the victims concerned about the aesthetic aspects.

Thorax: The reduction in thorax lesions amongst cyclists and motorcyclists seems to be due to a large increase in the number of younger people driving these vehicles and to a reduction in the percentage of female users of two wheeler passengers. This explanation is also valid for pedestrians.
For automobilists, we found the inverse effect due to the miniaturisation of these vehicles and especially in generalising the safety belt, from which the frequency of thoracic contusion type lesions primarily due to the safety belt.
The percentage of female and old person automobilists also increased (see tables 2, 3 and 4). These user categories are justly considered to be more fragile in the thoracic cage region. Further, women drive closer to the steering wheel than men, which to some extent applies to old people.

Neck & Dorso-Lombar Column: These lesions have reduced amongst pedestrians, cyclists and motorcyclists. They have increased amongst automobilists, but especially concern benign lesions such as wrenching of the cervical rachis.

Abdomen: Abdomen lesions are soft organ lesions. In frequency terms, they are not significant because they are rare but usually very severe.

Upper limbs : Motorcyclists have shown a significant reduction in the upper limb lesions. This can without doubt be explained by the same reasons as for the thorax lesions. For all other user categories, we noted a very slight increase in upper limb lesions.

Lower Limbs : On the contrary, for the lower limbs, the trend was more contrasted. The trend was to less lesions for all users (28% to 23.8%), except pedestrians (34% to 40.6%). This lesion typology trend of pedestrians makes us believe that the efforts employed to reduce light vehicle aggressiveness towards pedestrians has only shifted the injury risks from the head to the limbs.

Remark : It would be more interesting to compare severe injuries, however the data sample of the second investigation is still too small to draw out significant conclusions.

V. CONCLUSIONS

The lesion typology of road users has developed due to the influence of several factors:

- User category trends: less motorised bikes, more light vehicles;

- Population modification of each user group: less women and old people using two-wheeler transport.

- Safety measures taken in the period between the two investigations have contributed to reducing lesion frequency and especially severity for most of user categories. For example, the improvment of mopedists safety is efficiency of the obligation to wear a crash helmet for all moped users. The generalized use of safety belts for light vehicle passengers have contributed to reducing serious lesion frequency . It remains the unchanged situation of bicycle, van and lorry users.

If there is an improvment for teenagers, on the other hand young adults in the 18 to 30 age group remains the main group at risks. For this age group, there is a clear severity increase.

The accurate study of each road user type and the detailed study of trends in serious lesion typology can only be carried out when the second investigation phase is completed.

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ANNEX :

Table 8 : Distribution of Body Region Injuries Among Road User Types a compararison between the two investigations (in percentage by column)

1° investig. 2° investig.	Road Users: Pedes trian	Bicy- cle	Mope d	Motor byke	Car	Van	Lorry	All users
without CTLC*	42.8 45.2	45.6 38.1	61.1 43.1	67.2 57.3	44.4 46.2	50.0 40.0	50.0 40.0	49.7 46.0
Cranial Trauma	25.8 29.3	26.6 28.6	19.4 26.0	11.5 18.3	33.6 25.7	27.9 23.3	25.9 40.0	27.7 25.7
Loss of Conscious.	31.4 26.2	27.8 33.3	19.5 30.9	21.3 24.4	22.0 28.1	22.1 36.7	24.1 20.0	22.6 28.3
Head	18 13.3	14 11.3	10 3.8	8 4.6	16 10.2	20 7.4	11 19.2	14 9.3
Face	15 15.2	13 19.7	14 8.5	8 13.1	19 19.8	16 22.2	16 7.7	16 17.4
Neck/ Spine	5 3.0	5 4.2	5 3.8	7 4.6	11 14.4	6 7.4	12 3.8	8 10.6
Thorax	7 4.8	8 5.6	7 7.3	10 5.9	14 18.2	14 13.0	16 3.8	11 13.9
Upper Extremity	16 17.0	22 23.9	21 23.9	23 20.3	13 13.1	15 14.8	9 19.2	16 15.8
Abdomen	2 2.4	0 0	1 4.3	1 4.6	2 3.6	1 9.3	2 0	1 3.6
Lower Extremity	34 40.6	35 28.2	40 35.0	43 36.6	20 17.0	23 24.1	30 42.3	28 23.8
External/ Unspecified	3 3.6	3 7.0	2 13.2	1 10.5	5 3.6	5 1.9	4 3.8	4 5.4
1° investig 2° investig.	100% 100%	100% 100%	100% 100%	100% 100%	100% 100%	100% 100%	100% 100%	100% 100%
Average lesion by casualty	1.89 1.96	1.95 1.69	1.81 1.9	1.89 1.87	1.74 1.66	1.82 1.8	1.98 1.73	1.77 1.73

*Without CTLC : "Without Cranial Trauma or Loss of Consciousness "
Note : For the first investigation it means also unspecified.

Analysis of a Safety Advertising Claim on Vehicle Crashworthiness
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94-S5-W-18

ABSTRACT

The Insurance Institute for Highway Safety (IIHS) publishes a list of fatality rates per 10,000 registered vehicles. In a report, the VW Jetta had a rate of 1.1 which was 21.4% lower than the Cadillac Brougham at 1.4. VW used this information in comparative advertising and claimed the reason for the difference was vehicle engineering. An in-depth analysis of the crash data indicates that the Jetta is inherently less safe than the Brougham and that the observed difference is primarily due to an older occupant age, a lower fraction of single-vehicle crashes, and lower belt use by Brougham passengers as compared to Jetta.

If the Jetta fatality rate is adjusted to a comparable driver age and safety belt use as in the Cadillac Brougham, the Jetta has an adjusted rate of 2.0 which is 42.9% higher than the Brougham at 1.4. This difference is consistent with expected inherent vehicle rates based on the weight advantage of the Brougham. The analysis indicates the potential for misuse of field accident data, which are heavily influenced by driver and environmental factors. Inappropriate advertising may mislead the public and cause inaccurate perceptions of vehicle safety.

THE ADVERTISING CLAIM

VW ran print, radio, and TV commercials based on the results of an IIHS study of fatal crash injury rates. The IIHS study used FARS data on fatalities by make and model of 1985-1987 vehicles, and normalized the deaths by registered vehicles in Polk (1). This produced a fatality rate per 10,000 registered vehicles. While the IIHS study included an analysis of the data to account for driver age, gender, and vehicle wheel base differences, the unadjusted data have been widely used to compare vehicle crashworthiness.

The print advertising campaign by VW is shown in Figure 1. They compared the raw fatality rates for the Jetta with other vehicles, including GM's Cadillac Brougham. The advertising alleges that the lower rate in the Jetta is due to engineering.

FACTORS COMPLICATING CRASHWORTHINESS RATING

There are many factors involved in the occurrence and prevention of fatal crash injuries. The age, sex, seating position, safety belt use and alcohol involvement by the driver and passenger are just a few of the predisposing factors that significantly influence fatality rates. In addition, variations in exposure based on miles driven, road type, and time of day are also critical factors to consider. While many safety systems are intimately involved in protecting occupants from injury, vehicle mass is a primary factor in crash survivability.

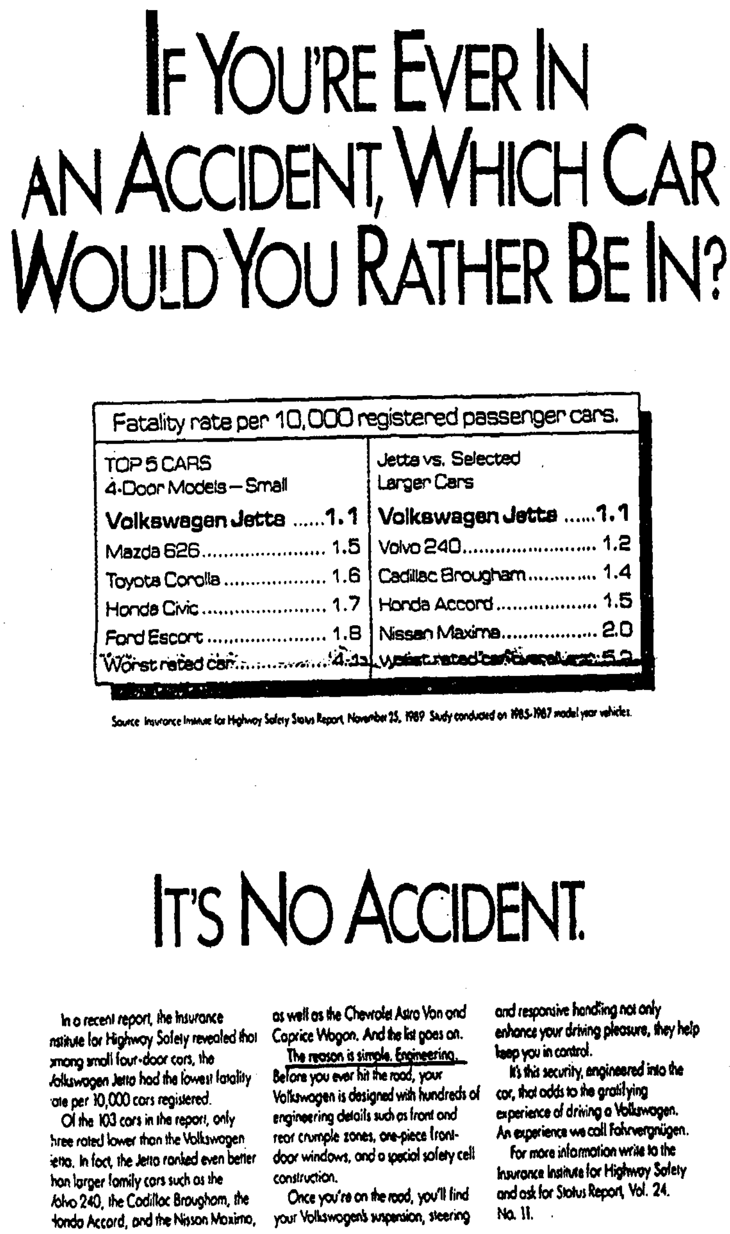

Figure 1: The VW Print Advertisement.

The public apparently wants information on the comparable crashworthiness of vehicles and many attempts have been made to provide objective data. However, analysis of field accidents is complicated by the over-riding influence of non-vehicle factors. The following analysis shows that the VW advertising claim cannot be substantiated by the available field information. The claim can be refuted by determining the influence of occupant age, safety belt use, and crash type on the underlying safety performance of the Jetta and Brougham.

OCCUPANT AGE

The tolerance of the human body to impact depends on many factors related to bone strength, muscle tone, and physiology. Age is a useful determinate of the average tolerance of people to impact loads occurring in vehicle crashes. There is also an age dependence of the bodies resistance to infection and ability to recover from injury. These are important factors in fatality risk, since deaths within 30 days of injury are included in FARS.

Evans has evaluated the risk of fatality as a function of the age and gender of occupants (2). If the the variation in risk with age is normalized to 1.0 for a 20 year old male, there is an increase in risk with age, and females are more vulnerable than males of equivalent age. Table 1 compares the risks for 20 year differences in age and indicates over a four-to-one variation in the averages. Injuries are more likely to be fatal if they occur to occupants in the older age group.

Table 1: Fatality Risk Versus Occupant Age

Age	Female	Male
20	1.3	1.0
40	1.9	1.6
60	2.9	2.5
80	4.2	4.0

Risk normalized to a 20 year old male from Evans(2).

SAFETY BELT USE

Safety belt use reduces the risk of fatal injury in motor vehicle crashes. The effectiveness of safety belts has been determined in reducing fatality risks (2,3). Table 2 shows comparable fatality risks assuming an unbelted occupant risk of 1.0.

Table 2: Fatality Risk Versus Restraint Use

Restraint	Risk
Unbelted	1.00
Airbag Only	0.79
L/S Belts	0.58
Belts & Airbag	0.53

Risks are normalized for an unbelted occupant. Lap-shoulder belt rates from Evans (2) and airbag rates from Zador and Ciccone (3).

Lap-shoulder belts are 42% effective in preventing fatality of unbelted occupants, so belt use reduces fatality risk to 0.58 compared to unbelted. The combination safety belt and airbag has an effectiveness of 47% (fatality risk of 0.53) and airbag only an effectiveness of 21%. While safety belt wearing rates have increased dramatically in normal driving, there are considerable differences among population groups by age, socioeconomic status, and education.

The current fatality data are influenced by the level of safety belt use in individual vehicle makes and models. For example, the relative fatality risk changes with the associated level of safety belt use as is shown in Table 3. Fatality rates would be 10% lower in crashes for a similar vehicle having a 60% safety belt use as compared to 40% use (0.75 v 0.83).

Table 3: Fatality Risk by Differing Levels of Belt Use

Use Rate	Risk
20%	0.92
40%	0.83
60%	0.75
80%	0.66

CRASH TYPE

The risk of fatal injury depends on the type, direction, and severity of crash. For example, multivehicle crashes are more likely to involve side loading of the vehicle than a single-vehicle accident. Vehicle crashworthiness is greater in frontal crashes because of the advantage of isolation from the point of impact and years of development of interior safety systems.

IIHS has compared fatalities by single or multivehicle crash and has identified a higher rate in multivehicle than single vehicle crashes for various vehicle size classes (4). The rate is 38% lower in a single vehicle versus a multivehicle crash for a vehicle of 105-109 inch wheel base (1.00 death/10,000 registered passenger car in multivehicle crashes versus 0.62/10,000 for single vehicle crashes). This indicates that the relative involvement rate in different crash types is an important factor in the overall fatality rate of a vehicle. For example, there is over a 15% difference in rate as the proportion of multivehicle crashes increases from 33% to 66% of the fatalities.

IMPORTANCE OF NON-VEHICLE FACTORS

Table 4 compares the relative risk for three non-vehicle factors: occupant age, safety belt use and crash type. An unbelted 80 year old woman in a multivehicle crash has an 11 times greater risk of dying than a 20 year old belted male in a single vehicle crash. While this analysis does not account for all of the inherent factors involved in fatal crashes, it provides perspective on the significance of non-vehicle factors in the field performance of vehicles.

COMPARING THE JETTA AND BROUGHAM

While the field data indicates a lower fatality risk in the Jetta than the Brougham, there are substantial non-vehicle factors that influence the observed rates. Table 5 provides information on the occupants and circumstances of the fatalities in the 1985-1987 FARS. There were 42 deaths in Jetta and 47 in Brougham crashes with several hundred thousand registered vehicles in use.

Table 4: Examples of Non-Vehicle Influences on Fatality Risk
• Unbelted 80 year old female in a multivehicle crash: $R = 1.0\ (4.2)(1.0) = 4.2$
• Belted 20 year old male in a single vehicle crash: $R = 0.58\ (1.0)(0.62) = 0.36$
• Relative Risk = 4.2/0.36 = 11.7

Table 5: Comparison of the Jetta and Brougham Fatality Risk

	Cadillac Brougham (Actual)	VW Jetta (Actual)	VW Jetta (Adjusted*)
Fatality Rate/ 10,000 Vehicles	1.4	1.1 (-21.4%)	2.0 (+42.9%)
Fatalities **	42	47	-
Vehicle years***	299,773	426,045	-
Average Age (yr)**	54.1	31.3	54.1
Belt Usage Rate**	43.0%	55.5%	43.0%
Single Vehicle Rate**	22.0%	48.0%	48.0%
Vehicle Weight (lb)	3900	2250	
Wt-Related Rate****	1.0	1.58 (+58.0%)	

* • Age-related fatality risk: (from Evans (2)) $R_a = \exp\ 0.0231(a-20)$, a = age; $R_{54}/R_{31} = 1.71$

• Lives saved by belts: (from Evans (2)) $S_{\%} = 0.42\ (\%)$, % = belt use rate; $S_{55}/S_{43} = 1.29$

• Belt use Related Risk: $R_{\%} = 1-S_{\%}$; $R_{43}/R_{55} = 1.07$

** From computer analysis of 1985-1987 FARS Files

*** From Polk data (from IIHS (1))

**** From Evans (2)

Further analysis of the 1985-1987 FARS indicated that the average age of victims in Brougham crashes is 22.8 years greater (72.8% difference) than in Jetta crashes. This represents a substantial difference. Safety belt use was 12.5 percentage points higher (29.1% difference), and the rate of single-vehicle crashes was 26 percentage points higher (118.2% difference) in Jetta crashes. Analysis of the 1984-86 NASS and 1988-90 NASS/GES indicates a mean age in Cadillac of 47 and Jetta 39, and safety belt use rate of 45% in Cadillac and 52% in Jetta. This demonstrates a consistent trend in fatal and tow-away crashes.

Method I: Adjusting for Occupant Age and Belt Use: Based on relationships developed by Evans (2), it is possible to adjust the Jetta data to a more comparable situation of age and belt use with the Brougham. This results in an adjusted rate of 2.0 for the Jetta assuming similar occupant age and belt use as in the Brougham crashes. The adjusted rate is 42.9% higher in the Jetta than in the Brougham indicating inherently poorer crash safety for the same occupant and belt use in a Jetta as compared with a Brougham.

Method II: Comparing Safety Based on Vehicle Weight Differences: There is a 1,650 lb weight advantage of the Brougham over the Jetta. Evans has determined a relationship between fatality risk and vehicle mass (2). The weight difference between the vehicles indicates that the risk of fatal injury would be 58.0% greater, on average, in a Jetta weight vehicle. This difference is similar to that found in the adjustment based on similar occupant age and belt use. This indicates that much of the inherent difference due to mass is offset by other factors.

Method III: Comparing Safety Based on Wheelbase and Proportion Single Vehicle Crashes: Table 6 shows the effect of vehicle wheel base--a vehicle parameter highly correlated with mass--and crash type differences between the Jetta and Brougham. These two factors are obtained using the actual wheel base for each vehicle. This approach provides an estimate of fatality rate based on vehicle size and the fraction of single vehicle crashes. The fatality rate in a Jetta-sized vehicle is 84.1% greater than in a Brougham sized car based on the observed difference in frequency of sigle vehicle crashes.

Table 6: Influence of Vehicle Wheel Base and Proportion of Single Vehicle Crashes on Fatality Risk

	%SV	Fatality Rate SV	Fatality Rate MV	Rate
Brougham	22%	0.39	0.70	0.63
Jetta	48%	1.0	1.30	1.16

Fatality risk per 10,000 registered vehicles based on IIHS data (4) for vehicles of wheelbase similar to the Jetta (97") and Brougham (122"). The proportion of single vehicle is from the 1985-1987 FARS.

The three methods used to compare the Brougham and Jetta on similar bases provide a consistent indication that the larger and heavier Brougham would be inherently safer for an individual driver or passenger.

STATISTICAL SIGNIFICANCE OF DIFFERENCES

An analysis was also made of the IIHS data for statistical significance in fatality rate differences for the Jetta and Brougham. Based on an assumed Poisson distribution in the field data, a 95% confidence interval was computed for the fatality rate data. Because of the small number of observed fatalities, the confidence intervals overlap. The difference in rates must be greater than 0.53 for statistical significance. The 95% confidence intervals are 0.98-1.82 for the Brougham and 0.79-1.41 for the Jetta.

Since the Jetta and Brougham rates are within 0.30, the difference is not statistically significant. The VW advertising did not alert the reader to the fact that the fatality rates were not statistically different and could be related to chance because of the small number of observations.

THE IIHS CRASHWORTHINESS RATING SCHEME

Virtually any safety rating approach will have problems in determining the underlying vehicle influence on injury and fatality rates in field accidents. There is one school of thinking that it may not be possible to isolate the relative crashworthiness of vehicles from the confounding factors of the driver, environment and crash circumstances. The non-vehicle factors vary greatly in real-world use of vehicles and crashes, and small differences dramatically influence fatality rates. Even so, research should continue to determine what can be understood from the accident and injury data.

The approach used by the IIHS to present and adjust raw fatality rates is a first step, but there are several issues that need further consideration. First, the exposure data is based on aggregate vehicle counts. It is not based on actual driving exposure or occupancy. In addition, the registration data is derived from a different source than the FARS. This introduces potential problems by distinct data sets, and the normalization is not based on miles driven or crash exposure, but vehicles in use.

Second, the fatality risk data involves sufficiently small sample sizes that differences, which on the surface appear to be substantial, may not be statistically significant. This is critical if the data are intended to inform the public about vehicle safety.

Third, the IIHS study adjusted the fatality data by analyzing the effects of the proportion of drivers younger than 30 years of age, the proportion of male drivers, and vehicle wheel base. This approach provided a "predicted" fatality rate based on a non-linear regression analysis. The "predicted" rate for the Jetta was 2.5 and the Brougham 1.2 are based on adjustments related to the fleet sensitivity to these factors. These figures are a closer measure of the intrinsic safety of the vehicles, but the IIHS analysis encompasses only a few of the critical non-vehicle factors, and the adjustments are not specific to particular vehicle make or model.

Several questions remain unanswered about the sufficiency of any approach. The influence of differences in safety belt use and crash type can be substantial and a valid method needs to properly consider the confounding influence of these and other factors. Alcohol use, rural-urban driving differences, and age-related risk taking behavior can greatly influence the interpretation of vehicle safety. A sensitivity analysis would seem appropriate to inform the user of the limits of applicability of the IIHS analysis.

Non-linear regression was used by IIHS to adjust the observed fatality rates to a "predicted" rate based on vehicle wheel base, and driver age and gender. The potential for colinearity effects among parameters influencing the results must be considered since so many parameters occur in combination. For example, young drivers, alcohol-use, and single-vehicle crashes occur frequently in combination. While the IIHS regression approach was based on rates and this minimizes the problems arising from colinearities, other statistical approaches, such as categorical analysis, and other exposure approaches, such as occupancy based analysis, may have merit.

EVALUATING OTHER FIELD DATA SOURCES

State accident data are available which include fatal and non-fatal injuries. Jetta and Brougham crashes from six states for 1985-1987 were analyzed. In this case, the data were normalized on the basis of exposed occupants rather than registered vehicles. This approach doesn't include driver or crash factors, but may be a more objective measure of vehicle crashworthiness, since it considers differences in occupancy rates and involves the same data file to normalize for exposure differences.

Table 7 indicates that death and incapacitating injury per 100 crash-exposed occupants are more frequent in the Jetta. The safety advantage for Brougham occupants holds up for all levels of outcome based on the KABC rating scheme.

Table 7: Occupant Injury Rate from Accident Data in Six States

	KA	KAB	KABC	
Brougham	1.8 ± 0.2	7.3 ± 0.3	22.9 ± 0.5	
Jetta	2.3 ± 0.2	8.9 ± 0.4	28.0 ± 0.6	
All Other	2.5 ± 0.0	9.9 ± 0.0	25.6 ± 0.0	
Crash Involved Occupants				
	KA	KAB	KABC	All
Brougham	124	511	1,601	6,991
Jetta	114	435	1,371	4,896
All Other	22,653	86,119	223,453	872,863

Based on police reported accidents in six state files (MI,TX, MD, PA, IN, WA) 1985-87 Model Year vehicles; Source CARDfile, National Highway Traffic Safety Administration.

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High Performance Cars, Age and Sex of the Drivers : Effects on Risk and Safety

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ABSTRACT

The type of vehicle driven, according to characteristics such as weight and power/weight ratio is an important criteria in risk and severity analysis. Age and sex of the drivers are also factors to be taken into account. The purpose of this paper is to analyse the role of these criteria in crash involvement and severity, and their effects on different types of accidents. The accident data used are from 1991. The results show the over-risk of high-powered and light vehicles, taking into account the use made of them by their drivers. The analysis highlight the influence of the "vehicle / driver" combination. Young male drivers are more sensitive to the type of vehicle driven, both in terms of involvement in certain types of accidents and in terms of increase of severity with the performance of the vehicle driven.

INTRODUCTION

There is a whole series of indicators which can measure road safety. Some of these relate to active safety and are concerned with exposure to accidents and others relate to passive safety and evaluate the consequences of accidents when these have occurred. The multicriteria aspect of the accident phenomenon must be taken into account by using global approaches, and it is important to reveal to the greatest possible extent the effects of interactions between the factors which determine road safety.

This paper is an attempt to assess the safety of the different categories of vehicles (defined on the basis of their weight and power/weight ratio), according to driver related effects and different types of accident. First of all, the available data and criteria taken into account are described, then cluster analysis shows clearly differentiated groups of crash-involved vehicle and driver combinations. The evaluation of crash involvement related to a measure of risk exposure is examined, and finally, crash severity is considered for single car crash.

DATA USED

The analysis presented here is based on both accident data and risk exposure data as estimated on the basis of the total distance covered. It mainly relates to 1991. The accident data was obtained from two sources, statistical notes and accident reports drawn up by the police. The distances covered have been estimated on the basis of a mobility survey.

Accident Data

Accident data were supplied by the police, from the statistical notes (BAACs) which they maintain and from the accident reports they draw up. Both these types of documents are systematically drawn up for every personal injury accident.

The Full BAAC File - The data in the BAACs (Statistical notes concerning personal injury accidents) is assembled in a national computerised file. The code, which provides make, model and version of vehicles, is correctly recorded for 87199 passenger cars, which corresponds to 46% of all crash-involved cars. However, an analysis of the make of crash-involved vehicles shows that this code is more often recorded in the BAACs in the case of French cars.

The 1/50th Personal Injury Accident Report File - The accident reports are drawn up to provide a basis for subsequent legal action. These documents contain a very precise description of events and quote the statements made by the parties involved. They contain a plan of the accident site and occasionally include photographs. In order to possess a data base which is intermediate between national statistical files and the data provided by specific studies, INRETS created a permanent document file which is representative of accidents occurring in France and which has a sampling rate of 1/50. Approximately 3000 accident reports are collected in this way every year and these are subjected to a specific type of coding, which is more detailed than that used in the BAACs. The accident report file for 1991 contains 3718 passenger cars for which make, model and version data can be used. This represents 87% of the passenger cars in the sample.

Mobility Data - A survey of the car fleet is conducted each year by questioning 10000 French households. The questionnaire, sent by post, contains a certain amount of data about the vehicles which are at the disposal of households. This data covers the principal characteristics of the vehicles, of the drivers and the use of the vehicles in terms of the distances covered annually and the way these distances are distributed over the network. The distance covered is assigned to the principal driver. This may be a source of bias in that young persons and women are more often occasional drivers. It is estimated that approximately 8% of all kilometres covered are done so by occasional drivers (1). The make, type and version of vehicles are known in 5718 cases (light commercial vehicles and camping cars were excluded).

When comparing travel data with accident data, we used accident report file, which is the most representative of the makes and types of French and foreign cars. Next, severity indicators were evaluated on the basis of criteria related to the vehicle, and to the age and sex of the user in single car crash. In order to improve reliability, it then became necessary to work on larger samples, which led to use of the BAAC files. The over-representation of French cars in the BAACs does not pose a problem, as long as there is no attempt to relate this data to other data concerned with distributions in the fleet, such as risk exposure, for example.

CRITERIA TAKEN INTO ACCOUNT

Vehicles Characteristics

Unladen weight and the power/weight ratio are relevant car characteristics from the safety point of view. Weight is an important factor in the amount of energy dissipated as a result of an impact, and the power per tonne provides a representation of the performance of a vehicle.

For the French fleet as a whole, the average weight is 905 kg and the power/weight ratio is 55 kW/t. On this basis, the study uses three categories of weight: less than 800 kg, between 800 and 1000 kg and over 1000 kg. There are also three categories of power per tonne: less than 50 kW/t, between 50kW/t and 75 kW/t, and a ratio of 75 kW/t or more.

In order to have a sufficiently large number in each class, 8 categories of vehicles were investigated, namely:

1 - less than 800 kg and less than 50 kW/t
2 - less than 800 kg and more than 50 kW/t
3 - from 800 to 1000 kg and less than 50 kW/t
4 - from 800 to 1000 kg and power/weight ratio between 50 kW/t and 75 kW/t
5 - from 800 to 1000 kg and 75 kW/t and above
6 - 1000 kg or more and less than 50 kW/t
7- 1000 kg or more and power/weight ratio between 50 kW/t and 75 kW/t
8 - 1000 kg or more and 75 kW/t and above.

On average, diesel vehicles are heavier and have a lower power/weight ratio than petrol vehicles. While diesel vehicles account for 19 % of the passenger car fleet, they account for 39 %

of category 3 and 89 % of category 6. Diesel vehicles also cover large distances: 20700 km per year as opposed to 11300 km per year for petrol vehicles (2).

Drivers Characteristics

Various studies have shown that the risk of crash involvement per distance travelled is higher for young drivers, particularly males (3, 4). Increased risk can also be observed for older drivers, especially women. However, as regards risk, age has a greater distinguishing capacity than sex, and if all age groups are considered the risk for a same distance covered for men is practically the same as for women.

The classes at greatest risk are those under 25 years of age. However, the small size of the samples selected on the dual basis of age group and vehicle category and the effect of the "occasional driver" phenomenon (which is important in the case of younger drivers) made it necessary to increase the size of the class of young drivers to include all drivers under thirty years of age. Age also has a marked effect on fatality rates. When involved in an accident, elderly persons are much more vulnerable: of 100 persons over the age of 65 who are involved in accidents, six are killed, whereas the average for the population as a whole is three (5). However, when vehicle type is taken into account for drivers over 65 years of age, the size of some samples becomes too small to permit risk comparisons. Only two age classes have therefore been considered in some cases: under thirty years of age and between 30 and 64 years of age.

Other Criteria

Location is one of the most distinguishing criteria as regards crash severity. In France, two-thirds of all accidents take place in urban areas. They are less severe than the accidents which occur outside urban areas, which are responsible for many more deaths: accidents which occur outside urban areas cause two-thirds of all deaths, while amounting to only a third of all accidents.

The types of collision are highly dependent on the age of those involved: young drivers are more frequently involved in single vehicle loss of control accidents and older drivers are more frequently involved in accidents at intersections (2). The type of collision should also, therefore, be taken into consideration in analysis of crash involvement, and even more so in the case of analysis of severity. So we considered more specifically single car crashes.

TYPES OF CRASH-INVOLVED DRIVERS

Multiple correspondence analysis has been carried out in order to reveal the links between the different criteria which define crash-involved vehicle and driver combinations. The factors which were obtained were then utilised for a hierarchical ascending classification which provided clearly differentiated groups and made it possible to locate the main types which are involved in crashes.

The sample which was analysed consisted of 3718 vehicle and driver combinations from the accident report data base for 1991. Only light vehicles were dealt with, light commercial vehicles and cars with caravans have been excluded. It was decided to use 18 active variables in order to define the factoriel axes:

. 6 describe the crash-involved driver: age, sex, profession, local user, trip purpose, manoeuvre,

. 4 describe the vehicle: type of vehicle, number of occupants, age, ownership,

. 8 relate to the environment: type of day, month, lighting conditions, atmospheric conditions, at an intersection or not, within a built up area or not, type of road, road layout.

The criteria which relate to the type of accident (type of collision, severity, number of vehicles involved, pedestrian involvement) and the offences which drivers had committed were added as illustrative variables. These variables are not used for calculating factors.

The factors, which are obtained, are then used in a hierarchical ascending classification. By examining the dendrogram a relevant number of classes can be defined: 6 clearly differentiated groups can be thus obtained. The 6 classes never separate the individuals on the basis of variable items in a strict way. "Young drivers" does not refer to all young drivers, but to the fact that this item is over-represented in the group considered.

Class 1 (31 % of crash-involved vehicle and driver combinations): this class represents crashes which occur outside built up areas (89% of class 1), away from intersections, in bad weather, on a bend. Single vehicle loss of control crashes are over-represented, as are, to a lesser extent, head-on collisions. These are severe accidents, occurring most often at night or at weekends, during leisure trips while the vehicle is carrying several passengers. The drivers are local, more than half of them are less than thirty years of age and are workers, farmers, or unemployed. Offences which are linked to alcohol and vehicles or speed (failure to control the vehicle) are over-represented, as are high performance medium weight vehicles (800 to 1000 kg and more than 75 kW/t) and those of more than 5 years of age.

Class 2 (29 % of crash-involved vehicle and driver combinations): this group consists of those involved in accidents in built up areas (88 % of class 2), in good weather and at an intersection. Female drivers, drivers aged between 30 and 64, home-to-work trips, local drivers alone in the vehicle are over-represented. This class is more specifically characterised by employees, intermediate professions. The vehicles are light (less than 800 kg) or of intermediate weight and power/weight ratios of between 50 and 75 kW/t. These accidents frequently occur during the week as the result of a change of direction manoeuvre and involve 2 vehicles. Accidents involving pedestrians are also over-represented. The frequency of offences involving a failure to give way is almost twice that for the entire sample. The consequences of such crashes are not very severe.

Class 3 (15 % of crash-involved vehicle and driver combinations): this relates to vehicles involve in accidents outside built up areas (89 % of class 3) on motor ways or trunk roads, in multiple collisions involving 3 or more vehicles, away from intersections, in bad weather. The drivers are between 30 and 64 years of age and are not local users. The drivers are more frequently senior executives, intermediate professions, craftsmen or shopkeepers. The manoeuvres which are responsible for the accidents are slowing down, overtaking or pulling out into a traffic stream. The vehicles are recent and the categories of more than 1000 kg and more than 50 kW/t are over-represented.

Class 4 (10 % of crash-involved vehicle and driver combinations): this group is characterised by drivers of under 30 years of age (98 % of class 4). They are involved in single vehicle loss of control crashes, in a collision with a fixed obstacle. More than half of these accidents occur at night-time and their consequences are severe. The vehicles are old, small (less than 800 kg), and on loan from the family or friends in almost eight out of ten cases.

Class 5 (8 % of crash-involved vehicle and driver combinations): these are retired persons (92 % of class 5). A large proportion of these accidents occur during the day-time, outside built up areas, on a minor road, in bad weather. Side-on collisions account for more than half the crashes in this group. These are severe accidents. Vehicles in category 4 (800 to 1000 kg and 50 to 75 kW/t) are slightly over-represented. The car is frequently carrying a passenger, and most of the drivers are male. Alcohol related offences are rare. Obviously, criteria which are correlated with retired persons are present in this class: drivers aged over 65, household vehicle, shopping or leisure trip.

Class 6 (7% of crash-involved vehicle and driver combinations): these are business trips (69 % of class 6). Drivers are most frequently professional drivers, senior executives or intermediate professions, craftsmen or shopkeepers. They are male, aged between 30 and 64. They are not local users and are alone in their vehicle at the time. Alcohol related offences are extremely rare. These accidents occur during the week, during the day, in good weather and in large towns or cities. The vehicles are recent and frequently belong to a company. The category of vehicles of more than 1000 kg and less than 50 kW/t (usually diesel) accounts for almost one third of this class. These accidents are not severe.

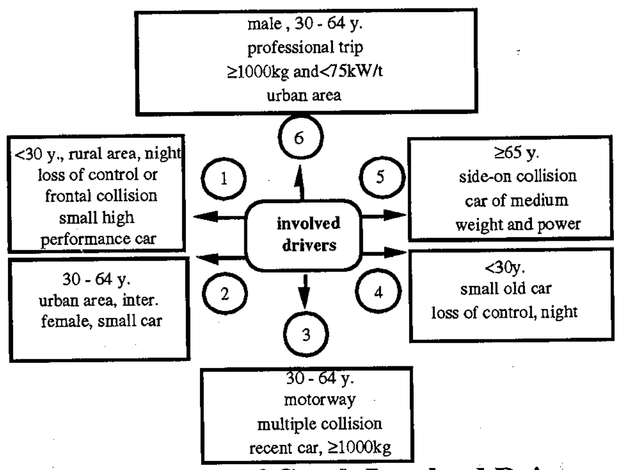

Figure 1. Types of Crash Involved Drivers

Figure 1 shows the categories of crash-involved vehicle and driver combinations which emerge from this cluster analysis. The individuals within each class are homogenous amongst themselves and well differentiated from the other classes. The names given to the classes involve a great deal of simplification. There are, of course, old persons who lose control of their vehicle or young drivers who are involved in crashes at intersections. The cluster analysis merely reveals the most discriminating characteristics, i.e. those which are over-represented in each class as compared with the population as a whole.

THE RISK OF CRASH INVOLVEMENT

In the context of road safety, distances covered are frequently used as a reference for accidents. In this case, risk is analysed by means of the rates of involvement in a personal injury accident for a particular distance covered. Its value is given by the proportion of individuals in a group of vehicle and driver combinations which are involved in a personal injury accident in relation to the proportion of kilometres covered by drivers in that group. What is involved is a relative risk, the risk being 1 for the population as a whole. Groups for which the risk is greater than 1 are therefore vehicle and driver combinations with an above average risk. We analyse the combination of driver age, type of vehicle and location of the accident.

Risk by Driver Age, Vehicle Type and Accident Location

In order to perceive the effect of driver age, the risk of crash involvement has been evaluated according to the type of vehicle, the age of the driver and the accident location. The average age of drivers differs according to the type of vehicle (Table 1).

Table 1
The Average Age of Principal and Crash-involved Drivers

Vehicle category (weight and power/weight ratio)	average age of principal drivers	average age of crash-involved drivers
<800 kg and<50 kW/t	42.1 y.	34.2 y.
<800 kg and ≥ 50 kW/t	43.9 y.	36.4 y.
800 to 1000kg, <50 kW/t	43.4 y.	36.9 y.
800-1000kg, 50-75 kW/t	45.3 y.	37.2 y.
800-1000kg, ≥75 kW/t	41.6 y.	28.2 y.
≥1000kg and <50 kW/t	41.4 y.	38.7 y.
≥1000kg, 50 to 75 kW/t	46.6 y.	40.6 y.
≥1000kg to ≥75 kW/t	47.8 y.	37.6 y.
All vehicles	44.1 y.	36.6 y.

There is a difference of more than six years between the average age of the main drivers of heavy powerful vehicles (47.8 years old) and those of lighter high performance cars (41.6 years old). Age differences between those involved in accidents also appear when the type of vehicle is considered. Thus, the average age of crash-involved drivers in high performance medium weight cars is less than 29 years, whereas the average age of crash-involved drivers of heavy cars of more than 50 kW/t is more than 37 years. The average age of drivers involved in accidents is younger than the average age of principal drivers given by the mobility survey, and this also applies to all categories of vehicle together (36.6 years old for those involved in accidents and 44.1 for all those who use the roads). The difference between the average age of principal drivers and that of crash-involved drivers is particularly high in the case of high performance medium weight cars.

The average distance covered varies according to the categories of vehicles. The way these distances are distributed over the network (figure 2) also reveals large disparities as regards the extent to which passenger car use is confined to urban areas.

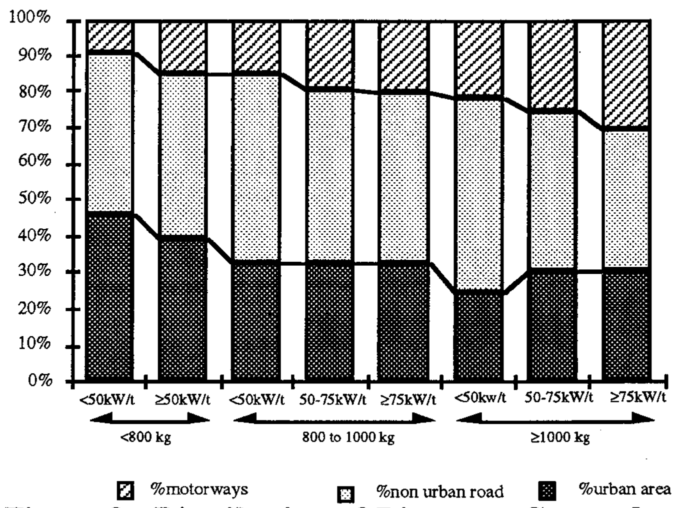

Figure 2. Distribution of Distances Covered over the Network According to Car Category

Almost half the kilometres covered by the category of small low performance vehicles are located in urban areas, whereas the majority of the kilometres covered by vehicles of over 1000kg are on non-urban roads and motor ways. This distribution is given on the basis of 100 for each vehicle category, however the distance covered differs in each case. The average annual distances covered increases with the weight of the vehicle. Those who drive little (less than 9000 km per year) have vehicles of less than 800kg and low power per tonne. Those who drive a great deal are in the category of vehicles of over 1000 kg and of less than 50 kW/t.

When the location is considered in analysis of the risk of crash involvement according to the distances covered, an amplification of the differences in risk outside urban areas can be perceived in the case of drivers of less than thirty years of age (figures 3 and 4). These risk assessments have been conducted for non-urban roads (the risk is equal to 1 for all vehicle and driver combinations on non-urban roads) and for urban roads (the risk is equal to 1 for all vehicle and driver combinations on urban roads).

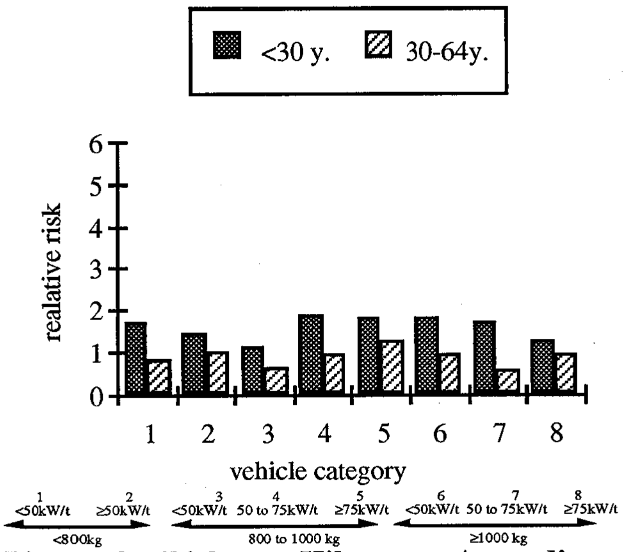

Figure 3. Risk per Kilometre According to Driver Age, Type of Vehicle in Urban Area

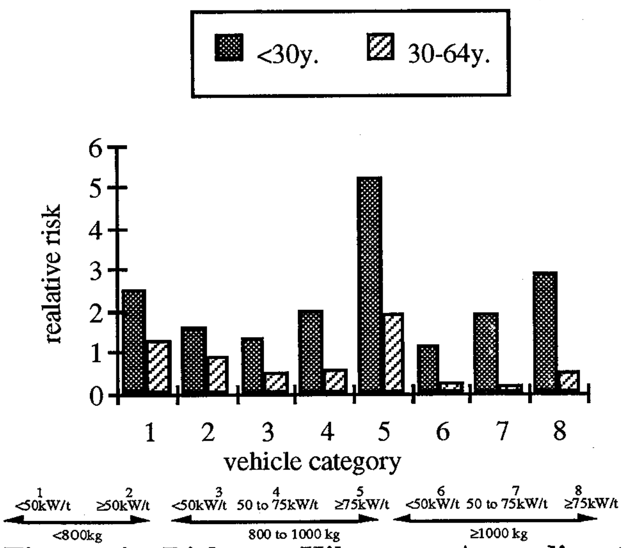

Figure 4. Risk per Kilometre According to Driver Age, Type of Vehicle in Rural Area

The highest relative risk was given for the category of drivers aged less than thirty with high-performance, medium-weight vehicles, in non-urban zones, which is a reflection of higher speeds. The "young-driver/high-performance vehicle/non-urban area" interaction appears to have particularly adverse effects on safety. Of course, the selection of a sports vehicle is often associated with high risk-taking, however, the consequences of such a choice also vary with the age of the driver.

Involvement by Driver age and Vehicle Type in Single Car Crash

Cluster analysis have shown that young drivers tend to be more frequently involved in single vehicle loss of control accidents. Figure 5 shows, for the non-urban network, involvement in single vehicle crashes not involving pedestrians as a proportion of all accidents for the two age classes and the eight categories of vehicles. It is clearly shown that the involvement of young drivers in single vehicle accidents is greater and that the "sports-vehicle/young-driver" interaction amplifies this difference. It can also be observed that whatever the age of the driver, vehicles of more than 75 kW/t are more frequently involved in single vehicle collisions.

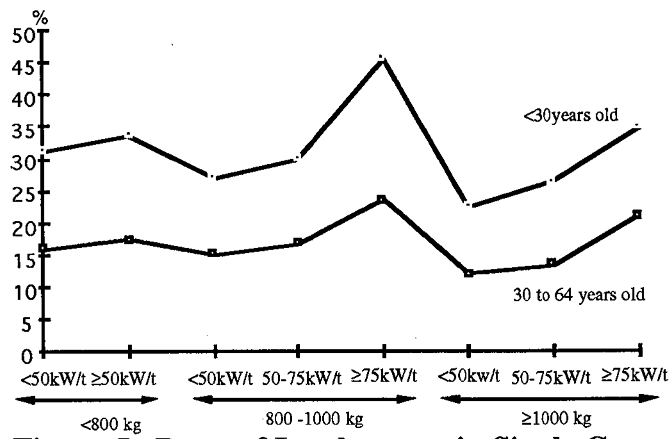

Figure 5. Rates of Involvement in Single Car Crashes per 100 Personal Injury Accidents in Non-urban Areas According to Driver Age and Car Category

CRASH SEVERITY

The attempt has been made to quantify the way in which car characteristics affect the rate of severity, which is defined as the probability of a driver who is involved in an accident being killed. This modelling task was carried out for single car crashes, without pedestrian involvement, outside built up areas. Logistical regression was used. The function which this model explains is the logit of the probability of belonging to a class under investigation, which is the logarithm of the ratio between the probability of a driver being killed and surviving, when the car has the characteristics described by explanatory variables. The logistical regression assumes that on average this function is a linear combination of explanatory variables (6). In order to construct the best model for the data an automatic variable selection technique (STEPWISE technique) has been used. The choice between K or K+ 1 variables is made when no variable provides additional information.

The form of the model is as follows EQ (1):

$$Log\left(\frac{p}{1-p}\right)=C+\sum_{i=1}^{k} a_i v_i \quad \text{EQ (1)}$$

where:

p= the probability of the driver being killed

C = constant

a_i = multiplying factor of variable i,

v_i = the explanatory variable i which is adopted after the STEPWISE procedure.

The sign of the coefficients indicates in which direction the variable a_i affects the relationship between the probabilities. The size of its effect is indicated by its absolute value.

The data was drawn from the BAAC for 1991 and 1992 taking only quantitative variables into account:

- vehicle weight (W)
- power/weight ratio for the vehicle (P/W)
- age of the vehicle (A)

We considered separately male and female drivers and two categories of driver age: those under 30 years old and those between 30 and 64 years old. The results are in Table 2.

Table 2
Estimate of Model Parameters for Single Car Crashes

Drivers	Model
male <30y.	$Log \frac{killed}{not\ killed} = -3.47 + 0.007 * P/W$
male 30-64y.	not significant
female <30y.	not significant
fem. 30-64y.	not significant

For drivers under 30 years old, the power/weight ratio has an effect on the probability of a driver being killed; other criteria have been dropped by the model. Thus, the probability of a young male driver involved in a single car crash when driving a 100kW/t car being killed is equal to 0.11 and when driving a 50kW/t car is 0.08. This probably reflects speed. This quantification confirms what other approaches have shown (7) about the effect the power / weight ratio.

For male drivers between 30 and 64 years old or for female, the variables which were introduced at the outset do not allow a good model to be produced.

CONCLUSION

Cluster analysis of crash-involved vehicle and driver combinations reveals clearly differentiated groups. The purpose of this paper was to compare groups of vehicle and driver combinations with regard to the impact which they have on safety in terms of crash involvement and severity. The category of young drivers with light, high performance sports-type cars emerges as having a high risk of crash involvement, particularly outside built-up zones and in the case of single vehicle loss of control accidents.

In single car crashes, it is possible to show the effect of the power / weight ratio, but only for young male drivers. It can be observed that severity rises significantly for younger male drivers with increasing vehicle performance whereas there is no significant rise in the case of older drivers or in the case of female drivers. This is therefore due to the effect of the high-performance / young-driver combination which has already been observed for the risk of crash involvement.

The choice of a high performance car is often associated with high risk taking, but the consequences are more serious in the case of young male drivers. Male drivers between 30 and 64 years or female drivers seems to be much less sensitive to the type of vehicle driven.

Only global approaches are capable of improving our understanding of road safety, and forecasts could be undertaken, in particular regarding changes in the fleet (weight and power of vehicles) and changes in the population of drivers (increasing proportion of elderly persons and females).

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