VEHICLE SAFETY COMMUNICATIONS IN THE UNITED STATES

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ABSTRACT

In the United States, passenger vehicle manufacturers have been working together, along with the U. S. government, to study wireless communications for vehicle safety applications.

From 2002-4, seven automotive manufacturers— BMW, DaimlerChrysler, Ford, GM, Nissan, Toyota, and VW— worked with the United States Department of Transportation (USDOT) to evaluate vehicle safety applications enabled or enhanced by communications. This project determined initial communication requirements for identified applications, performed some Dedicated Short Range Communications (DSRC) vehicle testing and helped develop the DSRC standards to support the requirements of safety applications. The project identified eight scenarios as high-priority for further research based on their estimated potential safety benefits. Of these eight application scenarios, four involved vehicle-to-vehicle (V-V) communications and four involved communications between vehicles and the infrastructure. Three of the vehicle-infrastructure communication applications involved intersections.

From 2005-6, BMW, DaimlerChrysler, Ford, GM, Nissan and Toyota worked together to develop and evaluate the Emergency Electronic Brake Light application (EEBL) as the first vehicle-to-vehicle cooperative active safety application in order to:

- Develop concepts of operation, system and communication requirements
- Establish a common V-V EEBL message set and demonstrate interoperability
- Perform common engineering tests
- Report to the industry on results
- Guide future V-V safety applications development

In 2006, DaimlerChrysler, Ford, GM, Honda and Toyota initiated two major vehicle safety communications projects with the USDOT. The first project is developing and field testing a Cooperative Intersection Collision Avoidance System using infrastructure-to-vehicle communications to address intersection crashes that result from signal Violations (CICAS-V). The second project, Vehicle Safety Communications Applications (VSC-A), is developing a common vehicle safety communication architecture, protocols and messaging framework necessary to achieve interoperability among different vehicle manufacturers' applications and an analysis of potential benefits versus market penetration for vehicle safety communications applications.

INTRODUCTION

Vehicle communications, both between vehicles and between vehicles and the infrastructure, offer the possibility to significantly improve crash avoidance and crash mitigation systems. Information could be exchanged over a wireless network that is difficult, if not impossible, to measure remotely with sensors such as radars, lidars or cameras. In addition, the cost of a vehicle communication system (transceiver and GPS receiver) is significantly less than, for instance, an ACC radar, making it feasible to widely deploy such a system.

DEDICATED SHORT RANGE COMMUNICATION (DSRC)

FCC DSRC Frequency Allocation

In the United States in 1997, ITS America petitioned the Federal Communications Commission to allocate seventy-five megahertz of spectrum in the 5.9 GHz band for ITS, in particular for DSRC. The following year, in 1998, Congress passed and the President signed into law the Transportation Equity Act for the 21st Century ("TEA-21"), which directed the Commission, in consultation with the USDOT, to consider the spectrum needs “for the operation of intelligent transportation systems, including spectrum for the dedicated short-range vehicle-to-wayside wireless standard,” DSRC. In October 1999, the Commission allocated the 5.9 GHz band for DSRC-based ITS applications and adopted basic technical rules for DSRC operations.

On December 17, 2003 the Commission adopted a Report and Order establishing licensing and service rules for the DSRC Service in the Intelligent Transportation Systems (ITS) Radio Service in the 5.850-5.925 GHz band (5.9 GHz band). Equipment in the DSRC Service comprises On-Board Units (OBUs) and Roadside Units (RSUs). An OBU is a transceiver that is normally mounted in or on a vehicle, or in some instances may be a portable unit. An RSU is a transceiver that is mounted along a road or pedestrian passageway. An RSU may also be mounted on a vehicle or hand carried, but it may only operate when the vehicle or hand-carried unit is stationary. An RSU broadcasts data to OBUs or exchanges data with OBUs in its communications zone.[1]

The ASTM DSRC Standard

Subsequent to the Commission's allocation of the 5.9 GHz band to the mobile service for use by DSRC systems, ITS America began to hold stakeholder workshops, panel discussions, and other industry meetings to develop a consensus on how to achieve national interoperability in the deployment of DSRC-based ITS user services. The Federal Highway Administration (FHWA), an agency of the USDOT, entered into a cooperative agreement with the American Society for Testing and Materials (ASTM) to develop a national, interoperable standard for DSRC equipment operating in the 5.9 GHz band.

On August 24, 2001, the Standards Writing Group selected a version of the Institute of Electrical and Electronic Engineers, Inc.'s (IEEE) 802.11 and 802.11a standard as the preferred technology to provide national interoperability for DSRC operations. IEEE 802.11, the Wi-Fi standard, denotes a set of Wireless LAN/WLAN standards developed by working group 11 of the IEEE LAN/MAN Standards Committee. IEEE 802.11p was adopted as the specification for the lower-layer DSRC standard, specifically for the Medium Access Control (MAC) and Physical Layer (PHY).

Band Plan

The Commission also decided that "some channelization of the DSRC spectrum may be essential to promote spectrum efficiency and to facilitate interoperability."[1] The DSRC spectrum was divided into 8 channels – one 5 MHz channel kept in reserve and 7 10MHz channels, channels 172, 174, 176, 178, 180, 182 and 184. In addition, channels 174 and 176 and also channels 180 and 182 may be aggregated into 20 MHz channels, designated as Channels 175 and 181 respectively. The ASTM-DSRC standard allows for a 10 MHz channel to support a data exchange rate of 27 Mbps and a 20 MHz channel to support a data exchange rate of 54 Mbps. In the center of the band, channel 178 was designated the "control channel". The basic concept is that a Road- Side Unit announces to OBUs 10 times per second the applications it supports on which channel. The On-Board Unit listens on Channel 178, authenticates the RSU digital signature, executes safety applications first, then switches channels and executes non-safety applications, then returns to Channel 178 and listens.

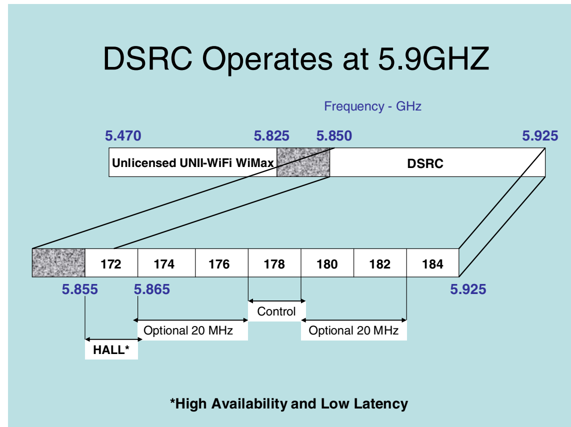

Figure 1. The DSRC band plan

Further, in a Memorandum Opinion and Order adopted on July 20, 2006[2], the Commission designated Channel 172 (frequencies 5.855-5.865 GHz) exclusively for vehicle-to-vehicle safety communications for accident avoidance and mitigation, and safety of life and property applications, and designated Channel 184 (frequencies 5.915-5.925 GHz) exclusively for high-power, longer distance communications to be used for public safety applications involving safety of life and property, including road intersection collision mitigation. The Commission recognized that vehicle-to-vehicle collision avoidance and mitigation applications are exceptionally time-sensitive and should not be conducted on potentially congested channels. By dedicating Channel 172 for public safety applications, the Commission significantly reduced the potential for interference that would otherwise be expected were the channel shared with non-public safety applications.

CRASH AVOIDANCE METRICS PARTNERSHIP

The Role of CAMP

In 1995, Ford Motor Company and General Motors Corporation formed the Crash Avoidance Metrics Partnership (CAMP). The goal of CAMP is to accelerate the deployment of Active Safety features in the United States by developing the pre-competitive enabling elements. CAMP is a mechanism for OEMs to work together, along with the US DOT and suppliers, on specific research projects. Since 1995, CAMP consortia have successfully completed projects on Forward Collision Warning Human Factors (Ford and GM), Driver Workload Metrics (Ford, GM, Nissan and Toyota) and Enhanced Digital Maps (DCX, Ford, GM, Toyota and Navteq) as well as several initiatives involving vehicle to vehicle / infrastructure communications to be discussed below.

The VSC Project

In 2002, the Vehicle Safety Communications (VSC) project was established using the CAMP mechanism to evaluate vehicle safety applications enabled or enhanced by communications. Seven automotive manufacturers—BMW, DaimlerChrysler, Ford, GM, Nissan, Toyota, and VW—formed the VSC Consortium (VSCC) to participate in this project with the USDOT. The following questions illustrate the focus and organization of the VSC project:

- What vehicle safety applications have the potential to be enabled or enhanced using external vehicle communications?
- Which communication-based vehicle safety applications have the highest potential safety benefits?
- What are the preliminary communication requirements for communications-based vehicle safety applications?
- Does initial testing confirm the technical feasibility of using DSRC for vehicle-safety applications?
- What are the elements of a security system for vehicle safety communications?

What Vehicle Safety Applications Have The Potential To Be Improved Or Made Possible With External Vehicle Communications? - The VSC project compiled and evaluated a comprehensive list of potential vehicle safety applications. This list represented the best efforts of the participants at the time of publication. It does not contain all vehicle safety applications (due to similarity) but does contain, at a minimum, examples and brief descriptions of representative safety applications. More than 75 applications were identified and analyzed resulting in 34 potential safety and 11 non-safety application descriptions. Details of this study are presented in the VSC project Task 3 Final Report[3]. It is likely that additional vehicle safety applications enabled or enhanced by wireless communications will be identified in the future, as advances in wireless technology become available.

Table 1.

Safety-Related Vehicle Communication Applications[3]

Category	Application
Intersection Collision Avoidance	Traffic Signal Violation Warning Stop Sign Violation Warning Left Turn Assistant Stop Sign Movement Assistant Intersection Collision Warning Blind Merge Warning Pedestrian Crossing Information Warning
Public Safety	Approaching Emergency Vehicle Warning Emergency Vehicle Signal Preemption SOS Services Post-Crash Warning
Sign Extension	In-Vehicle Signage Warning Curve Speed Warning Low Parking Structure Warning Wrong Way Driver Warning Low Bridge Warning Work Zone Warning In-Vehicle Amber Alert Warning
Information from Other Vehicles	Cooperative Forward Collision Warning Road Condition Warning Emergency Electronic Brake Lights Lane Change Warning Blind Spot Warning Highway Merge Assistant Visibility Enhancer Cooperative Collision Warning Cooperative Vehicle-Highway Automation System (Platoon) Cooperative Adaptive Cruise Control Road Condition Warning Pre-Crash Sensing Highway/Railroad Collision Warning Vehicle-to-Vehicle Road Feature Notification Cooperative Glare Reduction Adaptive Headlamp Aiming

Which Communications-Based Safety Applications Have The Highest Potential Safety Benefits? - For each vehicle safety application scenario, initial estimates of potential safety benefits were derived. These estimates were based on the accident analysis from the General Motors 44 Crashes report.[4] The VSC project team and the US DOT defined a set of analysis categories by which the potential safety benefits of application scenarios could be compared. The team used a methodology for analysis and ranking that included consideration of:

- Estimated Deployment Time Frame
  Near-term application systems were considered to be potentially deployable in the U.S. market between the years 2007 and 2011; mid-term applications deployable between 2012 and 2016; and long-term applications deployable beyond 2016.

- Estimated Effectiveness
  Defines the effectiveness of an application in

terms of the reduction of three crash-related factors: (i) functional years lost (number of years lost to fatal injury plus years lost of functional capacity to nonfatal injury), (ii) vehicles crashed (number of vehicles involved in various crash types in the U.S.), and (iii) direct costs (dollar expenditures related to the damage and injury caused by a crash),.

- Estimated Market Penetration
  Estimates the number of light-duty vehicles in the U.S. market that would be equipped with each vehicle safety application in each year after initial deployment.

- Estimated Cooperation from Infrastructure and/or Other Vehicles
  Estimates the probability of securing infrastructure cooperation and/or other vehicle cooperation. Cooperation required by the applications is in the form of relevant safety-related data exchange using infrastructure-to/from-vehicle communication and vehicle-to-vehicle communication.

For each application system, the VSC team used engineering judgment in estimating the application ranking attributes. The methodology used to estimate of the safety benefits and the relative ranking of the application scenarios is presented in the VSC project Task 3 Report[3]

The safety applications enabled or enhanced by communications that were estimated to have the greatest potential safety opportunity in each time period are listed in Table 2.

Table 2.
Vehicle Safety Communications Applications with Highest Potential Benefit[3]

Near-term	Mid-term	Long-Term
Traffic Signal Violation Warning (V-I)	**Pre-Crash Sensing (V-V)**	**Cooperative Collision Warning (V-V)**
Curve Speed Warning (V-I)	**Cooperative Forward Collision Warning (V-V)**	**Intersection Collision Warning (V-I)**
Emergency Electronic Brake Lights (V-V)	**Left Turn Assistant (V-I)**	
	Lane Change Warning (V-V)	
	Stop Sign Movement Assistance (V-I)	

V-I denotes communication required between vehicles and the infrastructure and V-V indicates communication between equipped vehicles is required.

This analysis was completed based on the assumptions available in late 2002 and early 2003. Subsequently, there has been considerable effort in the United States on Vehicle Infrastructure Integration (VII), which would significantly affect the estimates for cooperative infrastructure and vehicle deployment. VII will be discussed later.

<u>What Are The Communication Requirements For Communications-Based Vehicle Safety Applications?</u> - The eight near-term and mid-term safety applications enabled or enhanced by communications that were estimated to have the greatest safety opportunity were evaluated to establish preliminary communication requirements.[5] The proposed operational characteristics and preliminary communication requirements for the eight vehicle safety applications were described in terms of the following parameters:

Type of Communication: Considers the (i) source-destination of the transmission (infrastructure-to-vehicle, vehicle-to-infrastructure, or vehicle-to-vehicle communications), (ii) direction of the transmission (one-way or two-way), and (iii) source-reception of the communication (point-to-point or point-to-multipoint).

Transmission Mode: Describes whether the transmission is triggered by an event (event-driven) or sent automatically at regular intervals (periodic).

Update Rate: Defines the minimum rate at which a transmission should be repeated (e.g., 1 Hz).

Allowable Latency: Defines the maximum duration of time allowable between when information is available for transmission and when it is received (e.g., 100 msec).

Data to be Transmitted and/or Received: Describes the contents of the communication (e.g., vehicle location, speed, heading, etc.).

Maximum Required Range of Communication: Defines the communication distance between two units that is required to effectively support a particular application (e.g., 100 m).

The results of this analysis are shown in Table 3.

Table 3.

Preliminary Application Communication Scenario Requirements[3]

	Comm. Type	Trans. Mode	Min. Freq (Hz)	Latency (msec)	Primary data to be transmitted and/or received		Max. Req'd Comm Range (m)
Traffic Signal Violation Warning	Infrastructure-to-vehicle One-way Point-to-multipoint	Periodic	~10	~100	Traffic signal status Timing Directionality Position of the traffic signal	Stopping location Weather condition (if available) Road surface type	~250
Curve Speed Warning	Infrastructure-to-vehicle One-way Point-to-multipoint	Periodic	~1	~1000	Curve location Curve speed limits Curvature	Bank Road surface condition	~200
Emergency Electronic Brake Lights	Vehicle-to vehicle One-way Point-to-multipoint	Event-driven	~10	~100	Position Heading Velocity Deceleration	Bank Road surface condition	~300
Pre-Crash Sensing	Vehicle-to-vehicle Two-way Point-to-point	Event-driven	~50	~20	Vehicle type Position Velocity	Acceleration Heading Yaw-rate	~50
Cooperative Forward Collision Warning	Vehicle-to-vehicle One-way Point-to-multipoint	Periodic	~10	~100	Position Velocity Acceleration	Heading Yaw-rate	~150
Left Turn Assistant	Vehicle-to-infrastructure and infrastructure-to-vehicle One-way Point-to-multipoint	Periodic	~10	~100	Traffic signal status Timing Directionality; Road shape and intersection information;	Vehicle position Velocity Heading	~300
Lane Change Warning	Vehicle-to-vehicle One-way Point-to-multipoint	Periodic	~10	~100	Position Heading Velocity	Acceleration Turn signal status	~150
Stop Sign Movement Assistance	Vehicle-to-infrastructure and infrastructure-to-vehicle One-way Point-to-multipoint	Periodic	~10	~100	Vehicle position Velocity Heading;	Warning Turn signal status	~300

This preliminary analysis showed that:

- Message packet size is small, approximately 200 to 500 bytes (all 8 scenarios), not including the security overhead, which is approximately 200 bytes.
- Maximum required range of communications is short, about 50 to 300 meters (all 8 scenarios)
- Most applications are one-way, point-to-multipoint broadcast messages (7 of 8 scenarios)
- One application is two-way, point-to-point messages (pre-crash)
- Most applications can utilize periodic transmissions (6 or 7 of 8 scenarios)
- Most applications have allowable latency of 100 milliseconds (6 of 8 scenarios)
- One application has an allowable latency of 20 milliseconds (pre-crash)

It was therefore identified that a periodic common message broadcast at 10 Hz would enable most applications identified (both vehicle-to-vehicle and vehicle-to-infrastructure), and that the pre-crash sensing application has unique requirements. The contents of the preliminary common periodic message were elements such as latitude, longitude, time, heading angle, speed, lateral acceleration, longitudinal acceleration, yaw rate, throttle position, brake status, steering angle, headlight status, turn signal status and vehicle length/width. These preliminary communications requirements will need further refinement as prototype vehicle safety applications are developed and the need for bandwidth conservation (if any) becomes apparent.

Comparison of Alternative Wireless Communication Technologies: A wide variety of wireless communications technologies were examined for their ability to meet these communication requirements. These technologies included 5.9 GHz DSRC, 2.5-3G PCS and Digital Cellular, Bluetooth, Digital Television (DTV), High Altitude Platforms, IEEE 802.11 Wireless LAN, Nationwide Differential Global Positioning System (NDGPS), Radar, Remote Keyless Entry (RKE), Satellite Digital Audio Radio Systems (SDARS), Terrestrial Digital Radio, Two-Way Satellite and Ultra-wideband (UWB). It was concluded that DSRC is the only technology at this time that meets all of the application requirements, especially the ability to support low-latency wireless data communications between vehicles and between vehicles and infrastructure. This was primarily due to the short range nature of the communications - a few hundred meters supports most safety applications while not overloading the spectrum with messages from vehicles and infrastructure.

Does preliminary testing confirm the technical feasibility of using DSRC for vehicle-safety applications? - To answer this, both Field Testing and Evaluation and Simulation Testing and Evaluation were performed**.**[5]

Field Testing and Evaluation

The VSC project assessed the DSRC characteristics relevant to potential safety applications in real-world environments through field testing on test tracks and public roadways, using both vehicle-vehicle and vehicle-infrastructure wireless data transfer. The anticipated communications parameters for two potential vehicle-safety application scenarios were tested in detail: Traffic Signal Violation Warning and Emergency Electronic Brake Lights. The communication equipment used for this testing was developed by Denso.[6]

Testing focused on:

- Collecting and analyzing data in real-world intersection environments to determine communications characteristics.
- Vehicle-to-vehicle testing using test track and public roadway environments to send actual common message set data between vehicles.

Intersection Testing

At intersections, testing focused on the capability of a DSRC on-board unit (OBU) to receive packets sent from a dedicated roadside unit (RSU) stationed near an intersection. A key issue investigated was the degree to which a test vehicle could move through different types of intersections while maintaining communications with the RSU when variables such as buildings, terrain, roadway geometry and traffic conditions were presented. The findings from tests conducted at a representative intersection demonstrated an 85% successful transmission ratio while the test vehicle was approaching the RSU from 250 m, and a 99% success ratio while approaching from 100 m. The results were derived with an inverted OBU roof-mount antenna serving as the RSU antenna (clearly not optimized for RSU conditions), and with the antenna situated at a less-than-optimal position (intersection corner, 10 feet high above the ground).

Figure 2 shows the signal phase (red, yellow or green) as broadcast by an RSU interfaced to a synchronized signal controller and received by an OBU traveling through the intersection. For a safety application such as Traffic Signal Violation Warning, no major communications issues were uncovered in testing that conflicted with the preliminary requirements. These results show that the

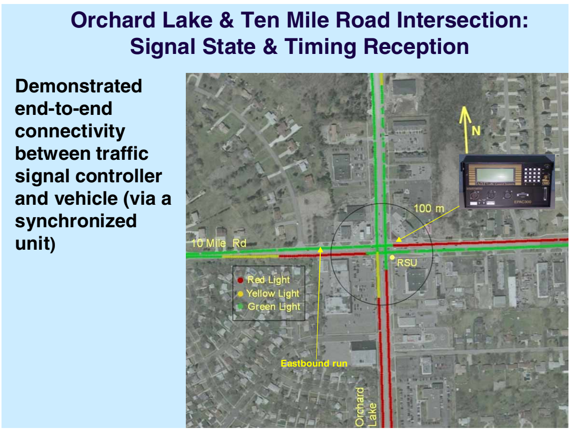

Figure 2. Signal phase broadcast from an RSU and received by an OBU

test equipment used, which is representative of the currently approved lower layer DSRC standard, can support communications for application scenarios like Traffic Signal Violation Warning.

Vehicle Data Exchange

For message sizes of 200 bytes, results showed 100% reception and no packet loss between two vehicles up to ranges that exceed 200 m in a vehicle following scenario, and ranges exceeding 600 m in both directions of travel. Reducing the transmit power from 20 dBm to 5 dBm reduced the maximum range to approximately 250 m in both directions of travel. Increasing the data rate from 6 Mbps to 27 Mbps resulted in higher packet losses and a reduction in communication range. Testing was conducted on an interstate freeway and a state highway. Seven test vehicles formed a caravan with information shared among all. In general, the results showed that in a freeway environment, there was communication between vehicles to 180 m range with transmission power of 20 dBm. In a freeway ramp environment, there was communication between vehicles to a 100-meter range with a reduced transmit power of 16 dBm. It should be noted that none of the test scenarios used the maximum transmit power allowed by the FCC. Based on the vehicle-to-vehicle testing, the performance of DSRC appears adequate for future vehicle-safety application development.

Simulation Testing and Evaluation

In order to study channel loading issues, VSCC simulated and evaluated DSRC performance in an urban intersection environment densely populated with DSRC-equipped vehicles and infrastructure. This was done to assess simulation test scenarios of high volume, signalized intersections. A simulation test environment was configured, containing both a high traffic volume intersection with a freeway nearby. Both environments were filled with dense vehicle traffic. Great care was taken so that both the environment and the vehicle traffic patterns reflected realistic, though stressing conditions.

The simulation testing completed during the VSC project indicated a requirement for a dedicated high-availability, low-latency channel for latency-critical safety applications. The simulation testing also showed that emergency message prioritization consistently improved the reception probability over routine messages by 5% to 40%, and reduced the safety communications latency across a wide range of simulation scenarios. The simulation results further illustrated that channel capacity is an issue that will need to be adequately addressed for large-scale deployment in stressing traffic environments. The FCC subsequently allocated DSRC Channel 172 as the high-availability, low-latency channel for collision avoidance systems.

What are the elements of a security system for vehicle safety communications? - Security is an important consideration for DSRC vehicle safety applications. For the system to be secure, the applications must be able to trust that the communication has been received unaltered and from a trusted source. In addition, the communication should be anonymous, at least to passive listeners. It should require a low amount of computational and communications overhead and be robust in the event of individual units being compromised. After preparing a threat model, the following defense was proposed:

- All on-board units (OBUs) and roadside units (RSUs) are issued certificates (OBUs are issued multiple) in a special, compact format.
- The certificates for RSUs contain authorization information such as the area in which the unit is permitted to operate and the type of information it is allowed to broadcast.
- OBU certificates do not contain the permanent vehicle-identity information.

- All messages are digitally signed. Any units suspected of being compromised are put on a revocation list that is flooded to all other units.

However, this security solution would come at a price. Each message transmitted would include significant overhead, and the message signatures would take time to process once they are received. Management of a public key infrastructure for RSUs would be necessary, according to the proposed scheme. In addition, there are piece costs, administrative costs, maintenance costs, and enforcement costs. Current efforts regarding DSRC security are being conducted in the VII program and the VSC-A project, discussed below.

THE EMERGENCY ELECTRONIC BRAKE LIGHTS PROJECT

During 2005 and 2006, six of the VSCC members (BMW, DCX, Ford, GM, Nissan and Toyota) decided to build and evaluate a safety application based on communications. The application chosen was Emergency Electronic Brake Lights (EEBL) because this is a near-term, vehicle-to-vehicle (V2V) application. The goal was to gain experience with the message protocol (when to send a message) and message content (necessary information in a message) required to successfully implement such an application. Three message protocols were implemented for evaluation – a periodic (10 Hz message), based on the "Common Message", an event-based message when hard-braking occurred and a "hybrid protocol" which used a combination of a lower-frequency periodic message with an event-based message.

A key to the successful implementation of an application of this type is path prediction – the ability to determine if the transmitting vehicle is in the path of the receiving vehicle. This is similar to the path prediction necessary for features such as Adaptive Cruise Control (ACC). However, because of the communication link between the vehicles, information can be added to the message which greatly facilitates this path prediction. Specifically, the last ten GPS positions, at 1 sec intervals, called "breadcrumbs", were added to the transmitted message for evaluation, as shown in Figure 3.

The OEMs involved in this project successfully developed and implemented an EEBL application as the first V2V communication-based safety application and demonstrated interoperability of the application between the vehicles of all the OEMs. All of the concepts of operation were implemented and resulted in correct warnings. Message sets for the three concepts of operation were defined. The systems implementation and the warning algorithm were OEM-specific but interoperability was established on the basis of the message set. As seen in Figure 4, the EEBL warning was received by the fourth (Ford) vehicle about 4 sec before that vehicle would have otherwise began braking in response to the hard braking of the lead (Toyota 2) vehicle. The experience gained in developing EEBL will be utilized in the VSC-A project (discussed later), where the final recommendations on message protocol and message content will be reached. In addition, the information from this project was transferred to the SAE for use in the development of the DSRC Message Set Dictionary (J2735).

CURRENT ACTIVITIES

In the United States, there are major activities underway related to communications-based vehicle safety applications.

Vehicle Infrastructure Initiative (VII)

The VII vision is that every car manufactured in the U.S. would be equipped with a communications device and a GPS unit so that data could be exchanged between vehicles and with a nationwide, instrumented roadway system. Realization of this vision could mean a significant reduction in highway fatalities, while at the same time offering dramatic improvements in transportation efficiency and mobility. Besides safety applications, such a system would enable features such as probe vehicle data, weather/road surface data, traveler information, electronic tolls, electronic payment, auto manufacturers' customer relations, etc. The US DOT, vehicle manufacturers, state and local DOTs and suppliers are developing the VII system. Proof-of-Concept testing is scheduled for 2007 and a deployment decision is scheduled for 2008.[7]

The Vehicle Safety Communications 2 Consortium (VSC 2) formed using the CAMP mechanism in 2006 to develop and test the VII safety applications. The five OEMs involved in this consortium (DCX, Ford, GM, Honda and Toyota) are engaged in two major projects, CICAS-V and VSC-A, in coordination with the rest of the VII Program.

CICAS

The Cooperative Intersection Collision Avoidance System (CICAS) program is a major government-

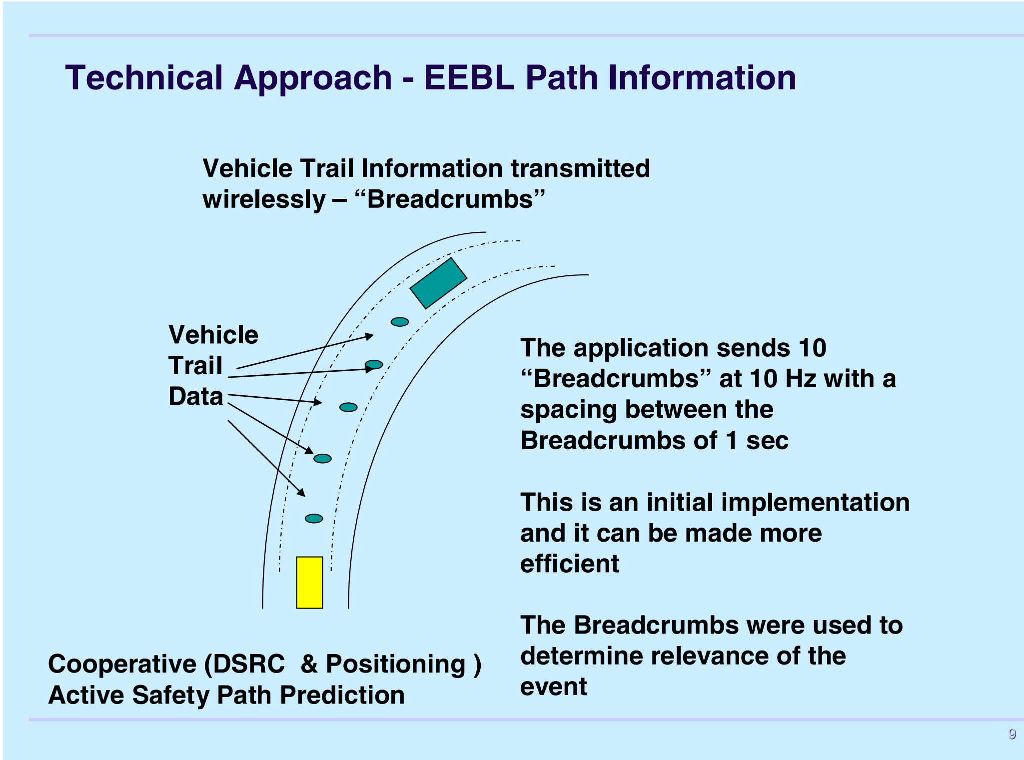

Figure 3. Vehicle path history sent over the communications link.

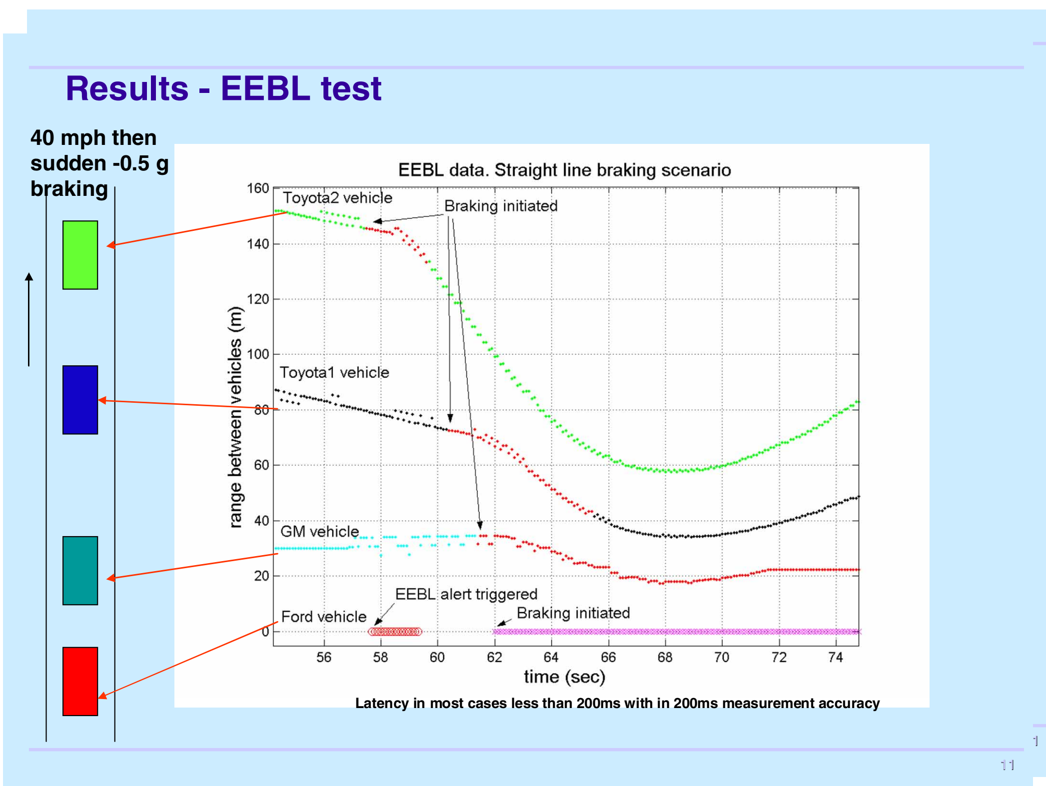

Figure 4. EEBL Test Results

industry initiative in the United States to develop and deploy a cooperative vehicle-infrastructure system to improve intersection safety. There are three operational concepts for CICAS being researched:

- CICAS-Violation (CICAS-V): a system that warns the driver via an in-vehicle device when it appears likely that the driver will violate a traffic signal or stop sign.
- CICAS-Stop Sign Assist (CICAS-SSA): a system that uses a Dynamic Message Sign to tell drivers on the minor road when it is unsafe to enter the intersection due to insufficient gaps in traffic on the main road.
- CICAS-Signalized Left Turn Assist (CICAS-SLTA): a system that uses a Dynamic Message Sign or an in-vehicle sign to tell drivers when it is unsafe to make an unprotected left turn at a signalized intersection.

The CICAS-V system is being developed by the VSC 2 Consortium, and the primary objective is to develop an effective prototype that is suitable for deployment. The CICAS-SSA project is being conducted under a partnership agreement with Minnesota DOT and its research partner, University of Minnesota. CICAS-SLTA is being conducted under a partnership agreement with California DOT and its research partner University of California Partners for Advanced Transit and Highways (PATH) Program. The primary objectives of these last two projects are to develop system designs for prototyping and field operational testing.

CICAS-V

CICAS-V is a warning system to reduce crashes at intersections resulting from unintended violations of traffic control devices (i.e., traffic signals and stop signs). The CICAS-V system is intended to mitigate potential causal factors that include driver distraction, obstructed/limited visibility due to weather or intersection geometry or other vehicles, the presence of a new control device not previously known to the driver and driver judgment errors.

The basic CICAS-V concept is that both the vehicle and the intersection would be equipped with DSRC radios. As the vehicle approaches, for example a signalized intersection, it would be informed that the intersection is CICAS-V equipped and that a map of the intersection is available on a service channel, along with positioning corrections and possibly road surface condition. After receiving this information, the vehicle would then download the map (if necessary) and position itself on this map, at the lane-level if necessary for complex intersections. Then the vehicle would receive information on signal phase (red, yellow or green) and, if yellow, the timing until the red phase. Based on this information, the vehicle would issue a warning to the driver, if necessary, and possibly send a message to the intersection of an impending violation. The intersection could potentially use that information for a countermeasure, such as warning other approaching vehicles or going to an all-red phase until the violator has cleared.

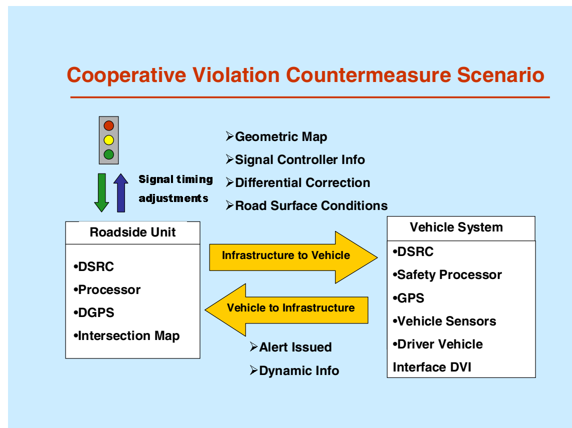

Figure 5. CICAS-V Communications

The CICAS-V project started in May, 2006. The first phase, which will last for two years, will develop and test a prototype design suitable for a Field Operational Test (FOT). Then, a second FOT phase is planned, with approximately nine months of data collection with naive drivers using fifty equipped vehicles and 25 equipped intersections. The collected data would be used to study safety benefits, unintended consequences and driver acceptance.

Vehicle Safety Communications – Applications (VSC-A)

In December, 2006, the VSC2 Consortium (DCX, Ford, GM, Honda and Toyota) also initiated the three-year VSC-A project with the US DOT. This project builds upon the previous work done in the first CAMP VSC project as well as previous NHTSA Active Safety projects. The scope of this project includes all safety applications that use communications, except for the intersection safety applications addressed in CICAS. The objectives of this project are to:

1. Assess how previously identified critical safety scenarios in autonomous systems could be addressed and improved by DSRC+Positioning systems.
2. Define a set of DSRC+Positioning based vehicle safety applications and application specifications including minimum system performance requirements.
3. In coordination with NHTSA and VOLPE, develop a benefits versus market penetration analysis, and potential deployment models for a selected set of communication-based vehicle safety systems.
4. Develop a scalable, common vehicle safety communication architecture, protocols and messaging framework (interfaces) necessary to achieve interoperability and cohesiveness among different vehicle manufacturers.
5. Develop accurate and affordable vehicle positioning technology needed, in conjunction with the 5.9 GHz DSRC, to support most of the safety applications with high potential benefits.
6. Develop a feasible and deployable security solution for vehicle-to-vehicle safety communications.
7. Develop and verify set of objective test procedures for the vehicle safety communications applications.

Therefore, this project will complete the pre-competitive analyses necessary to support deployment of this technology.

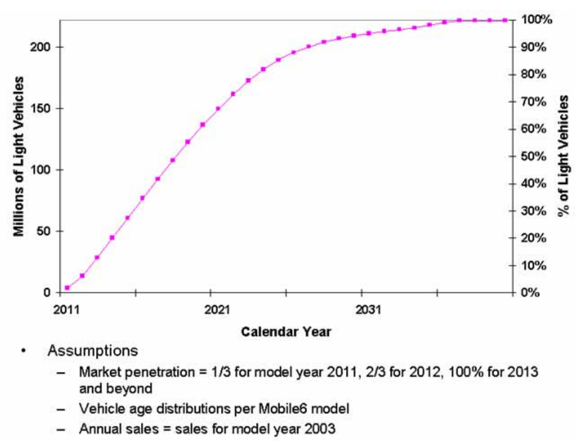

Figure 6. Possible Deployment of DSRC into the Vehicle Fleet

Figure 6[8], developed by the US DOT, shows the number and percentage of equipped vehicles in the United States, based on the deployment assumptions being discussed in the VII program. Of course, the effectiveness of vehicle-to-vehicle safety systems is proportional to the probability of an equipped vehicle being in conflict with another equipped vehicle when a critical event occurs. Other possible deployment models will be explored in the VSC-A project.

CONCLUSION

Vehicle communications have the possibility to transform automotive safety, enabling widespread deployment of effective Active Safety features. The results from the initial research in the United States are very encouraging. Work is now underway that will resolve the key pre-competitive issues needed for deployment, both for vehicle-to-infrastructure and vehicle-to-vehicle safety applications. In addition, deployment models are under investigation, both within the VII and VSC-A projects.

ACKNOWLEDGEMENTS

The authors would like to thank the many dedicated team members from all the OEMs involved in the vehicle safety communications projects discussed. In addition, special thanks are due to Michael Schagrin of the FHWA and Arthur Carter, John Harding, Raymond Resendes and David Smith of the NHTSA for their support during this work.

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Development of technical guidelines for visual drive recorders (VDRs)

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Paper No. 07-0062

ABSTRACT

In 2006, Transport Policy Council, an advisory group of Japan Ministry of Land, Infrastructure and Transport (JMLIT) consisting of vehicle safety experts, submitted a report on future vehicle safety measures to the Minister of JMLIT.
The projections in this report indicate that the number of traffic fatalities and injuries will dramatically decrease until 2010. This report also sets “zero fatalities” as the ultimate target.

To achieve this aim, however, it is necessary to identify and promote new active safety measures. Therefore, near-miss situation data as well as accident data, which would be recorded by an on-board VDR, should be analyzed and evaluated.
In October 2006, JMLIT organized a panel of experts to discuss and develop technical guidelines for such VDRs.

Introduction (The Japanese Government’s Stance on Measuring Transport Safety)

In 2006, the number of Japan's road traffic accident fatalities was registered at 6,352, approaching the 6,000 mark for the first time in 51 years. Moreover, the number of road traffic accidents and injuries both declined slightly compared to 2005. However, the number of road traffic accidents and injuries both remained at levels higher than one million throughout this time.

To improve this situation, the Japanese government has set goals for transport safety over the 5 year period from 2006 to 2010 in its '18th Fundamental Traffic Safety Program' as follows:

- To reduce the number of road traffic fatalities to below 5,500 by 2010, and to establish the safest road traffic in the world.
- To build a society having no traffic accidents as an ultimate goal.

In this report, road construction, road maintenance and driver’s education are listed as some of the safety measures needed to achieve these goals.

In addition to these principles, the Transport Policy Council, an advisory group within the Ministry of Land, Infrastructure and Transport that consists of vehicle safety measurement experts, submitted the report entitled ’Vehicle Safety Measures for Building

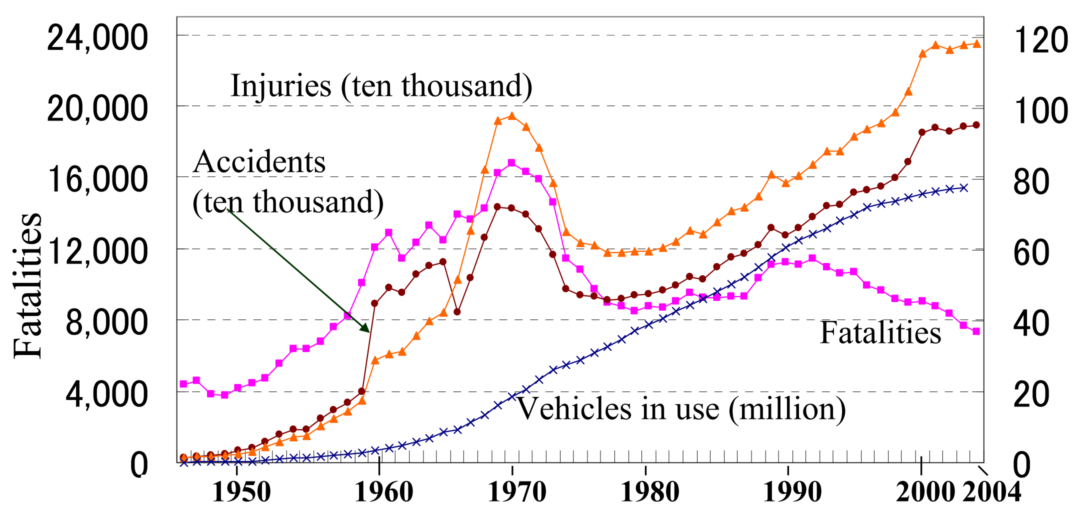

Figure1. Traffic Accident in Japan

a Society Free from Road Traffic Accidents' to the Minister of Land, Infrastructure and Transport last June.

This report indicates an objective to achieve a 750 annual fatality reduction in terms of fatalities that occur within 30 days of an accident injury ("within-30-day fatalities") and a 25,000 annual injury reduction in 2010 from the 2005 baseline.

To continue fatality reductions into 2010 and beyond, efforts will be exerted to enhance active safety measures.

Moreover, this report indicates that in view of future developments, such as the advancement of information technology and the diminishing youth population, the following measures need to be undertaken jointly by industry, academia and government.

- To promote vehicle safety measures specifically designed to increase the safety of heavy duty vehicles;
- To introduce vehicle safety measures intended to build a motor society friendly to pedestrians and elders;
- To formulate vehicle safety measures for reducing serious injuries and disabilities in addition to the reduction of fatalities and injuries in general.

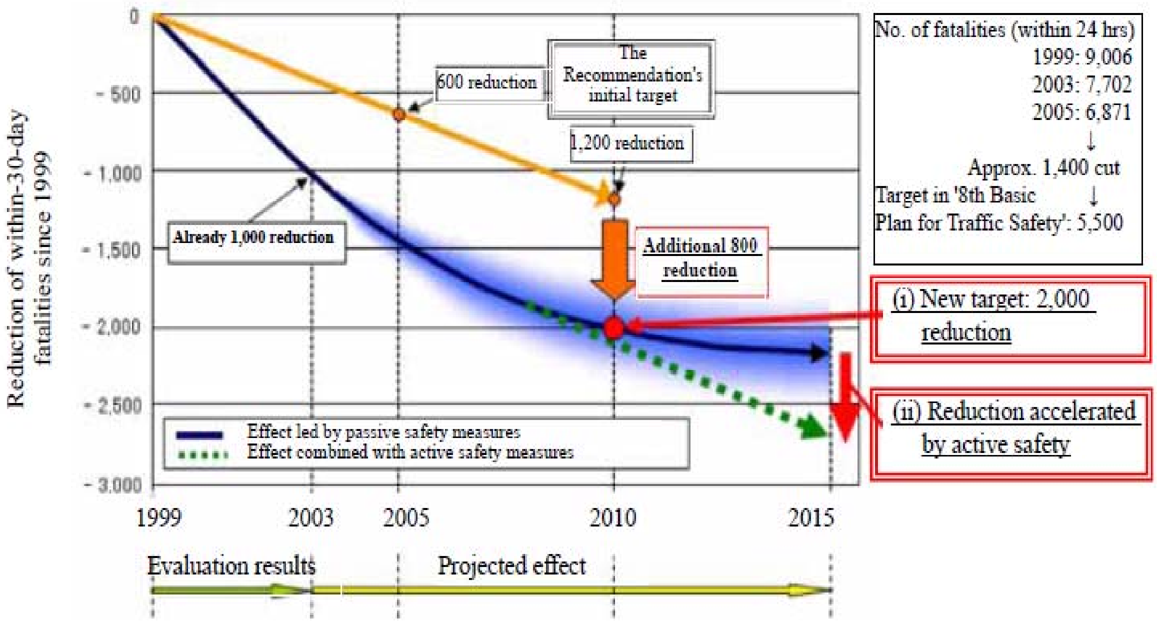

Figure 2. Schematic of New Target Setting

Overview of Current Vehicle Safety Measures

The Japanese government has promoted vehicle safety by establishing vehicle safety regulations, promoting the ASV (Advanced Safety Vehicle) project and improving safety assessment tests.

As a first issue, establishing vehicle safety standards has been promoted by analyzing accidents and evaluating the effect of some vehicle safety devices based on a cycle of setting a target, implementing safety measures, and evaluating the effect.

ASV technology and driver assistance technologies such as the adaptive cruise control system, damage mitigation braking system, night vision and so on have been introduced and commercialized in the Japanese market over the past several years. The variety of automobile assessment tests has expanded, now including the pedestrian protection test and the child restraint test. Regarding collision test results, the results of full-lap frontal crash, offset frontal crash and side crash tests have been integrated to facilitate the comparison of safe vehicle models in relation to collision configurations.

Thanks to the vehicle safety measures in effect, a 1,250 fatality reduction by 2010 as compared to the 1999 baseline is likely to be reached. Since the number of vehicles incorporating these safety technologies will further increase and because new safety measures will be added, a further reduction in fatalities will be possible.

However, effective vehicle safety promotion is mostly limited to passive safety measures. Because active safety technologies aren't understood well enough by users, these technologies don't spread widely. Passive safety technologies, however, are commercialized rapidly and widely.

In order to evaluate active safety technologies quantitatively, it is necessary to calculate how many accidents are prevented by this technology. However, the existing accident investigation techniques cannot collect data on how dangers have been evaded in near miss situations.

Therefore, the promotion of active safety technologies must be supported by the quantitative evaluation of their effects, which will necessitate further improvements in accident analysis and the establishment of performance evaluation techniques for new technologies.

Table1. Commercialized Technologies from ASV Project

No.	ASV technology	Status		
		1996	2001	2004
1	High-speed adaptive cruise control (ACC)	☆	☆☆☆	☆☆☆
2	Low-speed adaptive cruise control	☆	☆☆	☆☆☆
3	Lane keep	☆	☆☆☆	☆☆☆
4	Damage mitigation brake	☆	☆	☆☆☆
5	Drowsiness warning	☆	☆☆☆	☆☆☆
6	Rear & side obstacle warning	☆	☆☆☆	☆☆☆
7	Curve warning	☆	☆	☆☆☆
8	Night vision	☆	☆	☆☆☆
9	Parking assist	☆	☆	☆☆☆

☆: In-company test, ☆☆: Road running test, ☆☆☆: Commercial use

* Damage mitigation brake ……………Using radars or other onboard sensors, this system rapidly anticipates front crash risks and controls the brakes to mitigate crash damage.

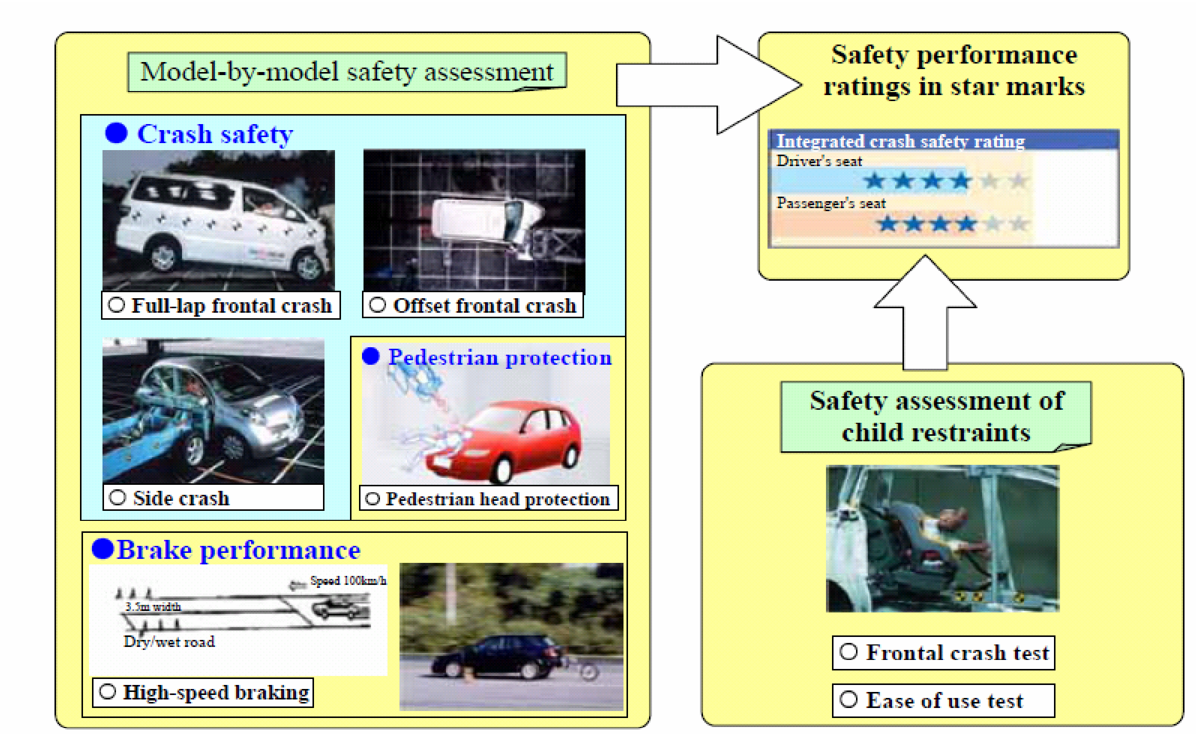

Figure3. Profile of Japan's Automobile Assessment

Table2. Fatality Reduction Effects of Vehicle Safety Measures (estimates of within-30-day fatalities)

	2003	2005	2010
Full-lap frontal crash	715	900	1,150
Side crash	288	350	600
Offset frontal crash & pedestrian head protection	-	0	50
Future measures	-	-	200
Total	1,003	1,250	2,000

* Recorded numbers for 2003 fatalities

The Necessity of VDRs

After proving substantially effective, it is disconcerting that the passive safety technologies in use are predicted to near their maximum potential after 2010.

Also, it is necessary to reduce the number of injuries and road traffic accidents by promoting active safety technology, instead of passive safety, which isn't expected to reduce the number of these well after 2010.

To spread the active safety technologies:

- As a short-term target, expansion of the use of ASV technology such as damage mitigation braking systems is promoted.
- As middle- and long-term targets, the effect of active safety technologies should be clarified, and if some technologies are effective, these technologies should be promoted in the market.

As the above mentioned, to expand the use and accelerate the development of active safety technologies, it is necessary to increase vehicle users' knowledge of safety technologies.

Therefore, the use of visual drive recorders (VDRs) is being considered. The VDRs, installed onboard, are designed to record the vehicle conditions (speed, acceleration, etc.) and the driver-occupant conditions (driving operation, seatbelt use, etc.) during an accident or in a near miss situation.

The VDRs are designed to record, at a certain frequency, vehicle behavior in an accident or rapid deceleration through video images of the inside and outside of the vehicle, as well as deceleration data from the ten seconds before and after the point of impact..

The VDRs' data will enable quantitative assessment of safety technologies for the promotion of truly effective active safety technologies, to enable in-depth accident analysis using visual data.

So that MLIT will pay attention to this point, we decided to organize a panel of experts as soon as possible to establish a technical guideline on the basic performance requirements of drive recorders and to determine the following:

- Examination of data items and specifications for drive recorders;
- Method of collecting the data recorded by drive recorders in widespread use;

Method of analyzing the collected data

Establishment of Performance Evaluation Techniques with VDRs

(1) The spreading situation of VDRs

In March 2006, 230,000 taxies were in use in the Japanese market. Of those vehicles, 34,000 have mounted VDRs and this number is increasing continuously.

Some taxi companies exert some effort to maintain transport safety, through educating their drivers and by using recorded data of VDRs.

Based on the above situation, to decide the specification of VDRs, we refer to the present VDR specification that is circulated in the market and that has more than ten kinds of different specifications.

(2) Configuration of road traffic accidents should be analyzed by VDRs

In Japan, rear-end collisions account for about 30% of total injury-inducing accidents. The proportion of crossing collisions and rear-end collisions to total accidents is more than 50%.

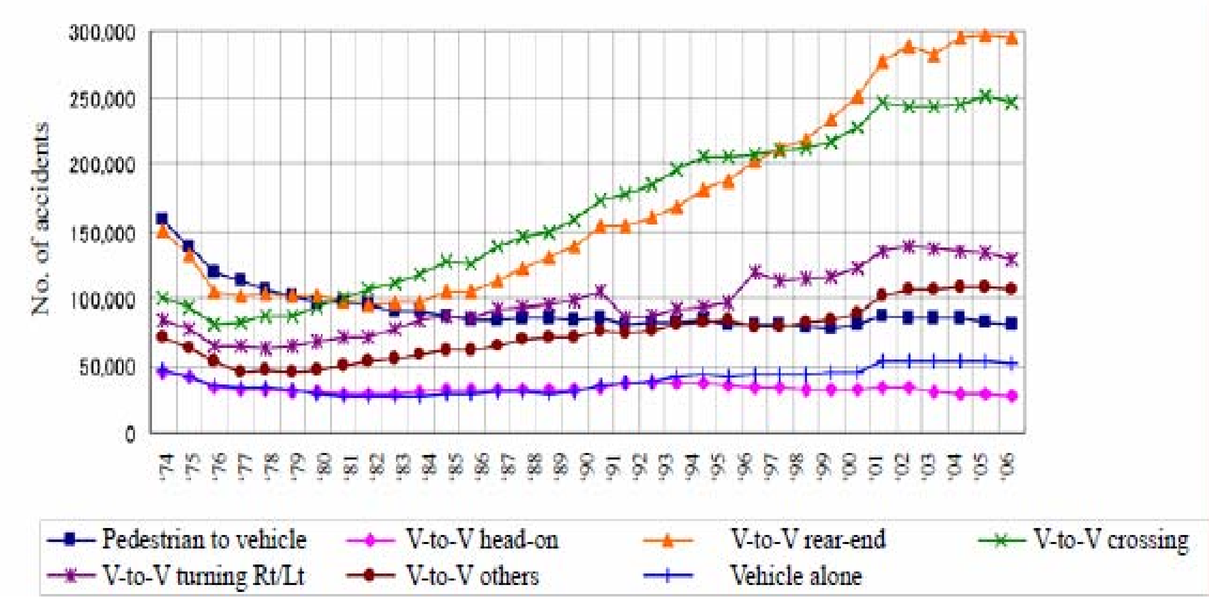

Figure4. Road Traffic Accidents by Configuration

Therefore, using VDRs, we think that it is important to evaluate safety devices in relation to rear-end collisions and crossing collisions. As a first step, we plan to evaluate safety devices in relation to rear-end collisions. Specifically, we plan to evaluate braking assist systems, damage mitigation braking systems, high-mounted stop lamps and so on, as safety devices prevent rear-end collisions. The following VDR specifications will be evaluated through experiments reproducing accidents and so on.

① Specification concerning image quality and horizontal visual angle

Using visual data of VDRs, we have conducted an experiment to establish the specification concerning image quality and horizontal angles that would make it possible to calculate the distance to the vehicle ahead and the relative speed of the vehicle ahead.

In general, when the horizontal visual angle becomes wider, it becomes easier to understand the outline of the accident. On the other hand, the image quality becomes poor, and detailed accident analysis becomes difficult. Therefore we have to look for the optimal VDR image specification.

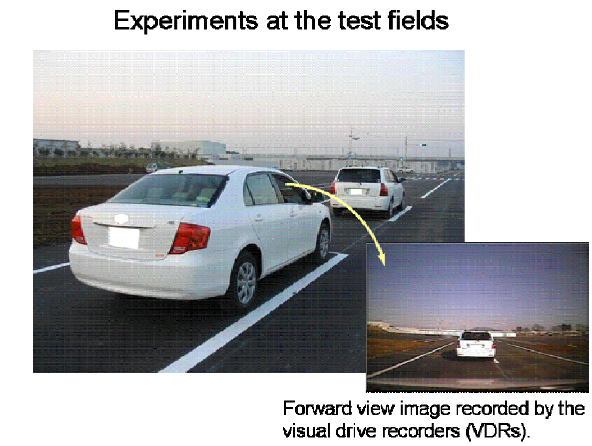

Figure5 Experimental situation (car-following).

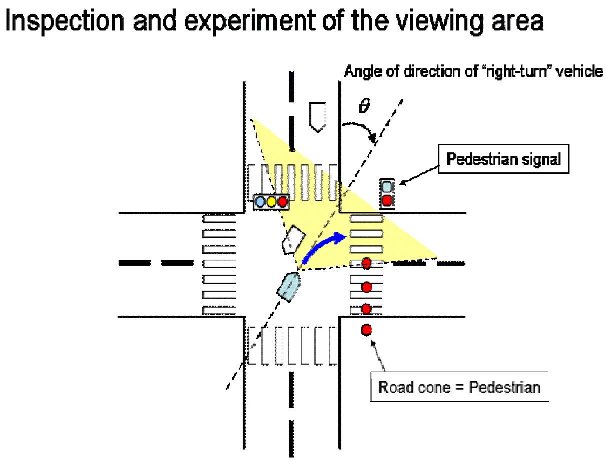

Fig.6 An example of the experimental geometry of "right-turn" at the intersection without "right-turn" lanes.

② Specification concerning sampling frequency of image and deceleration data

It is necessary to understand in detail the VDR data of rear-end collisions and near miss situations exactly. It is therefore necessary to adjust the sampling frequency of image and deceleration data.

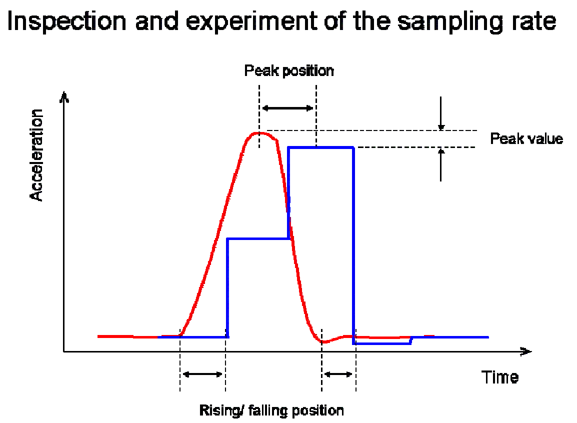

Figure7 Difference between the "true" curve and the recorded one by the visual drive recorders (VDRs).

Future Issues

The above investigation will be finished by this summer. After that, we will start to evaluate safety technologies for rear-end collisions. However, it is necessary to develop effective active safety technologies by further utilizing the data from VDRs. To achieve this goal, we need to discuss the follows items.

(1) Method of collecting the data recorded by VDRs in widespread use

If we promote evaluation of active safety technologies with VDRs, it is necessary for drivers who attached VDRs to cooperate voluntarily. In order to conduct this investigation practically, we need sampling data of vehicles that have active safety devices such as a braking assist system or a damage mitigation braking system. However, it is very difficult to collect the data, because the number of vehicles with mounted active safety devices is very small. Therefore we need to discuss the method of collecting the data efficiently.

(2) Method of analyzing the collected data

The data collected by VDRs occupies huge memory space for the included visual data. Moreover, each VDR manufacturer formats the visual data differently. Therefore we need to discuss the method of analyzing the collected data easily. Whether the format of every manufacturer's data should be unified will be addressed in this discussion.

(3) Sustainable analysis by using the collected data

We need to discuss the overall framework for sustainable analysis by using the collected data, as well as for the above implementation, examination, collection and analysis.

Actually, we intend to utilize VDR data to analyze traffic accidents at ITARDA (Institute for Traffic Accident Research and Data Analysis).

Conclusion (Summary)

We should expand the use and accelerate the development of active safety technologies, to promote the measurement of traffic accidents by vehicle safety technologies.

However, it is difficult to show quantitative effects of active safety technologies, which differ from the effects of passive safety technologies.

Recently, given the rapid advancement of electronic information technology and the development of new technologies such as VDRs, the establishment of quantitative methods for measuring the effect of active safety technologies is expected.

By the middle of this year we will decide the specification of VDRs; after that we will promote this project.

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INFLUENCE OF ROAD CHARACTERISTICS ON TRAFFIC SAFETY

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Paper Number 07- 0064

ABSTRACT

The objective of this traffic safety investigation was to find critical road sections using Post- and Pre-accident analysis approaches. The Post-accident approach analyzes the effect of road geometric characteristics on accident rate. The study was based on accident and road maintenance data in Western Sweden. A total of 2912 accidents from 2000 to 2005 on 1615 km median-separated roads was collected and combined with road characteristics (Speed, carriageway width, AADT, vertical and horizontal alignments, superelevation) for analysis (Post-accident approach).

The statistical analysis showed that road characteristics have great effect on accident ratio (AR defined as number of accidents per million vehicle kilometer

- AR and injury severity increase with increasing speed limit.
- A carriageway of 5,8m has the lowest AR, with a distinct tendency for AR to decrease with lane widths greater than 5.8m.
- AR decreases with increasing radii of curve for right and left-turn curves. Left-turn curves have higher AR than right-turn.
- Road sections with left-turn curve radii of less than 100m have highest AR; they are four times as high as those with curve radii greater than 500m and twice as high as right-turn curve radii less than 100m.
- The lowest AR were observed for superelevations of 3-4%. AR increases when superelevations increase or decrease from 3-4%.
- AR on downgrades is higher than on upgrades.

In a Pre-accident approach the IST-Checklist method 2005 has been used. A tool based on human behavior that assesses a place or a road section's inclination to trigger accidents. The purpose was to investigate applicability of IST on Swedish roads and then using it to find critical road sections. The results show that the method doesn't function as expected for blind tests made on Swedish road sections which showed weak correlation between real accidents and IST results.

The investigation approach and results are useful input for designing future active safety systems such as ABS and ESP that are sensitive to the road characteristics.

INTRODUCTION

Background

Road safety engineers are faced with the challenge of addressing safety issues within the three major traffic safety pillars: human, vehicle, and infrastructure. All three aspects must be part of a traffic safety plan and dealt with subject to budget limitations. Consequently, the cost efficiency of systems and countermeasures are decisive factor for policy making.

The European Commission (EC) funded RANKERS project (Ranking for European Road Safety) in the 6th Framework Research Program. The ambitious objective of this project is to develop scientifically-researched guidelines enabling optimal decision-making by road authorities in their efforts to promote safer roads and eradicate dangerous road sections. It was also designed to gain new knowledge by performing research and empirical studies of the road's interaction with the driver and their vehicle in order to identify optimal road recommendations and predict their impact on safety. The main output of the project will include an index used for assessing and monitoring road safety and a comprehensive catalogue of road infrastructure safety recommendations ranked according to their cost-effectiveness [1].

This road safety analysis is a part of RANKERS project. Its main purpose is to find areas with clusters of problems (black spots) and dangerous road sections by defining a methodology to better understand road characteristics that leads to traffic accidents.
Studying and analyzing accidents data on selected roads is the starting point to determine black spots. Finding road characteristics where most of the accidents occurred, a Post-accident approach is the method which has been used in this paper to find correlations between road geometry parameters and accident rate.
Another strategy to find black spots is from a human behavior perspective studying and analyzing traffic situations to evaluate how safe a road is to drive on. This pre-accident approach uses a tool called the IST-Checklist method 2005. The IST method has been developed by Intelligent System Transfer in Potsdam. It has already been applicable and successfully applied on parts of the German road network [2].

The idea behind applying the IST checklist is to examine its functionality on Swedish road network and apply it afterwards on the selected roads. The IST checklist is applied on a place or a road section to analyze its inclination to trigger accidents from human behavior knowledge. The evaluation is based on a checklist where the results suggests treatment actions. Another idea behind the IST checklist is to improve and gain new skills- and guidelines for new constructions to avoid accidents in the future [3].

Objective

The objective of this study was to use post- and pre-accident approaches to find critical road sections. A Post-accident approach was to evaluate the effect of the main road geometry characteristics on accidents, in other words to quantify and test possible changes in accident rate on roads where their geometrical parameters change. To achieve this aim the existing data stored by road administration, police and hospitals have been used.
In Pre-accident approach the IST-Checklist method 2005 has been used as a tool used to analyse traffic safety on the basis of human factors. It analyses the road environment's inclination to trigger traffic accidents. Evaluation of the IST checklist was to assess if the tool can be used on the Swedish road network in the future.

Limitation

Accident data was limited to personal injury accidents, while the road types of were limited to median-separated public roads in the western region of Sweden. The period of investigation was 6 years (2000-2005). Only the effects of the following parameters on accident rate have been addressed: speed, curvature, carriageway width, super elevation, and road grade.
From human behavior perspective the IST checklist 2005 method, has been tested only on two road sections of a total length of 5.6 km to evaluate and blind test their safety levels according to IST.

METHODOLOGY

Two different parallel methods have been used to achieve the mentioned objectives of this study, detailed methodology for each of them is explained separately in the following sections.

Post-Accident Approach

Existing accident and maintenance databases have been used to find correlations between road geometry characteristics and accidents. The maintenance data was from the Swedish Road Administration (SRA) is stored in a database called PMS (Pavement Management System) while accidents reported by police and hospitals collected in databases OLY and STRADA.
After choosing an area and a period of investigation the analysis method was carried out in four phases: 1- Collecting accident data, 2- Collecting road characteristics data, 3- Locating accidents and combining them with the road data, 4- Analyzing collected-combined data statistically to locate and identify black spots.
For evaluation of the effects of the road parameters, simple and multiple regression techniques were used, in which accident data was the dependant variable while geometry parameters were independent variables. For the results to be considered significant, final regression equations were to have regression coefficient, R^2, that was significant at the 0.05 level for simple regression analyses. In multiple regression analyses, each of the independent

variables included in the equation had to have R^2 that was significantly different from 0 at the 0.05 level.

The **Region of Investigation** was the Western region of Sweden which has been chosen for the investigation due to weather variations which are comparable with other regions in Sweden. Another reason is the amount of traffic on the selected public roads is 36% of the total Swedish traffic flow.

Accident Data have been collected from two national accident databases, OLY (Accident Database) and STRADA (Swedish Traffic Accident Data Acquisition). Both databases contain only personal injury accidents. OLY contains accidents based on police reports until the end of year 2002. After that OLY has been replaced by STRADA which is based on reports from police and hospitals to minimize accident reporting loss. Through the hospital report acquires a better picture of the injury severity [4] is also achieved. The accidents known by both the polis and hospitals are matched in the database.

In 2000-2005, a total of 3599 road traffic accidents involving personal injury (including fatal, severe and slight injuries) were reported to the databases. Of these, 690 accidents have been excluded due missing road data for accident location, or non-criteria accidents.

For every reported accident the following information has been recorded in both the OLY and STRADA databases: accident ID, date, type, place- and description, number of killed, severe and light injuries, weekday, time, road condition (wet, dry or snow) and lighting conditions.

Locating accidents are different in both databases. OLY uses start and end nodes and the accident locations are given as a distance from the start node to the accident location. STRADA is a GIS-based system (Geographical Information System) which permits mapping tools to locate accidents during both the registering and analyzing of data.

Road Data for the specific types of roads has been targeted to fulfill RANKERS project guidelines, which is separated-median public roads. The total length of the selected roads in 2005 was 810 km including 480 km motorway, 47 km 2+1 semi-motorway, 15 km semi-motorway and 147 km 4-laneway.

Sources used to collect road data were the PMS (Pavement Management System) and NVDB (National Road Database) databases, which are owned and maintained by the Swedish Road Administration (SRA).

The PMS (Pavement Management System) contains data for the road and its surface condition. Its main function is to supply information about road surface and road geometry which can be used to identify optimum maintenance strategies (repairs and rehabilitation activities). The system is to support decisions concerning when, where, and what countermeasures should be taken on paved roads. However it must be emphasized that the purpose of the system is not explicitly used for safety analyses.

Annual road measurements are collected with a special survey vehicle, Laser Road Surface Tester (Laser RST). The Laser RST scans and measures the transverse profile of the road at varying speeds up to 90 km/h with 17 laser sensors. They are placed on a support beam at the front of the test vehicle. The collected data is processed and verified according to purpose-designed statistical and mathematical procedures.

The parameters collected/calculated from the Laser – RST sensors are wheel rut, IRI (International Roughness Index), super elevation, curvature, texture and grade. They are stored for every 20 m road length. The database is completed with other road traffic information such as speed limit and AADT (Annually Average Daily Traffic).

The PMS database is constructed with links which they have unique ID. The links are assembled together by joints (knot point). Every joint represents a junction or an interchange.

To take advantage of the database for traffic safety purposes, measurements at accident locations have been extracted and recorded together with the accidents for further analysis. The chosen parameters are speed limit, carriageway width, curvature, super elevation and grade.

The **NVDB (National Road Database)** consists of road links connected to each other by joints (in the same way as PMS). Furthermore the links are divided into several sections. These sections are components of NVDB and every section has a unique ID. The nodes have identical names in NVDB and PMS which enable data interchange between them.

NVDB contains a huge amount of data which describes roads and traffic regulations. Presently just a small part of this data is of interest for accident analysis. Surface layer material and carriageway width are the only parameters in NVDB which describe roadway.

Using NVDB in this study was limited to the speed limit for OLY accidents and road opening day to make sure that the accidents have occurred on the desired type of roads.

Another use of NVDB is for boundary marking desired roads at STRADA then picking up corresponding accidents. Other interested attributes in NVDB are also available at PMS in more detail such as road type.

Combining Accident- Road Data has been done manually. Accidents during 2000-2002 were collected from OLY manually, while the rest (2003-2005) were gathered from STRADA with help of ArcGIS software. The collected accidents had to be completed by road data from PMS and NVDB for analysis. This part was the most time consuming in the method. The procedure began with selecting relevant accidents; deciding associated roads with driving direction and afterwards collecting road information for the accident locations. The road information had to be measured the same year when the accident occurred so that effect of road parameters on accidents could be studied.

After removing accidents that hadn't occurred on relevant roads and those that occurred before the road's opening day, a total of 1057 accident have been collected from OLY (OLY were in paper document form), while 1855 accident were collected from STRADA.

The next step was to provide and connect road data, from PMS and NVDB databases, to the data extracted and collected from OLY and STRADA. The step has been implemented manually [8].

Connecting accidents to road data can be done also by using a automated method called ArcMap handle [9]. ArcMap handle had been applied to some collected accidents in order to compare it with the manual method. It was found that the automated method is faster and more effective than the manual method, but it is less accurate. About 15% of accidents ended up being reported for the wrong direction of the road while 87 accidents (3.7%) were connected to wrong roads.

Several Parameters were used in the subsequent analysis; orientations of parameters are referenced to the vehicle's original travel direction. Relevant road data were:-

- Speed limit (50,70,90 or 110) km/h
- Road type (motorway, expressway, expressway 2+1, normal 2+1 and 4-lanesroad)
- Annual Average Daily Traffic (AADT which provided by SRA for years 2002 and 2005, interpolation has been used for other years)
- Carriageway width, W, [m] (Classified to four groups, $W \leq 5.8$ m, $5.8 < W \leq 7.5$ m, $8 < W \leq 11.7$ m and $W \geq 12$ m.
- Curvature, classified to left and right- curves and analyzed in terms of radius of curve [m]

$$Radius\ of\ \ curve\ [m] = \frac{10000}{Curvature} \tag{1}$$

Right and left curves divided according to length of the radius: greater than 1500, 1000, 500, 200 and 100 m.

- Grade divided into up and down-grades, where they subdivided to: 0 – 2%, 2 – 4% and 4 – 6%.
- Super elevation classified to negative and positive-super elevations, while each of them divided to: 0 – 1.5%, 1.5 – 2.5%, 2.5 – 3%, 3 – 4%, 4 – 5% and $\geq 5\%$.

The assignment of accident location by the police at the time of accident was not always precise. Errors of up to a couple of hundred meters can occur in accident localization. But accident localization can be considered as normal distributed around the real accident location. [5]. Because of this, an average value of around 200 m (100 m before and 100 m after the 20 m section where the accident occurred) has been taken for the mentioned parameters.

In the rest of sections where no accidents occurred, a mean value has been taken for the road parameters. In this case length of sections varies between 150 and 400, which is length of the NVDB sections.

Pre-Accident Approach (IST-Checklist)

The IST-Checklist Method was different from post-accident approach and was based on conflict and consequences. The IST-Checklist, pre-accident approach, takes the human behaviour into account to identify spots which can trigger accidents. The evaluation is made with IST-Checklist 2005 "Exercise Booklet" – a checklist with Yes/No answer to the relevant questions. The result is numeric where a low result indicates that a critical spot or section of road has a tendency to trigger accidents. The evaluation can be used as a ground for decision making. Certification in the method is required to perform the analysis. The IST-method includes sections before and after accident location in analyzing, rather than the spots where the accidents occurred [3]. For example, it assumes a driver requires 4-6 seconds to come to a right decision during driving when a crucial situation comes up. Therefore, the analysis section starts from the critical point to several meters before the point, depending on operating speed. IST has classified trigger factors and divided into three groups, axioms:

300-Meter-Axiom is the first rule and it treats the section up to a straining/decision point. The axiom is named after the length of the section that the driver needed to prepare before the straining/decision point. The length of the section is variable depending on driving speed and reaction time of the driver (See Figure 1). The axiom is divided into [3]:

- **Moderation of the transitional area**.
- **Straining point's perceptibility**.

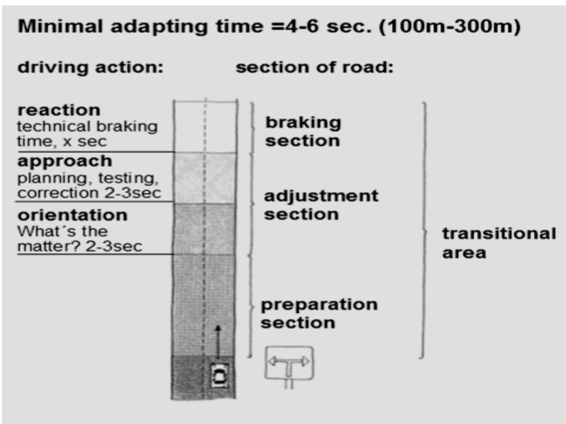

Figure 1. 300-m-axiom [2].

Field of Vision Axiom treats the roadway/ environments capability to create a simulating environment for the driver. The road with its environment together offers an integrated field of view which either stabilizes or destabilizes driver's behavior. For example a monotone environment cause fatigue which leads to speed increase or misdirection due to nonparallel lines or fences with the driving direction. This axiom is divided into three areas[3]:

- Optical density of the field-of-vision
- Lateral space structure
- Depth of space structure

The Logic Axiom treats driver's perception logic and road design. The road design has to be in accordance with the drivers expectations. For example if a road section looks or feels as a motorway, the real driving speed would be high (motorway speed) regardless the road's speed limit. The logic axiom is divided into five areas [3]:

- Avenue/town entrance effect
- City bypass irritation
- Effects of habits and routine
- Accumulation of straining points
- Signing

A Blind Test was carried out to evaluate the "IST-Checklist 2005" on the Swedish road system. This was done by comparing the results carried out from the checklist with the number of actual accidents on the road.

The IST checklist was implemented on a main road between Gothenburg and Stockholm. The road is a primary type 2-lane rural road of width 12 m , AADT of 10 000- 13 000 vehicles/day and speed between 70 – 90 km/h.

Two different road segments, A and B were chosen, one with many accidents and the other with few. The road sections have been documented in the form of photographs at a frequent interval of 20 m length. The next step was to identify straining points and divide the sections into segments. Section A, 3.6 km, was divided into 13 segments while section B, 2 km, was divided into 6 segments. All segments have been evaluated with the IST-Checklist to determine the safety level predicted in terms of numeric results. The last step was to assess the IST checklist by calculating correlation, using statistical analysis, between the numeric results of the evaluation and real accident data. Real accident data of the sections have been collected from STRADA. Accidents which were not a result of human factors have been excluded such as wildlife accidents and alcohol/drug related accidents.

ANALYSIS and RESULTS

Post-Accident Approach.

Statistical Results visualized in Figure 2 show the absolute number of accidents distributed over the six years of analysis. From the illustration it is clear that the length of the main roads increased yearly which partially explains an increasing number of traffic accidents in the region annually. However, this trend of increasing number of accidents does not mirror hazardousness inclination of the roads since other factors such as length of road section and AADT have not been taken into consideration. A short road section with little traffic flow could be more dangerous than a longer one with more traffic although the first causes less number of accidents. More about accident investigations are discussed in section 5.

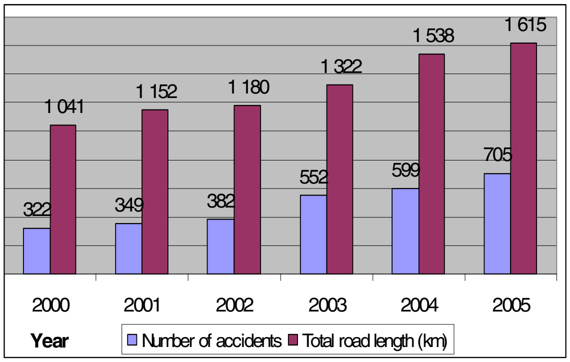

Figure 2. Number of accident together with main road length during the investigation period.

By dividing accidents according to accident types Figure 3 shows that rear-end and single accidents were the dominating accident types representing 49% and 32% respectively followed by overtaking, turning, pedestrian, crossing, head on and cycle/moped accidents.

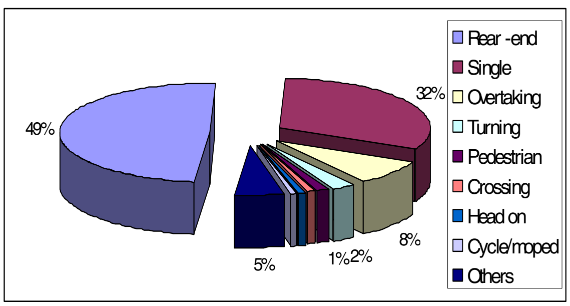

Figure 3. Distribution of accident type.

Accident Investigation by comparing the absolute number of accidents does not make much sense because of differing comparative conditions. Under comparative conditions, however, it is understood that section length and traffic volume exhibits an influence on the accident situation. For instance, the longer the roadway section is, the higher the accident possibilities are. Similarly, the higher the traffic volume is, the higher the accident possibilities are. Therefore, the length of investigated section and the traffic volume on that section (that is, vehicle kilometer traveled) must be considered in comparative accident investigations.

Accident rate **(AR)** is one way to normalize the results. It considers the length of a roadway section and the traffic volume to allow a direct comparison of different roadway sections with respect to traffic safety [6]. Accident rate (Equation 2) is accident per **M**illion **V**ehicle **K**ilometer (MVKm).

$$AR = \frac{accident \times 10^6}{AADT\, 365\, T\, L} \quad accidents\ per\ 10^6\ vehicle\ kilometers \qquad (2)$$

Where:

AR = Accident rate
AADT = Average annual daily traffic.
L = Length of investigated section, km
T = length of investigated time period, yr
365 = number of days/yr

After determining AR; statistical methods have been used to analyze the processed data including histogram graphs, simple and multiple linear regression analysis.

In examining the whole period, Figure 4 shows that AR is almost constant the first three years then increases rather strong after that. The substantial increase of AR in the year 2003 is most likely due to less accident report loss in STRADA rather than the roads have become more dangerous. From the year 2003 accidents from both police and hospitals have been reported to STRADA while before that only police reported traffic accident registered in OLY. A total of 297 (16%) could have been lost if only police reports considered in the last three year accident collection.

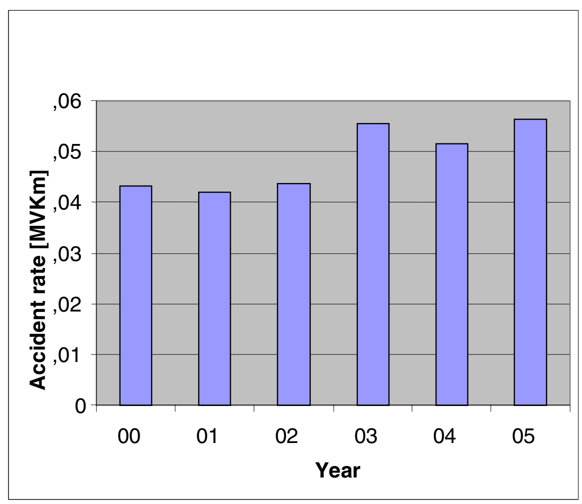

Figure 4. Accident rate on the main public roads in the Western Region of Sweden.

A comparison of the AR for various types of roads is done; Figure 5 reveals that motorways are safer than four-lane and 2+1 roads. However the AR for four-lane and 2+1 roads are almost equal.

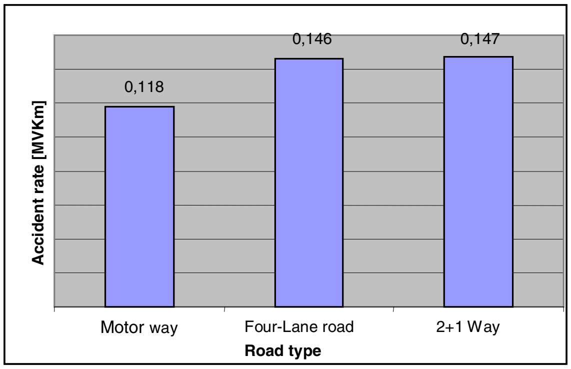

Figure 5. Accident Rate for different road types.

Figure 6 shows the outcome, in terms of injury severity, of the injured persons in the crashes investigated (based on police report information). The rate for killed persons have decreased to more than half in the year 2005 in relation to the first three years of analysis. Also severe injuries has decreased generally, apart from a deviation in the year 2005 in which the rate has increased compared to years 2003 and 2004. The light injury rate increasing is explained by the fact that accident rate has increased in the last three years (See Figure 6) fatal and severe injury rate have decreased. Light injuries increased on all three road types in the last three years, mainly on four-lane roads, while severe injuries decreased mainly on motorways. Fatalities have decreased generally on four-lane and motorway roads.

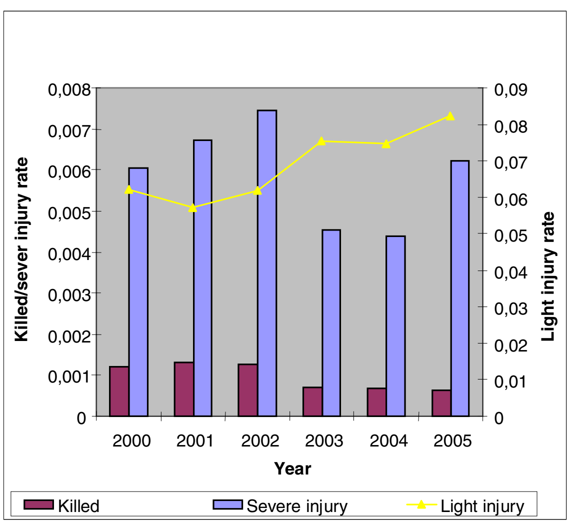

Figure 6. Injury severity rates during six years period

Linear Regression Analysis is a statistical method for modeling the relationship between two or more mentioned variables using simple and multiple linear equation. Simple linear regression (Equation 3) refers to a regression on two variables while multiple linear regressions (Equation 4) refers to a regression on more than two variables. A statistical software program, SPSS, has been used in regression analysis to find the effect of road attributes on accident rate. The dependent Y-variable represents accident rate. Independent X-variables included road speed limit, carriageway width, curvature, grade and super elevation.

$$Y = a + b \times X \qquad (3)$$

$$Y = a + b \times X_1 + c \times X_2 + d \times X_3 + \cdots \qquad (4)$$

Confidence of the result indicates in terms of significant value (P). The correlation was considered significant if (P) is zero or 5 % different from zero [7]. The correlation coefficient R^2 only gives a guide to the "goodness-of-fit" or how closely variables X and Y are related. It does not indicate whether an association between the variables is statistically significant.

Expressroads haven't been considered in the following analysis due to the insufficient number of accidents. Most of the accidents have been excluded due to lack of road information. The following relationships have been drawn between design and traffic-related variables and accident history of analyzing road parameters.

Influence of Speed Limit on accident rate (for all three road types) showed that the accident rate increases as speed limit increases from 70 to 110 km/h. However when the speed limits decreases from 70 to 50 km/h accident rate increases. As expected, the injury severity increases with increasing speed limit for motorway and four-lane road accidents. The selected equations have strong regression coefficient R^2 (0.64 to 0.99). However the least significant value P; was found for motorways, 0.1.

Influence of Carriageway Width on accident rate was the following:

- Carriageway width up to 5.8 m has the lowest accident rate; they usually are one-lane roads. Accident rate was up to 3 times less than other carriageway widths.
- A distinct tendency for accident rate to decrease with increasing lane width greater than 5.8 m. The regression coefficient R^2 was 0.86. However value of P was 0.24.
- Road categories with, $5.8 < W \leq 7.5$ m, had the highest accident rate. This category represents mostly two-lane roads without shoulder or with a narrow one (See Figure 7).

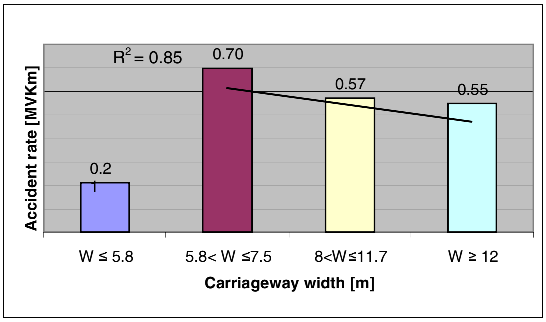

Figure 7. Influence of carriageway width on accident rate.

Influence of Curvature on accident rate has been shown in Figure 8. Statically analyzing left and right curves separately showed unchanged tendency of accident rate on curves for radii greater than 1500 m including straight sections. However a clear change of accident rate was noticed on curves with radii less than 1000 m as follow:

- Accident rate decreases with increasing radii of curve for both right and left curves with R^2, 0.7 and 0.88 and P value 0.16 and 0.19 respectively,
- Left-turn curves have a higher accident rate than right-turn curves.
- Road sections with left curve radii of less than 100 m have accident rate that are twice as high as road sections with right curve radii less than 100 m.
- Road sections with left curve radii of less than 100 m have accident rate that are four times as high as those on sections with curve radii greater than 500 m.

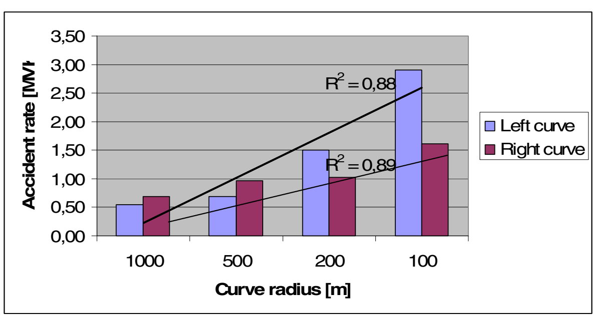

Figure 8. Influence of curve radius on accident rate.

Influence of Grade on accident rate showed:

- The accident rate on down grades is slightly higher than that on upgrades.
- Upgrades have little effect on accident rate, while accident rate increases with increasing downgrade with R^2 equal to 0.7, however the correlation is not statistically significant, P = 0.36.
- A sharp increase in accident rate on downgrades greater than 4 percent.

Influence of Super Elevation on accident rate resulted (See Figure 9):

- Super elevations of between ±3 and ±4 percent exhibited the most favorable results.
- Accident rate increases significantly for superelevations greater and less than the favorable percent, ±3 to ±4. The correlation coefficients, R^2, are generally high. However, only increasing accident rate were observed for decreasing negative super elevation (less than the favorable value) is statically significant with a P value of 0.02.
- Negative super elevations have higher accident rate than positive super elevations.
- 0 – 1 percent negative super elevations and positive super elevations ≥ 5 percent have the greatest accident rates which are about twice as high as that on the favorable percent, ±3 to ±4.

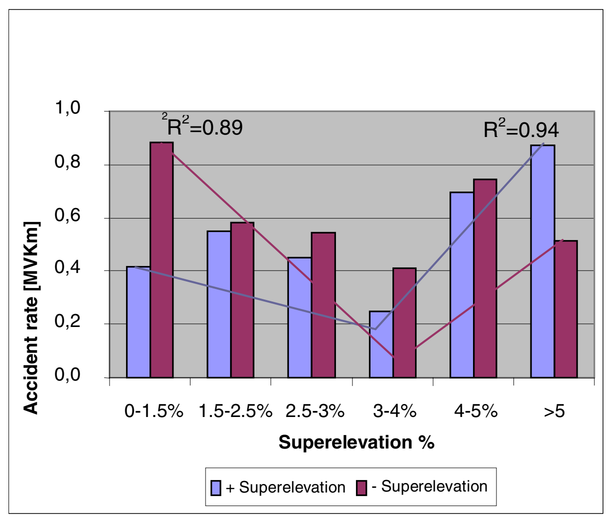

Figure 9. Influence of super elevation on accident rate

There was no significant correlation between traffic accident rate and road parameters together, when multiple linear regression analysis was applied to the collected data for all road types. The relationship did not become stronger when the SPSS program was allowed to choose parameters that together have influence on accident rate.

IST-Checklist Method 2005

Statistical analysis showed weak correlations between the low IST Checklist 2005 results and high accident frequency. The method should predict high accident rates when the checklist numerical scores are low. The overall correlation between IST and both sections was 0.05. Correlations increased slightly, but were still weak, when sections A and B analyzed separately. Results were -0.15 and 0.36 respectively.

When analyzing the sections separately according to driving direction, correlations for section A, east and west were -0.10 and -0.35, respectively while section B results were 0.63 and 0.03.

DISCUSSION and CONCLUSION

Post-Accident Approach

A Post-accident analysis approach was based on accident and road data. It is well known [10] that the reporting of injury accidents in official road accident statistics is incomplete. The fact that reporting is incomplete does, by itself, not introduce any bias in studies evaluating the relationship between road characteristics and accident rate. Results can be biased, however, if the level of accident reporting changes over time (relevant to before-and-after studies).

The locations of the accidents were only those provided by the police. An explicit assessment of the level of estimation, and its variation, is almost never done. It is, unfortunately, not possible to remove or control for this potential source of error. However to minimize effect of the errors; an average value of around 200 m has been taken for the road parameters. Another problem in determining the location of accident is when the reason of accident is not where the vehicle is stopped, which means that road measurements of another section should have used for analyzing the accident.

The Pavement Management System (PMS) was not fully accurate for estimating accident locations. In measuring the same road section, annual variations in the road geometry measurements were noticed. Parameters such as curvature, superelevation and grade have to be constant for the road section unless the section has been repaved or reconstructed. The 200 m average used in this study reduces the effect of this error source. On the other hand several sections had no measurements registered in PMS especially at motorway exit and slipways which led to excluding 10% of total collected accidents. Most of the sections of interest were on expressroad sections which have not been analyzed due to few numbers of accidents.

The roads chosen for analysis (Motorway, 2+1way and Four-lane roads) are among the safest road types in Sweden [11], therefore finding black spots on such roads was not an easy task.

Further investigation is required to study correlation between road surface data (unevenness, wheel rut and road condition) and accident rate.

The statistical relationship results generally showed high correlation coefficients, R^2. The main findings of the post-accident research presented in this approach can be summarized as follows:

- There is a strong statistical relationship between speed limit and accident rate, when the speed limit increase, 70 – 110 km/h, the accident rate and the severity of injuries will almost always increase. However when the speed limit decreases from 70 to 50 km/h, increases accident rate.
- Carriageway width less than 5,8 m has lowest accident rate, while two lane carriageway without shoulder or a narrow shoulder ,$5.8 < \text{width} \leq 7.5$, is the most dangerous.
- Accidents cluster at curves and left turn curves with radii less than 100 m.
- Superelevations of 3-4% are in the safest range. Accident rate increases with roads deviating from this range.
- Grade has a low effect on accident rate however downgrade road sections have slightly higher accident rates than upgrade sections.

Pre-Accident Approach

The safety tool “IST-Checklist method 2005” which is based on human behavior is a simple method as it is based on a checklist with Yes/No questions. However the method is very time consuming when it is applied to long road sections.

The results of this research indicate that the method does not function as expected; blind tests made on sections of a Swedish road show a low correlation between real accidents and a low result from the IST-Checklist 2005 method. This result doesn’t mean that the method is not applicable as a safety tool. The result, more likely, can be explained by a number of reasons - the main one being that due to the ‘human side' of this method, the analysis is highly subjective and therefore open for individual interpretation. However, it is the authors' opinion that the method is useful in analysing traffic accidents due to its consideration of a large number of important factors when it comes to traffic safety and road design. Other possible error sources are division of segments from straining points, errors in accident statistics and the omission of traffic flow (AADT). The latter is highly relevant for safety comparisons between road sections.

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OPTIMUM ROTOR PERFORMANCE IN AXIAL FLOW BY FINITE-STATE METHODS

by

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Abstract

Recent studies have pointed out that conventional lifting rotors in forward flight have efficiencies far lower than the optimum efficiencies predicted by theory. Finite-state inflow models have been suggested as a theoretical basis whereby to study the reasons for this efficiency deficit. In this paper, a finite-state inflow model is utilized to formulate the optimum circulation and inflow distribution for rotors in axial flow. The results show that a formal optimization with finite-state models can be done in closed form and that such an optimization recovers the classical uniform-flow condition (for an actuator disk with an infinite number of blades), the Prandtl solution (for an actuator disk with a finite number of blades), the Betz distribution (for a lifting rotor with an infinite number of blades) and the Goldstein solution (for a lifting rotor with a finite number of blades). Thus, it should be possible to use finite-state models to investigate optimum rotor performance in forward flight.

Notation

$\left[A_{nj}^{m}\right]$	special case of the matrix $\tilde{L}$
C_n^m, D_n^m	Fourier expansion coefficients for the pressure
C_P	power coefficient
C_{P_I}	induced power coefficient
C_T	thrust coefficient
$\left[E_{nj}^{m0}\right]$	expansion transformation matrix
H	rotor inplane force
$[I]$	identity matrix
j, n	polynomial number
k	Prandtl's tip loss correction factor
K	thrust deficiency
K_n^m	kinetic energy matrix
L_q	blade loading
$\tilde{L}^c, \tilde{L}^s$	cosine and sine parts for the L-matrix
$\bar{\bar{L}}$	$\tilde{L}$-matrix with the elements where m = 0 are multiplied by two
m, r	harmonic number
P_I	induced power
P_s	shaft power
P_n^m	associated Legendre function of the first kind
$\bar{P}_n^m$	normalized associated Legendre function of the first kind
ΔP	rotor disk pressure
Q	power or number of blades
Q_n^m	associated Legendre function of the second kind
$\bar{r}$	non-dimensional radial position
R	radius
t	time
$\bar{t}$	$=\Omega t$
T	thrust
u	horizontal component of induced velocity
U	inplane flow
v	vertical component of induced velocity
V	flow normal to the disk
V_∞	free-stream velocity
w	induced flow
W	inflow
x	distance on the blade from the center of the rotor
X	$=\tan\lvert\chi/2\rvert$

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α_n^m, β_n^m	induced flow expansion coefficients
η	climb rate $= v/\Omega R$
$\bar{\eta}$	ellipsoidal coordinate system component
θ	pitch angle
κ	swirl parameter = 2.2
λ	total inflow $= \eta + \nu$
Λ	Lagrange's multiplier
μ	advance ratio $= u/\Omega R$
ν	ellipsoidal coordinate or $\sqrt{1-r^2}$
$\bar{\nu}$	normalized inflow $= w/\Omega R$
ρ	density
τ_n^{mc}, τ_n^{ms}	pressure coefficients for Fourier series expansion
φ	angle between the lift and the thrust
ϕ_n^m	radial expansion shape function
Φ	pressure
χ	skew angle
ψ	angular position from rotor aft
$\bar{\psi}$	ellipsoidal coordinate
Ω	angular velocity

Introduction

Work-Energy principles indicate that the induced power P_I generated for a lifting rotor (i.e., the power that does not perform useful work) can be found by computing the shaft power and then subtracting the work done on the vehicle

$$P_I = P_S - TV - HU \qquad (1)$$

where T is the thrust perpendicular to the disk, V is the rotor velocity in the T direction, H is the rotor force in the inplane direction, and U is the rotor velocity in the H direction (See Figures 1 and 2). By necessity, the magnitude of this power must equal the power that is expended into the kinetic energy of the induced flow. It follows that simple, Glauert momentum theory can be used to compute the minimum possible induced power for a given flight condition. Based on these, one would predict that a rotating wing in forward flight would be almost as efficient as a fixed-wing aircraft. However, flight test data (as well as comprehensive simulations) give induced power several times as large as the ideal value. In an effort to determine the source of those deficiencies, Ormiston [1],[2] performed extensive runs with RCAS to try to determine why the actual results were differing from the ideal results. In these studies, the profile drag of the airfoil was assumed to be zero so that the induced power could be separated. The results of those studies similarly showed that there is an order-of-magnitude difference between ideal induced power and the actual induced power of rotorcraft. An obvious question is, "Why is there such a difference?"

Several potential sources of decreased efficiency can be identified in terms of the physics of an actual rotor as compared to an ideal actuator disk. First, an ideal disk produces thrust perpendicular to the disk whereas a true rotor produces a tilted thrust vector that results in swirl velocity. Therefore, there is lost energy. Second, an ideal rotor has an infinite number of blades whereas a true rotor has a discrete number. The fact that there are vortex sheets coming off the individual blades implies an upwash outside of the slipstream that further translates into lost energy. Third, an ideal disk can generate an arbitrary lift distribution over the span and azimuth. An actual blade, on the other hand, can only produce lift under the constraints of both allowable blade pitch changes and of the limits on airfoil lift coefficients at high angles of attack. The ultimate goal of the present research effort is to determine which of these contribute to the drastic increase in induced power and, consequently, what changes in rotor hardware (if any) might address the issue.

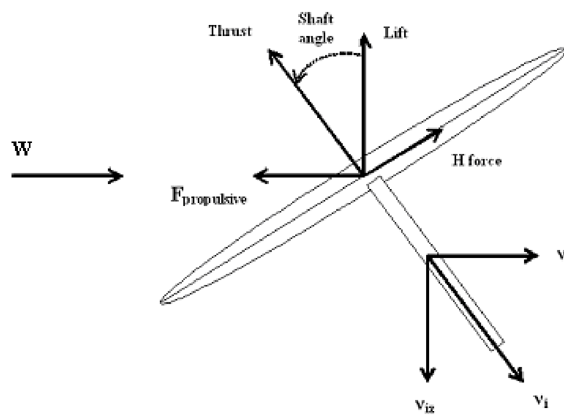

Figure 1: Basic illustrative problem for a rotor [1].

The scope of such a study is so broad that the use of large, comprehensive codes is prohibitive for these purposes. On the other hand, finite-state wake models are ideally suited to such task. These models expand both the pressure field and the velocity field in orthogonal expansion functions. Therefore, the computation of induced power (the dot product of thrust and induced flow) simplifies nicely into a quadratic cost function that allows classical optimization to be used for the minimum power under a variety of constraints. Thus, it is anticipated that such an approach can yield insight into this issue. As a preliminary step in such an endeavor, this present paper looks at the induced power of a non-ideal lifting rotor in axial flow to verify that dynamic wake models can indeed compute the proper induced power.

Since theory and experiment agree with simple momentum approaches for power in axial flow, such conditions provide the ideal test bed to verify that this optimization approach is viable. Future studies will then concentrate on induced power in forward flight.

Optimization with Finite-State Model

He inflow equations.

He [3] developed an unsteady induced-flow theory to be used in stability, vibration, control, and aeroelastic studies. The theory is based on an acceleration potential for an actuator disk. The induced flow, w, is expressed in a polynomial distribution (proportional to Legendre functions) radially and in terms of a Fourier series azimuthally. The way the induced flow is set up allows for all harmonics and describes the induced flow for any radial position.

The He theory provides the pressures on the rotor disk as a Fourier expansion. As more harmonics are added, that pressure converges to the lift concentrations on the blade and to zero lift off the blade. One of the issues to be addressed in this present work is whether or not such an approach can give adequate convergence to induced power. The form of this pressure expansion is as follows:

$$\Phi(\nu,\bar{\eta},\bar{\psi},\bar{t}) = \rho\Omega^2 R^2 \sum_{m=0}^{\infty}\sum_{n=m+1,m+3,\ldots}^{\infty} P_n^m(\nu) Q_n^m(i\bar{\eta}) \cdot\left[C_n^m(\bar{t})\cos(m\bar{\psi}) + D_n^m \sin(m\bar{\psi})\right] \quad (2)$$

The pressure at the rotor disk is obtained by the difference between the pressure above and the pressure below the disk.

$$\Delta P(\bar{r},\psi,t) = \rho\Omega^2 R^2 \sum_{m=0}^{\infty}\sum_{n=m+1,m+3,\ldots}^{\infty} \bar{P}_n^m(\nu) \cdot\left[\tau_n^{mc}(\bar{t})\cos(m\psi) + \tau_n^{ms}(\bar{t})\sin(m\psi)\right] \quad (3)$$

The power Q can be expressed as:

$$Q = \iint_A \Delta P(w+v)\, x\, dx\, d\psi \quad (4)$$

The He model also sets out the velocity field normal to the rotor disk in terms of the same Legendre Functions and variables, as given below.

$$w(\bar{r},\psi,\bar{t}) = \Omega R \sum_{m=0}^{\infty}\sum_{n=m+1,m+3,\ldots}^{\infty} \phi_n^m(\bar{r}) \cdot\left[\alpha_n^m(\bar{t})\cos(m\psi) + \beta_n^m(\bar{t})\sin(m\psi)\right] \quad (5)$$

$$\phi_n^m(\bar{r}) \equiv \frac{1}{\nu}\bar{P}_n^m(\nu) \quad (6)$$

where $\bar{t} = \Omega t$, and $\phi_n^m(\bar{r})$ are a complete set of functions that arise from the solution to Laplace's equation in ellipsoidal coordinates.

The form of the functions is:

$$\phi_n^m(\bar{r}) = \sqrt{(2n+1)H_n^m} \sum_{q=m,m+2,\ldots}^{\infty} \bar{r}^q \frac{(-1)^{(q-m)/2}(n+q)!!}{(q-m)!!(q+m)!!(n-q-1)!!} \quad (7)$$

where $H_n^m = \dfrac{(n+m-1)!!(n-m-1)!!}{(n+m)!!(n-m)!!}$

substitution of the induced flow and the pressure at the disk yields:

$$Q = \rho\Omega^3 R^5 \sum_{m,n}\int_0^{2\pi}\int_0^1\left[\lambda + \sum_{r,j}\frac{1}{\nu}\bar{P}_j^r(\nu) \cdot\left(\alpha_j^r\cos(r\psi) + \beta_j^r\sin(r\psi)\right)\right] \cdot\left[\bar{P}_n^m(\nu)\left(\tau_n^{mc}\cos(m\psi) + \tau_n^{ms}\sin(m\psi)\right)\right]\nu\, d\nu\, d\psi \quad (8)$$

$$Q = 2\pi\rho\Omega^3 R^5 \int_0^1 \sum_n\left[\lambda + \sum_j \phi_j^0\alpha_j^0\right]\bar{P}_n^0\tau_n^{0c}\nu\, d\nu + \pi\rho\Omega^3 R^5\int_0^1\sum_{m,n}\sum_j\left\{\left[\phi_j^m\alpha_j^m\right]\bar{P}_n^m\tau_n^{mc} + \left[\phi_j^m\beta_j^m\right]\bar{P}_n^m\tau_n^{ms}\right\}\nu\, d\nu \quad (9)$$

The functions P_n^m are Legendre Functions of the first kind, and ν is related to the radial position be $r = \sqrt{1-\nu^2}$.

The equations that relate the pressure coefficients in the pressure expansion (τ_n^{mc},τ_n^{ms}) to the velocity coefficients (α_j^r,β_j^r) are derived from the momentum equation of potential flow.

$$\left[K_n^m\right]\left\{\dot{\alpha}_n^m\right\} + V\left[\tilde{L}^c\right]^{-1}\left\{\alpha_n^m\right\} = \frac{1}{2}\left\{\tau_n^{mc}\right\} \quad (10)$$

$$\left[K_n^m\right]\left\{\dot{\beta}_n^m\right\} + V\left[\tilde{L}^s\right]^{-1}\left\{\beta_n^m\right\} = \frac{1}{2}\left\{\tau_n^{ms}\right\} \quad (11)$$

where $\dot{(\ )} = \dfrac{d}{d\bar{t}}$, $V = \dfrac{\mu^2 + (\lambda+\nu)\lambda}{\sqrt{\mu^2+\lambda^2}}$, λ is the total inflow, μ is the advance ratio, V is the flow parameter, and K_n^m is diagonal; $K_n^m = \dfrac{2}{\pi}H_n^m$. The $\left[\tilde{L}\right]$ cosine and sine matrices are given in closed form in terms of the wake skew angle, χ.

$$\Gamma_{jn}^{rm} = \frac{(-1)^{\frac{n+j-2r}{2}}}{\sqrt{H_n^m H_j^r}} \frac{2\sqrt{(2n+1)(2j+1)}}{(j+n)(j+n+2)\left[(j-n)^2-1\right]}$$

for r + m even

$$\Gamma_{jn}^{rm} = \frac{\pi}{2\sqrt{H_n^m H_j^r}} \frac{\operatorname{sgn}(r-m)}{\sqrt{(2n+1)(2j+1)}}$$

for r + m odd, j=n±1

$$\Gamma_{jn}^{rm} = 0$$

for r + m odd, j≠n±1

(12)

$$\begin{aligned} \left[\tilde{L}_{jn}^{0m}\right]^c &= X^m \Gamma_{jn}^{0m} \\ \left[\tilde{L}_{jn}^{rm}\right]^c &= \left[X^{|m-r|} + (-1)^l X^{|m-r|}\right]\Gamma_{jn}^{rm} \\ \left[\tilde{L}_{jn}^{rm}\right]^s &= \left[X^{|m-r|} - (-1)^l X^{|m-r|}\right]\Gamma_{jn}^{rm} \end{aligned} \tag{13}$$

where l = min(r,m), X = tan|χ/2|. The forcing functions, τ_n^m, are given in terms of the blade loading, L_q.

$$\begin{aligned} \tau_n^{0c} &= \frac{1}{2\pi}\sum_{q=1}^{Q}\left[\int_0^1 \frac{L_q}{\rho\Omega^2 R^3}\phi_n^0(\bar{r})d\bar{r}\right] \\ \tau_n^{mc} &= \frac{1}{\pi}\sum_{q=1}^{Q}\left[\int_0^1 \frac{L_q}{\rho\Omega^2 R^3}\phi_n^m(\bar{r})d\bar{r}\right]\cos(m\psi_q) \\ \tau_n^{ms} &= \frac{1}{\pi}\sum_{q=1}^{Q}\left[\int_0^1 \frac{L_q}{\rho\Omega^2 R^3}\phi_n^m(\bar{r})d\bar{r}\right]\sin(m\psi_q) \end{aligned} \tag{14}$$

Theorem on Induced Power.

A Rotor Induced-Power Theorem is used to verify the approach of this work. Let a rotor, Figure 2, be moving along an arbitrary, straight path through still air with a velocity W. Let χ be the angle between the flight path and a vertical to the rotor.

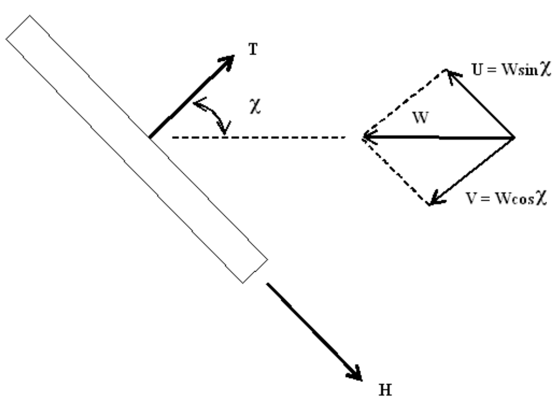

Figure 2: Inflow velocity components for a moving rotor.

It follows that the inplane component of air velocity as seen by the rotor is U = Wsinχ and the normal component is V = Wcosχ.

Let the rotor loading perpendicular to rotor plane be called T and the rotor load in plane be called H, each with a positive sense in the direction of the flight path (i.e., opposite to V and U). Let the blades in the rotor disk be rotating counter-clockwise at angular velocity Ω, when looking down on the rotor, and let ψ be the azimuth angle of a blade as measured from aft, ψ = Ωt. Let a generic point on the blade be a radial distance x from the center of rotation as shown on Figure 3.

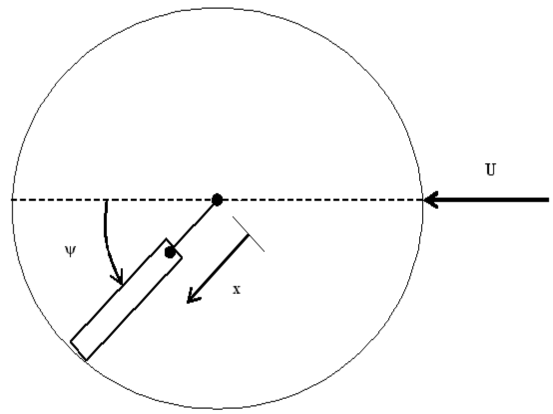

Figure 3: Rotor blade generic position and rotating angle.

Let φ be the inflow angle as seen in the local blade system, Figures 3 and 4. In that system, let dL be the incremental local lift per unit length (perpendicular to the total inflow), let dD be the incremental local induced drag per unit length, and let dT be the incremental thrust. Let w be the induced flow, opposite to L, Figure 4.

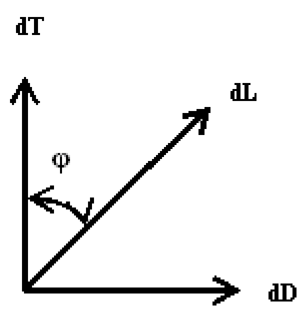

Figure 4: Geometry of the forces on the blade.

$$dT = dL\cos\varphi \tag{15}$$

$$dD = dL\sin\varphi \tag{16}$$

$$dH = -dD\sin\psi \tag{17}$$

Figure 5, taken from the work of Glauert [4], shows the geometry of the flow in the blade coordinate system. The relative flow due to rotor motion alone is Ωx +Usin(ψ) in the rotor plane and V perpendicular to that plane. The induced flow w must be parallel to the lift, so

it is added vectorally at the angle φ as shown (see Glauert). The resultant total inflow (due to rotor motion and due to induced flow) must be perpendicular to the local incremental lift, due to circulation considerations. Therefore, w can be considered perpendicular to the total flow vector. The resultant relationships gives rise to the geometry in the figure and to the following identities:

$$\tan\varphi = \frac{w\cos\varphi + V}{\Omega x - w\sin\varphi + U\sin\psi} = \frac{V + \dfrac{w}{\cos\varphi}}{\Omega x + U\sin\psi} \quad (18)$$

$$\sin\varphi = \tan\varphi\cos\varphi = \frac{V\cos\varphi + w}{\Omega x + U\sin\psi} \quad (19)$$

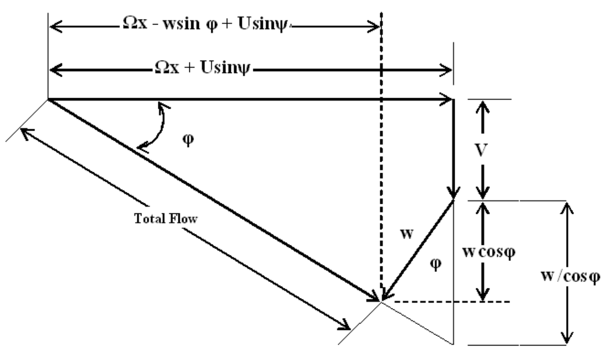

Figure 5: Geometry of the flow.

The above can be used to transform the induced power equations.

$$P_I = P_S - TV - HU \quad (1)$$

$$P_I = L\Omega x\sin\varphi - L\cos\varphi V + L\sin\varphi\sin\psi U \quad (20)$$

$$P_I = L(\Omega x + U\sin\psi)\sin\varphi - L\cos\varphi V \quad (21)$$

(where the differentials are omitted for clarity).

But $\sin\varphi = \dfrac{V\cos\varphi + w}{\Omega x + U\sin\psi}$. Therefore

$$P_I = LV\cos\varphi + L\omega - LV\cos\varphi = Lw \quad (22)$$

The induced power is, then:

$$\boxed{P_I = Lw} \quad \text{(work done by L on w)} \quad (23)$$

Thus, the incremental induced power can be found from the integral of the dot product of the local lift and local induced flow, which is the work done on the flow field. The above theorem is, strictly-speaking, exactly true only for axial flow because of the assumption that local lift is parallel to local induced flow. On the other hand, that assumption is less and less important as one transitions away from hover. Furthermore, it is exactly true that the work done on the flow field will equal the induced power. Therefore, Equation (23) seems a valid approach to computing the induced power from a dynamic wake model.

Induced power derivation from He model.

For the Peters-He model in its actuator-disk form, we have a skewed wake as shown in Figure 6 below.

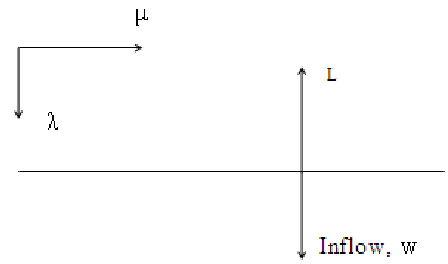

Figure 6: Normalized velocity components.

The power Q can be found from Equation (4) to be:

$$Q = \iint_A \Delta P(w+v)\,xdxd\psi$$

Notice that the power does not depend on the velocity component u. The pressure at the disk (as shown in equation (3)) is:

$$\Delta P = \rho\Omega^2R^2\sum_{m,n}\bar{P}_n^m(\nu)\left[\tau_n^{mc}\cos(m\psi) + \tau_n^{ms}\sin(m\psi)\right]$$

$$\text{Advance ratio } \mu = \frac{U}{\Omega R} \quad (24)$$

$$\text{Climb rate } \lambda = \frac{V}{\Omega R} \quad (25)$$

$$\text{Non-dimensional radial position } \bar{r} = \frac{x}{R} \quad (26)$$

$$\text{Non-dimensional inflow } \bar{v} = \frac{w}{\Omega R} \quad (27)$$

Note that rdr = -vdv, and λ and μ are constant.

The inflow is given by Equation (5).

Introducing the definitions for pressure change, v from the climb rate, and the induced velocity we obtain the expression for the power where the climb rate, λ, is a constant. The normalized Legendre function is $\bar{P}_1^0 = \sqrt{3}\nu$ by definition. Introduction of it into the expression for the power yields Equation (28). By the use of the simple relationship between power and power coefficient, we obtain the following,

$$Q = 2\pi\rho\Omega^3 R^5 \int_0^1 \sum_n \left[\lambda + \sum_j \frac{1}{\nu} \bar{P}_j^0 \alpha_j^0 \right] \bar{P}_n^0 \tau_n^{0c} \nu d\nu + \pi\rho\Omega^3 R^5 \int_0^1 \sum_{m,n} \sum_j \left\{ \left[\frac{1}{\nu} \bar{P}_j^m \alpha_j^m \right] \bar{P}_n^m \tau_n^{mc} + \left[\frac{1}{\nu} \bar{P}_j^m \beta_j^m \right] \bar{P}_n^m \tau_n^{ms} \right\} \nu d\nu \tag{28}$$

$$C_P = \frac{Q}{\pi\rho\Omega^3 R^5} = 2\left(\frac{\lambda}{\sqrt{3}} + \alpha_1^0 \right) \tau_1^{0c} + 2 \sum_{n=3,5,\ldots} \alpha_n^0 \tau_n^{0c} + \sum_{m=1,2,3,\ldots} \sum_{j=m+1,m+3,\ldots} \left[\alpha_j^m \tau_j^{mc} + \beta_j^m \tau_j^{ms} \right] \tag{29}$$

and

$$C_T = 2\{\tau_n^m\}^T \{C_n^m\} \tag{30}$$

A simple check using m = 0 only, and n = 1 only, provides the common expression that shows the Peters-He model agrees with the induced power from Momentum Theory. The lift and pressure coefficients for this special case are shown in equations (31) through (33).

$$\alpha_1^0 = \frac{1}{\sqrt{3}} \bar{\nu} \tag{31}$$

$$\tau_1^{0c} = \frac{\sqrt{3}}{2} C_T \tag{32}$$

$$C_P = \frac{2}{\sqrt{3}} (\lambda + \bar{\nu}) \frac{\sqrt{3}}{2} C_T = C_T (\lambda + \bar{\nu}) \tag{33}$$

Equations (29) and (30) provide the framework for a classical, quadratic optimization of power.

Optimization.

The classical quadratic optimization problem is stated as follows:

Minimize $\{x\}^T [A]\{x\}$ subject to $\{c\}^T \{x\} = q$ (given). Use of Lagrange's multiplier to include the constraint leads to the cost fuction.

$$J = \frac{1}{2}\{x\}^T [A]\{x\} - \Lambda\{c\}^T \{x\} \tag{34}$$

where Λ is the Lagrange multiplier. Optimizing, we obtain that for the change of the functional to be zero

$$\delta J = \{\delta x\}^T \left[\frac{1}{2}\left[A + A^T \right]\{x\} - \Lambda\{c\} \right] = 0 \tag{35}$$

$$\{x\} = \left[\frac{1}{2}\left([A] + [A]^T \right) \right]^{-1} \{c\}\Lambda \tag{36}$$

Notice that the matrix to be inverted is the symmetric part of [A].

The Lagrange multiplier must be chosen such that:

$$\Lambda = \frac{q}{2\{c\}^T \left[[A] + [A]^T \right]^{-1} \{c\}} \tag{37}$$

We may now apply this approach to the case for minimum induced power that we are presently discussing. For an actuator disk, with infinite number of blades that is lightly loaded, we will minimize C_P for a giver C_T.

$$C_P = \sum_{n=1,3,5,\ldots} 2\alpha_n^0 \tau_n^{0c} + \sum_{m=1,2,\ldots} \sum_{n=m+1,m+3,\ldots} \alpha_n^m \tau_n^{mc} \tag{38}$$

$$C_T = 2\{\tau_n^m\}^T \{C_n^m\} \tag{39}$$

Physically, the coefficients C_n^m are a Legendre-function fit to the function $\nu\cos\varphi$ and they are defined as:

$$C_n^0 = \frac{1}{2\pi} \int_0^{2\pi} \int_0^1 \cos\varphi \bar{P}_n^0(\nu) \nu d\nu d\psi \tag{40}$$

$$C_n^{mc} = \frac{1}{2\pi} \int_0^{2\pi} \int_0^1 \cos\varphi \bar{P}_n^m(\nu) \nu d\nu \cos(m\psi) d\psi \tag{41}$$

$$C_n^{ms} = \frac{1}{2\pi} \int_0^{2\pi} \int_0^1 \cos\varphi \bar{P}_n^m(\nu) \nu d\nu \sin(m\psi) d\psi \tag{42}$$

where

$$\cos\varphi = \frac{r + \mu\sin\psi}{\sqrt{(r + \mu\sin\psi)^2 + \lambda^2}} \tag{43}$$

Then, the relationship between the coefficients and the function cosφ becomes:

$$\nu\cos\varphi = \sum_n C_n^0 \bar{P}_n^0 + 2\sum_{m,n} \bar{P}_n^m \left[C_n^{mc} \cos(m\psi) + C_n^{ms} \sin(m\psi) \right] \tag{44}$$

Notice that, for axial flow, the advance ratio (μ) is zero. For an ideal actuator disk, the non-dimensional climb rate (λ) is arbitrarily small, whereas for tilted lift it will have a finite value.

From He's inflow equations (10) and (11) for an infinite number of blades, this is a steady system. Furthermore, all the coefficients associated with the sine component are zero, that is, β^m and τ^{ms} are zero.

Rearranging the equation with this in mind, it can be solved in matrix form for the induced velocity coefficients, as expressed by:

$$V\left[\tilde{L}^{c}\right]^{-1}\left\{\alpha_n^m\right\}=\frac{1}{2}\left\{\tau_n^{mc}\right\} \tag{45}$$

$$\left\{\alpha_n^m\right\}=\frac{1}{2V}\left[\tilde{L}_{nj}^{mr}\right]^{-1}\left\{\tau_j^r\right\} \tag{46}$$

Let the matrix $\tilde{L}$ with the m = 0 row partition multiplied by two will be called $\bar{\bar{L}}$. Then, the minimum induced power problem can be formulated as the optimization of a functional J, shown, subject to the constraint expressed by Equation (48). The optimization is carried out in to yield the optimum value for the pressure coefficients.

$$J=\frac{1}{2}\frac{1}{V}\left\{\tau_n^m\right\}^T\left[\bar{\bar{L}}_{nj}^{mr}\right]\left\{\tau_j^r\right\} \tag{47}$$

$$\left\{\tau_n^m\right\}^T\left\{C_n^m\right\}=\frac{\sqrt{3}}{2}C_T \tag{48}$$

$$\delta\left[J-\Lambda\left\{\tau_n^m\right\}^T\left\{C_n^m\right\}\right]=0 \tag{49}$$

$$\frac{1}{V}\left[\frac{1}{2}\left[\bar{\bar{L}}_{nj}^{rm}\right]+\frac{1}{2}\left[\bar{\bar{L}}_{nj}^{rm}\right]^T\right]\left\{\tau_n^m\right\}=\left\{C_n^m\right\}\Lambda \tag{50}$$

$$\left\{\tau_n^m\right\}_{optimal}=V\left[\frac{1}{2}\left[\bar{\bar{L}}_{nj}^{mr}\right]+\frac{1}{2}\left[\bar{\bar{L}}_{nj}^{mr}\right]^T\right]^{-1}\left\{C_n^m\right\}\Lambda \tag{51}$$

Equation (51) is the solution for this optimization problem, which will yield the minimum induced power for a lightly loaded actuator disk with infinite number of blades. In these equations Λ is the Lagrange multiplier of the optimization, that is chosen to give $\tau_1^0=\sqrt{3}/2\,C_T$, as it was explained for the constraint in the general formulation of an optimization process.

The general solution for the pressure coefficients can be applied to different cases. It is the purpose of this paper to show results for axial flow, but these coefficients can be also used to obtain pressure, circulation and inflow velocity for a variety of flows, including edgewise flow $(\chi=90^\circ)$. For axial flow, $\chi=0^\circ$, the elements in $\bar{\bar{L}}$ are zero except when r = m.

With the calculation of thrust and power coefficients, the determination of the figure of merit is simple. The general solution for the figure of merit that will be shown by the use of finite-state methods is:

$$K=F.M._{finite-state}=2\left\{C_n^m\right\}^T\left[\bar{\bar{L}}\right]^{-1}\left\{C_n^m\right\} \tag{52}$$

The conditions for each of the special cases will cause the coefficient vector or the L-matrix to change, but the general form will remain for all of the cases.

Special Case of Actuator Disk

For the case of an actuator disk Equation (43) reduces to the unity (λ = 0) and the coefficients in Equations 40 through 42 reduce to:

$$C_1^0=\int_0^1\sqrt{3}\nu\,d\nu=\frac{1}{\sqrt{3}}$$

and all the others become:

$$C_n^m=0$$

Therefore, the vector $\left\{C_n^m\right\}$ is the vector $\{1\ 0\ 0\ \ldots\ 0\}^T$ with as many elements as the number of terms that correspond to the harmonics studied in the problem and the optimization becomes simplified.

Momentum theory [5],[6] predicts that the minimum induced power for an actuator disk in axial flow will be achieved by constant pressure and constant inflow distributions. Results using the finite-state method show agreement with these predictions. Figures 7 and 8 show the constant profile for the pressure and the inflow respectively with a reduced amount of terms in the Fourier series. According to Momentum theory the lift distribution corresponding to this pressure and velocity should be linear. Finite-state methods agree with the predicted results, as it is shown in Figure 9.

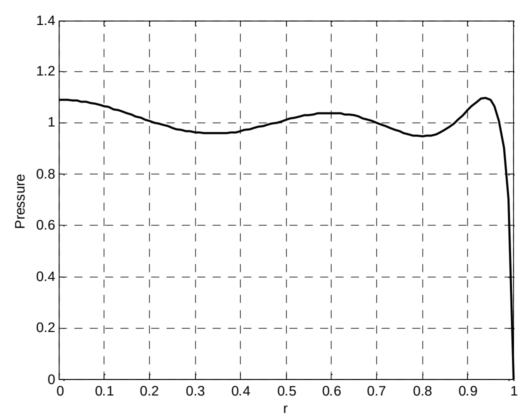

Figure 7: Pressure profile that provides minimum induced power for an actuator disk in axial flow with an infinite number of blades.

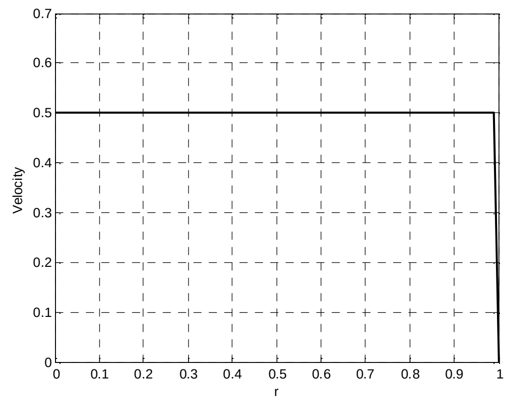

Figure 8: Velocity profile that provides minimum induced power for an actuator disk in axial flow with an infinite number of blades.

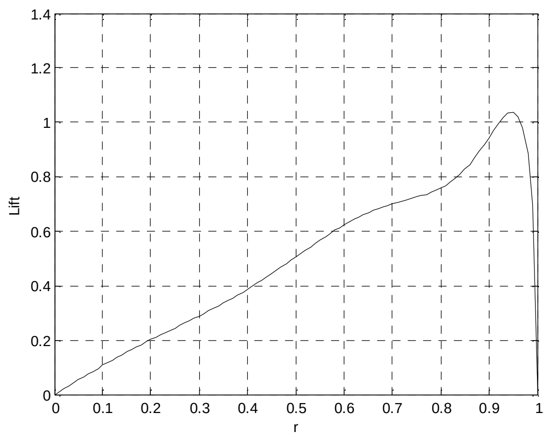

Figure 9: Lift distribution for optimum flow for an actuator disk with an infinite number of blades.

Closed-Form Expression.

Since the above shows that a formal optimization with the dynamic wake model gives the Glauert result for minimum power, it seems that it would be useful to consider some closed-form results under the Glauert hypothesis. From momentum theory [5],[6], one can show that

$$C_T = 2(\eta + \nu)\nu \tag{53}$$

$$C_P = 2(\eta + \nu)^2 \nu = (\eta + \nu) C_T \tag{54}$$

Because we optimize for a given C_T, it is very convenient to normalize all velocities on induced flow in hover. Thus, $\bar{\eta} = \eta / \sqrt{C_T / 2}$, $\bar{\nu} = \nu / \sqrt{C_T / 2}$, $\bar{\lambda} = \bar{\eta} + \bar{\nu}$. It follows that the proper normalization of induced power is

$$\bar{C}_P = \frac{\sqrt{2} C_P}{C_T^{3/2}} \tag{55}$$

The result is a normalized set of inflow equations. The thrust equation becomes:

$$1 = (\bar{\eta} + \bar{\nu})\bar{\nu} \tag{56}$$

which can be solved for normalized or flow due to a normalized climb rate. That value can then be used to determine the normalized induced power for an ideal actuator-disk rotor.

$$\bar{C}_{P_I} = \bar{C}_P - \bar{\eta} = \left[\frac{\bar{\eta}}{2} + \left(\frac{\bar{\eta}^2}{4} + 1 \right)^{1/2} \right]^{-1} \tag{57}$$

One can see that the ideal induced power ranges from a normalized value of unity in hover $(\bar{\eta} = 0)$ and then decreases with climb rate as $1/\bar{\eta}$. This is the Glauert result. We will use this ideal value to compare minimum power settings for various rotors. We will define a generalized figure of merit which is the ideal power, Equation (52), divided by the actual induced power.

Special Case of Lifting Rotor with an Infinite Number of Blades.

When the lift vector is tilted perpendicular to the vortex sheets, the ideal power is no longer attainable. Thus, uniform flow is no longer the optimum condition. Betz [7] determined that the minimum power is obtained when the induced flow at the individual blades is such that the vortex sheet remains along a helical path. Thus, the optimum inflow distribution is proportional to cosφ, Figure 5. For an infinite number of blades, it follows that the pressure field must follow this same shape. Thus, let the optimum pressure at the rotor be:

$$\Delta P = \frac{\Lambda V}{2} \cos\varphi = \frac{\Lambda V}{2} \frac{r}{\sqrt{r^2 + \lambda^2}} \tag{58}$$

where k is a Lagrange multiplier. Then the induced velocity, w is:

$$w = \frac{1}{2V} \Delta P = \frac{\Lambda}{4} \frac{r}{\sqrt{r^2 + \lambda^2}} \tag{59}$$

The thrust coefficient is :

$$C_T = 2\int_0^1 \Delta P \cos\varphi r dr = \Lambda V \int_0^1 \frac{r^3}{r^2 + \lambda^2} dr \tag{60}$$

dividing both sides by C_T, introducing the normalized values $\bar{\Lambda} = \frac{\Lambda}{\sqrt{C_T / 2}}$ and $\bar{V} = \frac{V}{\sqrt{C_T / 2}}$, and letting $y \equiv r / \lambda$ we obtain an expression that can be integrated to obtain a solution in closed form.

$$1 = \frac{\bar{\Lambda}\bar{V}}{2} \lambda^2 \int_0^{1/\lambda} \frac{y^3}{1 + y^3} dy \tag{61}$$

performing the integration on Equation (61) gives the value of the normalized Lagrange multiplier to be:

$$\overline{\Lambda} = \frac{4}{\overline{V}} \frac{1}{1-\lambda^2 \ln\left(1+\frac{1}{\lambda^2}\right)} \qquad (62)$$

To obtain the induced power coefficient, we must consider the power.

$$C_P = 2\int_0^1 \Delta P w r dr = \frac{\Lambda^2 V}{4}\int_0^1 \frac{r^3}{r^2+\lambda^2} dr \qquad (63)$$

Then, the normalized power coefficient is:

$\overline{C}_{P_i} = \frac{C_P}{2(C_T/2)^{3/2}}$, which provides the final expression for the normalized induced power.

$$\overline{C}_{P_i} = \frac{\overline{\Lambda}}{4} = \frac{1}{\overline{V}} \frac{1}{1-\lambda^2 \ln\left(1+\frac{1}{\lambda^2}\right)} \qquad (64)$$

For axial flow, $\overline{V} = \overline{\lambda} = \overline{\eta} + \overline{v} = \frac{\overline{\eta}}{2} + \sqrt{\frac{\overline{\eta}^2}{4}+1}$.

The result of this closed-form solution yields the expression for the ideal figure of merit for a lifting rotor with an infinite number of blades. Rearranging the previous equations, one obtains:

$$K = F.M._{Betz} = 1-\lambda^2 \ln\left(1+\frac{1}{\lambda^2}\right) \qquad (65)$$

The question remains if the use of finite-state methods will suffice to obtain the Betz distribution for a lifting rotor with an infinite number of blades. To verify this, the figure of merit is found by finite-state methods using the formulation described in the optimization section. These coefficients represent the general solution. To customize them to the present special case, some modifications were performed. Since the present cases are for axial flow, the matrix $\left[\overline{\overline{L}}\right]$ — defined by Equation (13) — simplifies to a diagonal in terms of Γ_{jn}^{mm}. It should be noted that these matrices are identical to $\left[A_{nj}^m\right]$ in Ref. 3. For an infinite number of blades in axial flow, $C_n^m = 0$ except when m = 0 so that only A_{jn}^0 enters the optimization. C_n^0 comes from the following integral over the wake skew angle,

$$C_n^0 = \frac{1}{2\pi}\int_0^{2\pi}\int_0^1 \cos\varphi \overline{P}_n^0(\nu)\nu d\nu d\psi$$

where $\cos\varphi = \frac{r}{\sqrt{r^2+\lambda^2}}$ and $rdr = -\nu d\nu$. With those C_n the thrust and power coefficients become:

$$C_T = 2\sum_{n=1,3,5} C_n \tau_n^{0c} \qquad (66)$$

$$C_P = \eta C_T + \sum_{n=1,3,5} 2\alpha_n^0 \tau_n^{0c} \qquad (67)$$

For this optimization, again the power coefficient is minimized for constant thrust, and the functional J becomes:

$$J = \eta C_T + \sum_{n=1,3,5,...} \frac{1}{2V}\left\{\tau_n^{0c}\right\}^T \left[A_{nj}^0\right]\left\{\tau_j^{0c}\right\} - \Lambda \sum_{n=1,3,5,...} C_n \tau_n^{0c} \qquad (68)$$

where Λ is the Lagrange multiplier. Performing the optimization (δJ = 0), the optimal pressure coefficients for this particular case are:

$$\left\{\tau_j^0\right\}_{optimal} = \left[A_{nj}^0\right]^{-1}\left\{C_n\right\}\Lambda V \qquad (69)$$

Introducing the above changes to the general optimization formulation, the figure of merit using finite-state methods is:

$$F.M._{finite-state} = 2\left\{C_n\right\}^T \left[A_{nj}^0\right]^{-1}\left\{C_n\right\} \qquad (70)$$

Figure 10 shows the comparison for the figure of merit from the finite-state method as compared to the Betz formula. It is seen that the finite-state method agrees satisfactorily with Betz result. The difference between them can be reduced by addition of more terms to $\left[A_{nj}^0\right]$ and {C_n}. However, the present approximation, which uses twenty terms is thought to be close enough so that the dynamic inflow model is verified.

What is most important about Figure 10 is the large drop in figure of merit with climb rate, even for an optimized rotor. The drop is due purely to the effects of tilted lift and swirl velocity. It may well be that the deficiency in rotor efficiency in forward flight is due to a similar phenomenon.

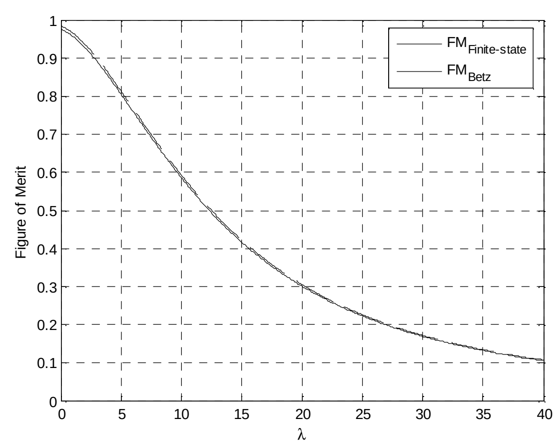

Figure 10: Comparison of the finite-state optimization to Betz distribution.

Figure 11 gives Figure of Merit as a function of climb rate η rather than λ. Since λ is determined by the total flow through the rotor, the Figure of Merit thus becomes a function both of climb rate η and thrust coefficient C_T. For larger climb rate, the effect of C_T is diminished.

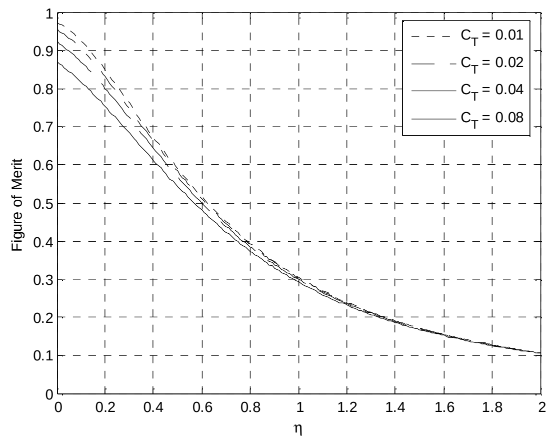

Figure 11: Figure of Merit versus climb rate for different thrust coefficients (infinite number of blades).

Figure 12 presents the induced power coefficient as a function of climb rate for a range of C_T values.

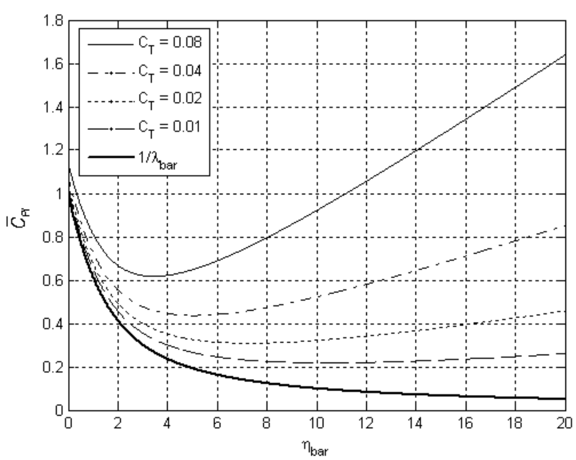

Figure 12: Induced power coefficient (helicopter convention) versus climb rate (infinite number of blades)

An important characteristic seen in Figure 12 is a "bucket" in the induced power for each thrust coefficient at a given climb rate. This is due to the fact that ideal power decreases with η whereas the figure of merit also decreases with η. Thus, there is an optimum climb rate. The lowest curve is for $C_T = 0$ and is equal to $1/\lambda_{bar}$. This ideal minimum power monotonically decreases with $\bar{\eta}$, so the "bucket" is not present, and the induced power coefficient does not increase for high climb rates.

Special Case of Finite Number of Blades.

The effect of a finite number of blades is a further loss in wake energy due to the individual vortex sheets from each blade. Goldstein worked out the exact effect for optimized rotors. Prandtl, on the other hand, worked out an approximate correction factor that agrees very well with Goldstein for moderate climb rates. Prandtl [5],[6],[7] introduces a correction factor, k, in the calculation of induced flow that accounts for the loss at the tip of the blades. Because of this tip loss, for a given thrust, there is more induced flow than predicted by momentum theory. Using these principles an approximation to the theoretical figure of merit for an actuator disk or a lifting rotor for a finite number of blades can be obtained using Prandtl formulation. The Prandtl k factor is applied as follows.

$$dL = (2\pi r dr)\rho(V+v)(2v)k \tag{71}$$

where

$$k = \frac{2}{\pi}\cos^{-1}\left[\exp\left(\frac{-Q(1-r)}{2\lambda}\right)\right] \tag{72}$$

where Q is the number of blades.

Because the Prandtl correction as applied to the Betz distribution agrees so closely with Goldstein, that it makes sense to do some calculations with the Prandtl factor to determine the magnitude of the effect of number of blades on figure of merit. Thus, the following formula can be used for the figure of merit computations.

$$K = F.M._{\text{Prandtl}} = 2\int_0^1 k\cos^2\varphi r dr \tag{73}$$

where,

$$\cos\varphi = \frac{r}{\sqrt{r^2+\lambda^2}} \tag{74}$$

where λ is the climb rate and φ is the inflow angle.

Figure (13) shows the effect of tip loss (as determined from Prandtl's k-factor) on Figure of Merit. The top curve, for the case φ = 0, is the effect for an actuator disk with a finite number of blades for a four-bladed, lightly loaded rotor. The middle two, coincident curves are the figure of merit for a rotor with tilted lift but infinite number of blades. The lowest curve is for tilted lift and finite number of blades (i.e., the Goldstein solution). One can see that blade number is also an important factor in the loss of ideal induced power.

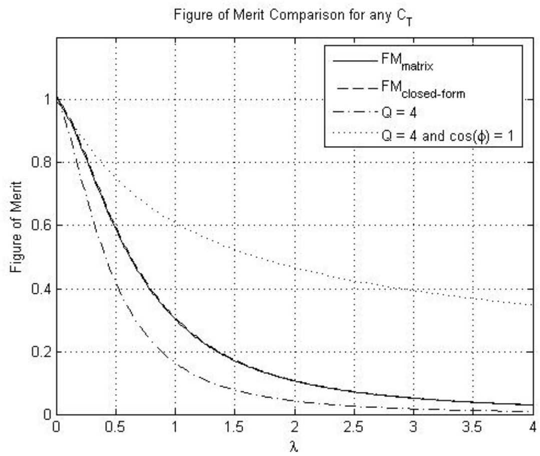

Figure 13: Effect of Tip Loss on Figure of Merit, Lightly-Loaded Rotor.

We now wish to see if the finite-state methodology can give the correct optimum distribution and figure of merit as Goldstein (i.e., as the Prandtl-corrected Betz). Makinen, [8],[9] showed that the inflow model can indeed match Goldstein provided that a correction is applied for the swirl kinetic energy. Thus, the added energy is added to the mass matrix; and the resultant induced flow is assumed parallel to the tilted lift vectors.

To be precise, the apparent mass matrix $\left[K_n^m\right]$ (diagonal), must be replaced to include the effect of the wake swirl. There are different swirl corrections that can be applied, but from Ref. 8 the following correction gives the best results.

$$\left[K_n^m\right] \Rightarrow \left[\sqrt{K_n^m}\right]\left[\left[I\right]+m\left(\frac{\kappa\lambda}{Q}\right)^2\left[\left[I\right]-\left[A_{nj}^m\right]^2\right]^{-m}\right]\left[\sqrt{K_n^m}\right] \tag{75}$$

where κ =2.2, Q is the number of blades, and λ is the total inflow. It should be noted that for an actuator disk (no lift tilt), κ is set to zero.

When the dynamics of the unsteady blade-passage is added to the dynamic wake model, (see Ref. 8) shows that the $\tilde{L}$ used in axial flow, $\left[A_{nj}^0\right]$, is replaced by the following.

$$\left[\tilde{L}\right]=\left[A_{nj}^0\right]+ 2\sum_{m=Q,2Q,3Q,\ldots}\left[E_{nj}^{m0}\right]^T\left[\left[A_{nj}^m\right]^{-1}+\left(\frac{m}{\lambda}\right)^2\left[K_n^m\right]\left[A_{nj}^m\right]\left[K_n^m\right]\right]^{-1}\left[E_{nj}^{m0}\right] \tag{76}$$

The $\left[E_{nj}^{m0}\right]$ matrix is the expansion transformation matrix (Ref. 8) defined as:

$$E_{nj}^{m0}=\int_0^1 \bar{P}_n^m(\nu)\bar{P}_j^0(\nu)\,d\nu \tag{77}$$

Performing the optimization for this case, and using finite-state methods, the figure of merit is obtained. The $\left\{C_n^m\right\}$ remains the same as for an infinite number of blades. There is no change in the values because physically these coefficients are a fit of the function $\nu\cos\varphi$, and for an actuator disk $\cos\varphi=1$.

$$K=F.M._{finite-state}=2\left\{C_n^m\right\}^T\left[\tilde{L}\right]^{-1}\left\{C_n^m\right\} \tag{78}$$

Once the theory has been verified, some useful plots of induced power for different numbers of blades at various climb rates can be obtained, as it is shown in Figure 14. The importance of this graph is that the effect of finite number of blades on the induced power can be noticed. It is seen that induced power increases for a decreasing number of blades. It is an expected result, as the ideal induced power exists for an infinite number of blades (for Prandtl is k = 1). The profile of the curves is similar to the one observed for infinite numbers of blades at different thrust coefficients. The "bucket" effect is present here also, and the general profile is maintained. Thus, the effect of these differences for finite number of blades affecting the induced power is as less critical as the increase in induced power due to lift tilt.

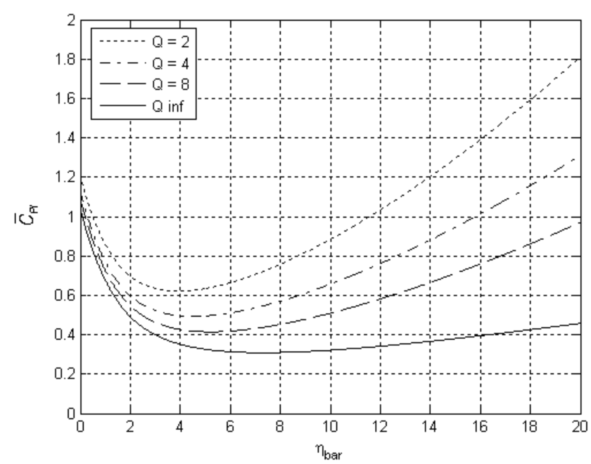

Figure 14: Induced power coefficient comparison for various numbers of blades. C_T = 0.02.

Finite-State methods should agree with the theory developed by Goldstein [10] for every flight condition in axial flow. There is no closed-form solution or expression that Goldstein developed for the theoretical figure of merit for a lifting rotor with a finite number of blades. However, Makinen [8],[9] was successful in the further development and application of the finite-state method to obtain circulation for a given induced velocity. These circulation results are in agreement with

Goldstein's circulation for an optimal propeller, as it is shown in Figures 15 and 16. The fact that the application of finite-state methods provides an accurate optimal circulation results in the confidence that the calculations of figure of merit for this special case will also be accurate.

Figures 15 and 16 show the circulation at any radial position of the blade using Prandtl's approximation, Goldstein's optimal circulation, and Makinen's results with the swirl velocity corrections made to the apparent mass matrix in Equation (75). Figure 15 is for a $\mu_0 = 5$ ($\lambda = 0.20$) and Figure 16 is for $\mu_0 = 20$ ($\lambda = 0.05$). It is noticed that Prandt and Goldstein's circulations give results that are very close to each other. Since there is such close agreement in both approaches, and there is a figure of merit expression for Prandt's approximation, the finite-state approach could be comparabe to Prandtl's approximation.

It is not surprising that the quadratic optimization with the dynamic wake model gives the correct figure of merit due to both lift tilt and finite number of blades. Figures 15 and 16 (from Ref. 8) show that the dynamic wake model (with swirl correction) gives the correct inboard (swirl) and outboard (tip loss) velocities.

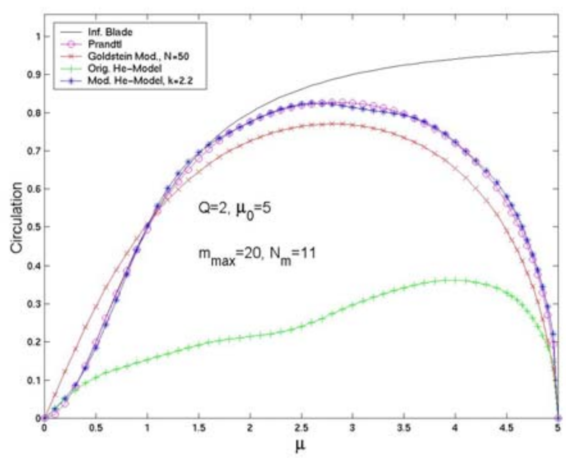

Figure 15: Circulation at any blade radial location for Prandtl, Goldstein, and using Finite-State methods. Plot obtained from [8],[9].

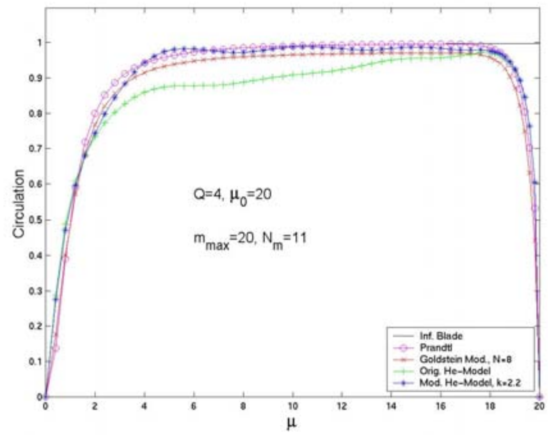

Figure 16: Circulation at any blade radial location for Prandtl, Goldstein, and using Finite-State methods. Plot obtained from [8],[9].

Future Work

Since the method has been validated, the theory can be applied to the same cases for skewed flow. Most of the approach for skewed flow is similar to that for axial flow. The case for an actuator disk with an infinite number of blades will be revisited. However some changes will be done for forward flight. For this case, momentum theory predicts that the optimum induced power is obtained for a constant pressure distribution (similarly as to what happened for axial flow) but the induced velocity profile will no longer be constant. For an actuator disk with an infinite number of blades, we have already applied the finite-state model and verified that it gives the Glauert solution of uniform pressure. However, to go on to the other cases, all harmonics (and their periodic coupling) will need to be included. The rest of the special cases, for an actuator disk with a finite number of blades and for the two cases for a lifting rotor, will provide results never obtained before. The results will hopefully provide the conclusion as to why the experimental minimum induced power for a helicopter is orders of magnitude greater to what theory predicts should be. These results could allow determining what changes, if any, should be introduced in the rotor to reduce the minimum induced power.

The formulation for the figure of merit in forward flight will remain similar to the general figure of merit shown by Equation (52):

$$K = F.M._{finite-state} = 2\left\{C_n^m\right\}^T \left[\bar{\bar{L}}\right]^{-1} \left\{C_n^m\right\}$$

However, the coefficients and the L-matrix will be different than the ones obtained before, and also different for each of the four cases.

The main difference for skewed flow is that when calculating the cosine of the inflow angle the advance ratio, μ, must be considered. Equation (43) again is:

$$\cos\varphi = \frac{r+\mu\sin\psi}{\sqrt{(r+\mu\sin\psi)^2+\lambda^2}}$$

where r is the radial position along the blade and ψ is the angle at which the rotating blade is with respect to the aft position of the rotor.

For skewed flow, the total inflow also changes. The total inflow for axial flow was defined before as:

$$\bar{\lambda} = \bar{\eta} + \bar{v} = \frac{\bar{\eta}}{2} + \sqrt{\frac{\bar{\eta}^2}{4}+1}$$

and it was derived from momentum theory for a uniform induced flow distribution. In forward flight, the total inflow becomes:

$$\bar{\lambda} = \bar{\eta} + \bar{v} \qquad (79)$$

where the normalized inflow is the solution of Equation (80) for given normalized climb rate and advance ratio.

$$1 = \bar{v}\sqrt{\bar{\mu}^2 + (\bar{v}+\bar{\eta})^2} \qquad (80)$$

These changes will affect the optimum coefficients, but the L-matrix will also be altered because the skew angle is no longer zero, and so there are more harmonics than the m = 0 for axial flow. The expression for this matrix will be obtained using He's formulation (Equations (13)).

With the results in forward flight, the study of minimum induced power will be complete for any flight condition.

Conclusions

The objective of this paper is to validate the use of finite-state methods to obtain accurate minimum induced power results. The theory is validated by the comparison to classical solutions for the figure of merit. The results compare favorably for a variety of flight regimes in axial flow. The current method was verified for: 1) an actuator disk with an infinite number of blades, which was in agreement with the predictions made by momentum theory; 2) for an actuator disk with a finite number of blades, which proves similar results as to the ones obtained by Prandtl; 3) for a lifting rotor with an infinite number of blades, which agrees with Betz's distribution; and 4) for a lifting rotor with a finite number of blades, which should agree with Goldstein's solution, but was compared to Prandtl's approximation modified to include a finite number of blades.

Because the method has been validated for all the cases in axial flow, it is hopeful that the formulation can be used to obtain results for skewed flow in all four special cases. These will result in the fulfillment of the complete scope of flight conditions for a helicopter, and will provide a greater understanding on what the requirements are for minimum induced power conditions.

Also, because of the results obtained by Ormiston [1],[2], a conclusion as to what makes the induced power to increase well above ideal values should be found. These studies will determine which of the three main causes for the increment of induced power is the most important: the fact that a real rotor has a finite number of blades, the limitations in lifting capabilities of the blades as airfoils, or the tilted thrust that produces swirl velocity.

Acknowledgements

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Addendum

Equations (52), (65), (73), and (78) give formulae for Figure of Merit for a lightly-loaded rotor. Thus, to be precise, they are actually formulae for thrust deficiency K. This thrust deficiency is a function of λ, the flow rate. In order to extend these formulae to apply to rotors with significant loading (i.e., ν not small relative to η) one must correct for the lift deficiency in the momentum equation (54). This is done as follows.

First, λ is computed without thrust deficiency

$$\lambda = \frac{\eta}{2} + \sqrt{\left(\frac{\eta}{2}\right)^2 + \frac{C_T}{2}}$$

and this λ is used to compute the thrust deficiency K. Next, K is used in the momentum theory to compute Figure of Merit.

$$F.M.\big|_{lightly-loaded} = \frac{K\left[\frac{\eta}{2} + \sqrt{\left(\frac{\eta}{2}\right)^2 + \frac{C_T}{2}}\right]}{\left[\frac{\eta}{2} + \sqrt{\left(\frac{\eta}{2}\right)^2 + \frac{C_T}{2K}}\right]} \tag{81}$$

For lightly loaded, $\eta^2 \gg 2C_T$, this reverts to F.M. = K. For hover, $\eta = 0$, this reduces to

$$F.M.\big|_{hover} = K^{3/2}$$

Thus, Equation (81) is the Figure of Merit for full loading.

REAL WORLD SAFETY BENEFITS OF BRAKE ASSISTANCE SYSTEMS

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ABSTRACT

The first brake assist system (BAS) was developed by Mercedes-Benz and introduced in 1996. It has been a standard feature on all Mercedes-Benz passenger cars since 1997. Recent statistical analyses of German accident data show significant safety benefits of this technology: Both the percentage of severe accidents involving pedestrians as well as the rate of rear end collisions are lower for vehicles equipped with BAS than vehicles without BAS. The conventional brake assist (BAS) is now completed by radar based adaptive brake assistance functions (BAS PLUS and PRE-SAFE® Brake) which have demonstrated their benefits both in internal and external tests.

FOCUSSING ON REAR-END COLLISIONS

The European Commission has set an ambitious goal for road safety in Europe: The road safety action programme aims at reducing the number of fatalities by 50% in the period from 2000 to 2010. The interim result for Germany is promising: Between 2000 and 2005, the number of fatalities was reduced by 29% in spite of a fleet increase of 6%. The last decade has seen a decrease in fatalities of 43% in Germany. While these improvements can be attributed to a variety of factors, advanced vehicle safety technology certainly plays a major role.

Having addressed the problem of loss of control-accidents very successfully by the introduction of ESP® [1], [2] which has been a standard feature in all passenger vehicles since 1999, Mercedes-Benz safety engineering focuses on avoiding and mitigating rear-end collisions. In Germany all accidents caused by conflicts between road users moving into the same or in the opposite direction („Unfall im Längsverkehr“) accounted for 21 percent of all fatalities and 17 percent of all severe injuries in 2005. In this category, collisions with another vehicle or with an obstacle on the road accounted for 470 fatalities and 8.611 severely injured persons [3].

The following main causal factors for these accidents are derived from in-depth accident analyses:

- Driver’s braking reaction comes too late.
- Driver’s braking reaction is not vigorous enough.
- Misinterpretation of the traffic situation by the driver, especially regarding the deceleration of the preceding vehicle

BRAKE ASSIST (BAS)

Function

It was in the early 1990s that Mercedes engineers conducting tests in the driving simulator found that while the majority of male and female drivers operate the brake pedal rapidly in an emergency situation, they often do not do so with sufficient force. The technical braking performance is therefore not used to the full, and the braking distance is considerably increased. These findings led to the development of the Brake Assist System (BAS) which supports drivers who apply the brake pedal quickly but not vigorously enough by directing maximum power assist to the brakes in emergency situations [4].

The system uses pedal application speed as an indicator for emergency situations. If an unusually high pedal speed is registered, the system infers an emergency braking situation and automatically increases the pressure in the wheel brake cylinders (see Figure 1). During this automatic full-force braking, wheel lock is prevented by ABS. If the driver takes his foot off the brake pedal, the automatic brake boosting is immediately terminated.

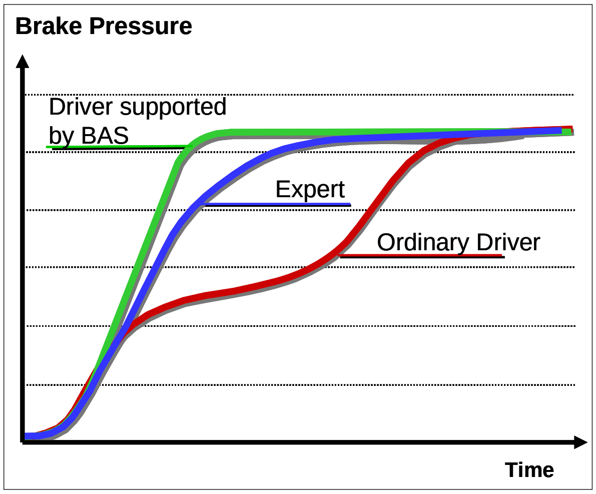

Figure 1. Illustration of typical brake pressure build-up in an emergency situation for ordinary drivers, driving experts and drivers supported by Brake Assist System (BAS).

This assistance system was invented by Mercedes-Benz, first introduced in 1996 and became a standard feature in all Mercedes-Benz passenger cars in 1997.

Benefits for Pedestrian Protection

Tests with ordinary drivers on a test track demonstrated that BAS contributes to a significant reduction in stopping distance by up to 45 percent on a dry road surface. In addition, tests in the Berlin dynamic driving simulator showed that this system is also a valuable contribution to pedestrian protection [5]: In a typical accident scenario, i.e. a child suddenly crossing the street in an urban area, the accident rate was significantly lower for subjects who drove with BAS (accident rate 32 percent) vs. subjects who did not have this assistance system (accident rate 58 percent).

Analysis of German Accident Data

The Federal Statistical Office Germany collects and processes data from all traffic accidents registered by the German police (e.g. 2.25 million accidents recorded in 2005). Since 1999 DaimlerChrysler annually obtains an anonymous sample of these accident data. Each sample contains 50% of all accidents with a certain severity (fine, injury) from the respective last two years. Among other variables, the samples contain data on accident type, year of the vehicle registration, vehicle category, model information for vehicles of DaimlerChrysler AG brands only, and classes of weight-to-power ratio for other brand models. The time of the accident is defined by the period of the samples. Each sample consists of more than 500.000 cases from the respective last two accident years. Hence, the annually obtained samples are overlapping regarding the accident year (e.g. the sample obtained in 2001 consists of accidents occurred in the years 1999 and 2000).

<u>Pedestrian Protection</u> The percentage of severe accidents (accidents involving fatalities or severe injuries) of all accidents involving pedestrians was calculated for vehicles registered between 1995 and 1997 vs. vehicles registered between 1998 and 2000. This percentage remains constant for competitors' vehicles but decreases for newer MB-vehicles which were all fitted with BAS as a standard feature (see Figure 2).

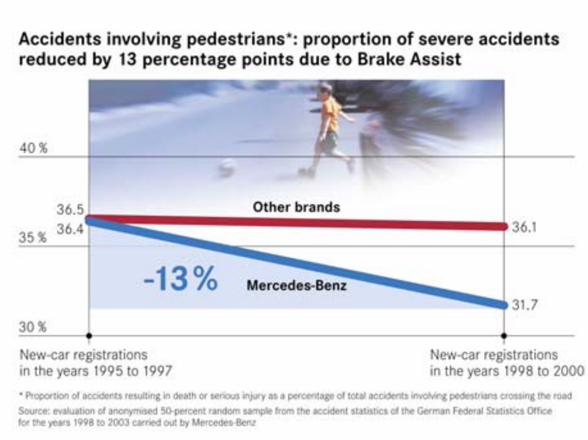

Figure 2. Fewer severe accidents for vehicles equipped with Brake Assist System (BAS)

__Rear-End Collisions__ – The rate of rear-end collisions caused per 10.000 newly registered vehicles was calculated for vehicles registered in 1996-1997 which were involved in an accident in 1998 or 1999 and compared to the rate for vehicles registered 1997-1998 which were involved in an accident in 1999 or 2000 (see Figure 3). Whereas this rate remains constant fort he other brands, it shows a reduction for Mercedes-Benz passenger cars which is mainly attributed to the presence of BAS in Mercedes-Benz cars registered 1997-1998 (BAS was made standard in 1997).

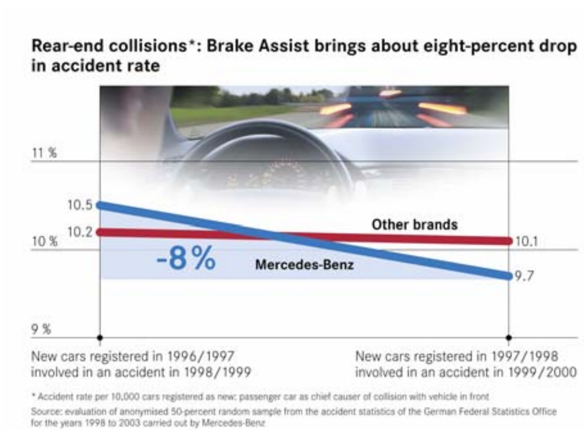

Figure 3. Newer Mercedes-Benz vehicles (equipped with BAS as standard feature) cause less rear-end collisions

ADAPTIVE BRAKE ASSISTANCE FUNCTIONS

Brake Assist PLUS

For the new S- and CL-Class, Mercedes-Benz has expanded Brake Assist into a preventive system which assists the driver even more effectively than before in critical situations. The Brake Assist PLUS system is based on radar technology: it registers the distance from detected vehicles ahead, warns the driver if the gap is too small and calculates the necessary brake force assistance if a rear-end collision threatens. If traffic tails back and the driver is obliged to operate the brake pedal, the new Brake Assist PLUS instantly builds up the braking pressure required to manage the situation.

While reflex-like operation of the brake pedal is necessary to activate the conventional Brake Assist System (BAS, which is still a part of the standard equipment), the new system already detects the driver's braking intention when the pedal is depressed and automatically optimises the brake pressure. This meets one of the major conditions for preventing rear-end collisions, namely the best possible deceleration for the situation in hand.

Preventive Brake Assist PLUS uses two radar systems to monitor the traffic situation ahead of the vehicle: a newly developed short-range radar based on 24-Gigahertz technology works together with the 77-Gigahertz radar of the DISTRONIC PLUS adaptive cruise control system. These systems complement each other: while the DISTRONIC radar is configured to monitor three lanes of a motorway to a range of up to 150 metres with a spread of nine degrees, the new 24-Gigahertz radar registers the situation immediately ahead of the vehicle with a spread of 80 degrees and a range of 30 metres.

Mercedes-Benz has intensively tested the effectiveness of this technology in the driving simulator and in practical trials: 110 male and female drivers took part in a series of tests in the driving simulator. They each had to cope with several typical critical situations on motorways and country roads derived from accident research. It was only possible to avoid accidents by hard braking. Thanks to the new Brake Assist PLUS system, the accident rate during this test series fell by three quarters compared to the average of 44 percent with conventional brake technology only (see Figure 4).

The new technology demonstrated its advantages particularly well when driving in a line of traffic at 80 km/h on a country road: when the vehicle ahead was suddenly braked, the radar-based Brake Assist system prevented an accident in 93 percent of cases – while more than one in two test drives ended in a rear-end collision without the system. Even in situations where a collision was unavoidable owing to a late response by the driver, the new system helped to reduce the severity of the impact. This was confirmed by the measured impact speed, which was reduced from an average of 47 to 26 kph thanks to Brake Assist PLUS.

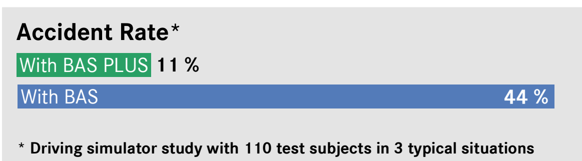

Figure 4. Results of dynamic driving simulator tests with 110 ordinary drivers: Accident Rate in 3 typical driving scenarios with high danger of rear-end collision

PRE-SAFE® Brake

Brake Assist PLUS is complemented by the system PRE-SAFE® Brake which goes one step further: If the driver does not react to the BAS PLUS warnings from the cockpit and the system detects a severe danger of an accident, the system triggers automatic partial braking and decelerates at up to 0.4 *g*. Autonomous partial braking provides the driver with a further clear prompt to take action, on top of the visual and audible warnings. If the driver immediately goes on to activate the brake, maximum braking force will be provided by BAS PLUS, and – depending on the given situation – it may be possible to prevent the accident at the last moment. If this is not possible, the PRE-SAFE® Brake system reduces the severity of the impact, which in turn reduces the risk of injury for the occupants of the car.

Since practice shows that drivers do not always react as quickly as is needed at critical moments – for example because they are distracted and fail to register the warning signals provided by Brake Assist PLUS, the newly developed PRE-SAFE® Brake intervenes in situations such as these, automatically braking if an acute danger of an accident is detected. The following timeline represents a typical rear-end collision situation:

- Around 2.6 seconds before the moment of impact calculated by the system the audible warning signal sounds. A red warning symbol in the instrument cluster also informs the driver that there is a danger of an accident.
- Approximately 1.6 seconds before the calculated accident – if the driver has not reacted to the warnings, the PRE-SAFE® Brake system activates autonomous partial braking.
- Around 0.6 seconds before the impact the driver has a final chance to avert the accident by swerving rapidly or applying full braking. This means that, after the PRE-SAFE® brake has intervened, the driver has around a second to act.

To assess the benefits of the new system 70 drivers took part in tests in the dynamic driving simulator in Berlin. The scenario involved the participants being deliberately distracted by an accident on the opposite driving lane while the queue of traffic in front suddenly braked at the same instant (see Figure 5).

Figure 5. Driving scenario used in dynamic driving simulator tests to deliberately distract subjects from primary driving task (car following scenario)

The results of the test, which reflects a real world situation, document the safety benefits offered by the radar based assistance systems: thanks to the rapid reactions of the drivers, and support from BAS PLUS and the PRE-SAFE® brake, a total of 70 percent of these test drives remained accident-free. In one third of the simulator tests the participants were unable to prevent a collision. Here automatic partial braking succeeded in reducing the severity of the accident by around 40 percent (see Figure 6).

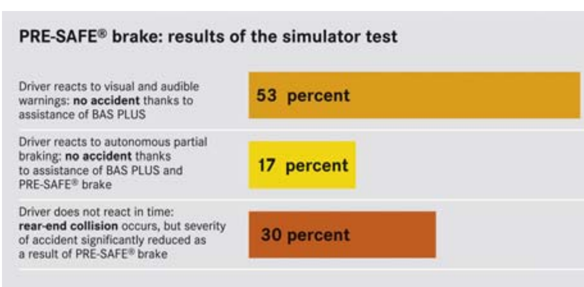

Figure 6. Results of dynamic driving simulator tests with deliberately distracted subjects in a car following scenario with sudden braking of lead vehicle

The PRE-SAFE® Brake system has also been tested thoroughly by the ADAC in 2006: Based on several tests on a test track as well as on crash tests, ADAC concluded the following safety benefits: In a specific accident situation PRE-SAFE® Brake reduced occupant load by 27 percent for the driver, by 30 percent for the front passenger and by 45 percent for the rear passenger [6].

CONCLUSIONS

Brake assistance systems contribute significantly both to the avoidance and the mitigation of rear-end collisions. Conventional brake assist systems such as the Merecdes-Benz BAS also contribute to pedestrian protection.

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DEVELOPMENT OF OBJECTIVE TESTS FOR EVALUATING LANE-KEEPING/ROAD DEPARTURE DRIVER ASSISTANCE SYSTEMS

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ABSTRACT

This paper describes a step-by step process for the development of test procedures for pre-production driver assistance systems. The process begins with a detailed engineering description of system performance and utilizes a universal description of the causal factors and resulting crash types as the foundation for a detailed analysis of crash data. The process ends with a set of objectives test procedures that can be applied to pre-production driver assistance systems that address lane-keeping/road departure performance. The quantitative estimates were obtained from national crash databases, namely, 2004 General Estimating system (GES) and 2004 Fatality Analysis Reporting system (FARS). There were 10,945,000 vehicles involved in crashes in 2004, of which 1,114,000 and 977,000 vehicles were involved in multi-and single-vehicle lane-keeping/ road-departure type crashes, respectively. Other factors such as trafficway flow, alignment, curvature, and speed were also analyzed to determine appropriate test conditions.

The results provide separate test conditions for single-and multi-vehicle crashes. The tests for multi-vehicle crashes include testing vehicles traveling in both directions; same and in opposite directions. Tests for vehicles traveling in the same direction involve driving that simulates undivided multi-lane roads. Testing for vehicles traveling in opposite directions involves driving that simulates both straight and curved two-lane undivided roadways. Single-vehicle crashes involve one test that represents a curved two-lane undivided highway with a narrow shoulder and another that represents a multi-lane undivided highway with a shoulder having a parked vehicle. All tests involve a driver traveling at speeds between 30 and 50 mph.

This is the first application of the new crash-analysis-based process for developing test procedures. Additional challenges in performing the tests and using the results to estimate crash avoidance benefits are not discussed in detail in this paper

INTRODUCTION

As new safety-related technologies are introduced into motor vehicles, there is a need to be able to assess the safety impact prior to production. Meeting this need requires new evaluation procedures. This paper addresses one aspect of a new methodology that is being developed for this purpose. The overall methodology is summarized in Figure 1. The complete development and methodology is contained in a forthcoming report [1].

Each of the rectangles in Figure 1 represents an activity and each parallelogram represents an output. The overall process begins with the identification of a candidate system or technology. The intermediate steps or activities create a database that is then used in the final activity to estimate the safety benefit (reductions in the number of crashes, injuries and fatalities).

The activities in this methodology include:

Activity 1. Describe the system design and performance.

The output of this activity is a detailed engineering description of the system and its performance. The performance description from this activity is the starting point for the remainder of the process.

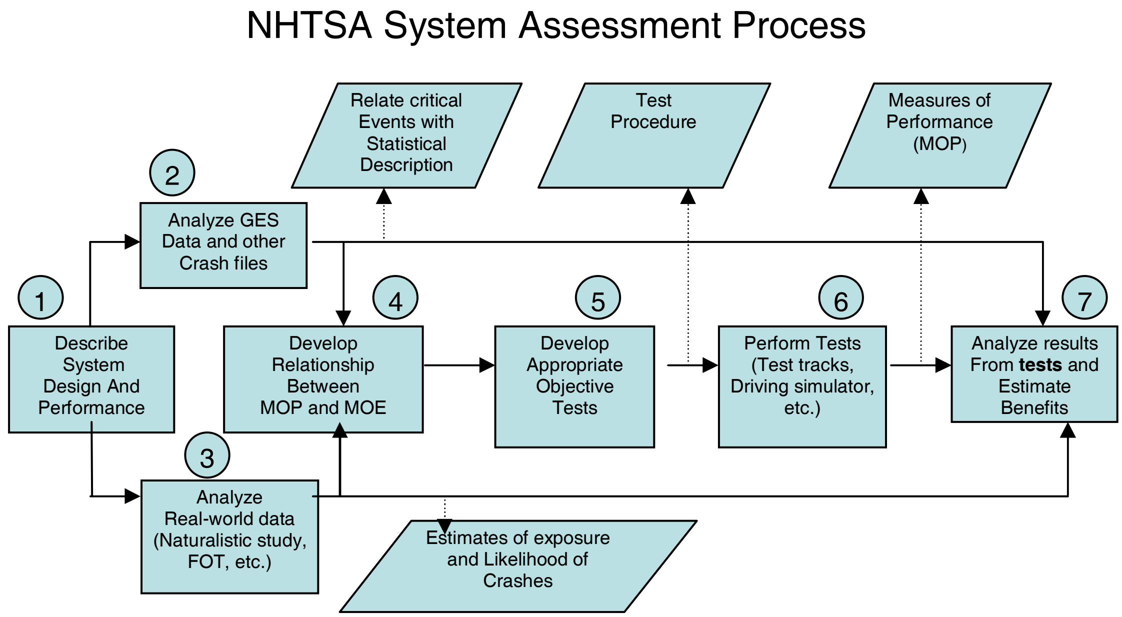

Figure1. Flowchart for NHTSA system assessment process.

Activity 2. Analyze GES and other crash data files.

The complete picture of the chain of events for each vehicle in the GES file (critical event, driver response, first harmful event) is summarized in Table 1. The Universal Description provides a high-level, but complete picture of crashes, the critical events that precede crashes, and how drivers try to prevent the crash. In this activity, variables and data elements are identified based on the performance description from Activity 1. The analyses in this activity are the foundation for most of the other activities.

Activity 3. Analyze real-world data such as naturalistic driving and field operational tests.

In this activity, data from naturalistic driving studies are analyzed to determine the level of exposure of critical events. The level of exposure from naturalistic driving data complements the results from analysis of the crash data files. These results are used for refining test conditions and for providing the baseline for estimating benefits.

Activity 4. Develop Relationships between Measures of Performance and Measures of Effectiveness.

The linkage between *Measures of Performance* from objective tests and *Measures of Effectiveness* is a key element of the benefit estimation process and quantifies how the system will assist drivers.

Activity 5. Develop Appropriate Objective Tests.

In this activity, test conditions for the system are developed. This activity is tightly coupled with Activity 2; and in practice, these two activities will probably be done simultaneously.

Activity 6. Perform tests.

In this activity, the tests developed in Activity 5 will be performed. The outcomes from these tests will include the Measures of Performance that are identified in Activity 4.

Activity 7. Analyze results from tests and estimate benefits.

This activity consolidates results from all of the preceding activities into the estimation of benefits.

Table 1.
Universal description: Showing the pre-crash critical event, crash avoidance maneuver, and type of crash for each crash-related vehicle (Imputed values from GES 2004)

Critical Event	Avoidance Maneuver / First Harmful Event	Non-Collision	Collision with non-fixed object	Collision with fixed object	Total
Subject vehicle loss of control	No maneuver	99,000	54,000	262,000	415,000
	Braking	22,000	46,000	71,000	139,000
	Steering	38,000	16,000	47,000	101,000
	Braking and steering	5,000	2,000	7,000	14,000
	Accelerating/Others	0	0	2,000	2,000
	Total	**164,000**	**118,000**	**389,000**	**671,000**
Action by subject vehicle	No maneuver	25,000	2,284,000	195,000	2,504,000
	Braking	6,000	215,000	44,000	265,000
	Steering	64,000	109,000	89,000	262,000
	Braking and steering	3,000	12,000	7,000	22,000
	Accelerating/Others	1,000	26,000	2,000	29,000
	Total	**99,000**	**2,646,000**	**337,000**	**3,082,000**
Action by another vehicle in subject vehicle's lane	No maneuver	2,000	3,064,000	1,000	3,067,000
	Braking	3,000	721,000	6,000	730,000
	Steering	7,000	199,000	18,000	224,000
	Braking and steering	2,000	64,000	6,000	72,000
	Accelerating/Others	0	21,000	0	21,000
	Total	**14,000**	**4,069,000**	**31,000**	**4,114,000**
Encroachment by another in subject vehicle's lane	No maneuver	3,000	1,413,000	1,000	1,417,000
	Braking	7,000	482,000	6,000	495,000
	Steering	21,000	395,000	79,000	495,000
	Braking and steering	4,000	80,000	6,000	90,000
	Accelerating/Others	1,000	11,000	1,000	13,000
	Total	**36,000**	**2,381,000**	**93,000**	**2,510,000**
Pedestrian and other non-motorist	No maneuver	0	60,000	0	60,000
	Braking	0	30,000	0	30,000
	Steering	0	12,000	1,000	13,000
	Braking and steering	0	7,000	2,000	9,000
	Accelerating/Others	0	1,000	0	1,000
	Total	**0**	**110,000**	**3,000**	**113,000**
Object or animal	No maneuver	2,000	217,000	2,000	221,000
	Braking	1,000	91,000	2,000	94,000
	Steering	13,000	70,000	42,000	125,000
	Braking and steering	0	11,000	3,000	14,000
	Accelerating/Others	0	1,000	0	1,000
	Total	**17,000**	**390,000**	**48,000**	**455,000**
Grand Total		**330,000**	**9,716,000**	**899,000**	**10,945,000**

FOUNDATION FOR OBJECTIVE TESTS

The analysis in this paper addresses driver assistance systems that help drivers in lane change/ road departure situations. The analysis uses GES data and forms the foundation for defining objective tests. The methodology for developing objective tests that can be used to establish the safety-related performance of driver-assistance systems builds on data from crash data files. The process consists of the following three steps:

1. Select the subsets of the Universal Description that are relevant to the safety performance of the system being evaluated.

2. Consolidate the analysis of these subsets into basic test conditions.

3. Refine the test conditions, including consideration of distributions of crashes, injuries, and fatalities.

Step#1. Select the subsets of the Universal Description that are relevant to the safety performance of the system being evaluated.

The process for identifying test procedures for lane-keeping/road departure systems begins with a detailed analysis of critical events that precede these crashes.

From the Universal Description, the following groups of the Critical Event (GES Variable V26) data elements have the potential of producing a lane-keeping/road departure-related crash [2,3,4]. Thus, they form the basis for identifying potential test-conditions. The numbers beside each data element are the SAS Code value.

- Subject vehicle loss of control:
  - 6; Traveling too fast for conditions
- Action by subject vehicle:
  - 10; Over the lane line on left side of travel lane
  - 11; Over the lane line on right side of travel lane
  - 12; Off the edge of the road on the left side
  - 13; Off the edge of the road on the right side
  - 15; Turning left at intersection
  - 16; Turning right at intersection
- Action by another vehicle in subject vehicle's lane:
  - 50; Other vehicle stopped
  - 51; Traveling in same direction with lower steady speed
  - 52; Traveling in the same direction while decelerating
  - 53;Traveling in same direction with higher speed
  - 54;Traveling in opposite direction
- Encroachment by another vehicle into subject vehicle's lane:
  - 60; From adjacent lane (same direction) over left lane line
  - 61; From adjacent lane (same direction) over right lane line
  - 62; From opposite direction over left lane line
  - 63; From opposite direction over right lane line
  - 64; From parking lane
  - 74; From entrance to limited access highway
- Pedestrian/animal etc:
  - 80-92; All pedestrian and animal data elements

Similarly, the major First Harmful Events (GES Variable A06) that are likely outcomes of lane or road departure events are:

- Non-collision
  - 1; Rollover/Overturn
- Collision with non-fixed object
  - 25; Motor vehicle in transport
  - 21, 22, or 24; Pedestrian, cyclist, or animal
  - 26; Parked motor vehicle
- Collision with fixed object
  - 31-59; All fixed objects

Step #2. Consolidate the subsets into basic test conditions.

In this section, crashes that result from these critical events are assessed to determine common characteristics. One obvious feature of these events is that the critical events lead to both multi-vehicle crashes and single-vehicle crashes. The predominant features of these two types of crashes are not the same, so they are analyzed separately in the following sections.

Multi-vehicle crashes - This section addresses critical events that lead to lane-keeping/ road-departure-related multi-vehicle crashes. The starting points for the analysis of multi-vehicle lane-keeping/road-departure-related crashes are those vehicles that were traveling too fast for conditions, plus the two groups of vehicles that experienced a critical event where there was excursion into another lane or encroachment by another vehicle from an adjacent lane and the first harmful event was collision with another moving vehicle.

A multi-vehicle crash is any crash that involves two or more vehicles. Each vehicle involved in a multi-vehicle crash interacts with one or more other vehicles during the crash. However, the data are not coded in a way that makes it possible to determine the details of these inter-vehicle combinations. This complicates more detailed analysis. To circumvent this problem, the following analysis uses only two-vehicle crashes. Also, since the objective of the analysis is to provide data for determining possible test procedures, the use of only two-vehicle crashes is justified. This judgment is supported by the fact that in this subset of crashes, more than two vehicles account for only 6% of the crashes, as is seen in Table 2.

Table 2.
Distribution of critical events leading to lane keeping/road-departure-related multi-vehicle crashes (Unimputed)

Critical Event (V26)	Two vehicle crashes	Greater than two-vehicle crashes	Total
Excessive Speed (6)	17,000	2,000	19,000
Over the lane line on the left side (10)	143,000	5,000	148,000
Over the lane line on the right side (11)	93,000	3,000	96,000
Off the edge of the road on the left side(12)	2,000	0	2,000
Off the edge of the road on the right side(13)	2,000	0	2,000
Turning left at intersection (15)	207,000	10,000	217,000
Turning right at intersection (16)	23,000	1,000	24,000
From adjacent lane (same direction) over the left lane (60)	117,000	11,000	128,000
From adjacent lane (same direction) over the right lane (61)	119,000	9,000	128,000
From opposite direction over the left lane line (62)	228,000	23,000	251,000
From opposite direction over the right lane line (63)	3,000	1,000	4,000
Total *	**956,000**	**64,000**	**1,019,000**

The description of the situation for each of the vehicles that experience a two-vehicle crash can be improved by comparing the critical event for both vehicles. This is accomplished in Table 3.

Legend for Table 3 and Table 4

Critical Event Number	Critical Event data element
6	Excessive speed
10	Over the lane line on the left side
11	Over the lane line on the right side
12	Off the edge of the road on the left side
13	Off the edge of the road on the right side
15	Turning left at intersection
16	Turning right at intersection
60	From adjacent lane (same direction) over the left lane
61	From adjacent lane (same direction) over the right lane
62	From opposite direction over the left lane line
63	From opposite direction over the right lane line

In Table 3 there are three broad combinations of critical events that describe the lane departure scenario:

- One vehicle exceeding a safe speed and the other is encroaching across a lane line(one vehicle is coded as 6 and the other is coded as 60-63)
- Both vehicles are encroaching across a lane line (both vehicles are coded as either 10-16 or 60-63)
- One vehicle is encroaching over a lane line and that encroachment is reflected in the critical event for both vehicles (one vehicle is coded as 10-16 and the other is coded as 60-63

From Table 3 it is seen that several combinations describe unattainable circumstances like combinations of 60 and 10 and the presence of code 63. Other combinations are intersection crashes where the vehicles are turning or traveling in opposite directions that do not include a relevant lane-crossing. These combinations are excluded from further consideration.

** The number of vehicles in Table 2 is based on unimputed values for the respective critical events, rather than the imputed values used in the Universal Description.*

Table 3.
Distribution of critical events for all two-vehicle lane-keeping/road-departure-related crashes. (Unimputed)

Vehicle 1 \ Vehicle 2		This vehicle… 6	10	11	15	16	Other vehicle… 60	61	62	63	Grand Total
This vehicle..	6	0	0	0	0	0	6,000	4,000	17,000	0	27,000
	10	0	6,000	5,000	1,000	0	8,000	125,000	57,000	1,000	203,000
	11	0	4,000	1,000	0	0	120,000	4,000	3,000	0	132,000
	15	0	2,000	1,000	4,000	1,000	6,000	26,000	258,000	1,000	299,000
	16	0	0	0	2,000	1,000	23,000	2,000	1,000	2,000	31,000
Other vehicle..	60	2,000	3,000	44,000	2,000	11,000	2,000	3,000	1,000	0	68,000
	61	1,000	48,000	1,000	17,000	1,000	2,000	2,000	0	0	73,000
	62	3,000	19,000	1,000	88,000	1,000	0	0	1,000	0	113,000
	63	0	1,000	1,000	1,000	0	0	0	0	0	3,000
	Grand Total	6,000	83,000	54,000	115,000	15,000	170,000	167,000	341,000	4,000	**948,000**

Table 4.
Distribution of critical events for all two-vehicle lane-keeping/road-departure-related crashes. Excludes irrelevant and inconsistent data (Unimputed)

Vehicle 1 \ Vehicle 2		This vehicle… 6	10	11	15	16	Other vehicle… 60	61	62	63	Grand Total
This vehicle..	6	0	0	0	0	0	6,000	4,000	17,000	0	27,000
	10	0	6,000	5,000	1,000	0	*	125,000	57,000	*	194,000
	11	0	4,000	*	0	0	120,000	*	*	0	124,000
	15	0	2,000	1,000	*	*	6,000	25,000	*	*	34,000
	16	0	0	0	*	*	22,000	2,000	*	*	24,000
Other vehicle..	60	2,000	*	44,000	2,000	11,000	*	3,000	*	*	62,000
	61	1,000	48,000	*	17,000	1,000	2,000	*	0	*	69,000
	62	3,000	19,000	*	*	*	0	0	1,000	*	23,000
	63	0	0	0	*	0	0	*	*	*	0
	Grand Total	6,000	79,000	50,000	20,000	12,000	156,000	159,000	75,000	0	**557,000**

Table 4, with the excluded combinations marked by the * , summarizes the critical events for each of the two vehicles in these crashes where at least one of the vehicles has a critical event of crossing a lane line or road edge. Each cell in this table represents the basic outline of a test procedure. The number of vehicles from the GES in each cell is a measure of the importance of that test procedure. From Table 4 it is seen that there are eight vehicle configurations that produce multi-vehicle lane-keeping/road-departure related crashes.

These lane-keeping / road departure related critical events that lead to two-vehicle crashes are summarized (in rank order) in Table 5.

Table 5.
Distribution of all vehicles involved in two vehicle lane-keeping/road-departure-related crashes placed in their descending rank order (Unimputed)

Critical events that lead to two vehicle crashes	Number of vehicles	Percentage %
This vehicle over the lane line on the left side (10)	273,000	25%
Other vehicle encroaching from adjacent lane (same direction) over the right lane (61)	228,000	20%
Other vehicle encroaching from adjacent lane (same direction) over the left lane (60)	218,000	20%
This vehicle over the lane line on the right side (11)	174,000	16%
Other vehicle encroaching from opposite direction over the left lane line (62)	98,000	9%
This vehicle turning left at intersection (15)	54,000	5%
This vehicle turning right at intersection (16)	36,000	3%
This vehicle, excessive speed (6)	33,000	3%
Total	**1,114,000**	100%

Table 6 organizes these events by actions that were taken by each vehicle.

Table 6.
Summary table of combination of critical events involving encroaching vehicles for lane-keeping / road-departure-related crashes (Unimputed)

Critical event situations	Encroach vehicle	Vehicle going straight	Total
Over the lane line on the left side (same direction)			
Excessive speed	5,000	5,000	10,000
No Excessive speed	221,000	221,000	442,000
Other vehicle over the lane line	14,000	-	14,000
Over the lane line on the right side (same direction)			
Excessive speed	8,000	8,000	16,000
No Excessive speed	206,000	206,000	412,000
Other vehicle over the lane line	14,000	-	14,000
Over the lane line on the left side (opposite direction)			
Excessive speed	20,000	20,000	40,000
No Excessive speed	76,000	76,000	152,000
Other vehicle over the lane line	14,000	-	14,000
Total	**577,000**	**537,000**	**1,114,000**

In summary, the lane-keeping/road-departure-related situations that lead to two-vehicle crashes are:

- **Over the lane line on the left side (same direction)**
  - Without excessive speed
  - With excessive speed
  - Coincident with encroachment by the other vehicle

- **Over the lane line on the right side (same direction)**
  - Without excessive speed
  - With excessive speed
  - Coincident with encroachment by the other vehicle

- **Over the lane line on the left side (opposite direction)**
  - Without excessive speed
  - With excessive speed
  - Coincident with encroachment by the other vehicle

Single-vehicle crashes - This section addresses critical events that lead to single-vehicle crashes. For the purposes of determining meaningful test conditions, not all of these combinations of events will be considered. Most of the events that lead to *Collisions with Non-fixed Objects* such as *Motor Vehicle in Transport*, *Pedestrians, Railway Trains and Animals* are not a relevant group. However, *Collision with a Parked Motor Vehicle* is a relevant combination. For this reason, this subgroup is the only one from this category that has been included for further analysis.

A summary of the relevant combinations of critical event and single-vehicle first harmful event is presented in Table 7.

Table 7.
Distribution of critical events that lead to single-vehicle lane-keeping/road-departure-related crashes subdivided by their first harmful events (Unimputed)

Critical Event (V26) \ First Harmful Event (A06)	Rollover	Parked vehicle	Collision with fixed object	Grand Total
This vehicle, excessive speed (6)	44,000	11,000	267,000	322,000
This vehicle over the lane line on the left side (10)	2,000	23,000	8,000	33,000
This vehicle over the lane line on the right side (11)	1,000	87,000	8,000	96,000
This vehicle off the edge of the road on the left side (12)	11,000	9,000	106,000	126,000
This vehicle off the edge of the road on the right side (13)	20,000	30,000	201,000	251,000
Other vehicle stopped in lane (50)	1,000	3,000	6,000	10,000
Other vehicle traveling in lane in the same direction with lower steady speed (51)	*	*	2,000	2,000
Other vehicle traveling in lane in the same direction while decelerating (52)	2,000	*	10,000	12,000
Other vehicle traveling in lane in the opposite direction (54)	1,000	*	4,000	5,000
Other vehicle encroaching from adjacent lane (same direction) over the left lane (60)	1,000	1,000	15,000	17,000
Other vehicle encroaching from adjacent lane (same direction) over the right lane (61)	3,000	*	16,000	19,000
Other vehicle encroaching from opposite direction over the left lane (63)	2,000	2,000	22,000	26,000
Pedestrian/Pedalcyclist/Animal/Object (80-92)	8,000	3,000	47,000	58,000
Grand Total	96,000	169,000	712,000	**977,000**

* Cells containing no data

This leads to the following six primary conditions that represent events that lead to single-vehicle lane-keeping/road-departure-related crashes.

Inappropriate action by the driver:

- Excessive speed
- Traveling Over the Lane Line
- Traveling off the edge of the road

Outside influence on driving conditions

- Another vehicle in the same lane
- Encroachment by another driver
- Encroachment by pedestrian, animal, etc.

The distribution of these crashes is shown in Table 8.

Table 8.
Distribution of conditions that lead to a single-vehicle lane-keeping/road-departure-related crash, shown by total and percentage (Unimputed)

Single-vehicle crash basic test conditions	Total	Percentage
Traveling off the edge of the road (12,13)	377,000	39%
Excessive Speed (6)	322,000	33%
Traveling Over the Lane Line (10,11)	129,000	13%
Encroachment by another driver (60,61,63)	62,000	6%
Encroachment by pedestrian, animal, etc (80-92)	58,000	6%
Another vehicle in the same lane (50,51,53,54)	29,000	3%
Grand total	**977,000**	**100%**

Summary of Step 2

The analysis during this step for the lane-keeping / road-departure system has identified 15 test conditions that are candidates for inclusion in the test program. Nine of these lead to multi-vehicle crashes and six of them lead to single-vehicle crashes.

Step #3. Refine test conditions using GES data.

In this step, several measures are used as the basis for developing more detailed test procedures. These measures include the type of roadway, the driver's crash avoidance maneuver, curvature of the road, and the distribution of traveling speed. As in Step 2, multi-vehicle crashes are treated separately from single-vehicle crashes.

Multi-vehicle crashes **-**For the purpose of facilitating the process of analysis, the discussion in this section is limited to two-vehicle crashes.

- Travel Speed

The details of traveling speed are summarized in Figure 2 [Two-vehicle, speed distribution]. There is insufficient data to obtain a meaningful distribution of speed for the conditions where one vehicle is encroaching and is traveling at excessive speed. The distributions of travel speed for the other four conditions are shown in this figure. It can also be seen that the distribution of travel speed is essentially the same for both vehicles. Based on these data and the need to address situations that produce significant injury, the 80 percentile speed is used as the basis for the two-vehicle test conditions. This is approximately 40 mph for all four situations. Note that in the opposite direction, this means that both vehicles are traveling at 40 mph. Other research [7] has shown that overtaking vehicles in the adjacent lane are a common element of lane change crashes. Thus, the speed of the confederate in the same direction tests should be higher than the subject vehicle.

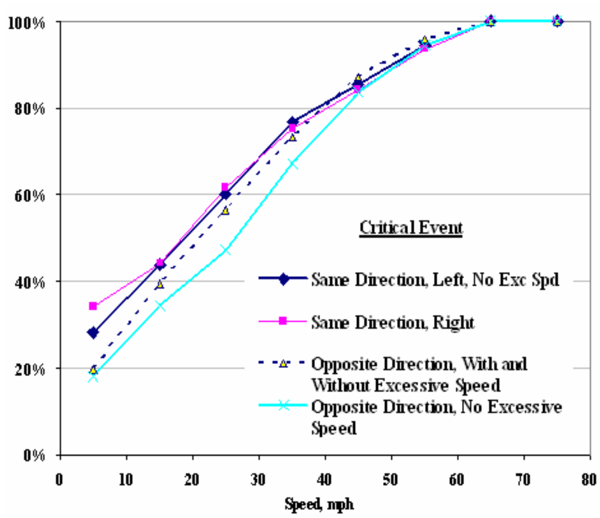

Figure 2. Speed distribution for two-vehicle lane-keeping/road departure -related crashes.

- Traffic way

From the distributions of traffic way for the two-vehicle crash data, situations where both vehicles are traveling in the same direction are evenly divided between undivided traffic ways and multi-lane divided traffic ways. However, the situations where the vehicles are traveling in opposite directions occur predominantly (greater than 80 %) on two-lane undivided traffic ways. Thus, the conclusion is that the test conditions should reflect two-lane undivided traffic ways for the test in opposite directions and should reflect both undivided and divided traffic ways in the tests traveling in the same direction. However, the lane configurations for multi-lane undivided and divided are similar, so there can be a single test for vehicles traveling in the same direction.

- Corrective Action

There is limited data in GES on the corrective action taken by each of the drivers. However, based on these data, it appears that more drivers take corrective action when the vehicles are traveling in opposite directions than when they are traveling in the same direction. These results are summarized in Table 9. Based on these results, the test conditions need to accommodate systems that address the situations where neither driver takes corrective action.

Table 9.
Known avoidance maneuvers in two-vehicle crashes for vehicles traveling the same direction and opposite direction

Same Direction	*Non-Encroaching vehicle*			
		No Maneuver	Brake	Steer
Encroaching Vehicle	No Maneuver	85%	3%	6%
	Brake	2%	0%	0%
	Steer	3%	0%	2%
Opposite Direction	*Non-Encroaching vehicle*			
		No Maneuver	Brake	Steer
Encroaching Vehicle	No Maneuver	58%	0%	17%
	Brake	8%	0%	0%
	Steer	8%	0%	8%

- Road Curvature

The distribution of road curvature is interesting for these crashes. For the crashes where both vehicles were traveling in the same direction, the likelihood of the crash being on a curve is only 7%. However, for crashes where the vehicles were traveling in opposite directions, the likelihood of the crash being on a curve is 44%. Thus, the test conditions for vehicles traveling in the same direction need only address straight roads; however, the test conditions for vehicles traveling in opposite directions need to address straight and curved roads.

Summary of Multi-vehicle crash test conditions based on GES data - Based on the detailed analysis above, it is concluded that two basic conditions will be tested:
(1) The host vehicle and a confederate vehicle traveling in the same direction and
(2) The host vehicle and a confederate vehicle traveling in opposite directions.

Same Direction:

- The lane-changing vehicle, the subject vehicle, should be traveling at 40 mph on a straight road that emulates either:
  - A divided multi-lane roadway, or
  - A multi-lane undivided roadway

In addition to this basic configuration of the two vehicles, it is necessary to establish the relative position and speed of the two vehicles. Other research [7] has shown that the vehicle that is not changing lanes, the confederate vehicle, is often overtaking the subject vehicle at a higher speed. For this reason it is recommended that the confederate vehicle should be traveling at a speed of 45 mph. A distance that corresponds to a time-to-collision of 3 seconds has been selected as the point at which the lane change begins. This provides an opportunity for warning, or automatic control, systems to effectively intervene. The analysis provided in the Appendix to this paper supports the additional criteria that the encroaching vehicle should cross the lane line at an angle of 3 degrees.

Opposite direction:

- Both vehicles traveling at 40 mph on a two-lane undivided roadway. Two test conditions should be used:
  - A straight road segment, and
  - A curve of appropriate radius

In addition to this basic configuration of the two vehicles, it is necessary to establish the relative position and speed of the two vehicles. The relative distance between the two vehicles is based on time-to-collision. A distance that corresponds to a 3-second time-to-collision is recommended. This provides an opportunity for warning, or automatic control, systems to effectively intervene. If both vehicles are traveling at 40 mph, this distance is 350 feet. The analysis provided in the Appendix to this paper supports the additional criteria that the encroaching vehicle should cross the lane line at an angle of 3 degrees. The radius-of-curvature for the second condition has not been established. The crash data files, such as GES and the Crashworthiness Data System do not include details on radius-of-curvature. Thus, it will be necessary to do additional analysis of naturalistic driving data, similar to the analysis in the Appendix, or other sources to determine this value.

The tests in both conditions should accommodate systems that assist drivers who would otherwise take no evasive action.

Single-Vehicle crashes - In the preceding section, it was determined that there are six basic pre-crash conditions that need to be considered. The conditions are summarized in Table 8 and repeated below:

- Excessive Speed
- Traveling over the lane line
- Traveling off the edge of the road
- Another vehicle in the same lane
- Encroachment by another driver
- Encroachment by pedestrian, animal etc

- Travel speed

The details of traveling speed for each of the six conditions are summarized in Figure 3.

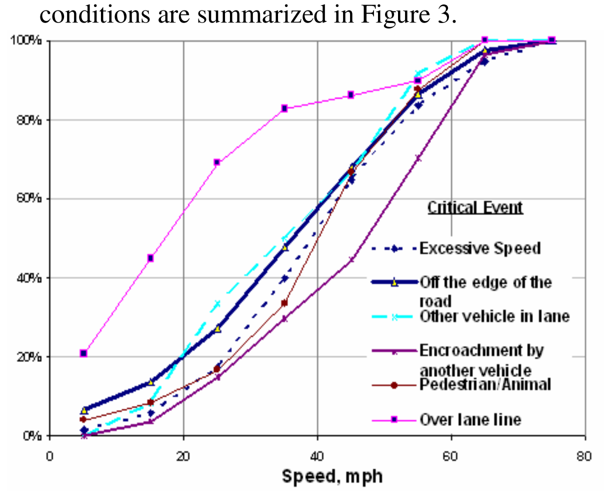

Figure 3. Summary of travel speeds for single-vehicle crashes for various critical events.

From this figure, it is seen that the speed distribution for "over the lane line" events that lead to crashes occur at lower speeds than do the other types of single-vehicle situations; in contrast, the events that begin with "encroachment by another vehicle", occur at higher speeds. Based on these data, and the need to address situations that produce significant injury, the 80 % speed is used as the basis for the single-vehicle test conditions. This is approximately 30 mph for "Over the lane line" situations, 60 mph for "Encroachment by another vehicle" and 50 mph for the other four types of events.

- Traffic Way

From the distribution of traffic way for the single-vehicle crashes, the single most common type of traffic way (ranging from 40 % for encroachment type events to 73 % for pedestrian/animal events) for these events is two-lane undivided highways (one lane in each direction). The second most common type of traffic way is two-lane divided highways (two lanes in each direction). For those events that are initiated by encroachment, about 25 % occur on divided highways with more than two lanes in each direction. Based on these data, the conclusion is that the test conditions should reflect two-lane undivided traffic ways as well as multi-lane divided traffic ways for all six conditions.

- Corrective Action

From Table 10 below, it's seen that, for events where this variable is known, 48 % of the drivers steered and 11 % braked, but 36 % did not attempt an avoidance maneuver.

Table 10.
Distribution of known avoidance maneuvers for single-vehicle lane-keeping/ road-departure-related events

Avoidance Maneuver Critical Event	No Maneuver	Brake	Steer	Brake and steer	Total
Traveling off the edge of the road (12,13)	63,000	11,000	41,000	3,000	118,000
Excessive Speed (6)	48,000	16,000	14,000	2,000	80,000
Encroach by another driver(60-64)	0	3,000	51,000	4,000	58,000
Encroach by pedestrian, Animal (80-92)	2,000	2,000	42,000	2,000	48,000
Traveling Over the Lane Line 10,11)	16,000	2,000	9,000	0	27,000
Another vehicle in the same lane (50-54)	1,000	5,000	16,000	5,000	27,000
Grand Total	130,000	39,000	173,000	16,000	**358,000**
Percentage	36%	11%	48%	5%	100%

Based on these data, the test conditions need to accommodate situations where the driver attempts no maneuver as well as those where the driver either steers or brakes.

- Road Curvature

The percentage of events that occur on curves for each category is shown in Table 11 below.

Table 11.
Percentage distribution of crashes for each critical event on curves

Category	% on Curve
Excessive Speed	50%
Off the edge of the road	35%
Over the lane line from adjacent lane traveling the same/opposite direction	27%
Pedestrian / Pedalcyclist/ Animal/ Object	27%
Other vehicle traveling in the same lane either topped/slower /steady speed	17%
Over the lane line	14%

From this table, it is seen that events that involve lane line crossings and encroachment by other vehicles occur on straight roads. The other four categories of events frequently (between 27% and 50%) occur on curves. Based on these results, the test conditions for single-vehicle events should include both straight and curved roads, except for lane line crossings and encroachment by other vehicles that would be tested only on straight road segments.

Two additional considerations are the types of crash that result from these single-vehicle events and the level of injury that results from these crashes.

- Types of crashes

The distributions of first harmful events for each of the six broad categories of single-vehicle lane-keeping / road-departure–related events are shown in Figure 4 below.

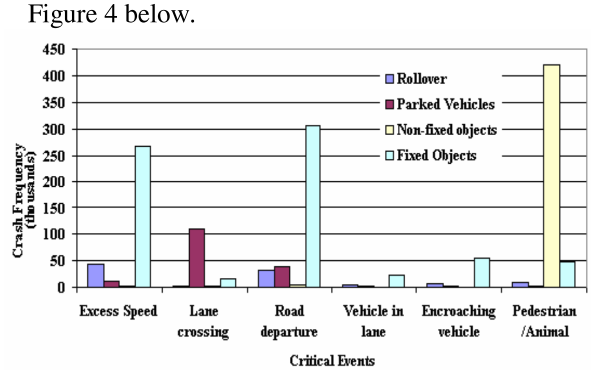

Figure 4. Distribution of first harmful event for single-vehicle lane-keeping/road-departure-related events.

Several helpful observations can be made from this table:

First: Consider the events that result from a pedestrian or animal (Category 6). This category was included in this analysis because of the potential for the avoidance maneuvers in these events leading to off-road crashes. This figure shows that although there are a few crashes of this type, the vast majority of the first harmful events are a collision with the pedestrian or animal. These collisions may occur either on or off the road. Thus, this type of event is not a good choice for evaluating the performance of lane-keeping / road-departure systems. For this reason, it will be dropped from further consideration.

Second: Categories 4 and 5 (actions by other vehicles) contribute only a small fraction to the total problem. For this reason, they will also be dropped from further consideration.

Third: The remaining three categories produce three main types of harmful event: (1) impacts with fixed objects (trees, poles, bridges, etc.), (2) rollovers, and (3) collision with parked vehicles.

The conclusions from this part of the analysis are that the test conditions should reflect the first three conditions of critical event (excessive speed, lane line crossing, and road departure) and should be based on environments that may lead to rollovers, crashes with fixed objects, and crashes with parked vehicles.

Summary of single-vehicle test conditions

Based on this analysis, two tests are needed:

- A test that combines the attributes of excessive speed and road departure. This test will be on a roadway that reflects a two-lane undivided roadway (This probably means a narrow shoulder). The vehicle should be traveling at 50 mph, and the event should occur on a curve of appropriate radius.

- A test on a roadway with sufficient shoulder width to accommodate a parked vehicle. The vehicle should be traveling at 30 mph on a straight section of road with a vehicle parked on the shoulder.

The radius-of-curvature for the first condition has not been established. The crash data files, such as GES and the Crashworthiness Data System do not include details on radius-of-curvature. Thus, it will be necessary to do additional analysis of naturalistic driving data, similar to the analysis in the Appendix to this paper, or other sources to determine this value. As noted in the discussion of two-vehicle test conditions, it is necessary to establish the relative position of the two vehicles for the second condition. A distance that corresponds to a 3-second time-to-collision is recommended. This provides an opportunity for warning, or automatic control, systems to effectively intervene. If the subject vehicle is traveling at 30 mph, this distance is 145 feet. The analysis provided in the Appendix supports the additional criteria that the subject vehicle should cross the lane line at an angle of 3 degrees for both test conditions.

The tests in both conditions should accommodate systems that assist drivers who would otherwise take no evasive action, as well as drivers who steer or brake.

CONCLUSIONS

Test conditions have been developed for systems that assist drivers in preventing crashes associated with lane changes or road departures. The resulting test conditions are based on data from GES. Table 12 provides a summary of these test conditions. The speeds shown in this table correspond to the 80th percentile of crashes in GES.

Table 12.
Summary table for test procedures for lane keeping/ road departure related systems based on data from GES conditions

Type	Roadway	Specifics	Speed (80 % of all crashes)
Two-vehicle; Opposite direction	- Two-lane - Undivided - Curve	- 350 ft separation (485 ft at 55mph) - 3 degree approach angle	40 mph, Both vehicles
Two-vehicle; Opposite direction	- Two-lane - Undivided - Straight	- 350 ft separation (485 ft at 55mph) - 3 degree approach angle	40 mph, Both vehicles
Two-vehicle; Same direction	- Multi-lane - Straight	- 3 degree approach angle	-40 mph, Lead vehicle. -45 mph, Following vehicle
Single-vehicle	- Two-lane - Undivided - Curve	- Narrow shoulder - 3 degree approach angle	50 mph
Single-vehicle	- Multi-lane - Straight	- Shoulder with parked vehicle - 3 degree approach angle	30 mph

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APPENDIX

The objective of this analysis is to determine the approach angle with respect to the lane line. The analysis uses data from a recent naturalistic driving study [5, 6]. This study provides details on 200,000 vehicle miles of travel. The data was generated by 241 participants driving for 43,000 hours over a span of 23 months.

There are 828 event files in the data base used for this analysis. Each event is a Crash or a Near Crash. Of these, 762 files were Near Crashes. Each file includes real time video of five views: frontal, rear, left side, right side, and driver's hand position; variables such as lane offset, lane width, delta time frame, vehicle speed, lateral and longitudinal acceleration.

The estimates of approach angle are based on the following variables:

Lane offset,X (in): Distance between vehicle's longitudinal center and the lane center.

Delta Frame, δt (Sec): Time increment between current step and preceding step of data collection.

Lane Width, W (in):Lateral distance across current lane.

Vehicle Speed, V (mph): Vehicle travel speed.

Figure A-1 shows the signature of offset in inches, during a right-to-left and left-to-right lane change maneuver. In these two examples, the right-to-left lane change took about 5 seconds, while left-to-right lane change took 3.5 seconds.

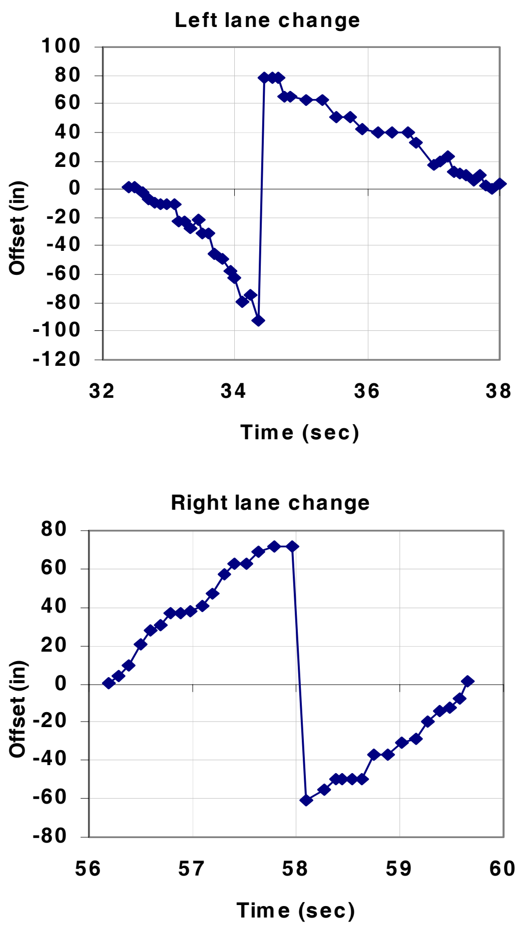

Figure A-1: Offset channel signature during a lane change maneuver.

Once the variables and their values are established, the approach angle is calculated: where

The approach angle is:

$$\theta = Sin^{-1}\left(\frac{V_L}{V}\right)$$

where V_L is the estimated lateral velocity of the vehicle and V is the vehicle travel speed. The angle θ is determined for each time frame by substituting values for V_L and V. If the vehicle's longitudinal center line is in the left of the lane center then the offset has a negative value, while it has a positive value on the right side.

Estimation of lateral velocity at each step uses the expression:

$$V_L = \frac{X_n - X_{n-1}}{\delta t_n}$$

where n is the frame number. These relationships are summarized in Figure A2

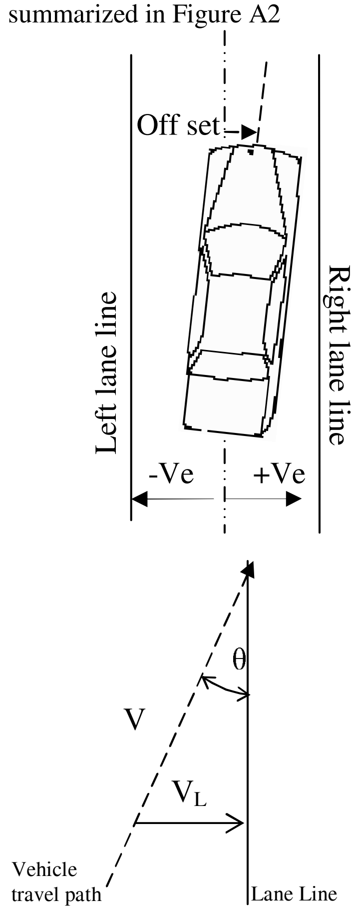

Figure A-2: Offset and angle of approach θ

The time at which the vehicle crosses the lane, T_{lc}, is the time when $Offset + \frac{1}{2} car\ width \geq \frac{1}{2} lane\ width$.

The approach angle θ at this instant is the vehicle's approach angle at the lane change event.

Figure A-3 shows the estimated values of θ for the same two examples in Figure A-1. An eight point moving average filter is used to reduce the noise in the data collection / calculation process. The filtered value of θ is also shown in the Figure A-3 and is used in estimating the value for θ_{lc}

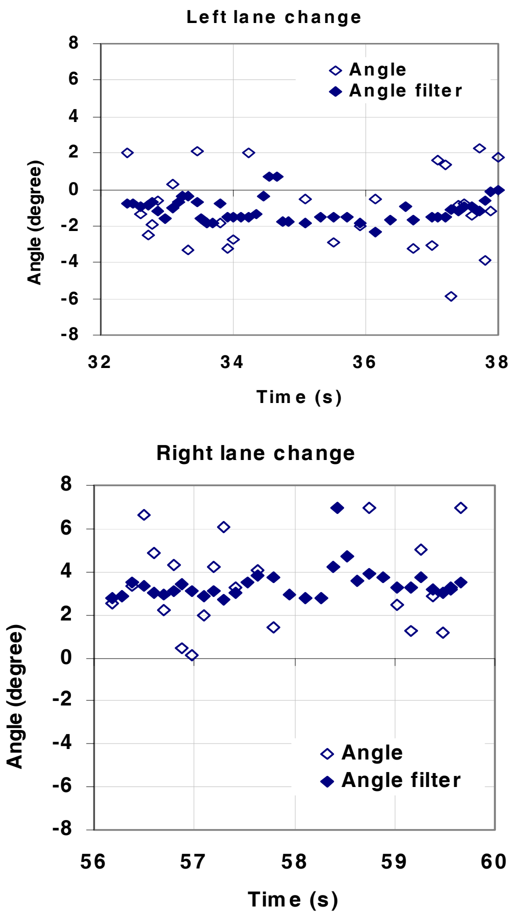

Figure A-3: Estimated angle θ

The lane change signature described in Figure A-1 was applied to the data in each of the 762 near crashes. A total of 223 lane change maneuvers were identified by the algorithm. These selected lane change maneuvers had a minimum speed of 10mph. Distribution of road alignment and road type is shown in Table A-1. Of the 223 lane changes, 30 were completed on curved roads while the rest was completed on straight roads. 53 of the lane changes took place on un-divided traffic way, of which 19 had only 2 lanes.

Table A-1:
Distribution of road alignment and road type

Number of lane changes		Road alignment				
Traffic_Flow	# of Travel Lanes	Curve Grade	Curve level	Straight grade	Straight level	Grand Total
Divided (median strip or barrier)	1		3		3	6
	2		5	4	37	46
	3	1	10	7	68	86
	4				27	27
	5		2		2	4
Not divided	2		2	1	16	19
	3		4		9	13
	4		1		9	10
	5				6	6
	6				1	1
One-way traffic	1	1	1		1	3
	2				1	1
	4				1	1
Grand Total		2	28	12	181	223

Summary

The results of the analysis are shown in Figure A-4. From this figure, it is seen that at least 60 percent of the events occur with a lane change angle less than 3 degrees for speeds greater than 20mph. This leads to the conclusion that 3 degrees is an appropriate approach angle for testing lane-keeping/road departure systems.

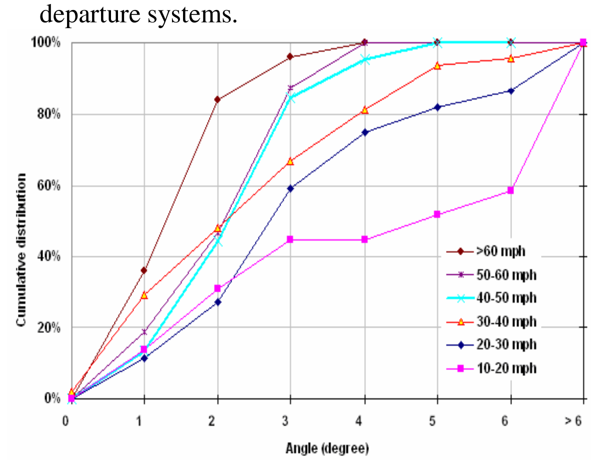

Figure A-4.Cumulative distributions of approach angles during a lane change maneuver.

MULTI-SENSOR DRIVER MONITORING AND ASSISTANCE SYSTEM USING STATE-OF-THE-ART SIGNAL MODELLING

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ABSTRACT

Driver assistance and performance monitoring systems are currently being applied in modern cars in order to enhance safety. However, these systems have to answer certain concerns raised by manufacturers, legislators and users. These include, degree of intrusiveness (warning messages, tactile feedback, taking control of the car), ability to respond to different driving contexts and system reliability under varying road and environmental conditions and driver reliability. By combining inexpensive and non-intrusive sensors with state-of-the-art signal processing, probabilistic theory and artificial intelligence for signal analysis and modelling, it is possible to present a solution to all the above concerns to a certain extent. To investigate this extent, highway scenario simulator experiments have been conducted including 30 drivers in normal physical condition and impaired conditions due to lack of sleep. A simulator equipped with a near-infrared eye-gaze tracker, strain gauges to measure force on the steering wheel column (SWC), and potentiometers to measure steering wheel and throttle angle has been used. In addition to these core sensors, two webcams have been implemented to view the driver and to track lane-keeping. Raw data have been obtained comprising eye movement, force on SWC, vehicle speed, lane deviation, and human activity from the webcam. The data are first processed up to a level where all signals are one dimensional and continuous. Secondly, metrics have been derived using derivatives, histograms and entropies of the signals. These metrics are then tested against a ground truth risk level obtained from a driver survey and from independent observers. After selecting the best metrics for driver performance indication, different time windows for metric derivation are compared and the driver sessions are classified by a Fuzzy Inference System The system works well on the simulator data, with a 98% correct classification rate and is now being implemented in real conditions on real roads.

INTRODUCTION

Active safety depends on how well the vehicle is equipped for accident avoidance and prevention. However, a well-equipped car can still be involved in a severe accident if the driver of the car is not monitored. Detection of low performance of the driver due to fatigue, sleepiness and inattentiveness is crucial for active safety systems to operate on time considering the condition of the driver. Any solution to this problem could significantly in reduce the number of the accidents because thousands of car accidents are caused by low driver performance and condition [1] Therefore, experimental studies in search of indicator signals and studies to define the best way of using these signals to obtain a high correct classification rate and low number of false alarms are conducted. Eye tracker systems become centre of attention in computer vision domain. Different eye tracking systems together with head tracking algorithm are suggested based on near infra-red or visible light using different hardware architectures. Eye closure metric PERCLOS is identified as a good psychomotor indicator and validated against EEG [2]. In [3] the steering wheel angle is considered as an indicator signal and Artificial Neural Networks (ANN) are used as decision mechanisms. There are studies to use statistics, regression analysis [4] and fuzzy systems [5] for decision making using the indicators. In addition to mainstream approach alternative signal modelling approaches are also suggested such as system identification (SI). [6] Despite the vast amount of research on the issue, the questions including degree of intrusiveness, the cost and feasibility of the system, and the final output form have not been satisfactorily addressed. In order to answer these questions, the best indicator signals which can be measured non-intrusively using a low-cost sensor system are investigated. The first section defines the proposed multi-sensor system from this point of view. Next, derivation of best metrics representing signal characteristics and extraction of high-level information from raw signals is discussed. These metrics are grouped under different combinations in search for an optimal feature space. In some feature spaces, some of the metrics are not included on purpose to observe the effect of missing sensor data on performance of decision making system. The effect of time window size during which the feature vectors are calculated, on the prediction performance is investigated and optimum window size is determined. Finally, the decision systems are investigated and the results of training and testing of decision systems are reported.

Multi-Sensor System Structure

Detection of driver vigilance and quantitative measurement of states are difficult problems due to three system design requirements:

* *Non-intrusiveness*: The measurement systems must be non-intrusive to driver.
* *Robustness and Reliability*: System should be as reliable as possible to represent the real vigilance state and robust to compensate sensor failures.
Low-cost and Feasibility: The sensors selected for measurement system should be low-cost and should be connected in a feasible way.

Low cost, non-intrusive sensors and measurement methods that can be connected to CAN system of the cars are selected. Robustness and reliability are addressed under decision selection fusing the information from different information channels using a multi-sensor system.

The metrics derived from eye movements are the most reliable indicators .Therefore, in the core of the multi-sensor system, a near infrared computer vision system is placed for eye tracking. Because in certain cases (e.g. bright sun light, tinned glasses, driver out of field of view) eye tracking system cannot give reliable results or any results at all, it should be supported by peripheral sensor systems. This consists of strain gauges to measure the force applied by driver on the steering wheel and two encoders for measuring the steering wheel angle and the throttle angle. In addition to this system, there are two webcams viewing driver and the road for human movement analysis and for lane tracking performance measurement respectively. In brief, the peripheral system supports the computer vision system for eye tracking and also adds extra information about the attentiveness level of the driver in terms of vehicle dynamics (e.g. speed via throttle angle, steering wheel angle, lane deviation via webcam) and human-car interface related measures (e.g. force on steering wheel). Multi-sensor monitoring system arrangement and experiment geometry can be seen in Figure 1.

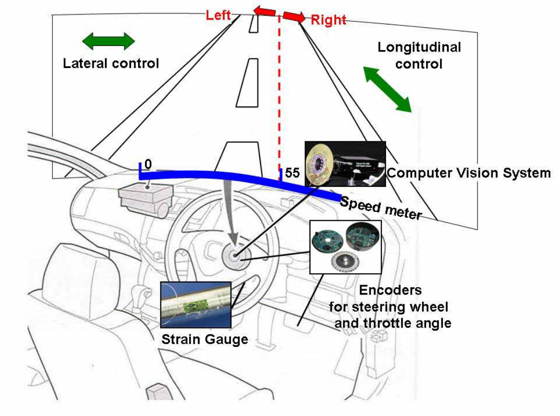

Figure 1. Multi-sensor system structure and experiment geometry

Experiment Design and Conditions

Thirty drivers with different level of driving skills and driving behaviour took place in the experiment and they drive the STISIM car simulator for about 1.5 hours. Each subject drove the same route twice under normal conditions and sleep-induced conditions. In the normal driving sessions drivers had their normal daily sleep need before taking part in the experiment, whereas in the 'sleep deprived' session they were requested to sleep at least 3 hours less than their usual sleep need. In order to induce sleepiness, this session took place between 2-4 pm in which the circadian rhythm of the body is known to decrease. Driving scenario is a monotonous highway scenario with no curvatures on the road, helping to induce sleepiness as well.
In order to separate the driving task into longitudinal and lateral control actions and to observe the distribution of the attention during the driving, drivers were given special instructions. Firstly, they were requested to keep their speed at 55 kmph during the session; therefore they needed to adjust their longitudinal control commands by changing throttle angle. Second instruction was to choose a lane and keep the lateral position of the car as stable as possible minimising lane deviation. In fact, these two requirements represent two rules that drivers should obey in a highway not to have any risk. The speedometer is arranged in front of the screen as a slide bar just underneath the road view. The drivers needed to look at different heights to check for the speed (speedometer) and for the lateral position (road view) changing their eye gaze. By this way the distribution of their attention during the experiment is expected to be measured from the gaze vector output of the computer vision unit.

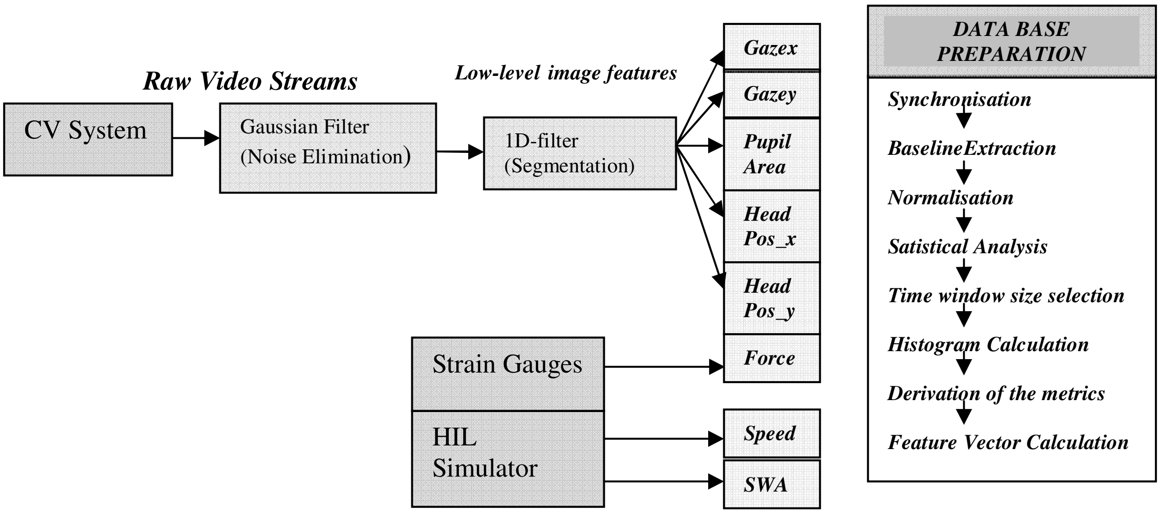

Figure 2. Data reduction and database preparation procedure

Data structure and analysis

The raw data obtained from the controlled experiment comprises the following list:

- Video stream containing near infrared frontal face images of the driver.
- Strain data from strain gauges on the steering wheel.
- Speed and steering wheel angle from the potentiomers in the simulator on steering wheel and on throttle respectively.

All the data should be reduced into one dimension first and then to some metrics/features characterising the signal. This data reduction procedure can be seen in Figure 2.

Metric Development- In order to derive the metrics all the information are reduced to one dimensional signals changing versus time and are synchronised. Development of good metrics depends on how well the nature of the signal is understood. Different metrics developed for this study are explained here briefly without giving details of low-level processing algorithms for the sake of brevity and focus.
**Visual Metrics:* The first metric group is derived using the raw signals from computer vision system. The near infrared video stream of driver faces is processed to segment the eye image containing pupil and glint features. An example of segmented pupil area and glint can be seen in Figure 3. The vector between the centres of the pupil and glint can be mapped to the real coordinate of where the eye gaze is directed. The gaze is the direction of the eyes when the fovea is centred on the scene being seen, thus at the time when the frame is captured the attention is focused on that point. The one dimensional visual signals are constructed measuring pupil area, x and y component of the gaze vectors and x and y components of the pupil centre to measure the head coordinates.

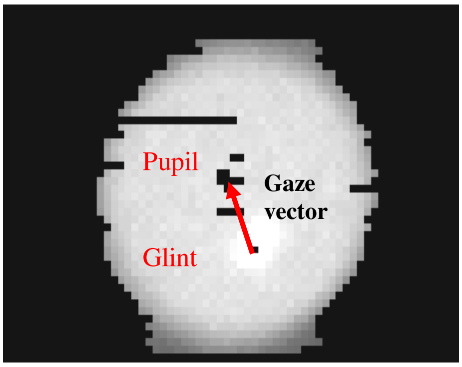

Figure 3. Segmented pupil area showing the pupil area, glint (corneal reflection) and defined gaze vector

Samples of gaze vector y component, pupil area and head x and y component measurements are given in Figure 4. In order to derive the metrics from one dimensional signal, an exploratory analysis is conducted. In this analysis, standard deviations, mean values and entropies of the signals are taken. In addition to these three variables, the histograms of the signals are taken over a predefined time window in order to follow signal value distribution over time. Each driving session is divided into 12-minute long sub-sections taken from start, middle and finish parts of the session. By constructing histograms of gaze x, gaze y and pupil area some characteristics that are not visible from signal-time diagrams are obtained. Three visual metrics are defined based on histograms: Eye closure metric 1(ECM1), Eye closure metric 2 (ECM2) and Attention division ratio (ADR).

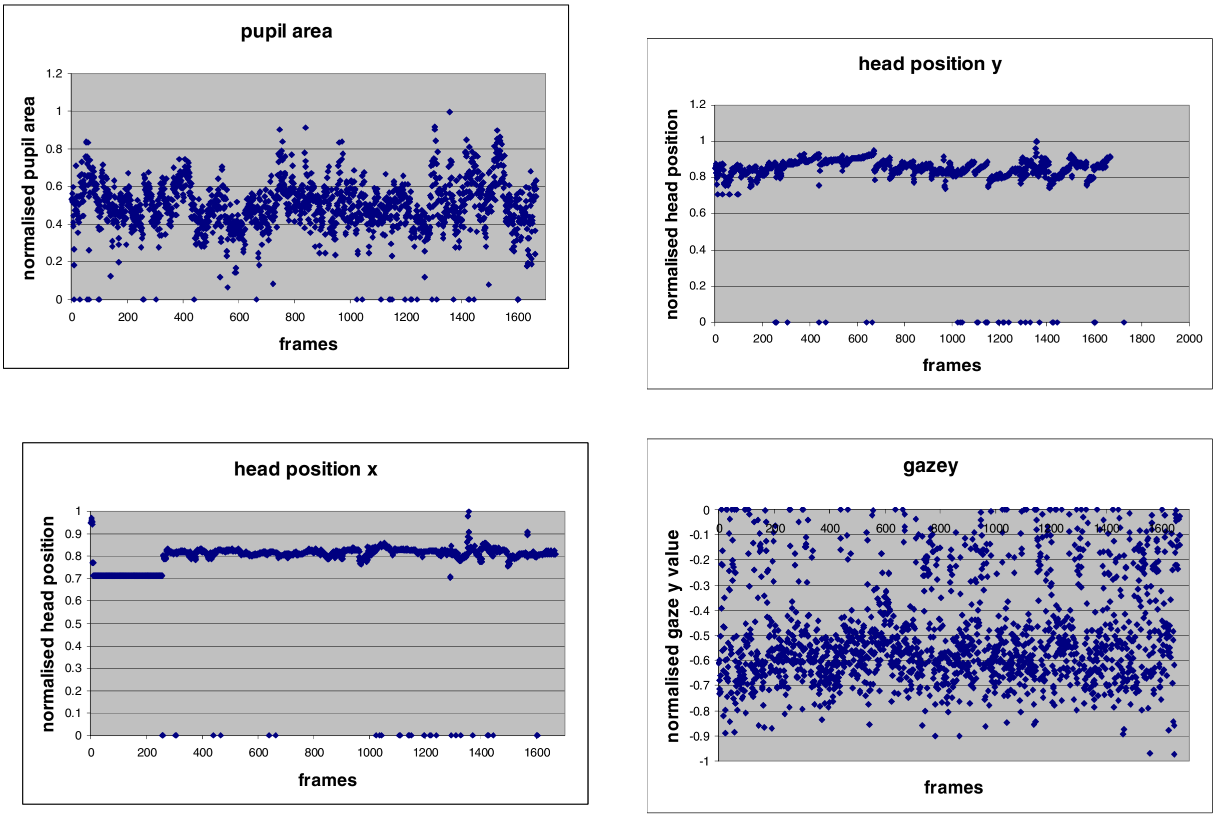

Figure 4. Samples of pupil area head position x and y and gazey

The histograms of gaze x, gaze y and pupil area are shown in Figure 5 for a normal/alert and impaired/drowsy driver. There are two clear observations that can be drawn from histograms:

1. Gaze y values between [-1 and -0.5] represents road scene changing eye gaze, thus the attention is on the road scene. For the values between [-0.5 and 0] the attention is focused on speedometer. Gaze y histogram has an equal distribution of attention to these two defined intervals at the start of the simulation for both alert and drowsy drivers. However, as the time proceeds the distribution of gaze y concentrates in speed checking region. Both alert and drowsy driver follows the same trend, however, the distribution change towards the speed checking interval is more rapid and dramatic in drowsy driver.
2. The number of closed eyes [0] and open eyes [1] and intermediate states if any can be seen in pupil area column of the histogram. As the time proceeds the proportion of number of closed eyes to the number of open eyes increases. Both alert and drowsy drivers follow the same trend however the proportion increases dramatically in drowsy state.

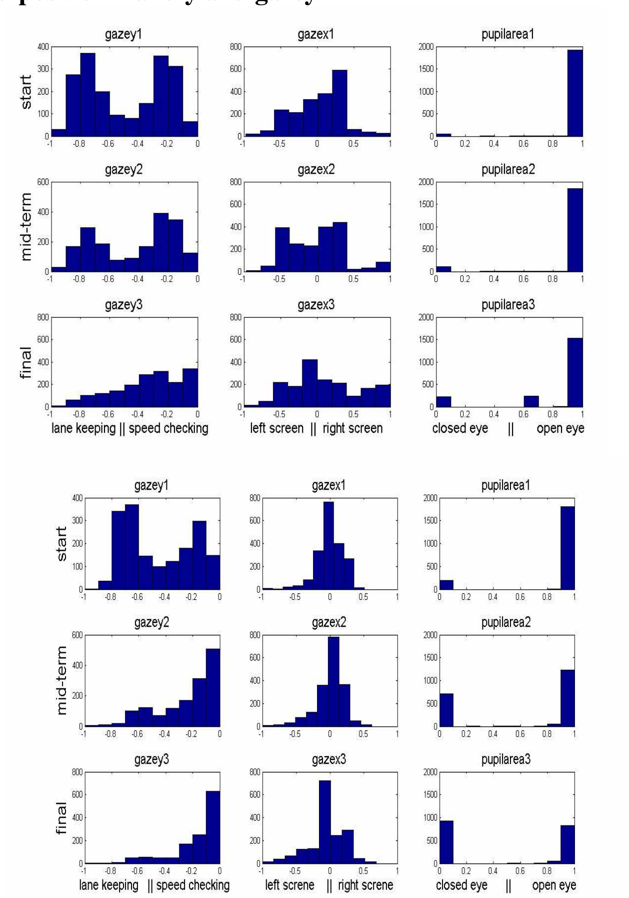

Figure 5. Histograms of alert (top) and drowsy (bottom) drivers

In the light of these observations ECM1 and ECM2 are derived from pupil area histograms of three sub-sessions of the whole driving session. These eye closure metrics are similar to PERCLOS measured by [7], however defined over a longer time period. The attention division ratio (ADR) is derived from the gaze y column of the histograms by dividing the number of gaze measurements in speed checking interval to the number of gaze measurements in road checking interval.(1)

Eye Closure Metric (ECM1) emphasizes the number of blinks by taking the proportion of fully closed to fully open eye cases, whilst ignoring the cases in between. The second metric of eye closure (ECM2) represents partially closed cases as well as fully closed eye cases in the denominator of the ratio. (2 and 3)

$$ADR = \frac{N_{gazey > -0.5}}{N_{gazey < -0.5}} \qquad (1)$$

$$ECM1 = \frac{\sum_{1}^{n} N_{pupilclused}(i)}{\sum_{1}^{N} N_{pupilwideopen}(i)} \qquad (2)$$

$$ECM2 = \frac{> PupilArea * 0.9}{< PupilArea * 0.9} \qquad (3)$$

In addition to these newly defined metrics, the entropies and standard deviations of the signals are also used. The entropy of the signals is calculated as in information theory given in (4).

$$entropy = \sum_{i-1}^{n} x_i \log x_i \qquad (4)$$

To sum up, the visual metrics are the standard deviation, entropy and mean value of gaze x, standard deviation and entropies of head motion x and y components, ECM1, ECM2 and ADR.

***Non-visual Metrics:** These are the metrics obtained from vehicle dynamics (speed and steering wheel angle) and human-car interface (force on steering wheel) signals. A sample of these signals can be seen in Figure 6.

As in the visual metric development the standard deviation and entropy is used to measure the scatter and complexity in the signal. In addition to this general approach, two control metrics are derived from the speed indicating longitudinal control performance. As can be noticed from Figure 6, the speed graph resembles the response of a PID controller. In fact, drivers are told to keep their speed at 55 kmph; therefore, driver acts like a PID controller to keep this reference value with some small deviations. These small deviations can be added up to give total steady state error of the driver after settlement. Integral of the standard error and integral of the average error is taken as performance indicators of longitudinal control as given by (5 and 6).

$$ISE = \int_0^T e^2(t)dt \qquad (5)$$

$$IAE = \int_0^T |e(t)| dt \qquad (6)$$

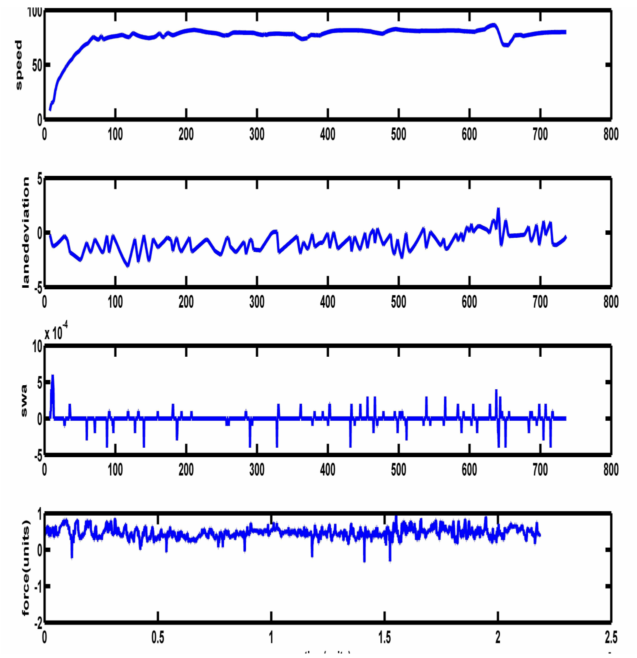

Figure 6. Sample data from non-visual information channel: speed (km/h), lane deviation (m), steering wheel angle (degree) and force (normalized to [-1, +1] N interval), time (simulator time unit is seconds)

Feature Spaces and Feature Selection

In order to find the best feature space to represent the signals, three different feature space has been constructed. The first feature space (F1) contains only the visual metrics, the second (F2) contains entropy and control values and finally the third feature space (F3) has visual metrics and standard deviations. The first feature space is constructed to observe how well the visual metrics can predict the drowsiness level of the driver. The second feature space leaves out the visual metrics so that it becomes observable how well the control and entropy related metrics can predict without using visual cues. Finally, the third space represents a visual metric space backed up by standard values of other metrics. The member of these three spaces can be seen in Table 1.

Apart from these three feature spaces a 'best feature space' is constructed after considering the results from correlation analysis. The ground truth risk level obtained from independent assessment and

Table 1. Different feature vectors are designed to investigate the best representation of the phenomena

Visual Cues (F1)	Entropy and Control (F2)	Visual Cues and Standard Deviations(F3)
Eye Closure Metric 1 Eye Closure Metric 2 Attention Division Ratio Gaze x Mean Gaze x Standard Deviation Head Motion in x Standard Deviation Head Motion in y Standard Deviation	IAE ISE SWA Entropy Gaze x Entropy Force on SWC Entropy Head Motion x Entropy Head Motion y Entropy	SWA STD Force on SWC STD Eye Closure Metric 1 Eye Closure Metric 2 Attention Division Ratio Gaze x Mean Gazex Standard Deviation Head Motion Standard Deviation Head Motion y Standard Deviation

Table 2. Best feature space members selected by p<0.05 criterion

FV Members	*P (signf.)*
ECM1	0.000
ECM2	0.000
AttDivRatio	0.002
Head motion-x Std	0.001
Head motion-y Std	0.000
IAE	0.019
ISE	0.042
SWA Entropy	0.007
Force Entropy	0.036
Force Std	0.022

surveys and metrics are taken into correlation analysis as in (*metric, ground truth drowsiness level)*pair for each metric separately . The metrics having high correlation coefficient ,r, and small values of signifance ,p, with ground truth drowsiness level as a result are selected as best metrics to construct best feature space. Best feature space members are given in Table 2 together with their p values. The members are selected by taking their p and r values into account. The metrics having $p<0.05$ and $r>0.2$ is considered as having high enough correlation to actual drowsiness level expressed by ground truth.

Decision Systems and Results

After constructing the feature spaces from calculated metrics, a decision system should be trained to detect impaired and normal states of the drivers. In order to train the decision systems, database containing the feature spaces are divided into train and test data groups. Supervised learning method is used and ground truth acted as teacher to shape the artificial intelligence system to produce rules using available metrics. Because the drowsiness level can be judged by people and the available information is fuzzy nature, the Fuzzy Inference system is chosen as a good candidate to mimic this decision making process. Thus the system is expected to behave like a co-pilot detecting the impaired driver and the level of the risk involved. Finally, the effect of the time window selection in calculating the metrics are analysed using different time windows and training separate FIS for each time window selection.

Fuzzy Inference Systems- FIS can be of mainly two types: Mamdani [8] and Sugeno-Takagi [9]. The first System constructs the rule base of the system from expert knowledge and is transparent to the designer of the system. Any rule can be added to or removed from a Mamdani FIS. On the other hand, Sugeno-Takagi system uses data to extract the rules in terms of linear relationships between the inputs to yield the output, thus it is data driven. If how the measured metrics were connected to the drowsiness level was known, the choice should be a Mamdani system. However, in our problem the rules expressing the relationship between the metrics and level of impairment and involved risk is not clear. Therefore, this investigation asks a two way question to find the best feature spaces and best decision system. For this reason, Sugeno-Takagi system is used to reveal the relationships mathematically to construct a rule base. A sub-clustering method is used in deriving the Sugeno-Takagi (S-T) based FIS.

The fuzzy C-means algorithm is an iterative optimization algorithm minimizing the cost function in (5).

$$J = \sum_{k=1}^{n} \sum_{i=1}^{c} \mu^{m}{}_{ik} \parallel x_k - v_i \parallel^2 \qquad (5)$$

where degree of membership μ_{ik} is given by (6).

$$\mu_{ik} = \frac{1}{\sum_{j=1}^{c} \left(\frac{\parallel x_k - v_i \parallel}{\parallel x_k - v_j \parallel} \right)^{2/(m-1)}} \qquad (6)$$

where

n : number of data points, c : number of clusters

x_k : k[th] data point

v_i : i[th] cluster center

μ_{ik}: degree of membership of k[th] data in i[th] cluster,

m : constant

When the input precisely matches with the centre of the cluster, this definition guarantees that the input will have zero membership coefficients for other clusters. It guarantees that the separate clusters are formed allowing the rules based on them to be defined. The mapping from the input space to output space is then performed using the rule base extracted by this method.

A Sugeno-Tkagi (S-T) FIS system is trained using 150 sessions of database collected from 30 subjects and tested using 18 sessions that are completely new to the trained system. The result of the S-T FIS trained for F1 feature space is given in Figure 7showing that the decision system was able to predict most of the cases.

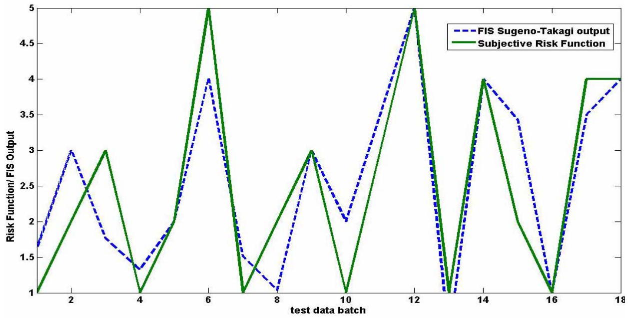

Figure 7. Output of S-T FIS vs Risk function over F1 space

The performances of F2 and F3 feature spaces are given in Figure 8 and 9 respectively. F2 feature space containing the control and entropy metrics and lacking the visual metrics is not successful in predicting the test data precisely.

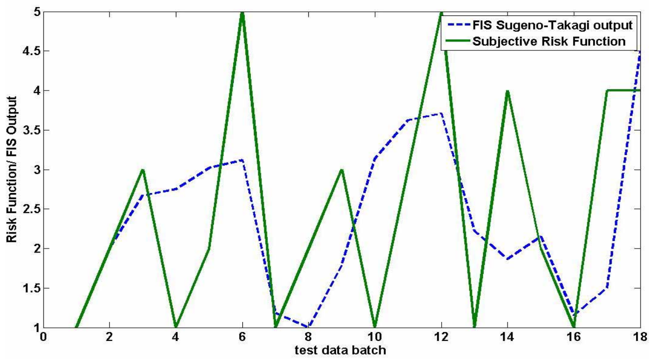

Figure 8. Output of FIS-S-T system vs Risk function over F2 space

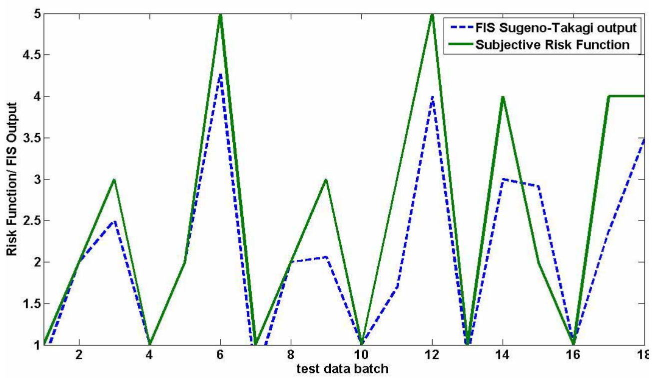

Figure 9. Output of FIS-S-T system vs Risk function over F3 space

Adding standard deviation values of non-visual metrics to visual metrics caused a drop in performance when compared to F1. However, F3 is still advantageous to F1 because it does not solely depend on the visual metric. When the visual metrics become completely unavailable F3 can still judge the drowsiness level based on non-visual metrics it contains. On the other hand F2 feature space shows that it is not enough to include only control and entropy related metrics, the visual metrics are of crucial role in the system.

The performances of these three feature spaces are summarised in Table 3.

PERFORMANCE COMPARISON	F1		F2		F3	
	Success (%)	**False Alarm (%)**	**Success (%)**	**False Alarm (%)**	**Success (%)**	**False Alarm (%)**
Mamdani	90	10	80	20	85	15
Sugeno-Takagi	98	none	90	10	95	5

Table 3. Performances of three feature spaces using S-T FIS for decision making

After observing the feature space performances from F1, F2 and F3, it is decided that the best feature space,F4, should be put under test to obtain an optimum performance form the available metrics. This feature spaces includes only the metrics having high correlations with ground truth as explained before. The test results from F4 space is shown in Figure 10.

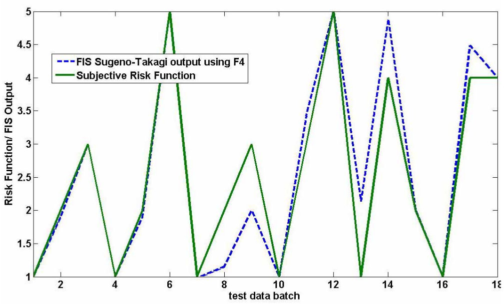

Figure 10. Test results of S-T FIS using F4 space

Feature space F4 was able to correctly identify 98% of the sessions; therefore, proving to be the best feature space. For the rest of the analysis including time windows, therefore, F4 will be used and tested.

The next step in our investigation is to analyse the effect of the time window on the performance of the decision system. For this reason, the time window is successively halved to obtain 6 min, 3 min and 1.5 min intervals corresponding to 1000, 500 and 250 frames of the video segments of the NIR computer vision system. The results of 6-min time window is given in Figure 11.

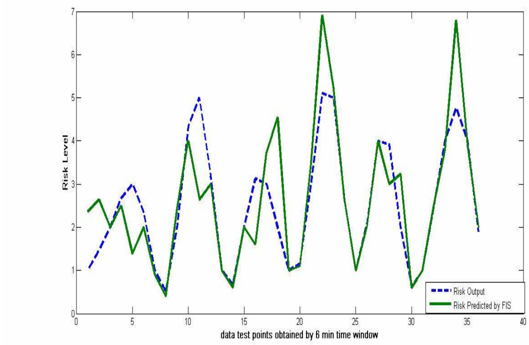

Figure 11. Output from S-T FIS using 6-min time window in calculating feature space

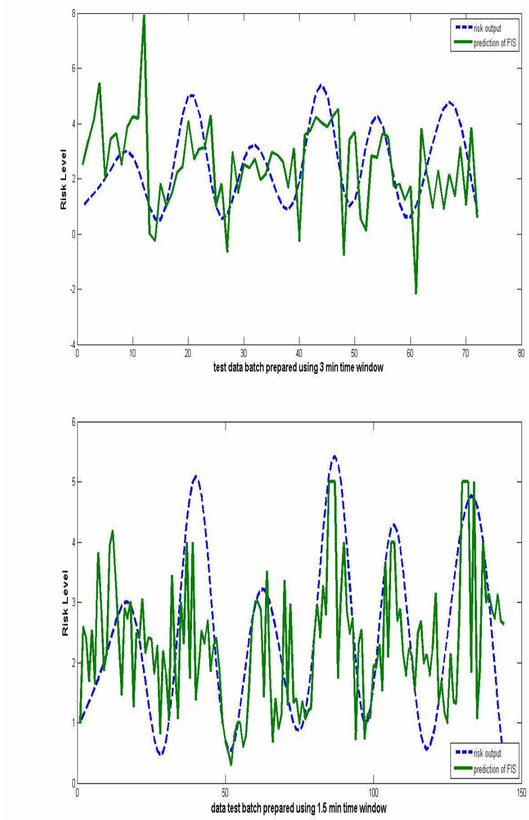

Figure 12. Output from S-T FIS using 3 and 1.5 min time window in calculating feature space

As the time window for the calculation of the feature vectors narrows down the system is able to track the general trend efficiently however after 3 min it begins to fluctuate. The fluctuation occurs because of the quantization and re-sampling between the data points. However, the system is able to give reasonable response for each time window. Preferably the 3 min time window is a good compromise between fast response and generalization capability or tracking capability of the general trend. These observations can be tracked from Figure 12.

CONCLUSIONS

In this study, a multi-sensor driver vigilance monitoring system is designed using the-state-of-the-art signal modeling techniques and Fuzzy Inference Systems. This study investigates three important aspects of monitoring system design problem: reliability, availability and robustness. In order to find an answer these three requirements, best feature space, the time window used in calculations and an optimum decision system are sought after. As can be seen from the results, the visual channels of information are proven to be the most powerful signals to detect the drowsiness and associated risk. In addition to conventional eye closure metrics, a new metric developed to measure the distribution of the attention of the driver. It has been found highly correlated to the involved risk level due to drowsiness. The best feature space is defined according to correlations with the perceived risk level. Finally, it is concluded that a Fuzzy Inference System using a feature space containing visual metrics of eye closure, attention distribution, head movement and non visual metrics of entropies of the steering wheel angle and the force on the steering wheel supported by control performances (IAE and ISE) of the longitudinal speed is the best. The best time window for calculating the metrics is identified as 3 minutes.

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OBJECTIVE TEST SCENARIOS FOR INTEGRATED VEHICLE-BASED SAFETY SYSTEMS

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ABSTRACT

This paper presents a set of crash-imminent test scenarios to objectively verify the performance of integrated vehicle-based safety systems designed to address rear-end, lane change, and run-off-road crashes for light vehicles and heavy trucks. National crash databases are analyzed to identify applicable pre-crash scenarios and guide development of track-based test procedures that can be safely and efficiently carried out. Requirements for an independent measurement system to verify the crash warning system performance are also discussed.

INTRODUCTION

In November 2005, the U.S. Department of Transportation (U.S. DOT) entered into a cooperative research agreement with a private consortium led by the University of Michigan Transportation Research Institute (UMTRI) to build and field test an integrated vehicle-based safety system designed to prevent rear-end, lane change and run-off-road crashes [1]. This four-year, two-phase program being carried out under this agreement is known as the Integrated Vehicle-Based Safety Systems (IVBSS) program within the U.S. DOT.

The IVBSS prototypes being developed will provide forward collision warning (FCW), lane departure warning (LDW), lane change warning (LCW), and curve speed warning (CSW) functions.

FCW alerts drivers when they are in danger of striking the rear of the vehicle in front of them traveling in the same direction. The LDW function provides alerts to drivers when a lateral drift toward or over lane edges is sensed without a turn signal indication.

LCW will increase a driver's situational awareness of vehicles in close proximity traveling in adjacent lanes in the same direction. The CSW function warns drivers when they are traveling too fast for an upcoming curve.

The integrated safety system for the light vehicle platform will include the FCW, LDW, LCW and CSW functions; the heavy commercial truck platform will include the FCW, LDW, and LCW functions only.

During the first two years of the IVBSS program, the industry team will design, build, and verify integrated safety system prototypes for use on passenger cars and heavy trucks. The prototype vehicles will undergo a series of closed-course track tests aimed at ensuring that the integrated system meets the performance requirements and is safe for use by unescorted volunteer drivers during a planned field operational test.

Following successful prototype vehicle testing, the industry team will develop field test concepts and build a vehicle fleet of 16 passenger cars and 10 heavy trucks for use in the field test.

Approximately 108 subjects will be recruited to participate in the light vehicle field operational test. Test participants will drive an IVBSS-equipped 2007 Honda Accord sedan as their own personal vehicle for six weeks. A trucking company will be selected to participate in the heavy truck field operational test. A fleet of ten equipped trucks will be driven by a pool of 15-20 professional drivers over a ten-month period. The field tests will begin in July 2008 and continue for about one year.

The procedures used to verify the crash warning system performance will consist of representative crash-imminent driving scenarios in which a crash warning should be issued, as well as driving scenarios in which a warning should not be issued [2]. Driving scenarios in which a warning should not be issued are also known as nuisance tests or "do not warn" scenarios.

The crash-imminent scenarios will be based on the most frequently occurring rear-end, lane change and run-off-road crash types being addressed by the IVBSS program. The nuisance tests or "do not warn" scenarios, on the other hand, will be developed from a variety of real-world driving conditions to test the capability and known limitations of state-of-the-art technologies in recognizing and classifying targets.

The remainder of this paper describes development of crash-imminent test scenarios that will be used in the IVBSS program to verify the prototype vehicle crash warning system performance. These tests are a subset of tests proposed in earlier research on crash warning systems [2, 5], as well as new scenarios that assess system operation when near-simultaneous warning conditions exist (called multiple-threat scenarios).

OVERVIEW OF TARGET CRASH PROBLEM

The most common pre-crash scenarios addressed by the IVBSS program appear in crash statistics reported in the 2000-2003 General Estimates System (GES) crash databases [3]. The following section contains a summary of the dynamically distinct vehicle movements and critical events occurring immediately prior to the crash that will form the basis for test scenario development.

Rear-End Pre-Crash Scenarios

Based on 2003 GES crash statistics, a light vehicle struck a lead vehicle in 1,677,000 police-reported (PR) rear-end crashes. A heavy truck was the striking vehicle in 46,000 PR rear-end crashes annually, based on 2000-2003 GES crash statistics.

Table 1 lists the most common pre-crash scenarios in rear-end crashes for striking light vehicles and heavy trucks in descending order based on their relative frequency of occurrence. The lead-vehicle-decelerating scenario encompasses crashes where the lead vehicle is struck while decelerating, and crashes where the lead vehicle has just decelerated to a stop and then is struck before turning at a junction or in the presence of a traffic control device.

Table 1. Target Rear-End Pre-Crash Scenarios

Rear-End Pre-Crash Scenarios	Light	Truck
Lead vehicle is decelerating	52%	35%
Lead vehicle is stopped	26%	32%
Lead vehicle is moving at constant speed	14%	22%
Following vehicle is making a maneuver*	5%	7%
Other scenarios where vehicle is striking	3%	4%
Total	100%	100%

* Passing, leaving a parked position, entering a parked position, turning right, turning left, making a U-turn, backing up, changing lanes, merging, corrective action, or other.

Lane Change Pre-Crash Scenarios

The lane change family of crashes typically consists of a situation in which a vehicle attempts to change lanes, merge, pass, leave or enter a parking position, drifts and strikes, or is struck by another vehicle in the adjacent lane while both are traveling in the same direction. Light vehicle and heavy trucks were changing lanes, passing, merging, turning, parking, or drifting in respectively 461,000 (2003 GES) and 48,000 (2000-2003 GES annually) PR lane change crashes.

Table 2 lists the most common pre-crash scenarios in lane change crashes for encroaching light vehicles and heavy trucks in descending order based on their relative frequency of occurrence. In the first scenario listed in the Table 2, the lane change maneuver refers to a vehicle changing lanes while maintaining constant longitudinal speed. The passing maneuver indicates that the vehicle is accelerating while changing lanes.

Table 2. Target Lane Change Pre-Crash Scenarios

Lane Change Pre-Crash Scenarios	Light	Truck
Vehicle changes lanes or passes	60%	48%
Vehicle turns	17%	29%
Vehicle drifts	14%	18%
Vehicle merges	5%	4%
Other scenarios where vehicle is encroaching	4%	1%
Total	100%	100%

Run-Off-Road Pre-Crash Scenarios

Run-off-road scenarios include crashes resulting from an unintentional road edge departure, as well as crashes where the driver loses control due to excessive speed on curves. The IVBSS program will target 549,000 PR run-off-road crashes involving light vehicles and 55,000 heavy truck PR run-off-road crashes annually.

Table 3 identifies target run-off-road pre-crash scenarios and their relative frequency. It should be noted that the heavy truck integrated safety system will not include the curve speed warning function and will not address loss of control due to excessive speed.

Table 3. Target Run-Off-Road Scenarios

Run-Off-Road Pre-Crash Scenarios	Light	Truck
Vehicle is going straight & departs road edge	47%	73%
Vehicle is negotiating a curve & departs road edge	21%	27%
Vehicle is negotiating a curve & loses control	31%	
Total	100%	100%

CRASH-IMMINENT TEST SCENARIOS

The crash-imminent test scenarios described in this section are based on the most common pre-crash scenarios previously identified in Tables 1-3. These scenarios represent the majority of driving conflicts that IVBSS functions will address on public roadways.

The test scenario figures that follow conceptualize each proposed test, but are not drawn to scale. The term subject vehicle (SV) and principal other vehicle (POV) refer respectively to the IVBSS-equipped vehicle (either light vehicle or heavy truck) and principal other vehicle involved in the crash scenario.

The subject vehicle's trajectory includes a red "x" that indicates the start of the abort path if no warning occurs by this point.

Rear-End Crash-Imminent Test Scenarios

Table 4 lists nine recommended scenarios to test the system's ability to sense and produce alerts for rear-end crash-imminent threats. The first four test scenarios follow directly from the most common rear-end pre-crash scenarios given in Table 1. The remaining five scenarios verify the system's ability to detect cars on curves, distinguish motorcycles in traffic, and recognize lead vehicles cutting in or out of traffic ahead.

Table 4. Rear-End Crash Threat Test Scenarios

No	Description
1	SV encounters slower* POV
2	SV encounters decelerating POV
3	SV encounters stopped POV on straight road
4	SV changes lanes & encounters slower POV
5	SV encounters stopped POV on curve
6	SV encounters slower motorcycle behind truck
7	SV encounters slower POV after cut-in
8	SV encounters decelerating POV1 after POV2 cut-out
9	SV encounters slower motorcycle

* Slower refers to a vehicle moving at slower constant speed
SV≡ Subject Vehicle, POV≡ Principal Other Vehicle

The first scenario, as shown in Figure 1, tests the ability of the system to recognize the dynamic state of a slower lead vehicle (constant speed) and issue an alert accordingly. This scenario should be conducted at a closing speed greater than 32 km/h (20 mi/h).

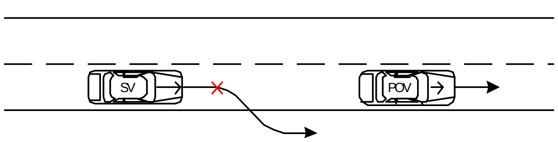

Figure 1. Slower Lead Vehicle

Figure 2 illustrates the second test scenario where the SV is initially following the POV at a constant time gap and then the POV suddenly decelerates. The objective of this scenario is to test whether a decelerating lead vehicle will be recognized and an alert is issued in a timely manner. This scenario should be performed under two different sets of initial conditions:

- Time gap ≤ 2 seconds and POV deceleration ≤ 2 m/s^2 (highway), and
- Time gap > 2 seconds and POV deceleration > 3 m/s^2 (arterial road).

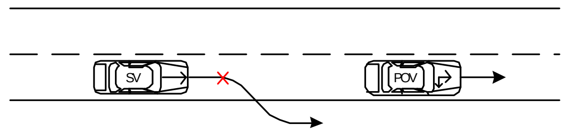

Figure 2. Decelerating Lead Vehicle

Figure 3 shows the third scenario that tests the ability of the FCW function to detect a stopped lead vehicle. This scenario should be conducted at a moderate speed (72 km/h (45 mi/h)) and a high speed (97 km/h (60 mi/h)).

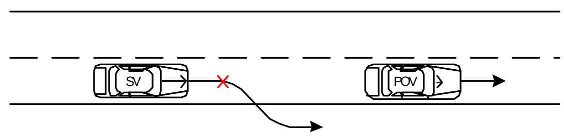

Figure 3. Stopped Lead Vehicle

The fourth test scenario involves the SV making a signaled lane change and then encountering a slower POV at a constant speed as indicated in Figure 4. This test verifies the ability to detect a slower vehicle and issue an alert in a timely manner following a lane change maneuver. The SV should complete its lane change just before entering the system's forward warning zone, and approach the POV at a closing speed below 16 km/h (10 mi/h).

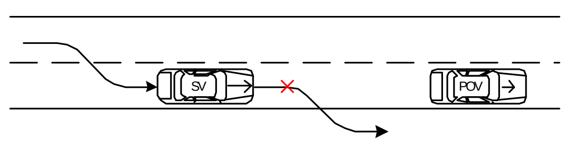

Figure 4. Slower Lead Vehicle after Lane Change

Figure 5 shows the schematic of the fifth test scenario dealing with a lead vehicle stopped on a curve. This test assesses the system's ability to detect stopped vehicles not in the direct line of sight and to issue a timely alert. It is recommended that a minimum radius curve (< 500 m), corresponding to a low vehicle speed and rural road setting, be used. This scenario should be conducted under two conditions:

- SV in transition from straight to curved road encounters POV at curve entry, and
- SV in the curve encounters POV at curve exit.

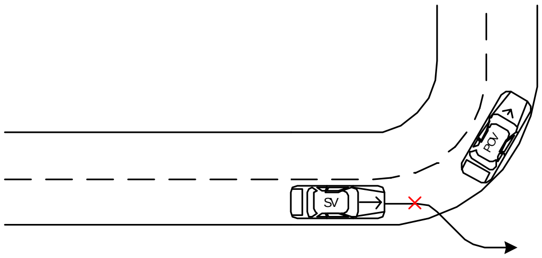

Figure 5. Lead Vehicle Stopped on Curve

The sixth test scenario will demonstrate the ability of the integrated system to discriminate between small and large targets closely following each other in the same lane ahead, and issue an alert based on proximity to the closer, small target. Figure 6 shows an SV closing on a slower motorcycle following a truck at the same speed.

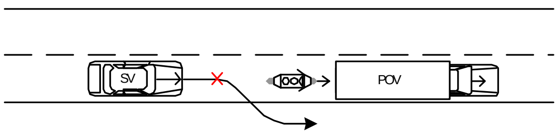

Figure 6. Slower Lead Motorcycle behind Truck

Figure 7 illustrates a slower lead vehicle cutting in ahead of the SV, testing the ability of the system to recognize a quickly emerging threat from adjacent lanes and to issue a timely FCW alert. The cut-in by the POV should be completed within the warning range of the system.

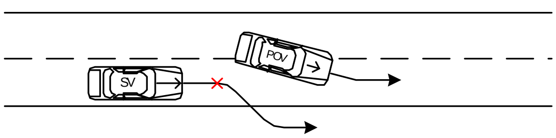

Figure 7. Slower Lead Vehicle Cut-in

The eighth scenario tests the system's ability to switch between targets in the same lane ahead, and to issue a timely FCW alert to the threatening target. Figure 8 shows one POV cutting out ahead of the SV while revealing another POV decelerating in front.

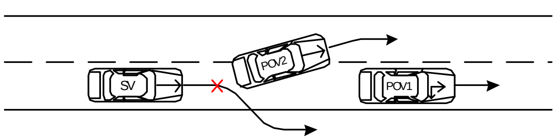

Figure 8. Lead Vehicle Cutting out Revealing another Lead Vehicle Decelerating

The final rear-end crash-imminent test scenario deals with a slower motorcycle ahead as shown in Figure 9. This test checks the ability to detect a small target and issue a timely FCW alert to prevent the host vehicle from striking the motorcycle.

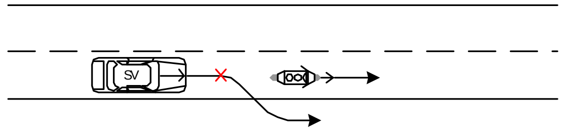

Figure 9. Slower Lead Motorcycle

Lane Change Crash-Imminent Test Scenarios

Table 5 lists five scenarios addressing the most common lane change crash-imminent threats previously described in Table 2.

Table 5. Lane Change Crash Threat Test Scenarios

No	Description
1	SV changes lanes & encounters adjacent POV on straight road
2	SV changes lanes & encounters adjacent POV on curve
3	SV changes lanes & encounters adjacent POV during merge
4	SV changes lanes & encounters adjacent POV after passing
5	SV changes lanes & encounters approaching POV

The first lane change scenario, shown in Figure 10, tests the ability to detect a vehicle in the adjacent lane, on both sides alongside the host vehicle, and to issue an LCW alert accordingly. It is recommended that lane change be performed at a lateral speed less than or equal to 0.5 m/s. This test should be conducted under two conditions:

- POV in the blind spot to the right of the SV; POV front bumper behind SV driver position
- POV in forward position to the left of the SV; POV rear bumper ahead of SV driver position.

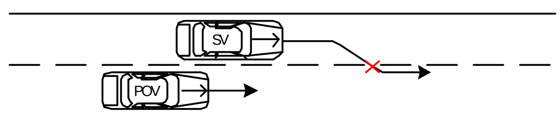

Figure 10. Lane Change on Straight Road

Figure 11 illustrates the second test scenario where the SV changes lanes to the left adjacent lane on a curve. The POV is in the blind spot of the SV. This test emulates a turning maneuver. A large radius curve is recommended for this test.

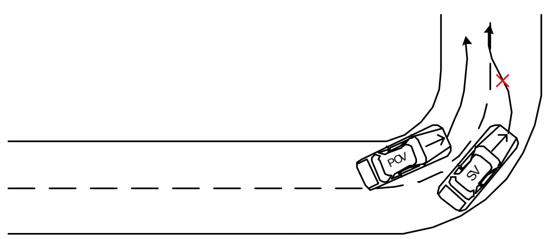

Figure 11. Lane Change on Curve

The third lane change test scenario depicts a merging scenario by the SV, as shown in Figure 12. This scenario tests whether a side collision threat during a merge maneuver where the lane markers disappear can be detected by the system. The SV may use the turn signal to indicate an intentional lane change.

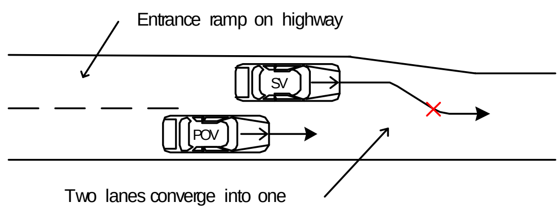

Figure 12. Lane Change/Merging

Figure 13 illustrates a passing maneuver with a side collision threat. The lane change maneuver should be performed with a lateral speed greater than 0.5 m/s and less than or equal to 0.8 m/s.

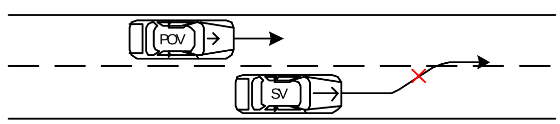

Figure 13. Lane Change after Passing

The fifth lane change test scenario given in Figure 14 deals with a POV moving at a speed faster than the SV in the adjacent lane. The SV initiates a lane change toward the POV at a low lateral speed (≤ 0.5 m/s), where the POV is inside a proximity zone extending 9 m back from the rear of the SV [4].

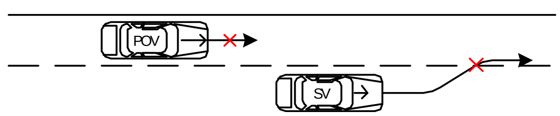

Figure 14. Lane Change onto Approaching Car

Run-Off-Road Test Scenarios

Table 6 lists five scenarios to test the system's ability to recognize the most common run-off-road pre-crash scenarios identified in Table 3. The first four scenarios address the LDW function for both light vehicles and heavy trucks. The fifth test scenario focuses on the CSW function for light vehicles only.

Table 6. Run-Off-Road Threat Test Scenarios

No	Description
1	SV departs road toward opposing traffic lane
2	SV departs straight road onto clear shoulder
3	SV departs curve onto clear shoulder below excessive speed
4	SV departs road (no lane marker) toward Jersey barrier
5	SV approaches curve at excessive speed

Figure 15 illustrates a run-off-road test scenario where the LDW function must recognize a crossing of the double solid line boundary into opposing traffic lanes. Crash statistics show that light vehicles and heavy trucks depart the left edge of the road respectively in 31 and 21 percent of road edge departure crashes on straight roads. This test should be conducted twice with two different lateral speeds:

- Low lateral speed below 0.5 m/s, and
- High lateral speed between 0.5 and 0.8 m/s.

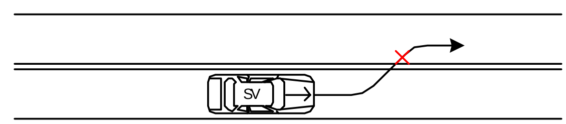

Figure 15. Lane Departure toward Opposing Traffic Lane

The second run-off-road test scenario addresses lane departure on to the shoulder of the right side of the road as shown in Figure 16. This test should be performed twice, with low and high lateral speeds as indicated above.

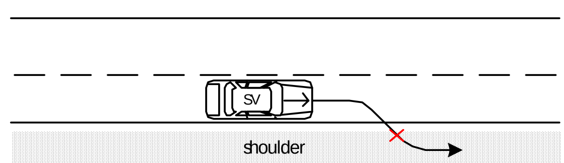

Figure 16. Right Road Edge Departure

Figure 17 depicts a road edge departure scenario on a curve to test the ability of the system to recognize curved roadways and issue timely LDW alerts. This test should implement a low lateral speed departure below 0.5 m/s. Moreover, this test should be performed for the following set of conditions:

- Small radius curve and low travel speed, and
- Large radius curve and high travel speed.

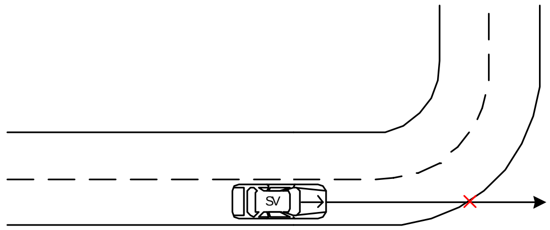

Figure 17. Road Edge Departure on Curve

Figure 18 illustrates the SV departing the left edge of a straight road bounded by a Jersey barrier instead of lane markings. This scenario tests whether the integrated system would produce a side collision warning even if lane tracking were unavailable.

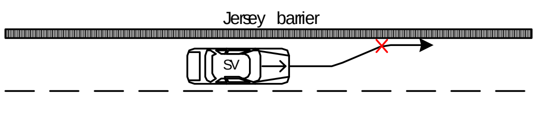

Figure 18. Road Departure toward Jersey Barrier

The last run-off-road test scenario, shown in Figure 19, addresses the performance of the CSW function. The SV approaches the curve at a speed that is unsafe to negotiate the curve. This test should be performed twice under two different environmental conditions:

- Warm temperature (simulated) and dry (wiper off) conditions, and
- Cold temperature (simulated) and wet (wiper on) conditions.

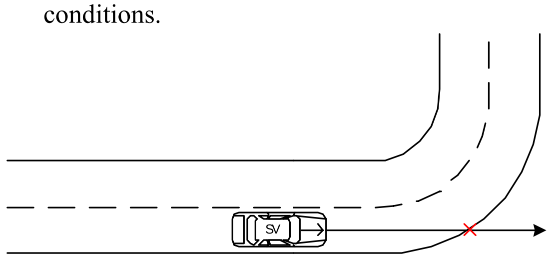

Figure 19. Approaching Curve at Excessive Speed

Multiple-Threat Test Scenarios

In this section, a set of crash-imminent scenarios to evaluate the ability of an integrated system to recognize and issue crash alerts in near-simultaneous threat events is proposed. The main purpose of these tests is to assess the integrated system's ability to recognize, prioritize and manage warnings when multiple collision threats exist.

There are very few police-reported crashes in the GES that involve one vehicle taking a prior evasive maneuver to prevent a crash and then being involved in another crash. In these cases, the GES does not identify the critical event associated with the prior evasive maneuver. Thus, the following three multiple-threat test scenarios were developed by combining selected crash-imminent test scenarios presented above for rear-end, lane change, and run-off-road crashes:

1. Rear-end and lane change crash-imminent threats
2. Rear-end, lane change, and run-off-road crash-imminent threats
3. Rear-end and run-off-road crash-imminent threats

Figure 20 illustrates the first multiple-threat test scenario. The SV is moving at a constant speed and encounters a stopped lead vehicle (POV1) ahead. The SV then attempts to change lanes to the right adjacent lane occupied by another vehicle (POV2). For safety reasons, the figure shows POV2 steering clear to avoid a collision. The integrated system should provide time for the driver to slow and avoid the rear-end collision and be made aware of an impending side collision.

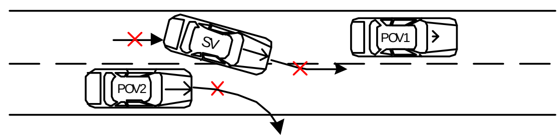

Figure 20. Rear-End and Lane Change Threats

The second multiple-threat test scenario, depicted in Figure 21, reverses the order of threats and includes a third threat. The SV driver encounters a vehicle (POV2) in an adjacent lane during a lane change maneuver. After receiving an LCW alert, the SV driver steers back into the initial lane and encounters a lead vehicle (POV1) decelerating ahead. After an FCW alert, the SV driver departs the right edge of the road onto a clear shoulder to avoid hitting POV1. Again, the warning system should provide time for the driver to slow down prior to the rear-end collision and to make the driver aware of an impending side collision.

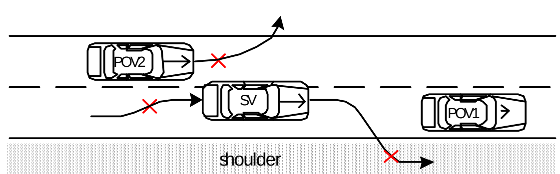

Figure 21. Lane Change, Rear-End and Run-Off-Road Threats

As shown in Figure 22, the third multiple-threat test scenario exposes the SV to a stopped POV in the same lane ahead. After an FCW alert, the SV driver departs the right edge of the road onto a clear shoulder and then stops.

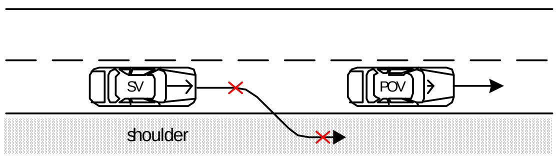

Figure 22. Rear-End and Run-Off-Road Threats

EVALUATION OF CRASH ALERT TIMING

Once a candidate set of test scenarios has been identified, they should be validated on a test track. Test procedure validation includes demonstrating that it is possible to perform the test in a safe and efficient manner, and that the data and information needed to assess system performance can be collected and produce repeatable results.

Crash-imminent alert timing is evaluated using quantitative metrics and data collected from a measurement system that is independent of the crash warning system under test. The quantitative metrics are based on kinematic equations for each scenario and expected driver response [6].

INDEPENDENT MEASUREMENT SYSTEM

The IVBSS program will use an independent measurement system (IMS) developed by the National Institute of Standards and Technology (NIST).

System Requirements

The main purpose of the IMS is to collect data needed to verify that the warning system issues proper alerts and to evaluate the alert timing for each crash-imminent test scenario. The IMS should be able to:

1. *Operate on closed-course test tracks and public road environments*: Certain IMS implementations may provide increased accuracy in test track conditions, for example, equipping every vehicle with differential global positioning system (GPS). However, equipping all vehicles during on-road tests is not feasible.
2. *Operate for light vehicle and heavy truck tests*: Heavy trucks with trailers present particular challenges during lane change or merge tests with fast approaching vehicles.
3. *Not affect warning system operation or performance*: The vehicle-mounted IMS must not interfere with warning system sensors by occluding their field of view or affect warning system operation if electrical connection to the vehicle's power or warning system data busses is required.
4. *Achieve accuracy greater than the warning system under test*: Prior work [2] suggests that test instrumentation errors should be no greater than a maximum of 2 m or 5 percent of the range being measured (95 percent confidence). Characterization tests to verify IMS accuracy are discussed below.

System Description

The independent measurement system under development for the IVBSS program is based on an earlier design that was used to assess the performance of a roadway departure collision warning system [7]. The earlier system included calibrated cameras to measure range to adjacent objects and to the road edge at distances up to 4 m [7]. The IMS is being extended to measure range and range-rate to longer-range objects, either in front of the vehicle or to the rear of the vehicle in the adjacent lane. The minimum requirements for the range measurement system include (desirable capability in parentheses):

- Range out to 60 m (100 m)
- Field of view (FOV) of 180 degrees (360 degrees) horizontal with 0.5 degrees (0.25 degrees) resolution, and
- 10 Hz (30 Hz) update rate.

Figure 23 shows a dual-head, laser-range scanner system that meets these requirements.

Figure 23. Test-bed Vehicle with Dual-head Laser-range Scanner

Measurement System Validation

Before the IMS can serve as a reference for judging warning system performance, its accuracy must be characterized and results documented. System validation of the laser scanner includes static and dynamic characterization tests aimed at obtaining quantitative measures of range error, range resolution, angular resolution and maximum range.

Static tests evaluate system performance from a stationary position and determine the “best case” system error and uncertainty. Table 7 summarizes the factors considered in the static tests.

Table 7. Static Test Variables

Variable Factor	Value Tested
Range to Target	1 m, 20 m, 40 m, 60 m, 72 m
Target Reflectance	99 % R, 50 % R, 2 % R
Target Angle of Incidence	0°, 30°, 60°
Field of Regard	-60°, 0°, 60° Sensor Azimuth

Static tests rely on repeated measurements under the same conditions. The test involves placing a target at a known range and measuring the error (difference between reference range and the mean value of measurements) and the uncertainty (standard deviation of measurements). Table 8 summarizes the laser scanner static test results.

Table 8. Static Test Results for IMS laser scanner

Variable	Value
Observed Field of Regard	184°
Range Error (1)	0.1 m - 0.01(r) ±
Range Resolution (2)	25 cm
Angular Error (3)	± 0.5°
Maximum Range for a 50% Target (4)	72 m
Maximum Range for a 2% Target (4) (5)	60 m < r < 72 m

Notes: (1) r = measured range; (2) over full range - 3σ; (3) estimate from rotation testing (4) 0.6 m x 0.6 m planar target; (5) 2 % target visible at 60 m but not at 72 m.

The static test results are used for calibrating the laser-scanner and provide a baseline for range accuracy.

Static tests do not characterize all sources of potential errors. Dynamic tests from a moving platform reveal timing and synchronization errors, which produce errors in range that are a function of vehicle speed. Since it is difficult to take consecutive measurements to a target from a known range while the vehicle is moving, target range measurements are combined from repeated trips around a surveyed course. This test requires a time measurement system (TMS) to capture the precise time the vehicle crosses over a surveyed point on the track [8].

Reflective strips at longitudinal distances of 0, 20, 40, and 60 meters from a cylindrical target serve as known reference ranges (see Figure 24). An emitter-detector switch mounted on the test vehicle’s bumper causes the TMS to time stamp when the vehicle crosses a reflector. GPS Universal Time Code time is chosen, since all IMS data use GPS as a time reference. Test data is gathered from at least 10 runs past the target. A complete characterization includes running the vehicle at speeds of 30 m/s (67 mi/h) and 10 m/s (22 mi/h).

As a final step in the validation process, the IMS is installed on each of the vehicle platforms and calibrated. Data collected using the IMS is compared with warning system data to ensure consistency. This step, combined with the results from the static and dynamic characterization tests will be used to demonstrate that the IMS data collected during crash-alert scenarios are accurate and reliable.

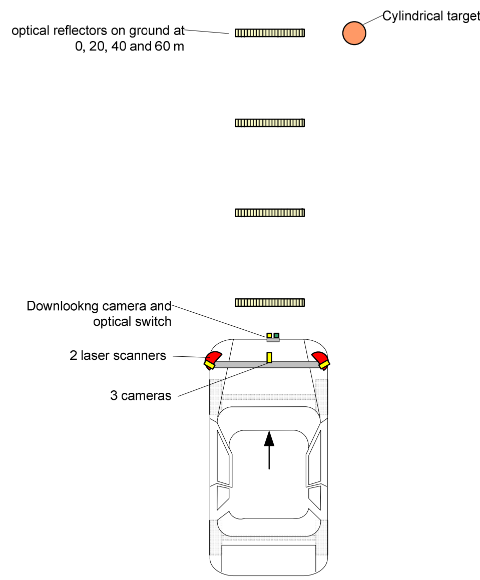

Figure 24. Dynamic Test Configuration

CONCLUSIONS

This paper introduces the IVBSS program and describes the set of test scenarios that will be used to verify that the IVBSS crash warning system meets its performance requirements and is safe for use by drivers prior to the start of planned field operational tests. The test scenarios are based on the most frequently occurring crash types represented in National crash databases.

The test scenarios identified will guide development of detailed test procedures that will include:

- Test track requirements,
- Initial kinematic conditions,
- Instructions for conducting each test,
- Expected system response,
- Test instrumentation and roadside props,
- Data to be collected,

- Analysis techniques, and
- Pass-fail criteria.

Activities are currently underway to develop the test procedures, characterize the independent measurement system, and select suitable test sites to accommodate both test platforms. Validation of the test procedures and the IMS will take place in the spring and summer months of 2007, with the final verification tests scheduled for September and October of 2007.

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CORRELATION BETWEEN JNCAP PEDESTRIAN HEAD PROTECTION PERFORMANCE TESTS AND REAL-WORLD ACCIDENTS

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Paper Number 07-0203

ABSTRACT

The pedestrian head protection performance test was introduced to the Japan New Car Assessment Program (JNCAP) in 2003. Fifty-four car models were tested in 2005. The tests rated total pedestrian head protection performance of cars into levels 1 through 5. Also, the Japanese government began regulating pedestrian head protection for passenger cars in 2005. It is expected that cars are becoming less aggressive in pedestrian accidents.

In such situations, we are interested in the effectiveness of the pedestrian head protection tests introduced in JNCAP.

We will use Japanese national accident data between 2001 and 2005. The pedestrian fatality/severe-injury rate (the number of pedestrians killed or severely injured divided by the total number of pedestrians involved in the accidents) is an index of crash safety for pedestrians. The logistic regression method is applied to adjust for confounding factors (gender of pedestrian, age of pedestrian, guilt of pedestrian, day or night accident and travel speed of the car).

As a result of the study, we saw a correlation between the fatality/severe-injury rate and pedestrian head protection performance levels (1 to 4) in test results, suggesting that passenger cars with better test results protect pedestrians from severe injury in real-world accidents. Also, we observed that fatality/severe-injury rate of car models without pedestrian protection design are higher than that of car models with pedestrian head protection design, suggesting that passenger cars with pedestrian protection design are safer than those without pedestrian protection design in case of pedestrian accidents.

INTRODUCTION

In the early 1990's, fatalities in car accidents were increasing every year, and car-to-car and single car accidents, which constituted to about 47% of all fatal accidents, were the most frequent [1]. The JNCAP tests and the government regulations were introduced in Japan from the middle of the 1990's to reduce the number of fatalities of car drivers or passengers. In Japan, the second most frequent accident type is car-to-pedestrian accident, which constitutes about 25% of all fatal accidents. Reducing fatalities of pedestrians is therefore important in Japan. To this end, JNCAP initiated pedestrian head protection performance tests in 2003, and the government introduced regulations in 2005. It is now expected that car manufacturers will build cars more friendly to pedestrians. In such situations, it is important to investigate if JNCAP pedestrian tests conducted in the laboratory using head impactors are related to real-world accidents.

In this paper, we examine the effectiveness of the pedestrian head protection tests introduced in JNCAP. To see this effectiveness, we set two objectives in our study. One objective is to determine whether JNCAP pedestrian head protection ratings relate to pedestrian safety in real-world accidents. We call this the "Correlation study." The other objective is to determine whether introducing the JNCAP tests had any real effect on pedestrian accidents with regard to injury severity. We call this the "Pedestrian test introduction effect study."

It must be acknowledged that pedestrian protection regulations were introduced only two years after the JNCAP pedestrian head protection tests began, so the regulations' effects are more or less included in our study.

METHOD

Accident Data

The study uses Japanese national accident data compiled by the Institute for Traffic Accident Research and Data Analysis (ITARDA). The accident data we deal with in this paper are car-to-pedestrian accidents, in which pedestrians were hit by passenger cars tested by JNCAP [2]. We focused on accidents where the front of the car hit the pedestrian in order to match the form of the pedestrian test in JNCAP. Also, pedestrians who were not injured are excluded from the analysis. As we have two objectives in our study, we established two accident databases. These are explained below.

Correlation Study - The car models tested in the JNCAP pedestrian test are presented in Table 1. They are classified into five pedestrian head protection performance evaluation levels.

Table 1.
Cars in JNCAP pedestrian tests

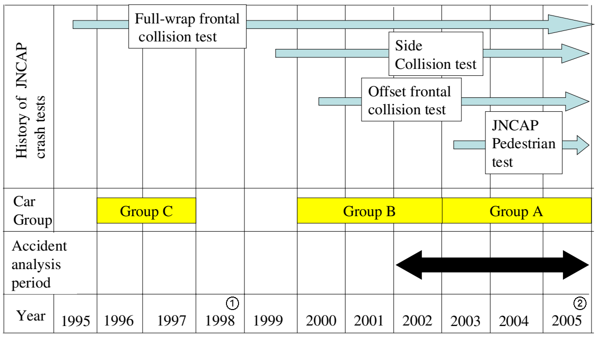
Level	Manufacturer	Model	Model code	Category
1	Suzuki	ALTO Lapin	HE21S	Mini-sized cars
	Suzuki	Jimny	JB23W	Mini-sized cars
	Mazda	RX-8	SE3P	Passenger Cars B
	Toyota	HARRIER	ACU30W	Passenger Cars C
2	Suzuki	wagonR	MH21S	Mini-sized cars
	Honda	LIFE	JB5	Mini-sized cars
	Subaru	R2	RC1	Mini-sized cars
	Subaru	SAMBAR	TV1	Mini-sized cars
	Daihatsu	HIJET	S320V	Mini-sized cars
	Mitsubishi	COLT	Z25A	Passenger Cars A
	Toyota	RAUM	NCZ20	Passenger Cars A
	Toyota	PRIUS	NHW20	Passenger Cars A
	Nissan	WINGROAD	Y12	Passenger Cars A
	Subaru	LEGACY Touring Wagon	BP5	Passenger Cars B
	Nissan	TEANA	J31	Passenger Cars C
	Honda	INSPIRE	UC1	Passenger Cars C
	Toyota	CROWN	GRS182	Passenger Cars C
	Toyota	Lexus IS	GSE20	Passenger Cars C
	Mitsubishi	GRANDIS	NA4W	1BOX & Minivans
	Nissan	PRESAGE	TU31	1BOX & Minivans
	Toyota	Probox VAN	NCP51V	Commercial cars
	Nissan	AD VAN	VFY11	Commercial cars
	Nissan	VANETTE VAN	SK82VN	Commercial cars
3	Daihatsu	MIRA	L250S	Mini-sized cars
	Suzuki	ALTO	HA24S	Mini-sized cars
	Daihatsu	Tanto	L350S	Mini-sized cars
	Suzuki	EVERY	DA64V	Mini-sized cars
	Toyota	WiLL CYPHA	NCP70	Passenger Cars A
	Toyota	PASSO	KGC10	Passenger Cars A
	Suzuki	SWIFT	ZC11S	Passenger Cars A
	Toyota	Porte	NNP10	Passenger Cars A
	Mazda	VERISA	DC5W	Passenger Cars A
	Nissan	TIIDA	C11	Passenger Cars A
	Toyota	Belta	KSP92	Passenger Cars A
	Nissan	NOTE	E11	Passenger Cars A
	Mazda	AXELA	BKEP	Passenger Cars B
	Honda	Edix	BE1	Passenger Cars B
	Volkswagen	Golf	1KAXW	Passenger Cars B
	Honda	CIVIC	FD1	Passenger Cars B
	Nissan	FUGA	Y50	Passenger Cars C
	Toyota	WISH	ZNE10G	1BOX & Minivans
	Honda	ODYSSEY	RB1	1BOX & Minivans
	Toyota	SIENTA	NCP81G	1BOX & Minivans
	Nissan	LAFESTA	B30	1BOX & Minivans
	Honda	ELYSION	RR1	1BOX & Minivans
	Mazda	PREMACY	CREW	1BOX & Minivans
	Nissan	SERENA	C25	1BOX & Minivans
4	Daihatsu	mira GINO	L650S	Mini-sized cars
	Toyota	Vitz	KSP90	Passenger Cars A
	Toyota	Ractis	NCP100	Passenger Cars A
	Honda	AIRWAVE	GJ1	Passenger Cars A
	Suzuki	ESCUDO	TD54W	Passenger Cars B
	Toyota	MARK X	GRX120	Passenger Cars C
	Toyota	Isis	ANM10W	1BOX & Minivans
	Honda	STEP WGN	RG1	1BOX & Minivans
5	Toyota	RAV4	ACA31W	Passenger Cars C

On this basis, there were 4,710 pedestrians in accidents, of whom 780 sustained fatal or severe injuries.

Pedestrian Test Introduction Effect Study - As in the correlation study, we focused on car-to-pedestrian accidents, in which pedestrians were hit by passenger cars tested by JNCAP. JNCAP primarily selects cars for tests among the top-selling car models in the market. We made three groups of car models classified by the test year in JNCAP. Group A contains car models in Table 1 excluding mini-sized cars. We define group A as car models with pedestrian head protection design (ppd). Group B contains car models tested between 2000 and 2002 in JNCAP (Table 2). We define group B as some car models with p.p.d. Group C contains car models tested between 1996 and 1997 in JNCAP (Table 3) and which do not have ppd.

We defined the ppd by JNCAP test year for the following reasons (Figure 1). The first car model with ppd seemed to be released in 1998 by Honda, so we define car models in Group C (without ppd) as those tested in JNCAP before 1998. We assume that car models tested in JNCAP pedestrian tests have some degree of ppd, so we define them as Group A (with ppd). For Group A and Group C, which include cars tested between 1998 and 2002, some cars may have ppd but some may not. JNCAP began offset frontal crash testing in 2000, and many models were re-tested at that time. We therefore selected test years 2000 to 2002 for Group B (with some ppd).

Mini-sized cars are not included in the accident data in all groups because there were no mini-sized cars in Group C. During that time, JNCAP did not test mini-sized cars.



① First car model designed to protect pedestrian's head released into the market
② Pedestrian head protection regulation started

Figure 1. Definition of car groups by JNCAP test years

Table 2.
Cars in JNCAP tests (Group B)

Manufacturer	Model	Model code	Category
Toyota	Vitz	SCP10	Passenger Cars A
Nissan	CUBE	AZ10	Passenger Cars A
Toyota	FUN CARGO	NCP20	Passenger Cars A
Toyota	COROLLA	NZE121	Passenger Cars A
Nissan	SUNNY	FB15	Passenger Cars A
Honda	CIVIC	EU1	Passenger Cars A
Nissan	WINGROAD	WFY11	Passenger Cars A
Toyota	PRIUS	NHW11	Passenger Cars A
Honda	Fit	GD1	Passenger Cars A
Toyota	bB	NCP31	Passenger Cars A
Subaru	IMPREZA Sports Wagon	GG2	Passenger Cars A
Nissan	MARCH	AK12	Passenger Cars A
Toyota	ist	NCP60	Passenger Cars A
Nissan	CUBE	BZ11	Passenger Cars A
Mazda	DEMIO	DY3W	Passenger Cars A
Toyota	MARK Ⅱ	GX110	Passenger Cars B
Subaru	LEGACY B4	BE5	Passenger Cars B
Nissan	BLUEBIRD SYLPHY	QG1 0	Passenger Cars B
Mitsubishi	LANCER SEDIA WAGON	CS5W	Passenger Cars B
Toyota	RAV4	ACA21W	Passenger Cars B
Nissan	PRIMERA WAGON	WTP12	Passenger Cars B
Nissan	X-TRAIL	NT3 0	Passenger Cars B
Honda	CR-V	RD5	Passenger Cars B
Subaru	LEGACY Touring Wagon	BH5	Passenger Cars B
Toyota	PREMIO	ZZT240	Passenger Cars B
Toyota	CALDINA	AZT241W	Passenger Cars B
Subaru	FORESTER	SG5	Passenger Cars B
Toyota	CROWN	JZS171	Passenger Cars C
Nissan	CEDRIC	HY34	Passenger Cars C
Nissan	SKYLINE	V35	Passenger Cars C
Nissan	STAGEA	M35	Passenger Cars C
Toyota	WINDOM	MCV30	Passenger Cars C
Toyota	BREVIS	JCG10	Passenger Cars C
Mazda	Atenza	GG3S	Passenger Cars C
Honda	ACCORD	CL9	Passenger Cars C
Mitsubishi	Dion	CR9W	1BOX & Minivans
Nissan	SERENA	PC24	1BOX & Minivans
Honda	Odyssey	RA6	1BOX & Minivans
Toyota	ESTIMA	ACR30W	1BOX & Minivans
Mazda	MPV	LW5W	1BOX & Minivans
Toyota	COROLLA SPACIO	NZE121N	1BOX & Minivans
Honda	STREAM	RN1	1BOX & Minivans
Toyota	IPSUM	ACM21W	1BOX & Minivans
Honda	STEPWGN	RF3	1BOX & Minivans
Honda	MOBILIO	GB1	1BOX & Minivans
Toyota	NOAH	AZR60G	1BOX & Minivans
Nissan	LIBERTY	RM12	1BOX & Minivans
Toyota	ALPHARD	ANH10W	1BOX & Minivans

Table 3.
Cars in JNCAP tests (Group C)

Manufacturer	Model	Model code	Category
Toyota	CORSA	EL51	Passenger Cars A
Nissan	PULSAR	FN15	Passenger Cars A
Toyota	CORONA	AT211	Passenger Cars B
Volkswagen	GOLF	1HADY	Passenger Cars B
Subaru	LEGACY TOURING WAGON	BG5	Passenger Cars B
Nissan	CEFIRO	A32	Passenger Cars B
Honda	CR-V	RD1	Passenger Cars B
Mitsubishi	DIAMANTE	F31A	Passenger Cars C
Honda	ODYSSEY	RA1	1BOX & Minivans
Mitsubishi	DELICA SPACE GEAR	PE8W	1BOX & Minivans
Honda	LOGO	GA3	Passenger Cars A
Nissan	MARCH	K11	Passenger Cars A
Toyota	STARLET	EP91	Passenger Cars A
Mazda	DEMIO	DW3W	Passenger Cars A
Nissan	SUNNY	FB14	Passenger Cars A
Nissan	BLUEBIRD	EU14	Passenger Cars B
Honda	ORTHIA	EL2	Passenger Cars B
Toyota	MARK Ⅱ	GX100	Passenger Cars B
Daimler Benz	Mercedes-Benz	202020	Passenger Cars B
Mitsubishi	LEGNUM	EA1W	Passenger Cars B
Nissan	LAUREL	HC35	Passenger Cars B
Honda	STEPWGN	RF1	1BOX & Minivans
Toyota	CROWN	JZS151	Passenger Cars C
Nissan	CEDRIC	HY33	Passenger Cars C

Logistic Regression Analysis

The logistic model we built is described by equation (1). P is the fatality/severe-injury rate (the number of killed or severely injured pedestrians divided by the total number of pedestrians involved in the accidents). The definition of fatality/severe-injury is that a person died or required medical treatment for a month (30 days or more) as a result of the accident.

$$Ln\frac{P}{1-P}=\beta_0+\beta_1\bullet \mathrm{X}_1+\bullet\bullet\bullet+\beta_k\bullet \mathrm{X}_k \qquad (1)$$

The six variables listed below are considered as confounders and are adjusted by logistic regression. Gender, age, and guilt are pedestrian factors, travel speed is a vehicle factor, and day or night is an accident factor. All of the variables are categorical. We categorized age in two ways, rough and detailed.

- Pedestrian's gender (male, female)
- Pedestrian's age (0-6, 7-64, 65+) or age (0-4, 5-9, 10-18, 19-39, 40-49, 50-59, 60-69, 70+)
- Pedestrian's guilt (guilty, not guilty)
- Vehicle travel speed (0km/h to 50km/h, more than 50km/h)
- day or night (day, night)

These variables were introduced into the logistic model by a stepwise selection procedure in statistical software SAS (ver.9) considering the first order of interaction.
After the models were made, we estimated the adjusted odds ratio to compare with the non-adjusted odds ratio estimated from the result without logistic regression adjustment. At the end of the study, we estimated adjusted fatality/severe-injury rate as shown in equation (2) for the correlation study and equation (3) for the pedestrian test introduction effect study in order to interpret the results more easily.

$$P_i=\frac{1}{1+e^{-(\beta_{01}+\beta_i\bullet(\text{Pedestrian head protection evaluation})_i)}} \qquad (2).$$

$$P_j=\frac{1}{1+e^{-(\beta_{02}+\beta_j\bullet(\text{Car group})_j)}} \qquad (3).$$

Analysis Patterns

When conducting logistic regressions, we made several analyses to detect the effect of categorization of age (rough or detailed) and limitation of travel speed (all travel speeds or eliminating high travel speed). If results change drastically, we must discuss the reasons.

For correlation analysis, we conducted four patterns of analyses (Table 4). The concept of Analysis A-1 is that it is a simple model in that there are three or fewer categories for each variable. Analysis A-2 has a more detailed categorization of age than Analysis A-1 as there are eight age categories. Analysis A-3 has the same categorizations as Analysis A-2, but we focused on accidents with vehicle travel speeds of less than 40km/h because the pedestrian impact speed with the car is thought to be 40km/h in the pedestrian test. Speeds exceeding this in real accidents may be beyond the scope of experiment. However, the travel speed is not so accurate, so we expanded the travel speed to less than 50km/h in Analysis A-4.

Table 4.
Analysis patterns for correlation study

Analysis No.	Number of accidents	Extra conditons on accident data	Variable				
			Day/night	Travel speed	Guilt	Gender	Age
A-1	4,710		1. Day 2. Night	1. 0km/h to less than 50km/h 2. More than 50km/h	1. Guilty 2. Not guilty	1. Male 2. Female	1. 0 to 6 2. 7 to 64 3. 65+
A-2	4,710		↑	↑	↑	↑	1. 0 to 4 2. 5 to 9 3. 10 to 18 4. 19 to 39 5. 40 to 49 6. 50 to 59 7. 60 to 69 8. 70+
A-3	4,391	Travel speed is 0km/h to less than 40km/h					↑
A-4	4,602	Travel speed is 0km/h to less than 50km/h					

We conducted two analyses for the pedestrian test introduction effect study (Table 5). Analysis B-1 has rough age categories, whereas Analysis B-2 has detailed age categories.

Table 5.
Analysis patterns for study of investigating the effect of introducing pedestrian test in JNCAP

Analysis No.	Number of accidents	Variable				
		Day/night	Travel speed	Guilt	Gender	Age
B-1	29,187	1. Day 2. Night	1. 0km/h to less than 50km/h 2. More than 50km/h	1. Guilty 2. Not guilty	1. Male 2. Female	1. 0 to 6 2. 7 to 64 3. 65+
B-2	↑	↑				1. 0 to 4 2. 5 to 9 3. 10 to 18 4. 19 to 39 5. 40 to 49 6. 50 to 59 7. 60 to 69 8. 70+

RESULTS AND DISCUSSION

Correlation Study

Correlation between Non-adjusted Fatality/severe-injury Rate and Pedestrian Head Protection Performance Evaluation - Figure 2 plots the fatality/severe-injury rate versus pedestrian head protection performance evaluation. The data of Figure 2 are presented in Table 6. The fatality/severe-injury rate of level one is higher than those of levels 2 and 3, and there is no difference between level 2 and 3. The 95% confidence interval of the fatality/severe-injury rate in level 4 is so wide that it is not significantly different from other levels.

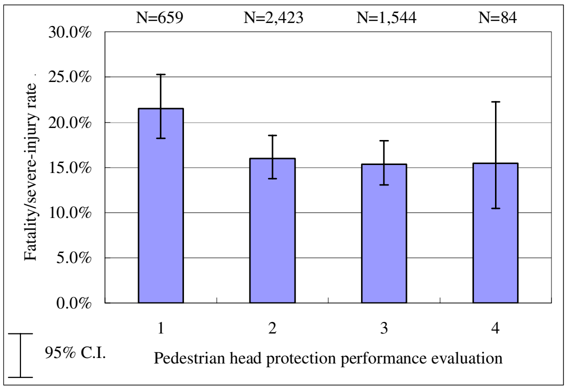


Figure 2. Fatality/severe-injury (non-adjusted) rate versus pedestrian head protection performance evaluation

Table 6.
Fatality/severe-injury rate (non-adjusted) versus pedestrian head protection performance evaluation

Pedestrian head protection performance evaluation	Injury severity			Total	Fatality/ severe-injury rate	95%Confidence int.	
	Fatal	Severe	Minor			Lower	Upper
1	32	110	517	659	21.5%	18.25%	25.27%
2	43	345	2,035	2,423	16.0%	13.76%	18.56%
3	28	209	1,307	1,544	15.3%	13.06%	17.96%
4	2	11	71	84	15.5%	10.47%	22.28%
Total	105	675	3,930	4,710	16.6%	-	-

Remark: There was no accident for evaluation level 5 car model.

The fatality/severe-injury rate (non-adjusted) will be converted to a non-adjusted odds ratio (Table 7) in order to compare the results of logistic regression analyses. Level 1 of the pedestrian head protection performance evaluation is a reference of the odds ratio.

Table 7.
Non-adjusted odds ratio

Pedestrian head protection performance evaluation	Odds ratio	95%Confidence int.	
		Lower	Upper
1	1.000	-	-
2	0.743	0.560	0.860
3	0.712	0.524	0.832
4	0.718	0.359	1.238

Correlation between Adjusted Odds Ratio and Pedestrian Head Protection Performance Evaluation (Analysis A) - Table 8 presents the regression coefficients of the logistic regression model. Only gender was not selected in the stepwise variable selection procedures. The adjusted odds ratio is estimated from the regression coefficients of the pedestrian head protection evaluation and presented in Table 9.

Table 8.
Regression coefficients of analysis (Analysis A-1)

Variable	Category	Regression coefficient	Standard error
Intercept		-0.3422	-
day/night	day	-0.5500	0.1421
	night	0.5500	0.1421
speed	0km/h - 50km/h	-1.0517	0.1194
	more than 50km/h	1.0517	0.1194
guilt	guilty	0.2300	0.0913
	not guilty	-0.2300	0.0913
age	0-6	-0.2600	0.1023
	7-64	-0.4654	0.0667
	65+	0.7254	0.0684
daynight X speedest	day X (0km/h - 50km/h)	0.2671	0.1196
	night X (0km/h - 50km/h)	0.2671	0.1196
daynight X guilt	day X guilty	0.0018	0.0906
	night X not guilty	0.0018	0.0906
pedestrian head protection evaluation	Level1	0.2841	0.1146
	Level2	0.0132	0.0988
	Level3	-0.0791	0.1039
	Level4	-0.2182	0.2509

AIC=3859.007, Adjusted R^2=0.1345

Table 9.
Adjusted odds ratio (Analysis A-1)

Pedestrian head protection performance evaluation	Odds ratio	95%Confidence int.	
		Lower	Upper
1	1.000	-	-
2	0.763	0.607	0.958
3	0.695	0.544	0.899
4	0.605	0.307	1.193

Table 10 lists the regression coefficients of the logistic regression model in Analysis A-2. The adjusted odds ratio is estimated from the regression coefficient of the pedestrian head protection evaluation and presented in Table 11.

Table 10.
Regression coefficients of analysis (Analysis A-2)

Variable	Category	Regression coefficient	Standard error
Intercept		-0.4344	-
day/night	day	-0.2934	0.0447
	night	0.2934	0.0447
speed	0km/h - 50km/h	-1.1677	0.1144
	more than 50km/h	1.1677	0.1144
guilt	guilty	0.2727	0.1038
	not guilty	-0.2727	0.1038
age	0-4	0.2472	0.2811
	5-9	-0.3714	0.1837
	10-18	-1.0522	0.3584
	19-39	-0.8035	0.2892
	40-49	0.3556	0.2688
	50-59	0.2537	0.2618
	60-69	0.0762	0.3113
	70+	1.2943	0.2061
guilt X age	guilty X 0-4	0.4394	0.2805
	guilty X 5-9	-0.1964	0.1821
	guilty X 10-18	-0.5825	0.3586
	guilty X 19-39	-0.0924	0.2887
	guilty X 40-49	0.7075	0.2689
	guilty X 50-59	-0.0219	0.2611
	guilty X 60-69	-0.4331	0.3112
	not guilty X 5-9	0.1964	0.1821
	not guilty X 10-18	0.5825	0.3586
	not guilty X 19-39	0.0924	0.2887
	not guilty X 40-49	-0.7075	0.2689
	not guilty X 50-59	0.0219	0.2611
	not guilty X 60-69	0.4331	0.3112
	not guilty X 70+	-0.1793	0.2059
pedestrian head protection evaluation	Level1	0.2580	0.1151
	Level2	-0.0129	0.0991
	Level3	-0.0897	0.1043
	Level4	-0.1554	0.2507

AIC=3795.672, Adjusted R^2=0.1617

Table 11.
Adjusted odds ratio (Analysis A-2)

Pedestrian head protection performance evaluation	Odds ratio	95%Confidence int.	
		Lower	Upper
1	1.000	-	-
2	0.763	0.605	0.961
3	0.706	0.551	0.905
4	0.661	0.336	1.304

Table 11 lists the regression coefficients of the logistic regression model in Analysis A-3. The adjusted odds ratio is estimated from the regression coefficients of the pedestrian head protection evaluation and presented in Table 13.

Table 12.
Regression coefficients of analysis (Analysis A-3)

Variable	Category	Regression coefficient	Standard error
Intercept		-1.9906	-
day/night	day	-0.2141	0.0489
	night	0.2141	0.0489
age	0-4	0.0104	0.2314
	5-9	-0.1559	0.1246
	10-18	-0.6064	0.1999
	19-39	-0.8040	0.1410
	40-49	-0.2076	0.1609
	50-59	0.2440	0.1221
	60-69	0.4102	0.1134
	70+	1.1093	0.0890
pedestrian head protection evaluation	Level1	0.1999	0.1281
	Level2	0.0402	0.1086
	Level3	-0.0524	0.1140
	Level4	-0.1876	0.2762

AIC=3306.635, Adjusted R^2=0.0944

Table 13.
Adjusted odds ratio (Analysis A-3)

Pedestrian head protection performance evaluation	Odds ratio	95%Confidence int.	
		Lower	Upper
1	1.000	-	-
2	0.852	0.652	1.103
3	0.777	0.590	1.023
4	0.679	0.321	1.436

Table 14 lists the regression coefficients of the logistic regression model in Analysis A-4. The adjusted odds ratio is estimated from the regression coefficients of the pedestrian head protection evaluation and presented in Table 15.

The odds ratios of Analysis A-1 to A-4 results are presented in Figure 3 for comparison. Level 1 of the pedestrian head protection performance evaluation is a reference of the odds ratio. There is almost no difference between A-1 and A-2, which means that using rough and detailed age categorizations does not affect the result. In Analysis A-3, the odds ratio increased but still the odds ratio tends to decrease with the pedestrian head protection performance evaluation levels. In A-3, we focused only on accidents in which the travel speed is less than 40km/h. However, the trend became weaker when excluded the high-speed accidents. In Analysis A-4, we focused on accidents in which the travel speed was less than 50km/h, which is 10 km/h faster than in A-3. The result of A-4 is similar to the result of A-2. In summary, analyses A-1 through A-4 indicate that the odds ratio tends to decrease with the pedestrian head protection performance evaluation level. There thus seems to be a correlation between the odds ratio and the pedestrian head protection performance evaluation.

Table 14.
Regression coefficients of analysis (Analysis A-4)

Variable	Category	Regression coefficient	Standard error
Intercept		-1.6662	-
day/night	day	-0.2727	0.0453
	night	0.2727	0.0453
guilt	guilty	0.2510	0.0916
	not guilty	-0.2510	0.0916
age	0-4	-0.0198	0.2209
	5-9	-0.2172	0.1207
	10-18	-0.7197	0.1956
	19-39	-0.7396	0.1305
	40-49	-0.2059	0.1513
	50-59	0.2572	0.1153
	60-69	0.4960	0.1061
	70+	1.1489	0.0848
pedestrian head protection evaluation	Level1	0.3026	0.1195
	Level2	0.0335	0.1034
	Level3	-0.0676	0.1087
	Level4	-0.2686	0.2647

AIC=0.0641, Adjusted R^2=0.1114

Table 15.
Adjusted odds ratio (Analysis A-4)

Pedestrian head protection performance	Odds ratio	95%Confidence int.	
		Lower	Upper
1	1.000	-	-
2	0.764	0.604	0.966
3	0.691	0.536	0.899
4	0.565	0.276	1.155

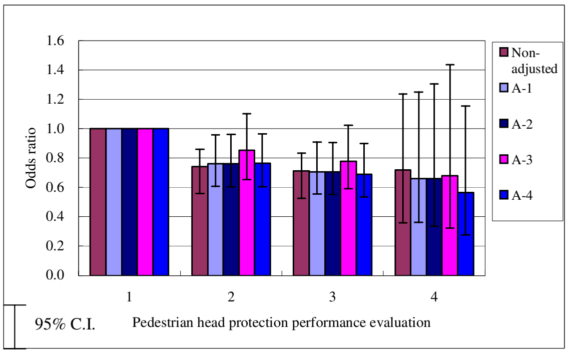


Figure 3. Comparison of non-adjusted and adjusted odds ratios

Adjusted Fatality/severe-injury Rate versus Pedestrian Head Protection Performance Evaluation (Final) - The odds ratio to fatality/severe-injury rate for Analysis A-1 is presented in Figure 4 and Table 16 to indicate the correlation it represents. We consider that Analysis A-1 is a representative result because the odds ratio tended to decrease with the pedestrian head protection performance evaluation level for all analyses (A-1 to A-4).

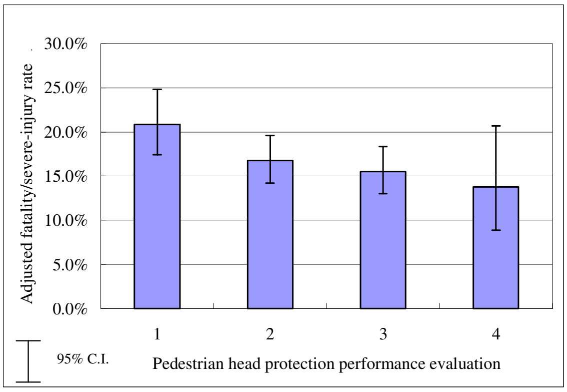


Figure 4. Adjusted Fatality/severe-injury rate (Analysis A-1) versus pedestrian head protection performance evaluation

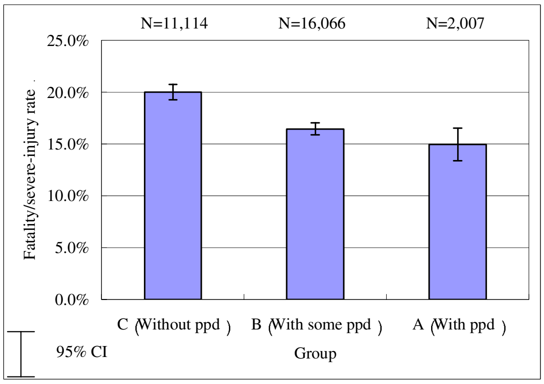


Figure 5. Fatality/severe-injury rate (non-adjusted) versus groups of with or without ppd

Table 16.
Adjusted fatality/severe-injury rate (Analysis A-1) versus pedestrian head protection performance evaluation

Pedestrian head protection performance	Adjusted fatality/ severe-injury rate	95%Confidence int.	
		Lower	Upper
1	20.87%	17.40	24.82
2	16.74%	14.22	19.62
3	15.50%	13.01	18.36
4	13.76%	8.89	20.69

Table 17.
Fatality/severe-injury rate (non-adjusted) by group

	Group	C	B	A
Pedestrian head prodection design		Without	With some	With
JNCAP test year		1996 - 1997	2000 - 2002	2003 - 2005
Injury severerity	Fatal	338	382	36
	Severe	1,884	2,260	264
	Minor	8,892	13,424	1707
Total		11,114	16,066	2,007
Fatality/severe -injury rate		19.99%	16.44%	14.95%
95% C.I.	Upper	20.74%	17.02%	16.51%
	Lower	19.25%	15.87%	13.39%

Pedestrian Test Introduction Effect Study

<u>**Non-adjusted Fatality/severe-injury Rate by Car Groups with or without PPD**</u> **-** Figure 5 plots the fatality/severe-injury rate versus car group with or without ppd. The data of Figure 5 are presented in Table 17. The fatality/severe-injury rate of group A is lower than that of group B, and the fatality/severe-injury rate of group B is lower than that of group C. Car Group C has no pedestrian protection design. Some cars in group B have pedestrian protection designs, and all cars in group A have pedestrian protection designs. With regard to the non-adjusted fatality/severe-injury rate, we can see that a car group with more pedestrian protection design is less aggressive to pedestrians.

The Fatality/severe-injury rate (non-adjusted) will be converted to a non-adjusted odds ratio (Table 18) in order to compare the results of logistic regression analyses. Group C is the reference of the odds ratio.

Table 18.
Non-Adjusted odds ratio

Group	Odds ratio	95%Confidence	
		Lower	Upper
C (Without ppd)	1.000	-	-
B(With some ppd)	0.788	0.740	0.838
A (With ppd)	0.703	0.617	0.802

<u>**Adjusted Odds Ratio by Car Group with or without PPD (Analysis B)**</u> **-** Table 19 lists the regression coefficients of the logistic regression model in Analysis B-1. The adjusted odds ratio is estimated from the regression coefficients of groups A to C and presented in Table 20.

Table 19.
Regression coefficients of Analysis (Analysis B-1)

Variable	Category	Regression coefficient	Standard error
Intercept		-0.5289	-
day/night	day	-0.3301	0.0414
	night	0.3301	0.0414
speed	0km/h - 50km/h	-0.8354	0.0915
	more than 50km/h	0.8354	0.0915
guilt	guilty	0.0270	0.0603
	not guilty	-0.0270	0.0603
age	0-6	-0.4223	0.1598
	7-64	-0.2007	0.0886
	65+	0.6229	0.0924
day/night X guilt	day X first	-0.1115	0.0340
	night X first	-0.1115	0.0340
speed X guilt	(0km/h - 50km/h) X first	0.2832	0.0613
	(more than 50km/h) X first	0.2832	0.0613
daynight X age	day X 0-5	0.1818	0.0592
	day X 6-64	-0.0216	0.0338
	night X 6-64	0.0216	0.0338
	night X 65+	0.1602	0.0348
speed X age	(stopping - 50km/h) X 0-5	0.0100	0.1544
	(stopping - 50km/h) X 6-64	-0.1693	0.0863
	(- 60km/h or more) X 6-64	0.1693	0.0863
	(- 60km/h or more) X 65+	-0.1593	0.0902
group	A	-0.1303	0.0453
	B	-0.0171	0.0279
	C	0.1474	0.0287

AIC=24700.418, Adjusted R^2=0.1390

Table 20.
Adjusted odds ratio (Analysis B-1)

Group	Odds ratio	95%Confidence	
		Lower	Upper
C (Without ppd)	1.000	-	-
B(With some ppd)	0.848	0.794	0.906
A (With ppd)	0.757	0.660	0.870

Table 21 presents the regression coefficients of the logistic regression model in Analysis B-2. The adjusted odds ratio is estimated from the regression coefficients of groups A to C and presented in Table 22.

Table 21.
Regression coefficients of analysis (Analysis B-2)

Variable	Category	Regression coefficient	Standard error
Intercept		-0.6517	-
day/night	day	-0.2245	0.0256
	night	0.2245	0.0256
speed	0km/h - 50km/h	-0.8699	0.0738
	more than 50km/h	0.8699	0.0738
guilt	guilty	0.0152	0.0625
	not guilty	-0.0152	0.0625
age	0-4	-0.1974	0.3197
	5-9	-0.7887	0.1902
	10-18	-0.5422	0.1685
	19-39	-0.2069	0.1271
	40-49	0.1841	0.1624
	50-59	0.3018	0.1341
	60-69	0.3085	0.1258
	70+	0.9407	0.1115
speed X guilt	(0km/h - 50km/h) X first	0.3331	0.0618
	(more than 50km/h) X second	0.3331	0.0618
day/night X age	day X 0-4	0.2406	0.1241
	day X 5-9	0.1286	0.0679
	day X 10-18	0.1102	0.0693
	day X 19-39	-0.0325	0.0520
	day X 40-49	-0.0997	0.0604
	day X 50-59	-0.0405	0.0474
	day X 60-69	-0.1213	0.0426
	night X 5-9	-0.1286	0.0679
	night X 10-18	-0.1102	0.0693
	night X 19-39	0.0325	0.0520
	night X 40-49	0.0997	0.0604
	night X 50-59	0.0405	0.0474
	night X 60-69	0.1213	0.0426
	night X 70+	0.1853	0.0366
speed X age	(0km/h - 50km/h) X 0-4	-0.2888	0.3074
	(0km/h - 50km/h) X 5-9	0.2861	0.1716
	(0km/h - 50km/h) X 10-18	-0.0186	0.1482
	(0km/h - 50km/h) X 19-39	-0.2941	0.1049
	(0km/h - 50km/h) X 40-49	-0.0448	0.1377
	(0km/h - 50km/h) X 50-59	-0.0389	0.1086
	(0km/h - 50km/h) X 60-69	0.1479	0.1023
	(more than 50km/h) X 5-9	-0.2861	0.1716
	(more than 50km/h) X 10-18	0.0186	0.1482
	(more than 50km/h) X 19-39	0.2941	0.1049
	(more than 50km/h) X 40-49	0.0448	0.1377
	(more than 50km/h) X 50-59	0.0389	0.1086
	(more than 50km/h) X 60-69	-0.1479	0.1023
	(more than 50km/h) X 70+	-0.2511	0.0917
guilt X age	guilty X 0-4	-0.3166	0.1294
	guilty X 5-9	-0.2954	0.0722
	guilty X 10-18	-0.1375	0.1015
	guilty X 19-39	0.2996	0.0913
	guilty X 40-49	0.2899	0.1169
	guilty X 50-59	0.1203	0.0957
	guilty X 60-69	-0.0422	0.0910
	not guilty X 5-9	0.2954	0.0722
	not guilty X 10-18	0.1375	0.1015
	not guilty X 19-39	-0.2996	0.0913
	not guilty X 40-49	-0.2899	0.1169
	not guilty X 50-59	-0.1203	0.0957
	not guilty X 60-69	0.0422	0.0910
	not guilty X 70+	-0.0819	0.0765
group	A	-0.1414	0.0458
	B	-0.0094	0.0281
	C	0.1508	0.0290

AIC=24292.762, Adjusted R^2=0.1620

Table 22.
Adjusted odds ratio (Analysis B-2)

Group	Odds ratio	95%Confidence	
		Lower	Upper
C (Without ppd)	1.000	-	-
B(With some ppd)	0.852	0.797	0.911
A (With ppd)	0.747	0.649	0.859

The non-adjusted and adjusted odds ratios are presented in Figure 6 for comparison. Group C is a reference for the odds ratio. There is almost no difference between the odds ratios of Analysis B-1 and Analysis B-2. The adjusted odds ratios of Analysis B-1 and Analysis B-2 are higher than the non-adjusted odds ratio. This means the odds ratio is increased after adjustments. Nevertheless, the odds ratio of group A is lower than that of group B, and the odds ratio of group B is lower than that of group C. We can see that car groups with more pedestrian protection design are less aggressive to pedestrians.

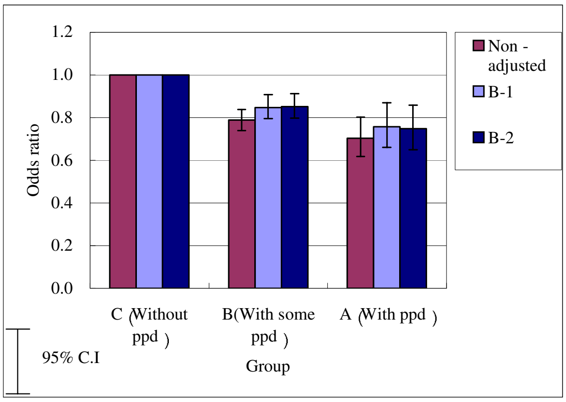


Figure 6. Comparison of non- adjusted and adjusted odds ratios

__Adjusted Fatality/severe-injury Rate by Group (Final)__ **-** The odds ratio to fatality/severe-injury rate is presented in Figure 7 and Table 23 to express the correlation in Analysis B-1. Because the results of Analyses B-1 and B-2 are almost the same, we consider that Analysis B-1 is a representative result.

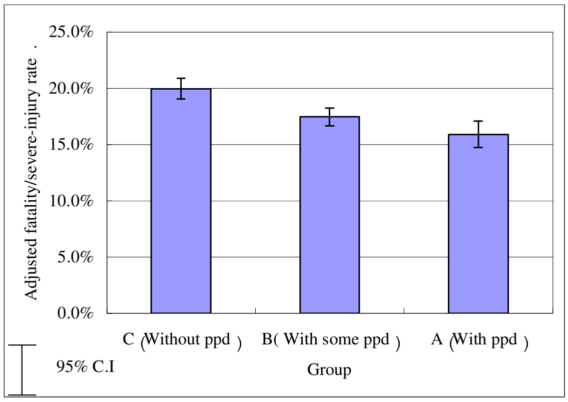


Figure 7. Adjusted fatality/severe-injury rate (Analysis B-1) versus groups of with/without pedestrian head protection performance design

Table 23.
Adjusted fatality/severe-injury rate versus groups of with/without pedestrian head protection performance design

Group	Adjusted fatality/ severe-injury rate	95%Confidence int.	
		Lower	Upper
C (Without ppd)	19.95%	19.07%	20.86%
B(With some ppd	17.45%	16.68%	18.25%
A (With ppd)	15.88%	14.73%	17.10%

CONCLUSION

We investigated the correlation between the pedestrian fatality/severe-injury rate estimated by the accident data and the pedestrian head protection performance evaluation in the JNCAP tests. We also examined the relation between the pedestrian fatality/severe-injury rate and car group with total or partial pedestrian head protection performance design and with or without such design. We adjusted the gender, age, and guilt of the pedestrian and travel speed and by day or night when an accident occurred. The study revealed a correlation between the fatality/severe-injury rate and pedestrian head protection performance levels (1 to 4) in test results, suggesting that passenger cars with better test results protect pedestrians from severe injury better in real-world accidents. We also found that the fatality/severe-injury rate of car models without pedestrian protection design is higher than that of car models with pedestrian head protection design, suggesting that passenger cars with pedestrian protection design are safer than cars without such design in case of pedestrian accidents.

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REAL-WORLD EXPERIENCE WITH ADVANCED AIR BAGS

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Paper Number 07-0207

ABSTRACT

The National Center for Statistics and Analysis's (NCSA) Special Crash Investigations (SCI) program provides the National Highway Traffic Safety Administration with an anecdotal data set that allows the agency to analyze in-depth clinical evaluations of real-world crashes that involve new and emerging technologies. One of SCI's responsibilities is to investigate alleged fatalities that are related to the deployment of air bags in minor to moderate severity crashes. The first part of this paper will compare the number of occupants fatally injured by deploying air bags for either a given model year or a 12-month release period to the number of air-bag-equipped vehicles in the corresponding fleet. In this paper sled-certified air bags with advanced features are defined as air bag systems with one or more advanced occupant protection features such as: multi-stage air bag inflators, seat belt sensors, weight sensors, seat position sensors, or automatic suppression systems. The number of fatalities for occupants injured by sled-certified air bags with advanced features will be compared to those injured by air bags without advanced features. Based on our most recent observations the number of fatalities associated with sled-certified air bags with advanced features is lower than that for air bags without advanced features [1]. An overview of the only published air-bag-related fatality attributed to a sled-certified air bag with advanced features will be provided.

NCSA's National Automotive Sampling System Crashworthiness Data System (NASS CDS) collects data on representative crashes through 27 field research teams who investigate about 4,500 crashes a year. The second part of this paper will analyze SCI and NASS CDS advanced-air-bag data through the end of 2005. A variety of advanced-air-bag-related topics for front-seat occupants will be discussed. Crash severity, occupant seat weight sensors and dual-stage air bag deployments will also be discussed.

BACKGROUND

The SCI program typically classifies frontal air bags into four vehicle categories:

- Predominately pre-1998 model year vehicles certified to unbelted barrier test requirements of Federal Motor Vehicle Safety Standard (FMVSS) No. 208 by barrier testing, or "barrier-certified" vehicles.

- Vehicles (1998 model years and above) certified to the unbelted sled test frontal impact requirements of FMVSS No. 208, or "sled-certified" vehicles.

- Vehicles certified to unbelted sled test requirements of FMVSS No. 208 that have air bag systems incorporating "advanced occupant protection features" (as defined in the abstract), but not certified to the advanced air bag requirements of FMVSS No. 208. In this paper these vehicles are referred to as sled-certified vehicles with "advanced features."

- Vehicles (2003 model years and above) certified to meet the advanced-air-bag requirements of FMVSS No. 208. Hereinafter these vehicles will be referred to as certified, advanced, 208-compliant (CAC) vehicles.

The distinction between the last two types of vehicles is significant, because only the CAC vehicles have been certified to meet the advanced-air-bag requirements of FMVSS No. 208, which are described in the next paragraph. Sled-certified vehicles equipped with air bags with advanced features and CAC vehicles were identified from information that vehicle manufacturers supplied to NHTSA.

The earlier barrier-certified air bag systems are used in vehicles that were certified to a fixed rigid-barrier crash test. In March of 1997, NHTSA issued a rulemaking that made it easier for automobile manufacturers to quickly reduce the inflation power of their air bags, certified to new sled test requirements of FMVSS No. 208. These sled-certified air bags are often referred to as redesigned air bags. Sled-certified air bag systems have been certified using an unbelted sled test option instead of the 30 mph rigid barrier crash test with an unbelted Hybrid III 50th percentile male anthropomorphic test dummy [2]. In May 2000, NHTSA amended FMVSS No. 208 to require the use of advanced-air-bag technology to provide improved frontal occupant protection to all occupants. These CAC air bags were phased in, beginning with vehicles manufactured for sale in the United States on or after September 1, 2003. The rule, with a few minor exceptions, states that light passenger vehicles manufactured for sale in the United States on or after September 1, 2006, are required to have advanced air bags that are certified to S14 [3] of FMVSS No. 208. This amended standard requires vehicles to be certified to meet the following requirements:

- Rigid barrier belted test (at a speed up to and including 30 mph), using a 50th percentile adult male anthropomorphic test dummy.

- Rigid barrier unbelted test (at a speed between 20 and 25 mph), using a 50th percentile adult male anthropomorphic test dummy.

- Rigid barrier belted test (at a speed up to and including 30 mph), using a 5th percentile adult female anthropomorphic test dummy.

- Rigid barrier unbelted test (at a speed between 20 and 25 mph), using a 5th percentile adult female anthropomorphic test dummy.

- Offset frontal deformable barrier belted test (at a speed up to and including 25 mph), using a 5th percentile adult female anthropomorphic test dummy.

- Protection for infants in rear-facing and convertible child restraints and car beds, using a 12-month-old anthropomorphic test dummy either by an automatic suppression feature or a low-risk deployment feature.

- Protection for children, using a 3-year-old anthropomorphic test dummy by an automatic suppression feature, a dynamic automatic suppression system that suppresses the air bag when an occupant is out of position, or a low-risk deployment feature.

    - It is important to note that a manufacturer must petition the agency to accept and put into a final rule a specific test procedure for a dynamic automatic suppression system. There is a requirement that low-risk deployment tests be performed. No manufacturer has successfully petitioned the agency for a dynamic automatic suppression test procedure and thus there are no vehicles certified to this option.

- Protection for children, using a 6-year-old anthropomorphic test dummy either by an automatic suppression feature, a dynamic automatic suppression system that suppresses the air bag when an occupant is out of position, or a low-risk deployment feature.

- Protection for adult female drivers, using an out-of-position 5th percentile adult female anthropomorphic test dummy at the driver position either by a dynamic automatic suppression system that suppresses the air bag when the driver is out of position or a low-risk deployment feature.

AIR-BAG-RELATED FATALITIES AND SERIOUS INJURIES

In October 1996, NHTSA began publishing summary tables for each confirmed air-bag-related fatality and seriously injured occupant. Since January 2001, SCI has published on its Web site quarterly reports of crashes in which a deploying air bag or a deploying module cover flap was determined to have caused a fatality or life-threatening injury to a vehicle’s occupant in a minor- to moderate-severity crash.

Beginning in January 2007, the SCI report of air-bag-related fatalities and serious injuries will be published biannually. An air bag causes fatal and life-threatening injuries when an occupant is either in the deployment path or moves into the deployment path of the air bag and is hit by the deploying air bag or cover flap. The deployment energy is then transferred to the occupant. For the remainder of this paper these cases will be referred to as "air-bag-related" fatalities and life-threatening injuries.

SCI classifies air-bag-related cases as either "confirmed" or "unconfirmed." Confirmed cases are those where the air bag has been confirmed by NHTSA as being the injury mechanism. Unconfirmed cases are crashes under active investigation where an air bag is either alleged to be, or suspected of being, the injury mechanism. Each SCI report consists of:

- A summary of the status of SCI investigations during the reporting period.
- A count of occupants who have sustained fatal or serious injuries in air-bag-deployment-related crashes.
- Tables and charts that show the amount of air-bag- related fatalities, that are normalized by the number of air-bag-equipped vehicles in a given fleet.

Each normalized table and chart consists of confirmed and unconfirmed cases. Summary tables are also published that list all confirmed air-bag-related fatalities and life-threatening injuries. Air-bag- related crashes are grouped into three categories:

- Children under the age of 13.
- Adult drivers.
- Adult passengers.

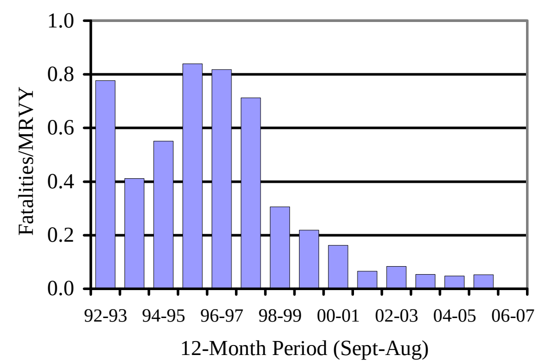
Cases involving children are further divided into two subgroups: infants seated in rear-facing safety seats (RFCSS) and children not seated in RFCSS.

Child Air-Bag-Related Fatalities

<u>Infants in Rear-Facing Safety Seats</u> **-** As of October 1, 2006, there were 26 confirmed cases of infants seated in RFCSS who sustained fatal injuries in air-bag-related cases. These fatalities occurred between the 1995 and 2004 crash years. Four of these fatalities involved an infant in a RFCSS that was held on the lap of a passenger. There were three unconfirmed cases that involved infants in RFCSS.

<u>Children Not in Rear-Facing Child Safety Seats</u> **-** There were 148 confirmed cases of children not in RFCSS who were fatally injured in air-bag-related crashes. These fatalities occurred between the 1993 and 2006 crash years. Of these crashes, 141 involved children who were fatally injured by a passenger air bag. Eight of these children who sustained passenger air-bag-related injuries were seated in forward-facing child safety seats. Of the 133 children who were fatally injured by a passenger air bag and who were not in a child safety seat, 127 were either unrestrained or improperly restrained. Eleven unconfirmed cases are under active investigation, where a child was not seated in a RFCSS and was suspected of sustaining a passenger air-bag-related fatal injury.

Figure 1 presents the number of children who sustained air-bag-related fatalities from a passenger air bag, normalized by the number of passenger air-bag-equipped vehicles in the fleet (in millions) over a 12-month release period.



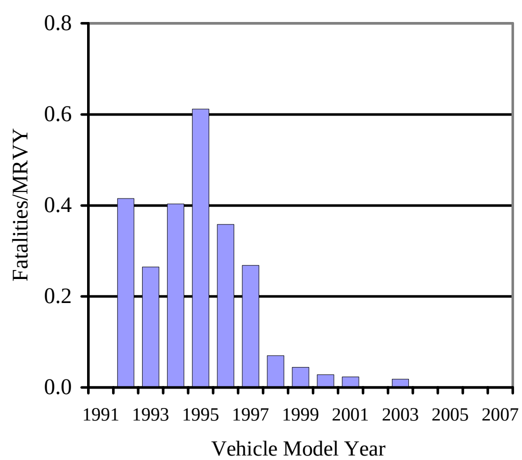
Source: NHTSA, NCSA (SCI Quarterly Report)

Figure 1. Children fatally injured by a passenger air bag, normalized by MRVY; confirmed and unconfirmed as of October 1, 2006.

R.L. Polk data on new registrations was used to estimate the number of passenger air-bag-equipped vehicles in each fleet. R.L. Polk is a company that provides automotive and marketing data. SCI calculates the fatalities per million registered vehicle years (F/MRVY) for specific vehicle model years and 12-month release periods. The F/MRVY for specific vehicle model years is calculated by dividing the count of occupants fatally injured by deploying air bags for a given vehicle model year, by the product of the number of new vehicles registered that are air-bag-equipped for the given year and the number of years the vehicles of that year have been on the road. Vehicles are estimated to be on the road for one-half a year during their first production year. The F/MRVY for a given 12-month release period is calculated by dividing the count of occupants fatally injured by deploying air bags for the given 12-month period by the sum of the total number of registered vehicles with air bags of the previous model years and one half the registered vehicles of the vehicle model year that corresponds to the production period of the crash. Each 12-month production period was aligned with the vehicle production year, September 1 through August 31.

The rate of child F/MRVY dropped significantly between the 1997-1998 production year and the 1998-1999 production year, from 0.712 F/MRVY to 0.305 F/MRVY, respectively. Fatality rates have continued to remain lower than those for the 1997-1998 vehicle production year. The most recent full year rate, the 2005-2006 vehicle production year, was 0.052 F/MRVY. A detailed explanation of how the denominator, MRVY, is calculated can be found on the Explanation page of the SCI report, which is published with the SCI summary tables on the Internet site shown at the end of this paper.

Figure 2 presents the number of children who sustained air-bag-related fatalities from passenger air bags normalized by the number of passenger air-bag-equipped vehicles in a fleet for a given vehicle model year.



Source: NHTSA, NCSA (SCI Quarterly Report)

Figure 2. Children fatally injured by passenger air bags by vehicle model year, normalized by MRVY; confirmed & unconfirmed as of October 1, 2006.

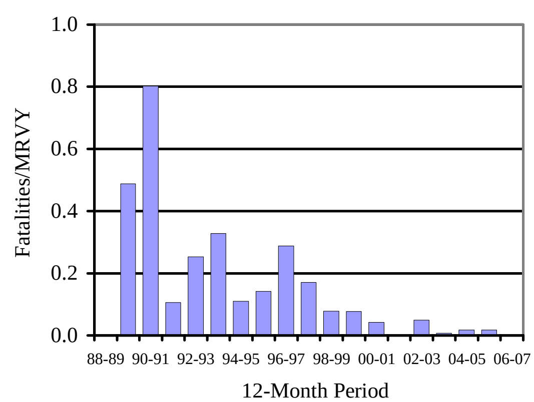
The rate of F/MRVY peaked at, 0.612, for 1995 model year vehicles. There was a significant drop in the fatality rate between the 1997 and 1998 model year vehicles. The rates continued to decrease for vehicles after the 1998 model year. No air-bag-related fatalities have been found for the 2002, 2004, 2005, and 2006 model year vehicles.

The rates shown in Figures 1 and 2 show air-bag-related fatalities for children in vehicles equipped with barrier-certified air bags, sled-certified air bags, and sled-certified air bags with advanced features. None of the air-bag-related fatalities sustained by children were caused by CAC air bags. There was one confirmed air-bag-related fatality in which an infant in a RFCSS sustained a fatal injury from a sled-certified 2003 model-year vehicle equipped with dual-stage air bags. This case is currently under review.

Adult Air-Bag-Related Fatalities

Adult Drivers - There were 88 confirmed adult-driver air-bag-related fatalities. These fatalities occurred between the 1990 and 2005 crash years. Twenty-seven fatally injured adult drivers were wearing seat belts. Some type of misuse of the driver's seat belt was found in three of these cases. In each case, the driver didn't use the lap and shoulder belt together. Fifty-four of the fatally injured adult drivers were not restrained by seat belts. The belt use of four adult drivers was unknown. Six cases where adult drivers were suspected of sustaining air-bag-related fatalities are under active investigation.

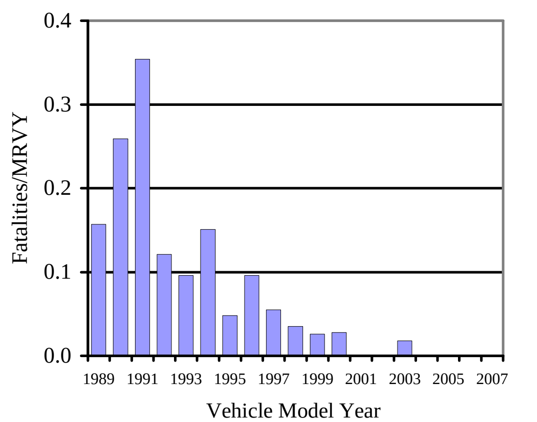
Figure 3 displays the number of adult drivers who were fatally injured by driver air bags normalized by the number of driver air-bag-equipped vehicles in the fleet over a 12-month release period.



Source: NHTSA, NCSA (SCI Quarterly Report)

Figure 3. Adults fatally injured by driver air bags, normalized by MRVY; confirmed and unconfirmed as of October 1, 2006.

In the 1990-1991 vehicle production year, the rate of F/MRVY reached its highest point at 0.802. After that production year, none of the fatality rates have been over 0.328 F/MRVY, the fatality rate for the 1993-1994 vehicle production year. The rate for the most recent full 2005-2006 vehicle production year was 0.018 F/MRVY. Figure 4 shows that the rate of adult drivers who sustained air-bag-related fatalities, normalized by the number of driver air-bag-equipped vehicles in a fleet for a given vehicle model year, has declined since the 1996 model year.



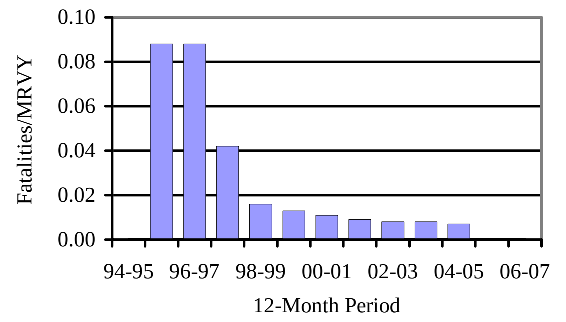
Source: NHTSA, NCSA (SCI Quarterly Report)

Figure 4. Adults fatally injured by driver air bags by vehicle model year, normalized by MRVY; confirmed & unconfirmed as of October 1, 2006.

There were no adult-driver air-bag-related fatalities found for the 2001, 2002, 2004, 2005, and 2006 model years. SCI is investigating two unconfirmed driver air-bag-related fatalities that involve 2000 and 2003 model year sled-certified vehicles that were equipped with dual-stage driver air bags. It is important to note that there were no air-bag-related fatalities of adult drivers that were attributed to CAC air bags.

<u>Adult Passengers</u> - Thirteen adult passengers sustained air-bag-related fatal injuries. These fatalities occurred between the 1996 and 2004 crash years. One of these passengers misused the seat belt by positioning the shoulder belt under the arm. Five adult passengers were restrained by their seat belts. The remaining 7 were not restrained by their seat belts.

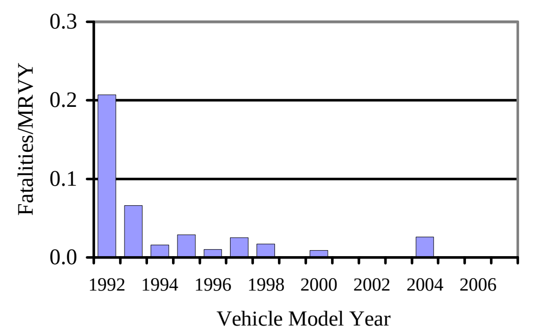
In Figure 5, the number of adult passengers who were fatally injured by passenger air bags normalized by the number of passenger air-bag-equipped vehicles in the fleet over a 12-month release period, shows a decrease in F/MRVY from 0.088 to 0.042, between the 1996-1997 vehicle production year and the 1997-1998 vehicle production year. There were no passenger air-bag-related fatalities in the last full vehicle production year.



Source: NHTSA, NCSA (SCI Quarterly Report)

Figure 5. Adults fatally injured by passenger air bags, normalized by MRVY; confirmed and unconfirmed as of October 1, 2006.

Figure 6 shows that after model year 1998, there have been six model years with no adult passenger air-bag-related fatalities. There were only two adult passenger air-bag-related fatalities after the 1998 model year. These fatalities occurred in 2000 and 2004 model year vehicles equipped with sled-certified air bags.



Source: NHTSA, NCSA (SCI Quarterly Report)

Figure 6. Adults fatally injured by passenger air bags by vehicle model year, normalized by MRVY; confirmed & unconfirmed as of October 1, 2006.

The one crash in the 2004 model year vehicle was the only published dual-stage air-bag-related fatality. This case is summarized in the paragraph below. None of the air-bag-related fatalities of adult passengers were attributed to CAC air bags. There was one unconfirmed air-bag-related adult passenger fatality involving a 2006 model year barrier-certified vehicle that is under active investigation by SCI.

The only confirmed adult passenger sled-certified dual-stage air-bag-related fatality involved a 56-year-old female passenger [66 inches, 190 pounds], who was restrained by her three-point lap and shoulder seat belt system, which included a buckle pretensioner. She sustained critical head and chest injuries in the crash. The case vehicle's 17-year-old male driver sustained moderate and minor injuries. The case vehicle was equipped with dual-stage frontal air bags; a front right seat weight sensor; and seat belt sensors. The crash was a multiple event crash. The case vehicle's total delta V was 19 mph for the first impact and 6 mph for the second impact. The passenger's multiple air-bag-related injuries included a subdural hematoma/hemorrhage (AIS-5), a diffuse axonal injury (AIS-5), an atlanto-occipital dislocation (AIS-2), a brain hemorrhage (AIS-5), and rib fractures (AIS-5).

Fatality Comparisons

An ideal comparison of the fatality rates of sled-certified air bags with advanced features and air bags without advanced features would involve dividing the number of occupants fatally injured by a specific type of deploying air bag (e.g. sled-certified with advanced features) by the number of vehicles equipped with the specific type of air bag in a given fleet. Although the information that was supplied by manufacturers was used by SCI investigators to determine whether a sled-certified air bag with advanced features was present in a case vehicle, the supplied information was not detailed enough to estimate the number of vehicles in a given fleet that were equipped with sled-certified air bags with advanced features. Since a breakdown of the number of sled-certified vehicles with advanced features in a fleet is not obtainable, the number of air-bag-related fatalities attributed to sled-certified air bags with advanced features and air-bag-related fatalities from vehicles without advanced features will be compared in the next paragraph.

The data provided by vehicle manufacturers shows that sled-certified vehicles were equipped with air bags with advanced features such as dual-stage air bags as early as the 1999 model year. With the exception of 2003 model year vehicles, the number of adult-driver air-bag-related fatalities for sled-certified vehicles equipped with air bags with advanced features, for all other model year vehicles was either less than or equal to that of vehicles equipped with air bags without advanced features. Similarly, excluding 2004 model year vehicles for adult passengers and 2003 model year vehicles for children, the number of child and adult passenger air-bag-related fatalities attributed to air bags in sled-certified vehicles equipped with air bags with advanced features was lower than or equal to those of vehicles equipped with air bags without advanced features.

CASE SELECTION

The second part of this paper evaluates CAC vehicle data for NASS CDS and SCI cases. Since NHTSA's Electronic Data System (EDS) does not have a variable that specifically states whether a vehicle is equipped with CAC air bags, the CAC vehicle data presented in this paper were found by querying EDS for vehicles that were on the list of CAC vehicles that were provided by vehicle manufacturers. Analysis for this study is limited to CAC vehicle models that were certified for a full production year.

The data from 561 cases, which included either single-event or multiple-event crashes, were analyzed for this paper. Twenty of these cases were published in SCI, and 541 of these were NASS CDS cases. This data was used to provide background information about the type of impact of the CAC vehicles in the study, and is not intended to represent CAC vehicle crashes nationwide. Of the 561 cases, there were 389 cases in which a CAC vehicle had a direction of force between 10 and 2 o'clock, deemed a "near-frontal impact" for an event in a crash. The 10-to-2-o'clock direction of force is within the range a frontal air bag will deploy, regardless of the plane of impact. Eighteen (5%) of these cases that had at least one near-frontal impact were SCI cases, and 371 were NASS CDS cases. Cases with a near-frontal impact were then segregated into cases with a single event. There were a total of 193 of these single-event cases. Five of these cases were investigated by SCI, and 188 were investigated by NASS CDS.

Event data recorder (EDR) data are evaluated in the last section of this paper. NCSA uses the generic term "EDR" to refer to recording devices that are found in certain air bag control modules. SCI and NASS field investigators are equipped with commercially available tools to download data from EDRs of two vehicle manufacturers. EDRs are the only source of data regarding the decision logic of a CAC vehicle's safety system. This data includes the status of automatic suppression systems, the deployment level of frontal air bags, and the change in forward velocity experienced by an air bag's sensing system.

CONFIGURATION

Figure 7 shows the impact plane for the event with the highest crash severity, of the 519 CAC vehicles in which the impact plane is known.

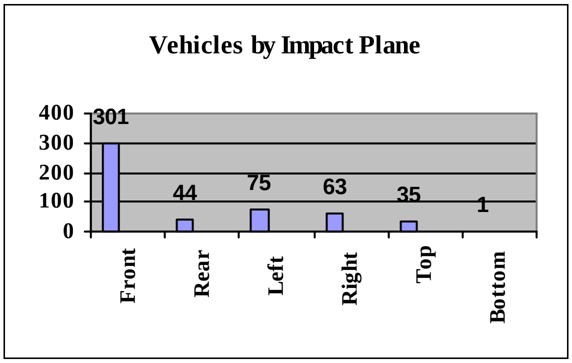


Figure 7. Impact configuration by impact plane in CAC cases published by SCI and NASS CDS.

Frontal impacts represented the highest number of known impacts, 301 (58%). Frontal impacts were followed by: left-side impacts, 75 (14%); right-side impacts, 63 (12%); rear impacts, 44 (8%); top impacts, 35 (7%); and an undercarriage (bottom) impact. The impact plane of an additional 48 vehicles was unknown. The analyses in each of the following sections, except the EDR section, are limited to vehicles that were involved in near-frontal-plane impacts in an event in the crash.

CRASH SEVERITY

The deployments of frontal air bags are based on a number of crash factors including deceleration, time, and the change in forward velocity experienced by the air bag sensing system mounted in the vehicle. Delta V as determined by WinSMASH is used in this analysis to indicate crash severity. WinSMASH is a crash reconstruction algorithm that is used in NHTSA's data collection programs. Figure 8 shows the highest longitudinal delta Vs for CAC vehicles, where the crash event with the highest crash severity was a frontal impact.

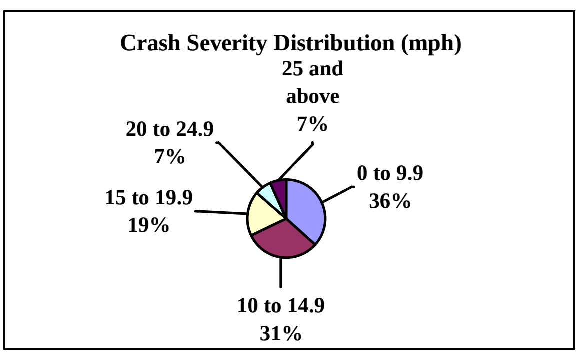


Figure 8. Maximum longitudinal crash severity of frontal impacts as measured by delta V in CAC vehicles in cases published by SCI and NASS CDS.

Since minor- to moderate-severity crashes range from 0 to 25 mph, the highest longitudinal delta Vs that were experienced by vehicles were first grouped in increments of: 0 to 9.9 mph; 10 to 14.9 mph: 15 to 19.9 mph; 20 to 24.9 mph; and 25 mph and above. There were 183 maximum longitudinal delta Vs that were known, and 84 that were unknown. Of the CAC vehicles with a known delta V, 171 (93%) had longitudinal delta Vs below 25 mph. The five groups: 0 to 9.9 mph; 10 to 14.9 mph; 15 to 19.9 mph; 20 to 24.9 mph; and 25 mph and above; made up 36 percent, 31 percent, 19 percent, 7 percent and 7 percent of the maximum longitudinal delta Vs experienced by CAC vehicles in frontal impacts, respectively. Figure 9 shows the maximum longitudinal delta V distribution for CAC vehicles in left- and right-side impacts.

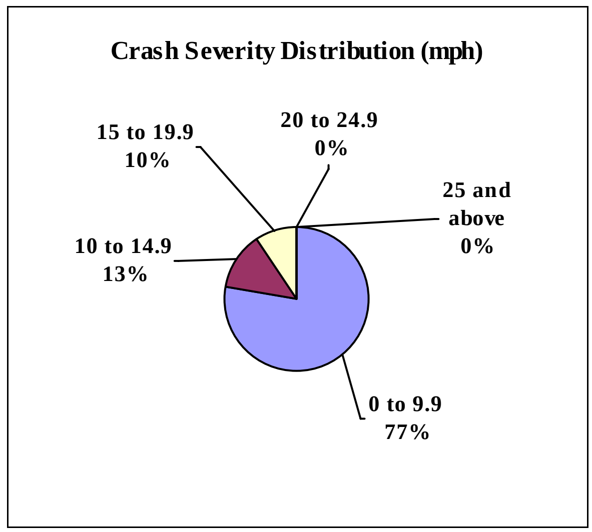


Figure 9. Longitudinal crash severity of side impacts as measured by delta V in CAC vehicles in cases published by SCI and NASS CDS.

All of the known impacts were below 20 mph. Forty-nine (77%) of the known impacts were between 0 and 9.9 mph. Impacts in the 10 to 14.9 mph range, were 13 percent of known impacts, while 10 percent of the known impacts were in the 15 to 19.9 mph range. The delta V for the 33 of the left- and right-side impacts were unknown.

CASE OCCUPANTS

Figure 10 presents the demographics of front-seat occupants in CAC vehicles that had a near-frontal-plane impact.

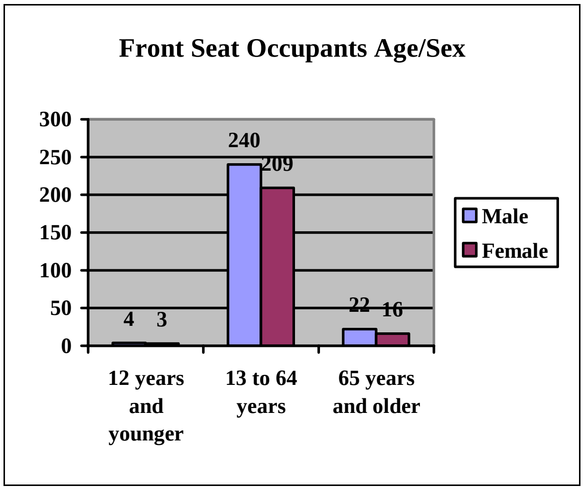


Figure 10. Front-seat occupant demographics in cases published by SCI and NASS CDS.

Front-seat occupants were divided into three age ranges: 12 years old and younger; 13 to 64 years old; and 65 and older. Occupants were then divided by sex. Cases in which the age or sex of an occupant was unknown were excluded from this analysis. There were only seven children 12 and younger seated in front seating positions in CAC vehicles. Four of the children were males, and three were females. The majority of the front-seat occupants, 91 percent, were in the 13 to 64-year-old age range. Front-seat occupants 65 and older were only 8 percent of the occupants. Two hundred sixty-six (54%) of the occupants were male, and 228 (46%) were female.

Figure 11 shows the front-row seating positions of drivers and front-right passengers in near-frontal impacts.

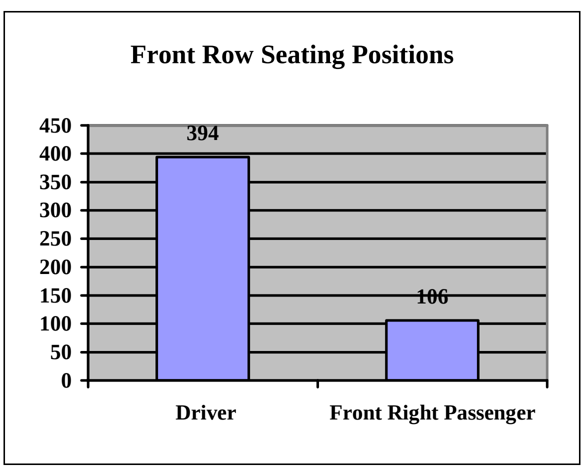


Figure 11. Front-row seating positions of vehicle occupants in CAC cases published by SCI and NASS CDS.

Drivers comprised 394 (79%) of the occupants known to be seated in the front row, and front-right passengers accounted for 106 (21%) of the occupants known to be seated in the front row.

OCCUPANT BELT USAGE

The seat belt usage for drivers and front-seat passengers whose vehicle had a near-frontal-plane impact is shown in Figure 12.

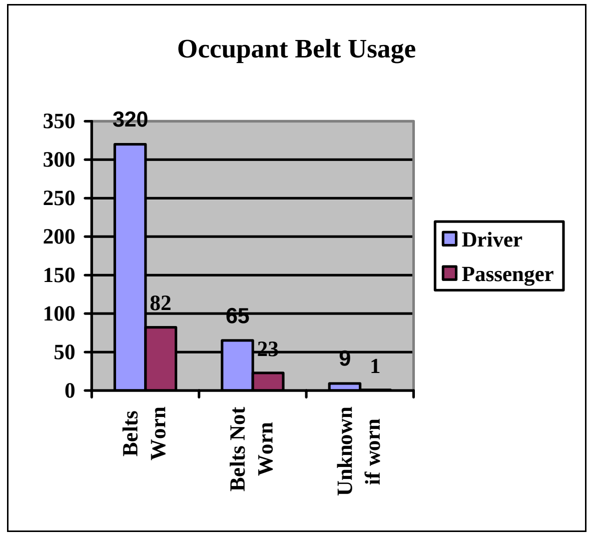


Figure 12. Seat belt usage of front-seat occupants in CAC cases published by SCI and NASS CDS.

Eighty-two percent of the occupants whose restraint use was known were restrained by seat belts. Restraint use among drivers was 83 percent, which was higher than that of front passengers, which was 79 percent.

OCCUPANT INJURY LEVEL

There were 459 occupants in CAC vehicles who were seated in either the front-right passenger or driver seating position of vehicles that had near-frontal impacts that were either not injured or sustained a known injury. These occupants were divided into two groups, according to the maximum abbreviated injury scale (MAIS) injury that they sustained. The first group is composed of occupants who were not injured and occupants whose most severe injury was a minor or moderate injury. These injuries ranged from MAIS 0 (no injury) to MAIS 2 (moderate). The second group consists of occupants whose injuries are usually considered life-threatening. This group ranges from MAIS 3 (serious) to MAIS 6 (maximum). Figure 13 shows the injury severity and belt use of frontal occupants.

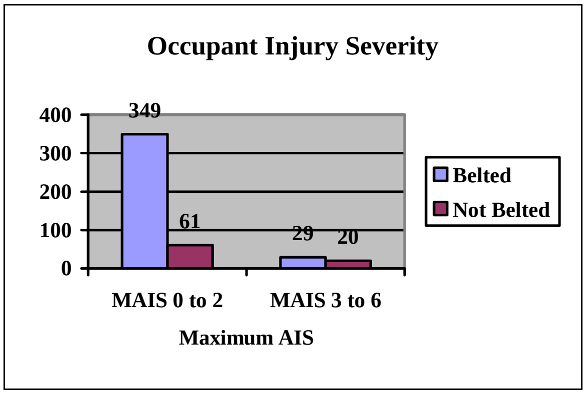


Figure 13. Most severe injury sustained by front seat occupants in CAC cases published by SCI and NASS CDS.

The first group, MAIS 0 to 2, represents 89 percent of the occupants. Eighty-five percent of the occupants in the MAIS 0 to 2 range were restrained by seat belts. Only 59 percent of the 49 occupants who sustained MAIS 3 to 6 injuries were restrained. None of the MAIS 3 to 6 injuries were air-bag-related.

AIR BAG DEPLOYMENTS

Figure 14 shows whether there was an air bag deployment in either the driver or front-right passenger seating position in a near-frontal impact when the occupant's seating position was known.

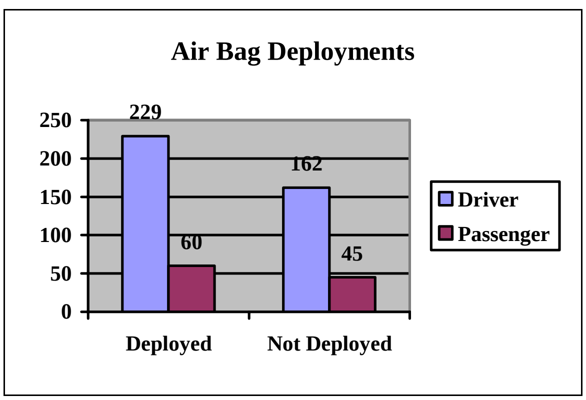


Figure 14. Air bag deployments by seating position in CAC cases for published SCI and NASS CDS cases.

There were 289 (58%) air bag deployments and 207 (42%) non-deployments. The percentage of deployments when the deployment status was known was similar for drivers and passengers, 59 percent, and 57 percent, respectively. There were 229 deployments into the driver seating position and 60 deployments into the front-right passenger seating position. With the exception of one deployment, all the deployments occurred during the crash. At this time the exact details of the one exception are unknown.

NHTSA's advanced air bag rule specifies that vehicle manufacturers meet performance standards, as specified on page 2 of this report, that relate to automatic suppression or a benign deployment of air bags. One way that vehicle manufacturers can meet the automatic suppression options in FMVSS No. 208 is to use seat weight sensors. The only automatic suppression option currently available to manufactures requires that vehicles be equipped with at least one telltale that emits yellow light, with the words "PASSENGER AIR BAG OFF" when the passenger air bag is deactivated. Telltales can be illuminated on the rearview mirror or instrument panel. Some vehicles have a sensing system that automatically deactivates the passenger air bag based on whether the weight in the passenger seat is consistent with a child or child seat. Sensors in the passenger's seat belt are often used to ensure that the belt's tension doesn't cause an inaccurate weight measurement. An EDR download is needed to determine the status of an automatic suppression system. In the future, NHTSA will pursue data on the status of automatic suppression systems when they become available.

OCCUPANT WEIGHT

Figure 15 divides occupants into weight ranges and indicates the number of air-bag deployments into an occupant's seating position, when both the occupant's weight and deployment status are known.

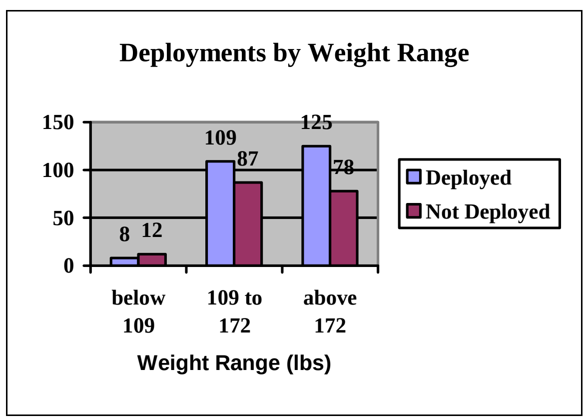


Figure 15. Air-bag deployments by weight range in CAC cases for published SCI and NASS CDS cases.

Since the advanced-air-bag section of FMVSS No. 208 includes tests that use the 5th percentile adult female anthropomorphic test dummy (108 pounds) and the 50th percentile adult male anthropomorphic test dummy (171.3 pounds), the weights of occupants involved in crashes with near-frontal impacts were divided into increments of: “below 109 lbs,” “109 to 172 lbs,” and “above 172 lbs.” Unlike the other two weight ranges, the “below 109 lbs” range had more non-deployments (12) than deployments (8). The weight range “above 172 lbs” was the largest of the three groups, with 125 deployments and 78 non-deployments. The “109 to 172 lbs” weight range had 109 deployments and 87 non-deployments.

EVENT DATA RECORDERS

There were 307 CAC vehicles that were equipped with EDRs in this study. NASS CDS cases that include CAC vehicles involved in crashes in the crash year 2002 (i.e., early 2003 model year vehicles) were excluded from the analysis in this section. Figure 16 indicates the number of EDRs that were downloaded by SCI and NASS field investigators.

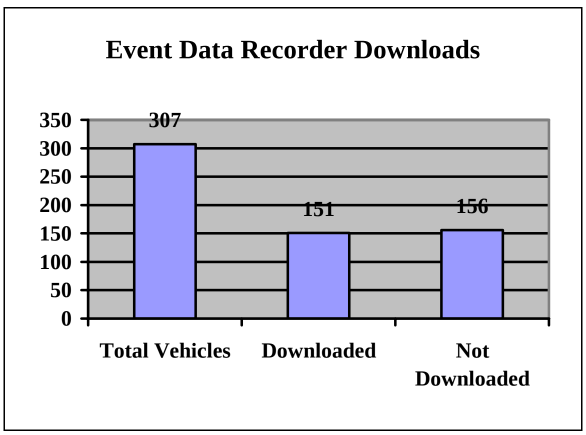


Figure 16. EDRs downloaded in CAC cases published by SCI and NASS.

One hundred fifty-one of 307 EDRs were successfully downloaded. The most common reason cited by the field investigator for not being able to download a CAC vehicle’s EDR was that the vehicle was not supported by software. This reason, which was selected 79 times, describes instances when field investigators were not equipped to read the EDRs of a specific vehicle make or model. The next most common reason cited, accounting for 45 of the selections, was that field investigators were not given permission to download the EDRs. Damage preventing the field investigators from accessing the EDRs accounted for 26 selections.

The EDR downloads included crashes with multiple events. Of the 151 downloads, there were 175 EDR recordings where air bags either deployed or didn’t deploy. Figure 17 shows that there were 68 (39%) deployments and 107 (61%) non-deployments.

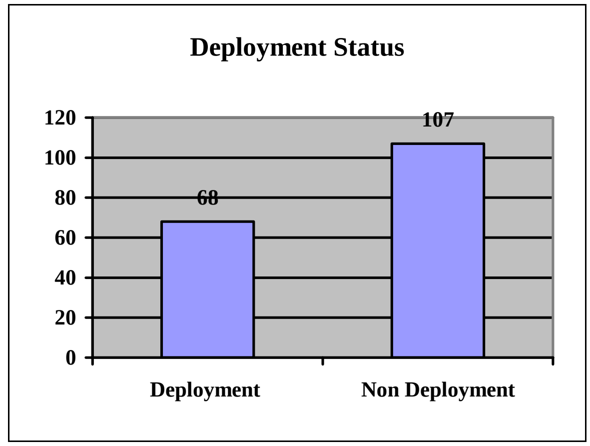


Figure 17. Air bag deployment status of downloaded EDR recordings in CAC cases published by SCI and NASS.

The average and median maximum longitudinal delta V experienced by the air bags’ sensing systems for the deployments were, 14.8 mph and 12.6 mph, respectively. The standard deviation of the maximum longitudinal delta V, for deployments was 8.6 mph. Non-deployments had an average and median maximum longitudinal delta V of 3.5 mph and 1.9 mph, respectively. The standard deviation of the maximum longitudinal delta V for non-deployments was 5.1 mph.

Figure 18 shows the number of EDR-recorded air bag deployments where the deployment stage is known.

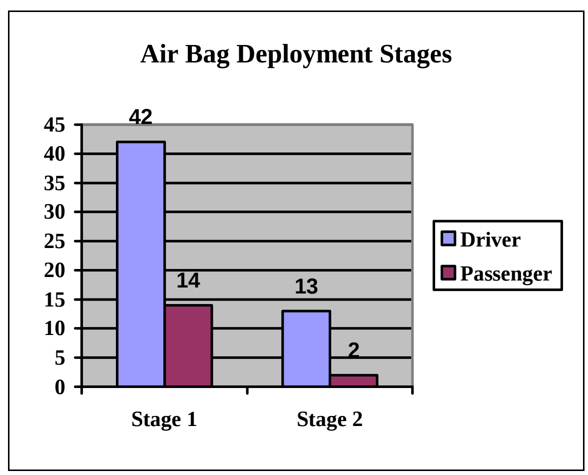


Figure 18. Air-bag deployment stages for frontal seating positions in CAC cases published by SCI and NASS.

There were a total of 56 “Stage 1” deployments and 15 “Stage 2” deployments. In each case, at least three-quarters of the deployments were in the driver's seating position.

CONCLUSIONS

The Analysis of SCI and NASS CDS air bag data show the following:

- The data evaluated from SCI shows an overall decrease in the number of air-bag-related fatalities for the model and production years that were not associated with barrier-certified air bags: post-1997 model years and post-1997-1998 production years.

- SCI has not investigated any cases where there was a fatality or life-threatening injury attributed to the deployment of air bags in vehicles that were certified to the advanced-air-bag section of FMVSS No. 208. SCI will continue to monitor the real-world crash performance of CAC vehicles.

- The data shows, as detailed in Figure 8, that 93 percent of the maximum longitudinal crash severities of this study's CAC vehicles involved frontal impacts were below 25 mph.

- Figure 12 shows that 83 percent of the drivers and 79 percent of the front passengers were restrained by seat belts. This percentage is consistent with the 81 percent nationwide seat belt use rate measured by NHTSA's National Occupant Protection Use Survey in 2006 [4].

- As indicated in Figure 13, NASS and SCI show that almost 90 percent of the known injury severities to front-seat occupants in front of air bags certified to the advanced standard were in the MAIS 0 to 2 range. The belt usage rate for the occupants who sustained the more serious injuries, MAIS 3 to 6, was significantly lower than that for occupants who sustained MAIS 0 to 2 injuries.

- EDR data will continue to play an essential role in the analysis of CAC vehicle safety systems. Downloaded EDR data provides field researchers with the only available information about the decision logic of key safety system features, such as, the stage the air bag was commanded to deploy.

SCI DATA AVAILABILITY

SCI summary tables are now published biannually on NHTSA's Internet site at the following Internet address:

http://www-nrd.nhtsa.dot.gov/departments/nrd-30/ncsa/sci.html

The SCI online data access page is located at:

http://www-nass.nhtsa.dot.gov/BIN/logon.exe/airmislogon

ACKNOWLEDGEMENT

Special thanks are due to Adam Toth of Bowhead Support Services for supplying the queries of the SCI and NASS CDS EDR data.

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[2] Kindelberger, John, et al., *Air Bag Crash Investigations*, 18th Enhanced Safety of Vehicles Conference 2003; Washington, DC: National Highway Traffic Safety Administration. Downloaded from the Web on February 2007 at www-nrd.nhtsa.dot.gov/pdf/nrd-01/esv/esv18/cd/files/18ESV-000299.pdf

[3] Title 49 Code of Federal Regulations (CFR) Part 571 Section 208, Occupant Crash Protection, S14, Advanced air bag requirements for passenger cars and for trucks, buses, and multipurpose passenger vehicles with a GVWR of 3,855 kg (8,500 pounds) or less and an unloaded vehicle weight of 2,495 kg (5,500 pounds) or less, except for walk-in van-type trucks or vehicles designed to be sold exclusively to the U.S. Postal Service. Downloaded from the Web on February 2007 at http://a257.g.akamaitech.net/7/257/2422/13nov20061500/edocket.access.gpo.gov/cfr_2006/octqtr/pdf/49cfr571.208.pdf

[4] *Traffic Safety Facts, Seat Belt Use 2006 – Use Rates in States and Territories*, Washington, DC: National Center for Statistics and Analysis, National

Highway Traffic Safety Administration. Downloaded from the Web on February 2007 at www-nrd.nhtsa.dot.gov/Pubs/810690.PDF

WHAT ACCIDENT ANALYSIS TELLS ABOUT SAFETY EVALUATIONS OF PASSENGER VEHICLES

-

CONTRIBUTIONS BY PRIMARY AND SECONDARY SAFETY TO OVERALL SAFETY AND CONSEQUENCES FOR SAFETY RATINGS

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Volkswagen AG
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AUDI AG
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Paper Number 07-0074

ABSTRACT:

In the past, the overall safety of passenger vehicles was dominated by secondary safety features, the ability of vehicles to reduce the consequences of accidents by mitigating injuries. In the last ten years, crash avoidance devices which can reduce the likelihood of accidents were introduced into cars. These devices support the braking of drivers, such as brake assists, or they reduce the likelihood of skidding, such as ESC, others will follow. Accident research clearly and increasingly shows the effectiveness of such devices under European road conditions. Although road conditions in the U.S. are different, there are positive indications as well.

In Europe, for belted occupants, ESC-effectiveness is estimated to be higher than airbag effectiveness. The accident data, indicating this, has been consistent for a couple of years. This paper provides accident data predicting the amount of safety benefit to be attributed to the different safety features in terms of risk reduction. This might help to overcome the problem that current 4 and 5 star cars are said to be in fact better than cars with fewer stars, while there is no significant difference between 4 and 5 star cars in real world accidents. It is the goal of the paper to quantify the degree of the total safety, reflected by a crash test based rating, like the current rating in Europe.

INTRODUCTION

Most of the European EU-member states see a long and steady decrease of fatalities. Volkswagen accident research has to increase its area of investigation, because in the area, where in the past a lot of severe accidents happened, the number of severe accidents dropped significantly. This is very positive news. When positive things happen, everybody is willing to take credit. The highway engineers, the colleagues, introducing more or less feasible and beneficial regulation on cars, the police, managing the traffic etc. This paper will deal with the effect of a car design tool, which is very likely to become the number three with regard to life saving potential: ESC. In the list of life saving features which was: Belt, structure, and airbag, we have now a very effective newcomer. The list now is: Belt, structure, ESC, and airbag as the number 4. The data presented here will underline these findings from the past year. They will show important implications for future accident research and for car rating attempts, because ESC not only reduces the number of fatalities, which is easily detected by accident researchers. It clearly shows its potential of crash avoidance. And accidents that do not happen are very difficult to detect in accident data bases.

GIDAS ACCIDENT DATA

The analyses in this paper are based on data supplied by GIDAS (German In Depth Accident Study). The advantages of this database are two-fold: (1) the number of cases is high enough to provide statistically significant results, and (2) each case is documented in great detail, permitting in-depth-analyses where required.

GIDAS is a unique project involving the German government and the motor vehicle industry. The cornerstone of the GIDAS-project was laid in 1973 and based on the recognition that official statistics were not sufficient to answer important questions that arise during accident research. For this reason, the German Federal Highway Research Institute ("Bundesanstalt für Straßenwesen", BASt) initiated a project, in which interdisciplinary teams analysed highway accidents from a scientific perspective – independent of the objectives and needs of law enforcement. The project underwent an important change in 1985, when the choice of the accidents for detailed analysis began to follow a random sampling plan.

accidents with recent models of group-cars involved.

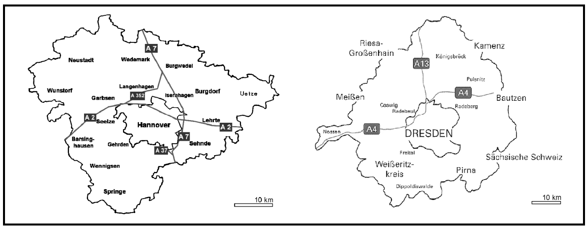

Figure 1. GIDAS Research Areas in Dresden and Hannover.

A second major improvement took place in 1999 when GIDAS was expanded to include cooperation with BASt and the German Association for Automotive Technology Research ("Forschungs-vereinigung Automobiltechnik e.V.", FAT). For this purpose, a second team was established at the Technical University of Dresden. Currently, the sampling criteria are as follows:

- road accident
- accident site in Hanover City and County or Dresden City and County
- accident occurs when a team is on duty
- at least one person in accident injured, regardless of severity

The data collected is entered in a hierarchical database. Depending on the type of accident, each case is described by a total of 500 to 3,000 variables, e. g accident type and environmental conditions (record Umwelt), vehicle-type, mass, drive train and the type of road it was on (record Fzg), the age, size, hours on the road and injury data for all persons involved (record Persdat and Verlueb). Each accident is reconstructed in detail including the pre-collision-phase. Available information includes initial vehicle and impact speed, deceleration as well as the collision sequence.

This database is representative of German national accident statistics, whereby severe cases are slightly over-represented.

SINGLE CASE ANALYSIS AT VW-GROUP-ACCIDENT-RESEARCH

With upcoming primary safety systems, VW implemented three brand research teams. The group accident research is located at Wolfsburg and performs on-scene accident research in an appr. 100 km radius of Wolfsburg. In addition to this at AUDI in Ingolstadt and at SVW in Shanghai, China, there exist local teams, providing on-scene accident investigation. The task for these teams is to increase the safety standard of all VW-Group products through detailed accident analysis of

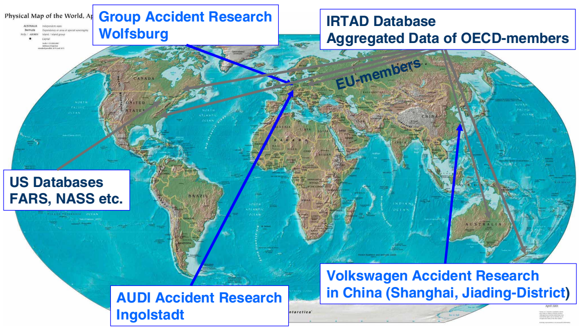

Figure 2. Main data sources of Volkswagen accident research

These teams consist of engineers, physicians and psychologists to gain a comprehensive understanding of the accident. These accident investigations include also technical analysis of the vehicle structure and suspension but also a complete reconstruction of the course of events of an accident, the medical analysis of injuries and the injury causing factors and last but not least a detailed view on accident causation by psychological analysis of the accident scene and interviews with the involved persons. The depth of the accident analysis depends on the willingness of the involved persons to co-operate. About 50% of the involved persons are willing to support us, even by answering the questions of our psychologists.

PROGRESS OF SECONDARY OR PASSIVE SAFETY

Significant progress was achieved by secondary or passive safety measures. The above mentioned GIDAS-database provides sufficient data, to investigate and quantify the progress.

Scenario	*Belted Occu-pant*	*Vehicle manu-factured 1995 or later*	*Airbag avail-able*	*Number of cases in GIDAS*
1	No	No	No	Ca.1 000
2	Yes	No	No	Ca.13 500
3	Yes	Yes	No	Ca. 630
4	Yes	Yes	Yes	Ca. 1 800

Figure 3. Scenarios and available data, describing the injury risk of passenger car occupants in accidents.

Figure 3 provides the scenarios which enable detection of the differences between driver populations. Comparing scenario 1 and 2, the difference should describe the benefit of using the belt. Scenario 2 and 3 describe the benefit of structural enhancements, achieved by implementing ECE R94 in Europe as a mandatory test for all passenger cars. And scenario 3 and 4 describe the additional benefit, achieved by front airbags. Looking into the data, regarding age and gender of the involved people, regarding collision mode and impact velocity, there is not much difference between the samples, so that the comparison is possible.

Belt	**No**	**Yes**	**Yes**	**Yes**
Manufactured	**..1994**	**..1994**	**1995..**	**1995..**
Airbag	**No**	**No**	**No**	**Yes**
Risk of				
MAIS 0..6	100%	100%	100%	100%
MAIS 1..6	78%	44%	38%	36%
MAIS 2..6	36%	12%	8,1%	7,0%
MAIS 3..6	16%	4,1%	2,1%	1,6%
MAIS 4..6	8,9%	1,8%	0,8%	0,5%
MAIS 5..6	6,5%	1,1%	0,6%	0,3%

Figure 4. Risk of MAIS-categories within the scenarios.

The conclusion of Figure 4 is that measures of passive safety were very beneficial in the past. This does not only hold for restraint systems, but also for the vehicle structure. The risk of high deformations and intrusions into the compartment decreased significantly. This topic was discussed in depth in former presentations.

THE DECREASE OF FATALITIES IN EUROPE

The effect of the findings of Figure 4 can be seen by the global data of most of the European member states. There is a positive trend in nearly all member states. Europe will reach a significant decrease of fatalities in the time period 2000..2010 of appr. 25%.

To make data from different countries comparable, in Figure 5 the year 1980 was chosen as 100% for all countries. Greece has its own development. There is also an unexplained increase in Spain between 1985 and 1990. With the exception of the period of reunification, Germany showed the highest decrease in the observed time period. This can also easily be seen, when the estimated progress for the time period 2000 and 2010 is estimated. This progress is relevant, because EU declared the goal of reducing fatalities in this period by 50%. This goal will be achieved only by Germany, if the current trend follows. On average, EU will achieve 25%. This is already a great success for European road safety.

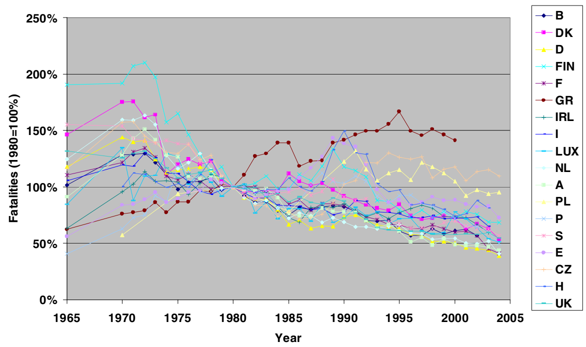

Figure 5. The positive trend of fatalities in Europe.

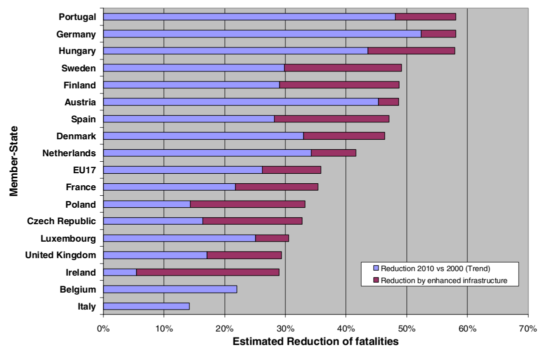

Figure 6. The expected decrease of fatalities in Europe in the time frame 2000..2010 and the additional progress that could be achieved, if infrastructure was enhanced so that 50% of rural traffic were on autobahns.

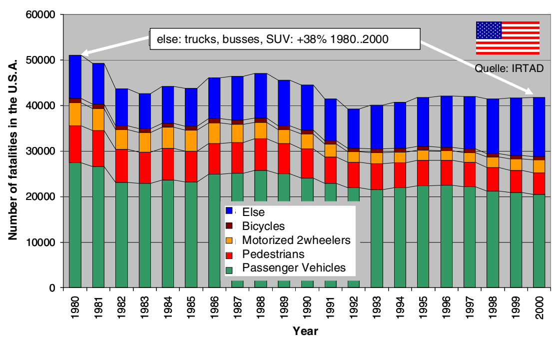

Figure 7. Number of fatalities in the U.S.A.

The main purpose of showing Figure 6 was to underline that European car fleet increased safety significantly in the past. This is not a trivial world wide effect, as the figures of U.S.A. (Figure 7) show. In the U.S., the absolute number of fatalities is not significantly changing. So the safety concepts in Europe are successful, including European car design.

It is difficult and probably not possible, to identify the reasons of these different developments. Europe has a very high belt usage rate, the U.S. has a high portion of SUVs, the increasing number is reflected by the blue bar of Figure 7. Europe is still dominated by European built cars. There is ECE R94 applied in Europe, FMVSS 208 in the U.S. etc.

THE MARKET PENETRATION OF ESC

In the past, Volkswagen and AUDI published a couple of papers, regarding ESC-effectiveness (Figure 8). The high effectiveness of ESC now has world-wide acceptance. Today we can add additional figures that show that ESC has potential to reduce property-damage accidents as well. A study, conducted by Volkswagen, together with the Volkswagen insurance (Volkswagen Financial Services), clearly showed a reduction of property damage volume by 9%.

	Effectiveness VW and AUDI ESP	Germany 2002		
		2002 Involved	Reduction by ESP	2002 Sum with VW and AUDI ESP
Minor injuries	16,5%	247.618	40.932	206.686
Hospitalization	24,9%	44.176	11.001	33.175
Fatalities	35,2%	4.004	1.411	2.593

Figure 8. Estimated reductions of fatalities and injuries, if current findings for Volkswagen and AUDI ESC would hold for the complete German fleet.

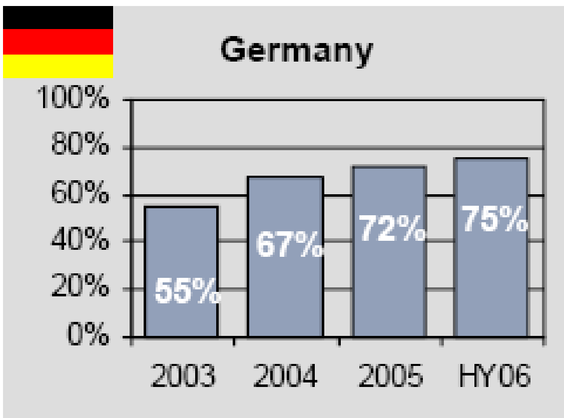

Figure 9. ESC-share in new car registrations. (Data kindly provided by Robert-Bosch-AG)

Another approach, which shows the crash avoidance potential of ESC, can be derived from GIDAS data. The share of ESC-equipped vehicles is published by Robert-Bosch-AG as shown in Figure 9. Together with the vehicle age distribution of Figure 10, we can compute the number of ESC-vehicles in German car fleet. We can compare this to the share of ESC-vehicles in GIDAS. This provides the chance to identify "lost accidents." These are accidents that did not happen, because ESC prevented them from happening.

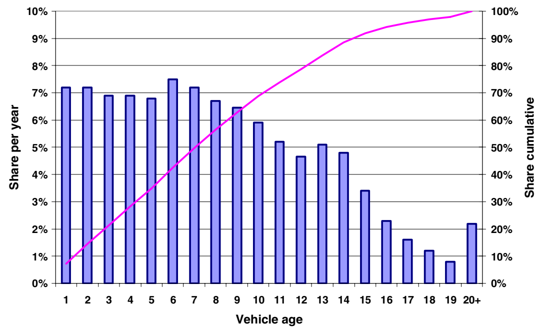

Figure 10. Vehicle age distribution in Germany. (Data kindly provided by Dr.Schepers, BASt)

To do so, we use the following formula:

A_Y Number of vehicles with system (Exposure)

A_N Number of vehicles without system (Exposure)

$A = A_N + A_Y$ Total number of vehicles (Exposure)

R_Y Accident risk with system

R_N Accident risk without system

P_E Observed frequency of system in exposure data

$$P_E = \frac{A_Y}{A}$$

P_A Observed frequency of system in accident data

$$Eff = \frac{R_N - R_Y}{R_N} \quad \text{Effectiveness of system}$$

From

$$P_A = \frac{A_Y * R_Y}{A_N * R_N + A_Y * R_Y}$$

and using the substitutions

$$R_Y = R_N * (1 - Eff) \quad \text{and} \quad A_Y = P_E * A$$

one can derive

$$P_A = \frac{P_E * (1 - Eff)}{1 - P_E * Eff}$$

or

$$Eff = 1 - \frac{P_A * (1 - P_E)}{P_E * (1 - P_A)}$$

This formula permits estimates of the effectiveness of a system to be calculated, when an observed frequency in exposure data and in accident data is available. As GIDAS reflects all accidents with injuries, this estimation explains, how many accidents with injuries are no longer accidents with injuries and thus disappear from GIDAS due to the effectiveness of ESC. So this research goes beyond the knowledge, derived from the observation that 80% of the skidding accidents will no longer occur. This proves the capability of ESC to avoid injury accidents.

Figure 11 provides for the years 2000 to 2004 the observed frequency of ESC-cars in GIDAS data base. The comparison to fleet data together with the formula, derived above, shows an effectiveness of ESC to avoid accidents of about 40%. This value is rather stable.

Taking into account that every year, the share of ESC-cars increases by 5 to 8%, we can expect that the positive trend in Germany will continue for a couple of years. And there are additional measures under development that will make this trend continue, when ESC has reached its 100% in the market.

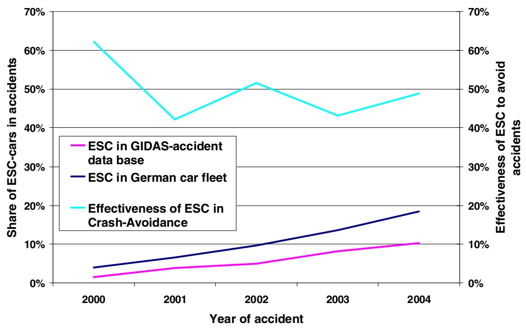

Figure 11. Effectiveness of ESC in avoiding accidents with injuries, derived from GIDAS data base and German fleet data.

These findings include a warning for all accident researchers, when studying their results. Due to lack of data, normally a risk is described as the ratio between the number of persons injured at a certain severity level, divided by the number of persons in the data base. This is frequently done, e.g. to compare the risk of young drivers and the risk of elderly drivers, or male vs. female drivers etc. When we know that injury accidents disappear from our data base, this means that in such computations, both, numerator and denominator are changed. The result is unpredictable. So after the introduction of ESC, there is even more careful data analysis necessary, before we can come to conclusions. When preparing this paper, the authors lost a lot of time, due to this effect in GIDAS data base. The effect has to be studied more in depth. Methodology has to be provided to analyze data, taking into account these effects of "disappearing accidents." It is not only ESC responsible for this effect, it is also the airbag. The likelihood that an accident is completely without injured persons, increased significantly due to the on-going enhancement of the restraint systems. This is a very positive effect, but for the accident researcher, things became more complicated: With current knowledge, we would not rely on a comparison on the basis of accident data before 2000 compared to data of accidents after 2000.

ACCIDENT AVOIDANCE CAPABILITY OF ESC FOR DIFFERENT DEGREES OF SEVERITY

The results of the preceding chapter can be applied to the different MAIS-classes to compute the injury mitigation capability of ESC. This was done by the same calculation. Instead of all involved persons, we look for persons with an injury of MAIS X+. Relevant for all these results is Figure 10. The results depend on these estimations. The higher the market share of ESC in the GIDAS area, the higher the effectiveness of ESC and vice versa. According to the increased market share of Volkswagen and AUDI cars in the Hannover area, we would expect an ESC above average in this area. In the Dresden area, there might be less so that for GIDAS, the combination of both areas, the German average might be a good estimation.

Cases without ESC from GIDAS								Share of
Year	MAIS 0+	MAIS 1+	MAIS 2+	MAIS 3+	MAIS 4+	MAIS 5+	MAIS 6	Non-ESC
2000	3489	1501	351	118	59	46	44	96,1%
2001	3185	1355	276	97	59	51	46	93,5%
2002	2553	1055	262	100	64	46	41	90,3%
2003	2725	1130	246	87	56	41	36	86,4%
2004	2799	1107	229	71	48	29	25	81,6%
Cases with ESC from GIDAS								Share of
Year	MAIS 0+	MAIS 1+	MAIS 2+	MAIS 3+	MAIS 4+	MAIS 5+	MAIS 6	ESC
2000	47	19	2	0	0	0	0	3,9%
2001	125	48	9	1	0	0	0	6,5%
2002	125	47	7	2	1	1	0	9,7%
2003	213	77	9	5	2	1	1	13,6%
2004	266	96	16	4	3	2	2	18,4%
Expected cases with ESC, due to its market share, if there were no ESC-effectiveness								
Year	MAIS 0+	MAIS 1+	MAIS 2+	MAIS 3+	MAIS 4+	MAIS 5+	MAIS 6	
2000	143	61	14	5	2	2	2	
2001	222	94	19	7	4	4	3	
2002	275	114	28	11	7	5	4	
2003	430	178	39	14	9	6	6	
2004	630	249	52	16	11	7	6	
Resulting effectiveness of ESC								
Year	MAIS 0+	MAIS 1+	MAIS 2+	MAIS 3+	MAIS 4+	MAIS 5+	MAIS 6	
2000	67,1%	69,1%	86,1%	100,0%	100,0%	100,0%	100,0%	
2001	43,7%	49,2%	53,2%	85,2%	100,0%	100,0%	100,0%	
2002	54,6%	58,6%	75,2%	81,4%	85,5%	79,8%	100,0%	
2003	50,4%	56,8%	76,8%	63,6%	77,4%	84,5%	82,4%	
2004	57,8%	61,5%	69,0%	75,0%	72,2%	69,4%	64,5%	
Wheighted effectiveness of ESC. Every year wheighted with ist ESC-share.								
	MAIS 0+	MAIS 1+	MAIS 2+	MAIS 3+	MAIS 4+	MAIS 5+	MAIS 6	
	53,5%	58,2%	69,1%	72,2%	76,2%	75,8%	70,4%	

Figure 12. Computation of ESC effectiveness for every injury severity class.

Figure 12 is computed from GIDAS data together with the ESC-share in German car fleet. So accident data and fleet data are combined. Possible different mileages between ESC and non-ESC-cars are neglected. But it is assumed that the mileage exposure of ESC-cars, which tend to be the larger cars, is higher than the mileage exposure of non-ESC-cars. The expected cases with ESC, due to its market share, if there were no effectiveness of

ESC, are computed by the following formula, which also allows to derive the effectiveness of ESC. You get the identical result, when you use the formula, mentioned in chapter “The market penetration of ESC.”

The overall effectiveness was computed as a weighted average of the yearly effectivenesses. The alternative was to make one large class, adding the respective data of 2000..2004 and computing an effectiveness from this data. This provides an even higher effectiveness, so that we think, this approach is more conservative and as an average of four estimations statistically more reliable.

N_{ESC} GIDAS - cases with ESC

N_{noESC} GIDAS - cases without ESC

$N_{\exp ESC}$ Expected GIDAS - cases with ESC

p fleet share of ESC

eff effectiveness of ESC

$$N_{\exp ESC} = \frac{N_{noESC}}{1-p} * p$$

$$eff = 1 - \frac{N_{ESC}}{N_{\exp ESC}}$$

From Figure 12 it can clearly be seen, what was estimated from former effectiveness estimations based of the observed ESC-effectiveness of Volkswagen and AUDI ESP. Volkswagen and AUDI accident research found in their field studies an 80% reduction of skidding accidents by ESC. From this research, we predicted a fatality reduction as provided in Figure 8. This research was often blamed to over-estimate the benefit of ESC. We heard these arguments with a certain degree of satisfaction, because it is not our problem, when the observed Volkswagen and AUDI ESP effectiveness is higher than the overall effectiveness of ESC in general. But the figures provided show that there is a significant benefit of ESC which has to be taken into account in future analysis.

	MAIS 0	MAIS 1	MAIS 2	MAIS 3	MAIS 4	MAIS 5	MAIS 6
2000	57,0%	33,0%	6,7%	1,7%	0,4%	0,1%	1,3%
2001	57,5%	33,9%	5,6%	1,2%	0,3%	0,2%	1,4%
2002	58,7%	31,1%	6,3%	1,4%	0,7%	0,2%	1,6%
2003	58,5%	32,4%	5,8%	1,1%	0,6%	0,2%	1,3%
2004	60,5%	31,4%	5,6%	0,8%	0,7%	0,1%	0,9%

Figure 13. Distribution of the AIS-Classes for different accident years and belted non-ESC passenger car occupants.

Figure 13 provides for the years from 2000 to 2004 the MAIS-distributions for belted occupants in non-ESC cars. This shows that there are also increases in passive safety in this time-frame. This distribution can be used to compute the ESC-effectiveness for the police-recorded data.

	uninjured	injured no hospital	injured hospital	injured fatally	Share of no-ESC-pc	Reduction by ESC
MAIS 0	99,7%	0,0%	0,2%	0,0%	60,5%	50,5%
MAIS 1	0,0%	82,3%	17,3%	0,3%	31,4%	55,4%
MAIS 2	0,0%	39,4%	60,0%	0,6%	5,6%	67,8%
MAIS 3	0,0%	29,1%	68,2%	2,8%	0,8%	63,8%
MAIS 4	0,0%	27,0%	55,1%	17,9%	0,7%	76,7%
MAIS 5	0,0%	11,5%	23,0%	65,5%	0,1%	100,0%
MAIS 6	0,0%	0,0%	0,0%	100,0%	0,9%	70,4%
Distribution Without ESC	60,3%	28,5%	9,9%	1,3%		Sum 100,0%
With ESC	29,8%	12,4%	3,9%	0,4%		46,5%
Reduction	50,5%	56,6%	61,0%	71,9%		Average 53,5%

Figure 14. Computation of ESC-effectiveness (i.e. risk reduction) for injury categories of police data.

Figure 14 provides the relative probabilities describing the relationship between MAIS and police-recorded severity classes. Note that the reduction by ESC is not directly taken from Figure 12, because Figure 12 describes the effectiveness for MAIS 3+ and not MAIS 3. But the effectiveness used in Figure 14 can easily be derived from that provided in Figure 12.

THE PREDICTED AND OBSERVED DEVELOPMENT OF FATALITIES INFLUENCED BY ESC

The calculations of the preceding chapter can be used to predict the number of fatalities for Germany, if market penetration of ESC continues in a foreseeable manner. By starting this calculation with 1997, it can also be studied how far ESC explains the progress, already seen in the past.

Figure 15 computes in the column “Progress expected by ESC” the progress to be expected, when the fatalities of the preceding year are used to predict a new fatality number from the increasing share of ESC-vehicles and the assumed effectiveness of 71,9%. For all years besides 2002, this computation underestimates the decrease of fatalities. 541% means that the expected decrease (4023-3926) is 541% of the actual decrease of (4023-4005).

This underestimation of the decrease of fatalities means that additional effects influenced the positive trend in Germany. It is the authors’ opinion that these are mainly the better compartments of current vehicles and the airbags. [11]. Beginning with 2006, the 100% of the progress is explained by ESC, because no other predictions were included.

For the near future, there are at least two factors to be considered as well, the ongoing change of vehicle fleet towards more stable compartments etc. But on the other hand the economic growth has also to be considered, because we know that under better economic conditions, people are more willing to drive.

Scenario 1 Things go on like today: 75% of the new cars are equipped with ESC 71,9% Fatality reduction by ESC Beginning with 2006, data a predicted according to scenario					
		Passenger Cars			
Year	Share of ESC-cars	Passenger car fatalities expected due to higher share of ESC	Actual number of passenger car fatalities	Progress explained by ESC	Progress compared to 2000
1997	0,00%	5622	5249	0,0%	119,4%
1998	0,66%	5224	4741	4,9%	107,8%
1999	1,98%	4696	4640	44,8%	105,6%
2000	3,93%	4574	4396	27,1%	100,0%
2001	6,52%	4312	4023	22,5%	91,5%
2002	9,73%	3926	4005	541,0%	91,1%
2003	13,62%	3884	3774	52,2%	85,9%
2004	18,38%	3631	3238	26,7%	73,7%
2005	23,46%	3102	2833	33,6%	64,4%
2006	28,67%	2705	2705	100,0%	61,5%
2007	34,07%	2573	2573	100,0%	58,5%
2008	39,47%	2441	2441	100,0%	55,5%
2009	44,87%	2308	2308	100,0%	52,5%
2010	50,27%	2176	2176	100,0%	49,5%
2011	55,67%	2044	2044	100,0%	46,5%
2012	61,07%	1911	1911	100,0%	43,5%
2013	66,47%	1779	1779	100,0%	40,5%
2014	71,87%	1647	1647	100,0%	37,5%
2015	75,00%	1570	1570	100,0%	35,7%
2016	75,00%	1570	1570	-	35,7%
2017	75,00%	1570	1570	-	35,7%
2018	75,00%	1570	1570	-	35,7%
2019	75,00%	1570	1570	-	35,7%
2020	75,00%	1570	1570	-	35,7%

Figure 15. Estimated progress by ESC for passenger car occupants, if 75% of new car registrations are ESC-equipped cars.

Figure 16 adds the data of the other traffic participants, so that the influence of this progress on all traffic fatalities in Germany is shown. Every other effect is neglected in the data. The 505% of 1999 mean that the progress achieved by decrease of passenger car fatalities (4741-4640) is 505% of the progress achieve, when all road traffic fatalities are taken into account (7792-7772).

The message of Figure 16 is that in 2010 Germany will achieve a drop of fatalities compared to 2000 to 62,7%. So ESC alone is nearly able to reach the goal of EU-commission, to achieve a 50% fatality reduction. So when the commission realizes today that it will not achieve its goal, (compare the predictions of the authors in [11]), the message is clear: Make ESC available EU-wide by convincing the customers, providing incentives, doing what you can to promote ESC.

If in 2007 Germany would have started to sell ESC in 100% of all cars (Figure 17), the car occupant fatalities would go down to 46,5% in 2010 (53,5% less than 2000) or in absolute numbers to 2044. In this case, when 100% ESC in the fleet (not only registrations) is reached, Germany's car occupant fatalities would go down to 957, to 21,8% of the 2000-level, which was also a low level, because in the nineties, after an increase in the period of reunification, there was a steady decrease as well.

	Total number of road traffic fatalities	Progress explained by passenger cars	Progress compared to 2000
1997	8549	-	113,9%
1998	7792	67,1%	103,9%
1999	7772	505,0%	103,6%
2000	7503	90,7%	100,0%
2001	6977	70,9%	93,0%
2002	6842	13,3%	91,2%
2003	6613	100,9%	88,1%
2004	5842	69,5%	77,9%
2005	5361	84,2%	71,5%
2006	5233	100,0%	69,7%
2007	5101	100,0%	68,0%
2008	4969	100,0%	66,2%
2009	4836	100,0%	64,5%
2010	4704	100,0%	62,7%
2011	4572	100,0%	60,9%
2012	4439	100,0%	59,2%
2013	4307	100,0%	57,4%
2014	4175	100,0%	55,6%
2015	4098	100,0%	54,6%
2016	4098	-	54,6%
2017	4098	-	54,6%
2018	4098	-	54,6%
2019	4098	-	54,6%
2020	4098	-	54,6%

Figure 16. Scenario 1 of Figure 15, but progress computed for all road traffic fatalities, to show the effect of ESC for road traffic in general.

Scenario 2 Actions to increase share of ESC-equipped cars Beginning with 2008, all new cars are equipped with ESC 71,9% Fatality reduction by ESC Beginning with 2006, data a predicted according to scenario					
		Passenger Cars			
Year	Share of ESC-cars	Passenger car fatalities expected due to higher share of ESC	Actual number of passenger car fatalities	Progress explained by ESC	Progress compared to 2000
1997	0,00%	5622	5249	0,0%	119,4%
1998	0,66%	5224	4741	4,9%	107,8%
1999	1,98%	4696	4640	44,8%	105,6%
2000	3,93%	4574	4396	27,1%	100,0%
2001	6,52%	4312	4023	22,5%	91,5%
2002	9,73%	3926	4005	541,0%	91,1%
2003	13,62%	3884	3774	52,2%	85,9%
2004	18,38%	3631	3238	26,7%	73,7%
2005	23,46%	3102	2833	33,6%	64,4%
2006	28,67%	2705	2705	100,0%	61,5%
2007	34,07%	2573	2573	100,0%	58,5%
2008	41,27%	2397	2397	100,0%	54,5%
2009	48,47%	2220	2220	100,0%	50,5%
2010	55,67%	2044	2044	100,0%	46,5%
2011	62,87%	1867	1867	100,0%	42,5%
2012	70,07%	1691	1691	100,0%	38,5%
2013	77,27%	1514	1514	100,0%	34,4%
2014	84,47%	1338	1338	100,0%	30,4%
2015	91,67%	1162	1162	100,0%	26,4%
2016	100,00%	957	957	100,0%	21,8%
2017	100,00%	957	957	-	21,8%
2018	100,00%	957	957	-	21,8%
2019	100,00%	957	957	-	21,8%
2020	100,00%	957	957	-	21,8%

Figure 17. Scenario of ESC-promotion by additional incentives, so that beginning with 2008 all new cars are equipped by ESC.

Figure 18 shows, what this means in terms of all traffic fatalities. The column “Additional benefit cumulative” shows, how many lives could be saved, if we would run into a 100% ESC-fleet instead of a 75% ESC fleet like in scenario 1 of Figure 16. By 2010 this would mean cumulative 265 fatalities less.

	Total number of road traffic fatalities	Progress explained by passenger cars	Progress compared to 2000	Additional benefit compared to Scenario 1	Additional benefit cumulative
1997	8549	-	113,9%	0	0
1998	7792	67,1%	103,9%	0	0
1999	7772	505,0%	103,6%	0	0
2000	7503	90,7%	100,0%	0	0
2001	6977	70,9%	93,0%	0	0
2002	6842	13,3%	91,2%	0	0
2003	6613	100,9%	88,1%	0	0
2004	5842	69,5%	77,9%	0	0
2005	5361	84,2%	71,5%	0	0
2006	5233	100,0%	69,7%	0	0
2007	5101	100,0%	68,0%	0	0
2008	4925	100,0%	65,6%	44	44
2009	4748	100,0%	63,3%	88	132
2010	4572	100,0%	60,9%	132	265
2011	4395	100,0%	58,6%	176	441
2012	4219	100,0%	56,2%	221	662
2013	4042	100,0%	53,9%	265	926
2014	3866	100,0%	51,5%	309	1235
2015	3690	100,0%	49,2%	408	1643
2016	3485	-	46,5%	613	2256
2017	3485	-	46,5%	613	2869
2018	3485	-	46,5%	613	3481
2019	3485	-	46,5%	613	4094
2020	3485	-	46,5%	613	4706

Figure 18. Scenario 2 of Figure 17, but progress computed for all road traffic fatalities. The last two columns show the additional benefit per year and cumulative that can be achieved, when scenario 2 occurs instead of scenario 1.

Scenario 3 Scenario 2 and actions to increase the change to new cars in the fleet Increase of new car registrations by 1% of fleet (14% of new car registrations) 71,9% Fatality reduction by ESC Beginning with 2006, data a predicted according to scenario					
	Passenger Cars				
Year	Share of ESC-cars	Passenger car fatalities expected due to higher share of ESC	Actual number of passenger car fatalities	Progress explained by ESC	Progress compared to 2000
1997	0,00%	5622	5249	0,0%	119,4%
1998	0,66%	5224	4741	4,9%	107,8%
1999	1,98%	4696	4640	44,8%	105,6%
2000	3,93%	4574	4396	27,1%	100,0%
2001	6,52%	4312	4023	22,5%	91,5%
2002	9,73%	3926	4005	541,0%	91,1%
2003	13,62%	3884	3774	52,2%	85,9%
2004	18,38%	3631	3238	26,7%	73,7%
2005	23,46%	3102	2833	33,6%	64,4%
2006	28,67%	2705	2705	100,0%	61,5%
2007	34,07%	2573	2573	100,0%	58,5%
2008	42,27%	2372	2372	100,0%	54,0%
2009	50,47%	2171	2171	100,0%	49,4%
2010	58,67%	1970	1970	100,0%	44,8%
2011	66,87%	1769	1769	100,0%	40,2%
2012	75,07%	1568	1568	100,0%	35,7%
2013	83,27%	1367	1367	100,0%	31,1%
2014	91,47%	1166	1166	100,0%	26,5%
2015	100,00%	957	957	100,0%	21,8%
2016	100,00%	957	957	-	21,8%
2017	100,00%	957	957	-	21,8%
2018	100,00%	957	957	-	21,8%
2019	100,00%	957	957	-	21,8%
2020	100,00%	957	957	-	21,8%

Figure 19. Scenario of a two incentives promoting ESC. Firstly, beginning with 2008, all new cars are equipped with ESC. Secondly, new car registrations are increased by 14%, so that additional 1% of fleet are changed into new cars. Only the ESC-effect is reflected, other effects like better restraint systems, better compartments are only reflected up to 2005.

Scenario 3 now deals with the velocity of the change of fleet. It was assumed that 1% more than the current 7,2% (i.e.8,2%) are exchanged per year. This would mean, that we reach the 100% ESC fleet already in 2015 one year earlier. Additional 846 fatalities would not take place.

Figure 21 combines all these scenarios and clearly shows that for the next 10 years we can expect a very steady decrease of fatalities in all countries that implement ESC in a significant amount into the car fleet.

ESC is only the beginning of this process. LaneDepartureAlert, Drowsiness monitoring, Side assist and other tools will support the driver, so that accidents become more and more unlikely to happen. Car-to-car-communication will provide a situation that cars organize their use of junctions e.g. by themselves and co-operate in organizing a as far as possible error-free traffic flow.

	Total number of road traffic fatalities	Progress explained by passenger cars	Progress compared to 2000	Additional benefit compared to Scenario 2	Additional benefit cumulative
1997	8549	-	113,9%	0	0
1998	7792	67,1%	103,9%	0	0
1999	7772	505,0%	103,6%	0	0
2000	7503	90,7%	100,0%	0	0
2001	6977	70,9%	93,0%	0	0
2002	6842	13,3%	91,2%	0	0
2003	6613	100,9%	88,1%	0	0
2004	5842	69,5%	77,9%	0	0
2005	5361	84,2%	71,5%	0	0
2006	5233	100,0%	69,7%	0	0
2007	5101	100,0%	68,0%	0	0
2008	4900	100,0%	65,3%	25	25
2009	4699	100,0%	62,6%	49	74
2010	4498	100,0%	60,0%	74	147
2011	4297	100,0%	57,3%	98	245
2012	4096	100,0%	54,6%	123	368
2013	3895	100,0%	51,9%	147	515
2014	3694	100,0%	49,2%	172	686
2015	3485	100,0%	46,5%	204	890
2016	3485	-	46,5%	0	890
2017	3485	-	46,5%	0	890
2018	3485	-	46,5%	0	890
2019	3485	-	46,5%	0	890
2020	3485	-	46,5%	0	890

Figure 20. Scenario 3 of Figure 19, but progress computed for all road traffic fatalities. The last two columns show the additional benefit per year and cumulative that can be achieved, when scenario 3 occurs instead of scenario 2.

We are not of the opinion that we will have a VISION-ZERO traffic without any accidents, any fatalities. Appr. 10% of our fatalities in car crashes are suicide. A system that prevents suicide from happening is not possible in a free society. But we will reduce the number of accidents not only by some percents, but by a significant factor in a foreseeable future of 20 years or so.

When studying these scenarios it becomes clear that all efforts, all resources are needed to reach this ambitious goal. With this background it is unbelievable, why most of the efforts of scientific institutes, involved in safety research, are still related to passive safety issues. Passive safety was very successful in the past, that is acknowledged without any reservations. But for the future, we have to emphasize on issues that provide similar progress of safety, as passive safety did in the past. All discussions on passive safety enhancements are dealing with very small portions of safety progress, in some cases, it is even unclear, whether there is progress or whether negative side effects dominate (compatibility discussion). So it is worth to study, how the world of ESC-cars will look like. This is done in the following chapter.

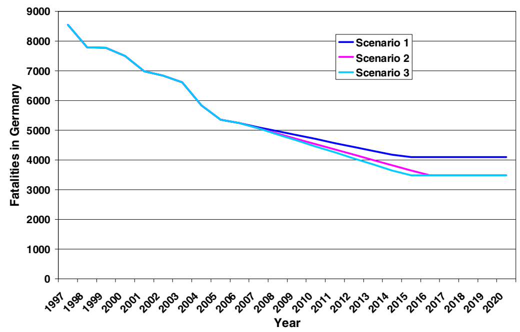

Figure 21. Decrease of total number of fatalities in Germany. For 2007 and the following only the effect of ESC and the different scenarios of introducing ESC into the fleet are reflected.

INFLUENCE OF FLEET CHANGE ON COLLISION MODES

In the past, Volkswagen and AUDI published a couple of papers (see references), regarding ESC-effectiveness (Figure 8). Our first computations of the high effectiveness of ESC are now world-wide accepted and the data is rather clear. This does not mean that ESC is effective in every single case, but in general, there is a positive effect in the German accident data. It must be stated that American data was not available to the authors, to make similar analysis for the U.S.A. The different road situation in the U.S. with more straight roads, more cross-roads might lead to different results. The authors are not able to investigate the influence of these differences, because no comparable in-depth data like GIDAS was available to the authors.

Figure 22 is an example of an observation that ESC positively influenced GIDAS data. In the nineties, skidding accidents were at a level of 10 to 15%. A decrease started in 1998 with the fleet penetration of ESC. When we look deeper into the data, we see that the average age of the skidding drivers did not change. It is approximately 30 years, the non-skidding drivers are 10 years older (Figure 24). This means that ESC supports all drivers, not only drivers that have special skills. The normal driver will not realize ESC in his normal driving situations. It helps, when it is needed, the driver probably is not aware of the intervention of ESC. This is part of the success of ESC, only experts can willingly create a situation of ESC-intervention. Volkswagen and AUDI researchers did a lot to implement an ESC that does only intervene when necessary and as far as possible, prevents the driver from playing with ESC.

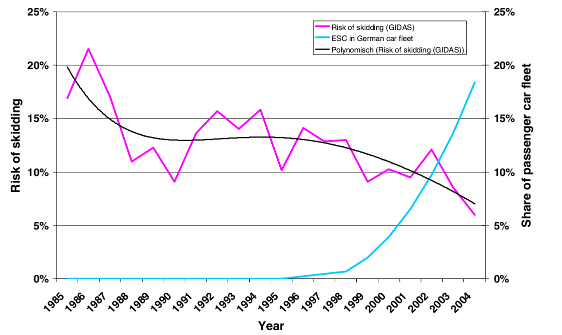

Figure 22. The risk of skidding and the market penetration by ESC.

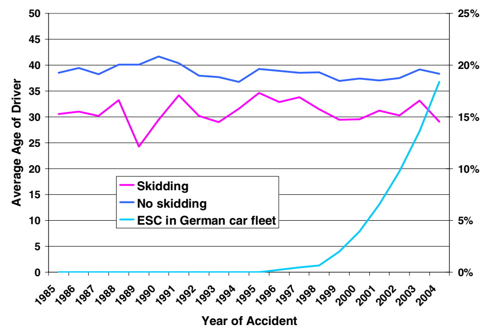

Figure 23. Skidding accidents and the average age of drivers. Drivers involved in skidding tend to be younger. The age mean value is not influenced by ESC.

The increase of the share of females in Figure 24 is in line with the general observation that females more often have a car of their own, are more often driving, so that this increase is more or less surprisingly low and not an indication of anything else.

The next figure (Figure 25) deals with the question, whether ESC influences collision modes positively. The effectiveness of ESC for different collision modes has to be examined. The idea of this computation is to take into account the crash-avoidance capability of ESC. The 100% accidents, as observed in the sample of cars without ESC, will be reduced to 46,5%, due to the 53,5% crash-avoidance capability of ESC. So the distribution of accident types of ESC-cars, as described in Figure 25, in fact is the distribution of the 46,5% accidents still occurring after implementing ESC. This distribution is given in column 3 of Figure 26.

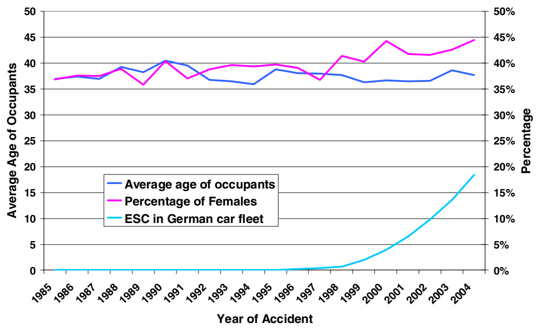

Figure 24. Average age of occupants, involved in accidents is constant versus time, share of female occupants increased.

Accident type		
	GIDAS: Passenger car	
	with ESC	without ESC
Driving accident	191	3673
Accident caused by turning off the road	329	3888
Accident caused by turning into a road or by crossing it	478	6916
Accident with pedestrian crossing the road	208	2421
Accident involving stationary vehicles	67	924
Accident between vehicles moving along in carriageway	540	6413
Other accident	108	1312
Unknown	25	66
Sum	1946	25613

Figure 25. Number of accidents for different types of accidents for passenger vehicles with and without ESC as found in GIDAS.

Accident type	Distribution		53,5% crash-avoidance capability of ESC
	with ESC	without ESC	
Driving accident	9,8%	14,3%	4,6%
Accident caused by turning off the road	16,9%	15,2%	7,9%
Accident caused by turning into a road or by crossing it	24,6%	27,0%	11,4%
Accident with pedestrian crossing the road	10,7%	9,4%	5,0%
Accident involving stationary vehicles	3,4%	3,6%	1,6%
Accident between vehicles moving along in carriageway	27,7%	25,0%	12,9%
Other accident	5,5%	5,1%	2,6%
Unkown	1,3%	0,4%	0,6%
Other accident	100,0%	100,0%	46,5%

Figure 26. Distribution of accident types for passenger vehicles with and without ESC. For ESC-cars, the 53,5% crash-avoidance capability of ESC (compare Figure 14) is taken into account in a separate computation.

Figure 26 provides two columns to be compared to the original data, the distribution of vehicles without ESC. Figure 27 shows the result, when effectiveness computation is conducted for these two columns. It is mathematically clear that the comparison of two distributions (sum is 100% in both cases) provides positive and negative effectiveness. Taking into account the crash-avoidance potential, overcomes this problem. The result is seen in the second column of Figure 27.

Accident type	Comparison of distributions	ESC effectiveness
Driving accident	31,4%	63,3%
Accident caused by turning off the road	-11,5%	40,3%
Accident caused by turning into a road or by crossing it	8,9%	51,3%
Accident with pedestrian crossing the road	-13,3%	39,4%
Accident involving stationary vehicles	4,4%	48,9%
Accident between vehicles moving along in carriageway	-11,0%	40,6%
Other accident	-8,5%	41,9%

Figure 27. Effectiveness, derived from the distributions of Figure 26. Only when taking into account the crash-avoidance capability of ESC, meaningful results are achieved.

The column “Full ESC Effectiveness” of Figure 27 shows that the highest effectiveness of ESC is seen for driving accidents. A car is driving on difficult road conditions or changing road conditions, is e.g. skidding, and an accident occurs. This is a very typical ESC situation attributed to small and winding European roads. The lowest effectiveness ESC shows for pedestrians. It is surprising that ESC even shows effectiveness even in this case. These phenomena have to be studied more in depth to understand, whether and why this is possible. One possible explanation is the fact that ESC cars are more able to obey the steering input of the driver. It shall also be noted at this point that a group of accident researchers uses the double pair approach to estimate probabilities. These researchers would assume that pedestrian accidents do not change (the double pair in this case are the accidents of the pedestrians with the ESC-cars vs. the accidents with non-ESC-cars). They would find an effectiveness of ESC between the effectiveness of column “Full ESC Effectiveness” of Figure 27 and zero for pedestrians. Everything else is positive. But the authors are of the opinion that this is not an adequate analysis, because of the arguments given above.

Impact type	Comparison of distributions	ESC effectiveness
Front	7,5%	57,0%
Side	-5,1%	51,1%
Rear	-76,8%	17,8%

Figure 28. ESC-effectiveness for different impact types. All passenger vehicles. Same calculation as in Figure 25 to Figure 27.

Figure 28 provides the results of a similar calculation for front, side and rear impact. ESC is mainly beneficial for front- and side impact, less beneficial for rear impact, but it is beneficial for all collision modes. What does this mean for a car rating: Whatever the estimation of the benefit of the conducted test procedure is: More than 50% of the possible benefit is attributed to the fact whether the vehicle is equipped by ESC or not. For sure passive safety measures will not completely prevent injuries from happening, so the fact that a car is ESC-equipped describes probably 60 or 70% of the car’s safety potential.

Single Vehicle Accident	62,50%
Skidding before accident	74,30%
Roll-over	79,40%
Roll-over with MAIS 1+	71,40%
Roll-over with MAIS 2+	51,60%
Roll-over with MAIS 3+	58,70%
Roll-over with MAIS 4+	41,50%
Roll-over with MAIS 5+	58,90%
Roll-over with MAIS 6	78,10%

Figure 29. ESC-effectiveness for different accident situations. Computation always takes into account the crash avoidance capability of ESC.

The situation is even more clear, when single-vehicle accidents or accidents with skidding or roll-over accidents are taken into account. The countermeasure is clearly ESC and nothing else. All other measure, imaginable, are far below the level, expressed by the effectiveness provided in Figure 29.

CONCLUSIONS

- There is a high benefit in ESC in crash avoidance and in injury mitigation.
- The crash avoidance capability of ESC can be derived from the share of ESC-cars in the fleet and in the accident data. ESC-equipped cars will have approximately 50% less accidents than other cars.
- The number of severe injuries will decrease by more than 60% for cars, equipped with ESC.
- The number of fatalities will decrease by more than 70% for cars, equipped with ESC.
- The positive trend in German fatalities will continue for the next decade, if 75% of newly registered cars are equipped with ESC.
- ESC alone will decrease the fatality figures of 2000 to a level of 55%, if 75% of newly registered cars are equipped with ESC.
- If 100% of the newly registered cars are equipped with ESC, ESC alone will decrease the fatality figures of 2000 to a level of 46%.
- The most valid measure of roll-over protection, of frontal impact protection, of side impact protection is ESC. ESC will reduce the risk in all of these accidents by more than 50%. This must be taken into account regarding future regulations and new car assessments.
- When rating a car, more than 50% of the safety rating figures or stars or whatever should be attributed to ESC. This means that a rating, which takes into account passive safety only, is incomplete and possibly misleading.
- Governments should change their safety politics to stop the further increase of weight and cost of the car by more and more inefficient passive safety requirement and should prioritize active safety measures.
- Tools like side assist, lane departure alert, and drowsiness monitoring should be studied instead, because they have similar potential to ESC.
- Accident research must take into account the crash avoidance potential of systems like ESC, because when they neglect it, they will achieve misleading results, because ESC not only changes the enumerator of benefit calculations by reducing severe injuries and fatalities, but it also changes the denominator of all accidents, because a lot of accidents disappear from the accident data file.
- Accident research, benefit studies, prioritizations should be made prospective. They should try to predict the future of the car fleet, because collision mode distribution will change significantly.

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A REALISTIC CRASH TEST SETUP TO ASSESS THE REAL WORLD PERFORMANCE OF ADVANCED ROLLOVER SENSING SYSTEMS

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Paper Number 07-0362

ABSTRACT

To protect occupants during a rollover event, restraint control modules with integrated Rollover Sensing (RoSe) function have been developed. These devices are able to trigger belt tensioners and curtain airbags if the vehicle's roll angle and roll rate indicate that the vehicle is going to tip over. Especially in the case of tripped rollovers, however, the optimum deployment time for curtain airbags is before the vehicle has build up a significant roll angle. To cope with this challenge the advanced rollover sensing function from Bosch uses the lateral velocity of the vehicle as additional input to its deployment decision.

Based on a new crash test setup developed by Dekra the performance benefit of this advanced rollover sensing system can be shown under realistic circumstances. The test does not only cover the rollover phase but also the skidding phase before the vehicle passes onto the soil and rolls over. First tests have been performed to investigate both the repeatability of the movement and the behaviour of the vehicle during such tests. To steer the car, an optically controlled guidance is used combined with a time-based activation of the steering without braking. The vehicle with rightwards steered front wheels runs for a short time on a μ-split path. Several sensors are used to measure the relevant kinematics (velocity, acceleration, yaw-, roll- and pitch-rate). Additionally the movement is filmed by several high-speed cameras.

In the article the authors describe the test method and the results and discuss the benefit of this new method to assess the performance of an algorithm for advanced rollover protection.

INTRODUCTION

According to the NHTSA Traffic Safety Report 2005 [1] rollover crash events still contribute significantly to the crash fatalities on the roads of the United States. Although only 2.6% of all vehicle crashes can be attributed to rollovers, 21.1% of the occupant fatalities in 2005 are related to vehicles having a rollover crash. These statistics dramatically illustrate the severity of this crash type.

RESTRAINT DEVICES FOR OCCUPANT PROTECTION DURING ROLLOVERS

The best way to protect occupants from any rollover injury is to prevent a rollover. Electronic stability control (ESC) systems can help to reduce the risk of rolling over. However, such systems mainly address so called on-road rollovers induced by lateral tire friction occurring e.g. in massive skidding situations. In case of a vehicle leaving the roadway, stability control systems come to the limit, since they cannot prevent wheels from furrowing into the ground resulting in a rollover. As crash statistics show these so-called soil trip rollovers account for a significant number of the rollovers in the USA.

In case a rollover cannot be prevented, the vehicle's passive safety design has to prove of value: A high roof stability as well as intelligent restraint devices like rollover curtains and belt tensioners can help to reduce the occupants' injury level. Special rollover curtains that remain inflated for several seconds can prevent occupants from being fully or partially ejected during a rollover. Belt tensioners can fix a buckled occupant in the seat thereby keeping the occupant's head at the maximum possible distance from the side windows and from the vehicle's roof which might be subject to intrusion.

ROLLOVER SENSING - MAKING A TRIGGER DECISION FOR ROLLOVER RESTRAINTS

The protection potential of rollover related restraint devices like rollover curtains or belt tensioners is strongly correlated to the time they are triggered: The earlier these devices are deployed, the higher their protection effectiveness can be. On the other hand an inadvertent deployment must be avoided under all circumstances, even in the case that a vehicle already has started to roll but doesn't roll over completely in the end, i.e. not reaching a roll angle ≥ 90°. Making an early but robust deployment decision is a question of the rollover sensing performance. Today the RoSe function is an integral (but for most vehicles still optional) part of the restraints control module.

Existing RoSe systems typically calculate a deployment decision using a roll rate sensor that is integrated into the restraints control module. The deployment decision is based on a comparison of the vehicle's actual roll rate with a critical roll rate threshold. This threshold depends on the vehicle's current roll angle and on its physical properties such as mass, centre of mass, track width and moment of inertia.

If the vehicle's roll rate exceeds the critical threshold, the rollover sensing system can predict whether the vehicle will roll over, see Figure 1. In case a complete rollover is certain the restraints control module deploys occupant restraint devices accordingly. This approach generally produces early and robust deployment decisions in rollover situations that do not involve tripping.

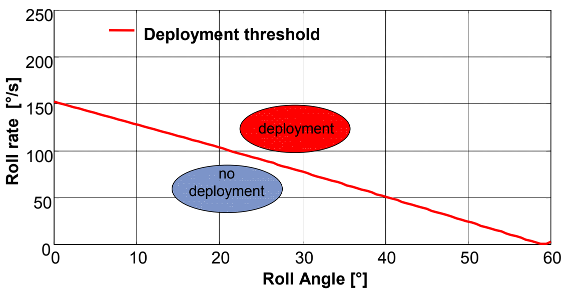

Figure 1. Example of standard rollover criterion for the deployment decision of rollover restraints

In the case of tripped rollovers, however, the rollover event is primarily induced by lateral forces. In this case a deployment decision is needed very early. This is due to the fact that the lateral forces can push the occupant's head into the deployment zone of a curtain airbag before the vehicle has built up a significant roll angle. Thus in the case of tripped rollover events, existing RoSe algorithms must be calibrated accordingly in order to produce an optimal trade-off between the requirements for early deployment and the need for high robustness against misuses. Investigations of rollover test data have shown that this conflict can effectively be resolved by incorporating information about the vehicle's driving state into the deployment decision [2].

ADVANCED ROLLOVER SENSING

Today's RoSe system analyze the roll movements of the car in order to make deployment decision. However, valuable information about a rollover risk can be derived before the vehicle has build up a significant roll angle. In the specific case of tripped rollovers the vector of the vehicle's velocity changes from longitudinal direction to lateral direction as the vehicle starts to skid, see Figure 2.

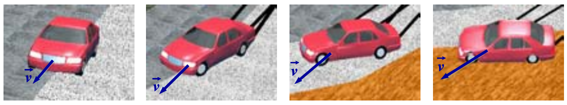

Figure 2. Change of vehicle velocity direction relative to the vehicle in a pre-roll phase

The kinetic energy thereby takes effect on the car's lateral movement, and is finally transformed into rotational energy as the wheels furrow into the soil and decelerate the car laterally. The higher the lateral velocity v_y of the car and the lateral deceleration a_y, the higher the amount energy E_{kin} which can be transformed into rotational energy E_{rot}. To differentiate how the lateral velocity indeed is inducing a roll movement, the so-called "roll effectiveness", is introduced:

$$e_{roll} = f(\Delta v_y, \Delta \varphi_x)$$

This roll effectiveness describes the relation between the decrease of lateral velocity Δv_y (due to the lateral deceleration) and the building up of a roll angle $\Delta\varphi_x$.

Taking into account that the transformation from E_{kin} to E_{rot} is caused by the lateral forces (represented by a_y) and presuming that e_{roll} determines how these lateral forces contribute to a roll movement in that situation, together with v_y (indicating how much kinetic energy is left to be transformed into rotational energy) a deployment criterion can be defined as follows:

$$a_y > a_{y,crit} = f(e_{roll}, v_y)$$

Figure 3 shows an exemplary embodiment of the Equation above corresponding to the calibration for a generic sedan. The rollover and non-rollover events are separated by the $a_{y,crit}$-surface in the

(e_{roll}, v_y, a_y)-plane. If the vehicle's lateral velocity is below the critical sliding velocity (CSV), the deployment is inhibited by an asymptotic threshold for the lateral acceleration. A similar situation occurs if the roll effectiveness is zero (e.g. during a side crash). In the case of a high lateral velocity and a high roll effectiveness, the deployment threshold converges to the static stability factor (SSF) of the vehicle.

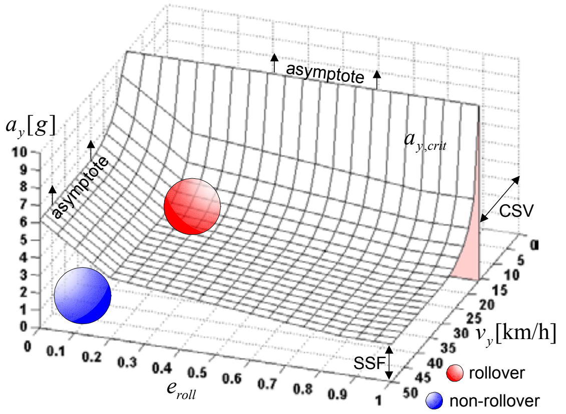

Figure 3. Illustration of an advanced rollover sensing and deployment criterion

ESTIMATION OF THE VEHICLE'S LATERAL VELOCITY

Having a rollover criterion incorporating the lateral velocity v_y leads to the need to calculate v_y during all driving situations. Based on vehicle dynamics formulas this can be achieved by using the following signals:

1. Yaw rate
2. Lateral acceleration
3. Steering angle
4. Longitudinal vehicle velocity
5. Longitudinal acceleration

All of these signals except the last one are available in vehicles equipped with a Vehicle Dynamics Control system, such as ESP. While the first three signals are provided from sensors dedicated to the ESP function, the longitudinal vehicle velocity is an estimate that the ESP system calculates by means of a model-based approach that incorporates information from all ESP sensors including the wheel speed sensors.

ROLLOVER TESTS TO VALIDATE THE SYSTEM PERFORMANCE

To validate the performance and robustness of this new approach, a realistic rollover test setup is necessary. A test setup that does not only cover the rollover phase alone, but also the pre-roll phase.

Established rollover crash tests

Today several rollover crash test setups are established for different purposes: to analyse the stability of the vehicle's structure, to analyse the biomechanical loads on the occupants and to develop and test deployment algorithms for rollover protection systems like curtain airbags. Using these tests, different aspects of real-world rollovers can be considered.

Figure 4 gives a simplified view of the motion sequences of interest. The triggering is the first crucial event. When a rollover occurs, the car can either tilt to the side only or run into one or even multiple rolls. With regard to occupant protection it is of interest how the car is damaged and how the occupants move, receive impacts and sustain injuries during the rollover.

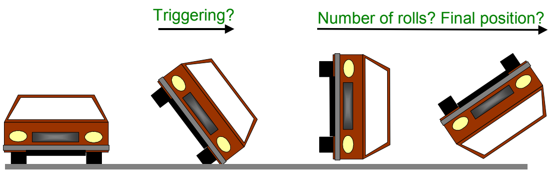

Figure 4. Points of interest to describe rollover kinematics

For the calibration of conventional rollover protection systems as well as for the evaluation of their robustness, tests are carried out in the transition zone between "roll-events" and "no-roll-events". The boundary between these two events helps to find the optimum compromise between performance and robustness.

In order to cover as many real world rollover situations as possible, several rollover crash tests are in use today (for example: Embankment rollover tests, corkscrew rollover tests, curb-trip rollover tests and sand-pit rollover tests, see Figures 5 to 8.)

The only rollover test procedure, which is regulated by law so far is the so-called "FMVSS-208 rollover test", Figure 9. In this test, a car is inclined under 23° on a sled. Test velocity is 49 kph.

Dekra and Bosch as well as other suppliers have been using all of these tests for many years [3, 4, 5].

Figure 5. Embankment rollover test

Figure 6. Corkscrew rollover test

Figure 7. Curb-trip rollover test

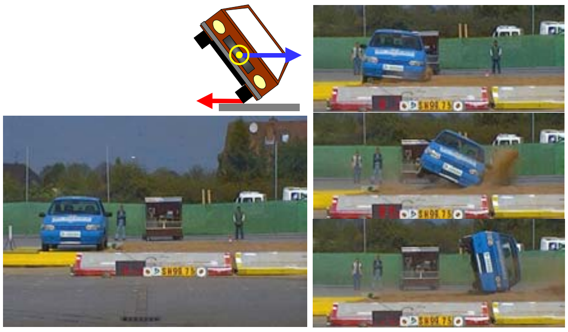

Figure 8. Sand-pit rollover test

Figure 9. FMVSS-208 rollover test

New rollover test setup and procedure

Although the above mentioned tests cover a wide range of rollover aspects, none of these tests is able to address the vehicle's skidding behaviour prior to a real-world soil-trip rollover. Since the advanced rollover sensing approach described above is dedicated to analyse the vehicle's behaviour not only during the roll-phase but already in the critical driving situation leading to the rollover, a new test setup was necessary.

The goal of Dekra and Bosch was to develop a test addressing the driving dynamics in the pre-rollover phase in a realistic and reproducible way as well as the rollover event itself. This new set up has been validated by a roll test, a non-roll test and several reproducibility tests to analyse the repeatability of the vehicle's kinematics.

Test vehicle

The tests presented in this paper were carried out with an SUV-type Opel Monterey RS 3.2 (see Figure 10.) with Electronic Stability Control system. The overall length of this vehicle was 4.330 mm. It was 1.835 mm wide and 1.825 mm high. The wheelbase was 2.320 mm and the wheel track 1.410 mm (front wheels), respectively 1.462 mm (rear wheels).

Figure 10. Test vehicle Opel Monterey RS 3,2

The fuel tank of the vehicle was filled up to 10% of its volume. 196 kg of additional load (measurement equipment, etc.) was fixed in the trunk area and on the rear seats. The wheel loads of the fully equipped car (without dummies) are shown in Table 1. The total weight was 2,094 kg. The distance between the vehicle's centre of gravity (without dummies) and the front axle was 1,205 mm. All four wheels were equipped with General Tyre XP 200, Dimension 245/70 R16. The tread depth was 1.5 mm. The tyre pressure was 2.3 bar for the front wheels and 3.0 bar for the rear wheels.

The test vehicle was equipped with a yaw-, pitch- and roll-rate sensor (IMAR sensor) near to the centre of gravity, see Figure 11. Tri-axial acceleration sensors (x, y, z) were installed at the foot of the B-pillars. Additional unidirectional low-g and high-g acceleration sensors were installed at the housing of the IMAR sensor .

Table 1.
Wheel loads of the test vehicle (without dummies)

	tire left [kg]	tire right [kg]	axle [kg]
front	494	512	1,006
rear	538	550	1,088

Figure 11. IMAR sensor near the centre of gravity

The occupants of the vehicle were represented by two 50th percentile male Hybrid-III dummies. Both dummies were belted in position in the driver and passenger seat, Figure 12. Since the test was mainly dedicated to observe the vehicle's behaviour, no dummy loads have been measured. However, to indicate direct contacts of the dummy's body parts with the interior of the car, colour paintings were put at the head, shoulders, arms and upper legs.

Figure 12. Dummies for driver and passenger

Test setup and vehicle path

The test setup comprises three different phases:
A guided acceleration phase, a skidding phase and a rollover phase. In the first phase the vehicle is guided by an optically controlled steering system at a distance of 250 meters. The vehicle is guided into

straight forward direction while accelerating by its own engine to the predefined velocity. With this velocity the test vehicle enters the second phase of the test setup: the skidding area. In this area the ground is prepared to offer specific high/low-friction conditions. The low-friction conditions are achieved by using synthetic foils which had been watered, see Figure 13.

As the vehicle enters the low-friction area, the vehicle's front wheels are steered rightwards to the maximum possible steering angle as fast as possible. As a result of the steering manoeuvre the vehicle turns slightly to the right with a superimposed yaw motion. In the next step the right front wheel passes the high-friction part of the ground for a short distance. This helps to further increase the yaw motion with the vehicle hurling. At the end of the low friction area the vehicle enters the third phase of the test setup, a sand pit. The vehicle enters the sand pit with a yaw angle of approx. 40 °.

A top view of this motion sequence is given with Figure 14. Figure 15 illustrates the rollover occurring in the sand pit from a side view perspective.

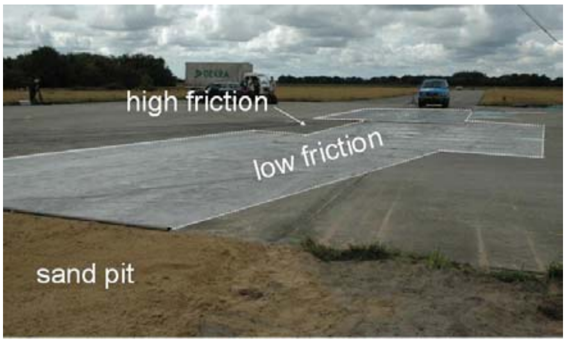

Figure 13. Test vehicle reaching the special prepared part of the test ground

With this motion path of the vehicle prior to the rollover and with the characteristics of the sand pit, the requirements for a realistic rollover crash test scenario have been met. Before the rollover, the vehicle trajectory is similar to a driving situation in a curve in which the vehicle is not following the turn line intended by the driver. After entering the soil the vehicle shows a relatively slow roll motion onto the side and roof which is typical for a rollover in soil. There was also a movement of the vehicle in forward direction when the rollover began.

Figure 14. Movement of the test vehicle on a special prepared part of the test ground into a sand pit (rollover test)

Figure 15. Rollover of the test vehicle on the sand pit

Figure 16 shows the vehicle laying on the roof in final rest position.

Figure 16. Vehicle in final position

Reproducibility aspects

To achieve a good comparability of different test runs and of different vehicles a test setup should ensure a good reproducibility. This aspect was addressed by analyzing the vehicle's trajectories in four test runs. These reproducibility tests were carried out using the same test vehicle.

Figure 17 shows the trajectories of a target point on the roof representing the vehicle's centre of gravity. The trajectories of all four tests are close together. The velocity of the test vehicle at the reference point entering the skidding area was in a range of v = 55.0 – 55.6 km/h with a side-slip angle β = 0°. At the reference line which represents the border of a sand pit, the velocity of the vehicle was in the range v = 44.5 – 48.7 km/h, and the side-slip angle in a range of β = 31° - 40°.

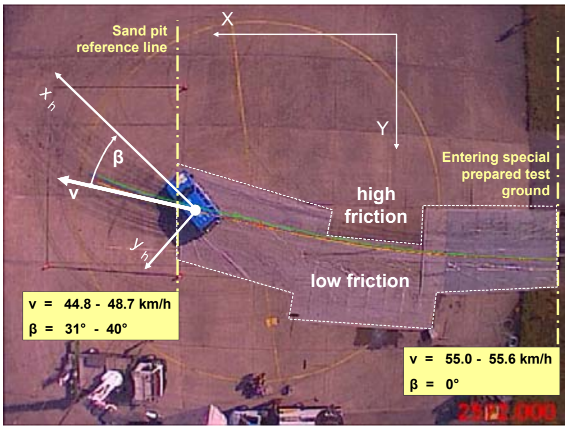

Figure 17. Reproducibility tests analyzing the vehicle's movement prior to rollover

Measurements taken at the vehicle

<u>Rollover</u>

The final rollover test was performed with the vehicle reaching the sand pit at a velocity of v = 41.8 km/h with a side-slip angle β = 39°. Figure 18 shows the signals of the roll rate, the pitch rate and the yaw rate sensor for this test with the vehicle rolled over onto the roof. These signals have been measured with the IMAR Sensor, and filter class CFC 60 was used.

The yaw rate begins to increase shortly after the vehicle enters the skidding area (defined as t = 0.0 s). As the right front wheel reaches the high-friction area (t = 0.2 s). This is due to the fact that a yaw force is induced by the high steering angle of the front wheel when entering the high-friction area. The yaw rate starts to increase strongly here and reaches its maximum of 59 °/s at t = 2.56 s as the vehicle's right front wheel digs into the sand. At this point of time the yaw rate decreases down to 25 °/s (t = 3.1 s) and increases again up to 41 °/s (t = 3.4 s). This is followed by an abrupt inversion to -30 °/s at t = 3.6 s. Finally the yaw rate increases again and comes to zero as the vehicle reaches its final position.

Both pitch rate and roll rate oscillate near zero until the sand pit is reached (at t = 2.4 s). There the pitch rate decreases down to –66 °/s (t = 3.4 s) and drops abruptly back near to zero. The roll rate decreases down to –148 °/s (t = 3.2 s) followed by a relatively smooth changeover into a steep increase to –70 °/s (t = 3.45 s). After that it takes several seconds until the roll movements of the car come to an end and the roll is zero.

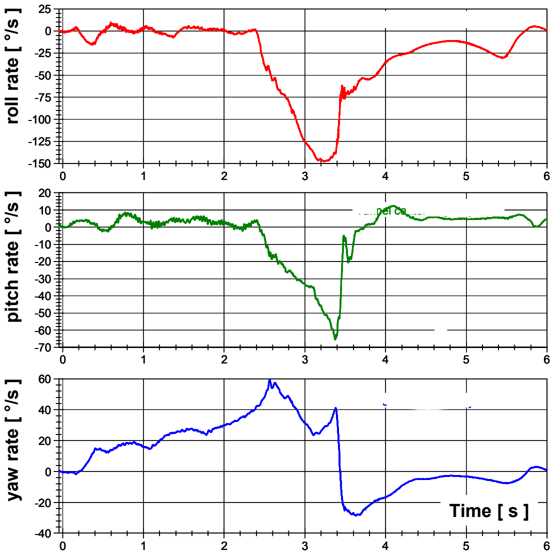

Figure 18. Time histories of roll rate, pitch rate and yaw rate for the rollover test.

The results of the integration of the signals are shown in Figure 19, which demonstrates the roll angle, the pitch angle and the yaw angle. Corresponding to the characteristics of the appropriate rates of angle velocity, the yaw angle began to increase while the vehicle was entering the special prepared test ground with the inclination of the steering angle of the front wheels to the right and reached a maximum of 90 °at t = 3.4 s. Pitch and roll angle remained at zero until the vehicle reached the sandpit (t = 2.4 s). Subsequently, the pitch angle decreased to -45 ° (t = 3.9 s) and the roll angle decreased to -171 ° (t = 6.5 s).

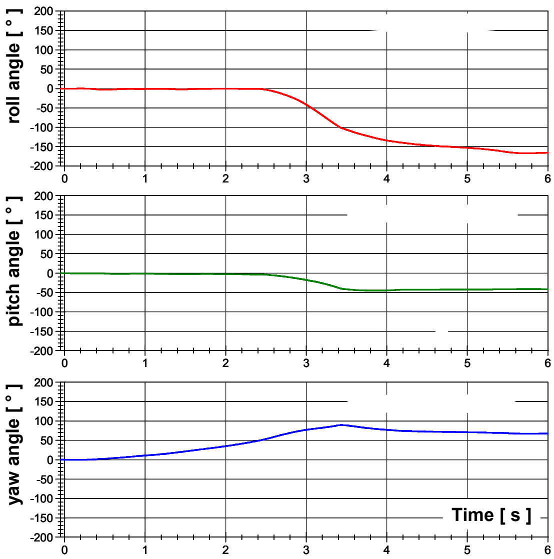

Figure 19. Time histories of roll angle, pitch angle and yaw angle for the rollover test.

No-roll event

Prior to the final rollover test and after the reproducibility tests, a dedicated no-roll test was performed using the same test setup with different friction conditions. This test was performed to find out test parameters for a non-deployment test. The starting velocity of the vehicle was 54.5 km/h. At the point where the vehicle entered the sand pit, the velocity was 42.5 km/h. While entering the sand pit the side-slip angle was $\beta = 22°$. This is 17° less than for the rollover test. Due to the lower side-slip angle the car did not come to a complete rollover.

Figure 20 shows the top view of the test vehicle's movement on the skidding area until it enters the sand pit. The no-roll event of the vehicle on the sand pit is illustrated by a side view to the scene in Figure 21.

In Figure 22 the time histories of the roll rate, the pitch rate and the yaw rate are shown as measured by the IMAR Sensor and filtered with class CFC 60.

It can be seen that the yaw moment induced by the high friction area (t=0,2s) is lower than in the roll-test. This is correlated to a higher friction coefficient at the low-friction area. So the transition of the inclined front wheel from low friction to high friction did not induce such a high increase of the yaw rate as it was the case for the final rollover test. Thereby also the yaw angle with which the vehicle enters the sand pit is affected positively. Most decisive for the roll behaviour, however, is the roll rate. It reaches a maximum of 32°/s at t=2,2s indicating that the rotational energy is not high enough to make the vehicle roll over. The vehicle reaches a maximum roll angle of approx. 20° and than falls back onto the wheels.

From this test is can be shown that a definition of roll and no-roll events can easily be achieved by changing the friction conditions, without the need to change the general test setup.

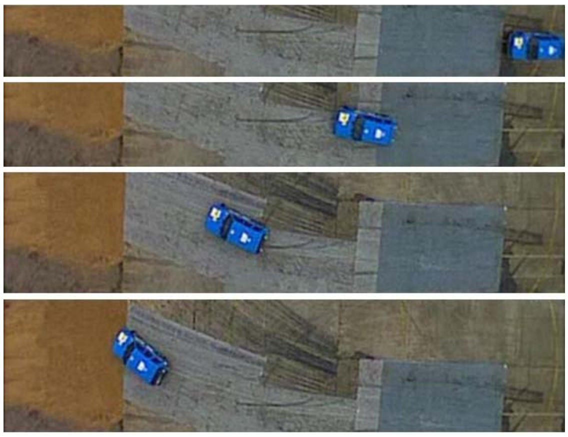

Figure 20. Movement of the test vehicle on a special prepared part of the test ground into a sand pit (no-roll event)

Figure 21. No-roll event of the test vehicle on the sand pit

The roll angle, pitch angle and yaw angle as results of an integration of the signals shown in Figure 22 are demonstrated in Figure 23.

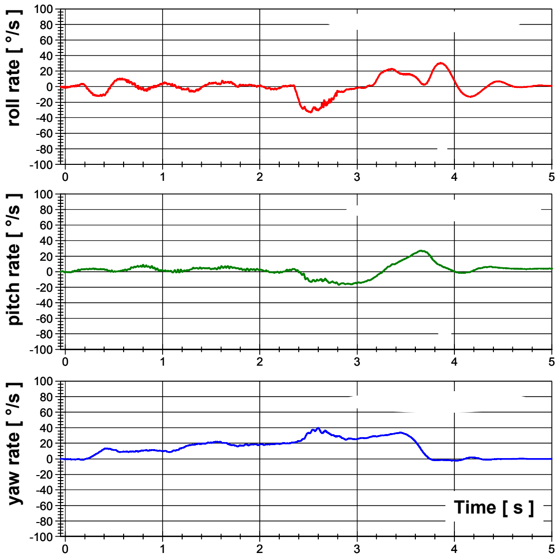

Figure 22. Time histories of roll rate, pitch rate and yaw rate for the no-roll event on the sandpit.

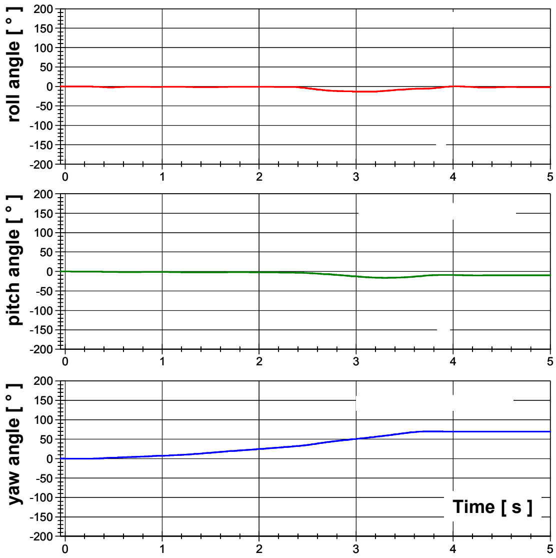

Figure 23. Time histories of roll angle, pitch angle and yaw angle for the non-roll event.

BENEFITS OF THE NEW ROLLOVER TEST SETUP

With the new rollover test setup it is possible for the first time to simulate soil trip rollover situations under a realistic circumstances. With this setup not only the rollover phase on a sandpit but also the skidding phase before the vehicle passes into the soil is covered. Thereby, advanced rollover sensing systems can be tested in a realistic and comprehensive way. The test setup is easy to accomplish and delivers reproducible results. For this reasons Bosch has added this test to list of it's final validation tests for the new Bosch advanced rollover sensing system which started in to series production in 2006.

SUMMARY

A significant improvement of occupant safety during tripped rollovers can be achieved by incorporating information about the vehicle's driving state before the rollover crash into the rollover sensing system. By estimating the vehicle's lateral velocity, important information can be gained to better judge a rollover risk and come to a reliable deployment decision on the basis of the lateral acceleration, roll rate and roll angle. This enables the advanced rollover systems to make a deployment decision for restraint devices more quickly while increasing the robustness against misuses.

To calibrate such advanced rollover sensing systems and to test their robustness a new kind of rollover test has been developed. In contrast to existing rollover tests this new test incorporates not only the roll phase of the vehicle but also the pre-roll phase. The new test setup shows a good reproducibility. The test setup offers parameters allowing for an easy pre-definition of roll- and no-roll events.

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ANALYSIS OF A SAFE ROAD TRANSPORT SYSTEM MODEL AND ANALYSIS OF REAL-LIFE CRASHES ON THE INTERACTION BETWEEN HUMAN BEINGS, VEHICLES AND THE INFRASTRUCTURE.

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ABSTRACT

The objective of this study was to evaluate whether a simple model for a safe road transport system, which includes the interaction between human beings, vehicles and the infrastructure could be used to optimise the components of the system.

Real-life crashes with a fatal outcome were classified according to the vehicle's active and passive safety system. For each crash, classification was also made of the infrastructure with EuroRAP, and human behaviour in terms of speeding, seat belt use and driving under the influence of alcohol. The ideal situation was simulated, when all the above factors were altered to what is expected in a safe system.

All fatal crashes where a car occupant was killed that had occurred in Sweden during 2004 were included: in all 215 crashes with 248 fatalities. The data was collected through the in-depth fatal crash data collection from the Swedish Road Administration.

It was possible to show both the model as well as where the highest potential could be found in a systems perspective. The model could handle more than 90% of the crashes. In general, it was found that impact severity was higher than the expected crash protection of a modern and safe vehicle, even when the occupants were belted and not speeding. The most common and weakest part of the system was therefore the road in the form of speed infrastructure relations. The human criteria were fulfilled in 28% of single collisions and in 80% of side impacts. A safe car, according to the given criteria, would have influenced the outcome in 41% of the accidents on 50km/h- and 70km/h-roads, and 32% on 90km/h-roads.

The future road transport system must be more compatible and more effective in limiting the consequences of road crashes. When prioritising preventive measures, the model might be an instrument to support that process.

INTRODUCTION

Today the road transport system is not a tolerant man–machine system for its users, in that it has the potential to be one of the most significant public health issues in society. Haddon [1] put forward most of the prevention aspects on road casualties, but still the components in the system are hardly compatible with each other. Different kinds of legislation directed towards vehicle manufacturers, road users and road designers have been developed but remain independent from each other, with the road user being the unstable link between the car and the road.

To achieve a safe road transport system that avoids fatal and severe injuries being sustained, some elementary safety requirements must be fulfilled. By increasing the number of constraints on the occupants, such as the use of seat belts, adhering to speed limits and driving a safe car, the road environment must be constructed in such a way that it allows drivers to make small mistakes without this leading to fatal or serious injuries. The interaction between the different components of the road transport system, such as the vehicles, the roads, the roadside area and the road users, is thus important.

Since 2001 the European Road Assessment Programme (EuroRAP), a sister programme to EuroNCAP, has focused on actions that are needed to make European roads safer. EuroRAP provides independent safety ratings of roads in Europe [2]. The EuroRAP rating score takes into consideration how well a road protects the user from fatal or serious injuries. The rating focuses on three different crash types: head-on collisions, run-off-the-road and side collisions at intersections. By rating the safety of a road in this way, taking into account all considerations, the rating is summarised by a weighting factor based on the distribution of the crash types. The protection afforded pedestrians and cyclists is the fourth crash-type characteristic under consideration. These four crash types account for about 80% of all fatal and serious accidents on major roads outside urban areas [3]. EuroRAP consists of two test protocols, both designed to evaluate road standard: road protection score (RPS), and risk mapping.

In EuroRAP it has been concluded that the modern car cannot, on its own, provide sufficient protection for its occupants in a two-car crash at speeds above 70 km/h. In order to avoid fatal or serious injuries in crashes at speeds higher than 70 km/h, the road environment must be designed to eliminate frontal two-car crashes at higher speeds, or to lower the severity of single-car crashes into roadside areas. When a crash occurs, the vehicle and the road must work together as a system to provide protection for the vehicle occupants and other road users.

The safety level of the road has a significant correlation to speed limits and therefore plays an important part in the EuroRAP star-rating programme. The Swedish Road Administration uses the definition of safe speed for different road environments (See Table 1) [4,5]. Speeds over 70 km/h place higher demands on the road environment to meet the envisaged safety requirements for a four-star road. In such cases, the road design should be more forgiving.

Table 1. The Swedish Road Administration's definition of safe speed

Road type	Safe speed (km/h)
Roads with potential conflicts between cars and unprotected road users	30
Junctions with potential side impacts between cars	50
Roads with potential head-on collisions between cars	70
Roads where head-on collision/side impacts are impossible	>100

To prevent the three crash types, different measures need to be taken. A joint statement for the crash types is that a road with a four-star rating should produce limited crash energy that a car with a four-star rating is able to absorb by the vehicle's crumple zones and safe restraints systems. To avoid head-on collisions with fatal outcomes this means that the speed limit on the road should be 70 km/h, or in the case of higher speed limits lanes of opposing traffic should be separated with a barrier or a wide central reservation. To prevent run-off-the-road accidents, the road must have a clear safety zone adapted to the speed limit. A safety zone is a recovery area, which the vehicle leaving the roadway needs in order to stop safely, or which helps to reduce the crash energy to an acceptable level so that it will not result in a fatal or serious injury. For side impacts in intersections the speed limit must be 50 km/h, or there must be a roundabout to limit the severity of the crash.

Aim

Integrated crash studies that focus on illustrating the interaction between human beings, vehicles and the infrastructure are rare. The objective of this study was to evaluate whether a simple model for a safe road transport system, based on EuroRAP classification and including human beings, vehicles and the infrastructure, could be used to optimise the components of the system.

METHODS AND MATERIAL

The EuroRAP classification model was used to design a simple model for a safe road transport system [2]. In an ideal situation: the driver uses a seat belt, follows the speed limits and is sober; the vehicle has a four- or five-star rating by EuroNCAP; and the road has a four-star rating by EuroRAP. In such circumstances no one should be killed or seriously injured in a car crash. To evaluate whether it is possible to use this model, real-life crashes with fatal outcomes were classified, adapted to the model criteria. All fatal crashes where a car occupant was killed that occurred on public roads in Sweden during 2004 were included: 215 crashes in all, with 248 fatalities. In total, 205 passenger cars, 5 SUVs and 5 MPVs, were included in this study. Crashes where there was a suspicion of suicide were excluded. The data was collected through the in-depth fatal crash data collection from the Swedish Road Administration.

Both two-vehicle and single-vehicle crashes, as well as both belted and unbelted occupants, are included in this study. The material was divided into four different groups: run-off-the-road crashes, head-on collisions, accidents at intersections and "other" including vehicle–animal collisions, rear-end collisions and multiple collisions.

In-depth studies

Investigators at the Swedish Road Administration's seven regions carry out the in-depth studies soon after a fatal crash has occurred [6]. Information is compiled to provide a complete picture of the crash. The investigators collect evidence about what has happened before, during and after the crash. Information such as brake marks, direction of the impact forces on the vehicle and time when the ambulance arrives is collected. The investigation also includes information about road design, vehicles and human beings. No analysis is made by the investigators at the scene of the accident. The analyses carried out in this study are based on the SRA's data.

The road All information is collected about the design of the road such as: road type, road width, surface, speed limits, roadside area, distance to e.g. trees or rocks, and visibility. Photos of the road are taken in both directions and degree of slopes is also measured.

Photos and information of the road quality from the crash were used to classify the infrastructure based on the EuroRAP Road Protection Score (RPS). The RPS ranges from 1 to 4, where 4 is the rating for a high road-safety standard, giving a relative risk rating for fatal and serious injuries. The RPS rating is based on data gathered from real-world crashes and crash tests. The score is based on well-known facts from real-life crashes and crash tests. Underlying these limits are the biomechanical criteria for how much a human being can be exposed to during a crash without sustaining severe injuries.

Point RPS - Instead of using the EuroRAP RPS for the total road route, the classification was made based on the spot where the crash occurred. The crashworthiness of the road was classified according to the type of central reservation, roadside area and intersection, in order to highlight the local risk of the crash and how these three components influence the crash outcome. The road's potential to protect the road user from serious injury has in all cases been defined. Both the individual scores for one of the three crash types and also the combination of them were calculated. Table 2 describes the requirements for a road to achieve a four-star rating. The material was classified depending on collision type.

Table 2. Criteria for the four-star rating of a road in the safe transport model.

The Road	EuroRAP ★★★★
To prevent:	
Head-on collisions	70 km/h >70 km/h separated lanes
Run-off-the-road accidents	50 km/h 70 km/h guard-rail or Safety zone >4 m 90 km/h h guard-rail or Safety zone >10m 110 km/h guard-rail or Safety zone >10m
Accidents at intersections	Roundabout or 50 km/h >50 km/h grade separated

The vehicle The investigators compile information on the age of the vehicle, the condition of the vehicle, which safety system the vehicle is equipped with and whether this was activated or not, and use of the seat belt. They also determine how the collision forces were loaded on the vehicle and how the collision object influenced the crash. Impact deformations and degree of intrusion in the vehicle is also documented.

Crashes with fatal outcome were classified according to the vehicle passive safety system using EuroNCAP. For crashes where the outcome was more difficult to estimate, a consensus group with significance experience from both real-life crashes and crash tests was used to estimate the crash safety properties of the vehicle.

The model used also requires that the vehicle, apart from being at least four-star rated by EuroNCAP, should be fitted with a side airbag, head-protection airbags and Electronic Stability Control. This is due to the fact that these systems have been shown to effectively reduce fatalities [7,8]. Table 3 shows the requirements for a safe car in the model.

Table 3. Criteria for the vehicle in the safe transport model.

The vehicle
EuroNCAP ★★★★
ESC
Side airbag
Head-protection airbag

Driving conditions All crashes are followed up using police reports, medical journals and a post-mortem report. This includes information about the age of the occupants, gender, seat belt use and fatal injuries. For each crash, human behaviour was classified in terms of speeding, seat belt use and driving under the influence of alcohol, or whether there was a suspicion of suicide. Only excessive speed could be detected from this material. Table 4 shows the criteria which the occupants are required to meet in the safe transport model.

Table 4. Criteria for the car occupants in the safe transport model

Driving conditions
Use of the seat belt
Speed limits followed
Driver not under the influence of alcohol

Analyses begin at the stage where a crash has occurred, and focus on finding the reason for the fatal outcome, not the reason why a crash has occurred. This could be due to one or a combination of all the three parts of the system. For all crashes, the ideal situation was simulated, when all the above factors were changed to the expected outcome in a safe system.

RESULTS

It was possible to use the model for a safe road transport system to classify the in-depth fatal crash data collection from the Swedish Road Administration. The model could handle 91% of the crashes. When only crash types specified in EuroRAP (run-off-the-road crashes, head-on collisions and accidents at intersections) were included, the model could handle 96%.

In Table 5 and Table 6, it is shown that of the three components, the human being, the vehicle and the road, the last one was the most common and weakest part, causing non-surviving crash severity (180 cases out of 248). Eight crashes resulted in fatal outcome despite all safety criteria in the model being fulfilled. According to the criteria, the human being fulfilled the requirements in 106 cases and the vehicle was rated by EuroNCAP as four- or five-star in 45 cases. In seven crashes, there was no specified evidence about whether the occupants were using their seat belts.

Table 5. Classification of the crash using the criteria for a safe road system (except for the vehicle, where only EuroNCAP classification was used).

Human	Vehicle	Road	N
not safe	not safe	not safe	89
not safe	not safe	OK	29
not safe	OK	not safe	9
not safe	OK	OK	8
not declared	not safe	not safe	4
not declared	not safe	OK	2
not declared	OK	OK	1
OK	not safe	not safe	59
OK	not safe	OK	20
OK	OK	not safe	19
OK	OK	OK	8
			248

Table 6. The number of occupants who could be saved by reducing crash severity to sustainable levels by changing at least one component in each crash: the road, the vehicle and/ or the human behaviour.

All crashes	Fatalities		n=248
By changing:	**Human**	**Vehicle**	**Road**
	59	81	120
In combination	40	42	53
Total	99	123	173

Roads

Almost half of all fatal crashes (47%) during the study period involved a vehicle running off the road. Head-on collisions and accidents at intersections also constitute a major problem since they accounted for respectively 32 and 13% of the total number of fatalities. The remaining eight percent of the fatal crashes were classified as the collision type defined as “other”. Seventy-seven percent of the crashes occurred on standard two-lane, single-carriageway roads with one lane in each direction, and eight percent occurred on roads less than sex metres wide. Only 15% occurred on motorways or roads with a 2+1 configuration.

Twenty-six percent of the crashes occurred on four-star roads, and of these, 35% of the fatal injuries were caused by the road alone or in combination with a low standard of car safety and/or failure in human behaviour such as not wearing a seat belt. In 16 of the total number of fatalities on the four-star roads, the main problem was the road, even if it was rated as the highest safety level (See Table 7). Five of these were collisions with heavy vehicles on roads where the speed limit was 70 km/h. Crashes with animals, moose and deer, account for three of these accidents. The others were run-off-the-road crashes. Three were caused by failure of the guard-rail and one occurred on a motorway with a safety zone, but in this case the vehicle safety level was low. Two of the crashes occurred on roads where the speed limit was 50 km/h, and in these two cases the speed probably exceeded the limit.

In total, 45% of the crashes occurred on roads with a two-star rating (See Table 8). Of these, 91% of the fatalities were caused by the road alone, or in combination with the vehicle and/or a human being.

Table 7. The number of occupants who could be saved on four-star roads by reducing crash severity to sustainable levels by changing at least one component in each crash: the road, the vehicle and/ or the human being.

All crashes at	★★★★	**EuroRAP**	roads
	Fatalities		n=66
By changing:	**Human**	**Vehicle**	**Road**
	25	27	16
Possible	2	3	2
In combination	6	6	4
Total	33	36	22

Table 8. The number of occupants who could be saved on two-star roads by reducing crash severity to sustainable levels by changing at least one component in each crash: the road, the vehicle and/ or the human being.

All crashes at	★★	**EuroRAP**	roads
	Fatalities		n=112
By changing:	**Human**	**Vehicle**	**Road**
	16	39	78
Possible	1	1	3
In combination	17	15	19
Total	34	55	100

Vehicles

The safety standard of the vehicle was insufficient in 75% of the total number of crashes. Side airbags and head-protection airbags could have had an effect in 17 out of 23 of the crashes at intersections. The potential of Electronic Stability Control, ESC was also high, since more than a quarter of the total number of crashes started with loss of control. Airbags were missing in 63% of all frontal impacts and in 80% of all side impacts. Improvement in the vehicle safety level would have had more effect on the crashes occurring on roads with speed limits of 50- and 70-km/h than on 90- and 110-km/h roads (See Appendix Tables A-E).

If all the cars that were rated by EuroNCAP as four- and five-star had been equipped with ESC and head-protection airbags, 20 lives could probably have been saved (See Figure 1-3). The potential for reducing the number of fatalities was highest in single-vehicle collisions. In the case of side impact at intersections, changes in both the road and the vehicle are required.

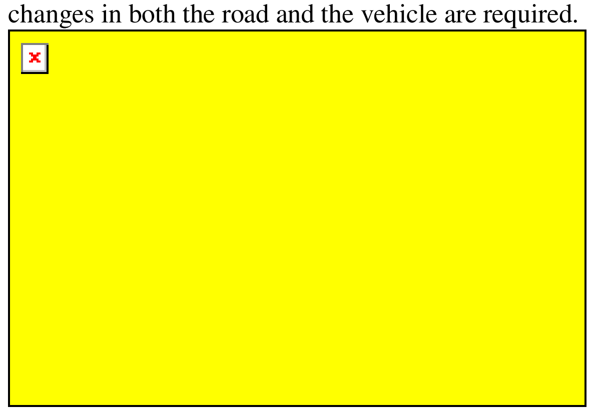

Figure 1. Single-vehicle crashes - The number of occupants in cars with a four- or five-star rating by EuroNCAP who could be saved by changing at least one component in each crash: the road, the vehicle and/ or the human behaviour. The effect of

ESC and airbag has been taken into consideration of the outcome.

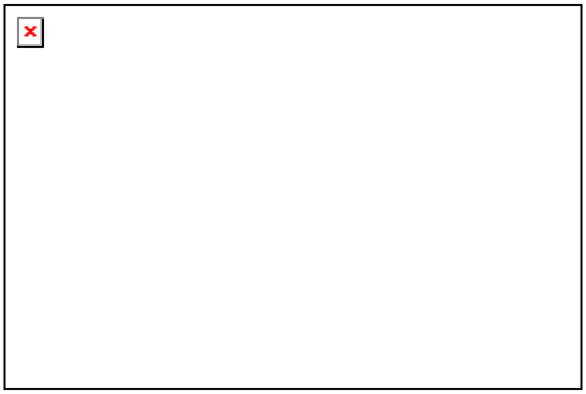

Figure 2. Head-on collisions - The number of occupants in cars with a four- or five-star rating by EuroNCAP who could be saved by reducing crash severity to sustainable levels by changing at least one component in each crash: the road, the vehicle and/ or the human behaviour. The effect of ESC and airbag has been taken into consideration of the outcome.

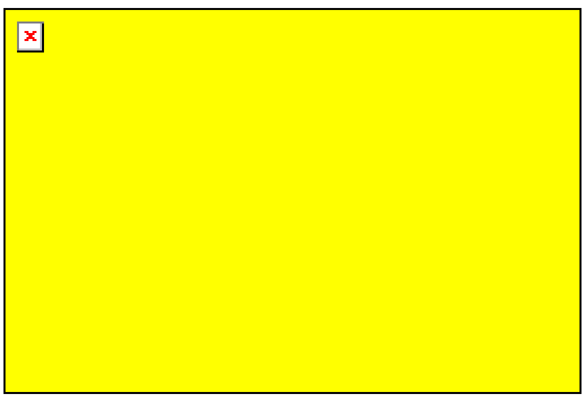

Figure 3. Intersection collisions involving cars rated by EuroNCAP as four- or five-star. In order to save the occupants' lives, changes in both the vehicle and the road are necessary. None of these vehicles was fitted with a head-protection airbag.

Human beings

Forty percent of the occupants who were killed were not wearing seat belts, and more than a quarter of them were driving under the influence of alcohol or other drugs.

Twenty-five percent of the occupants were over 65 years of age. In two cases, where both were over 80 years old, the fatal outcomes were mainly correlated to a lower biomechanical tolerance level than the model criteria. Both were run-off-the-road crashes.

When the human criteria were fulfilled, the standard of the vehicles was more often of a good safety level compared with the accidents where the human requirements were not fulfilled (See Appendix Figure 1-2). The behaviour of the occupants was most critical in single-vehicle collisions. With a change in human behaviour, almost half of the occupants in single-vehicle collisions that did not fulfil the criteria would have survived (See Appendix Table F-G).

A sustainable transport system

In the crashes where at least one component was not fulfilled according to the criteria in the model, an estimation was made regarding which of the components would change the crash conditions so as not to exceed human tolerance (See Table 6). Given the standard of the car and the human behaviour for 120 occupants, a four-star road would have reduced the severity of the crashes to survivable levels. In 81 cases, a four-star car with ESC and side collision protection would have made it possible to survive the collision, and the human being would have changed the outcome in 59 cases by using a seat belt and/or not speeding and/or being sober. For the rest of the crashes, change is required in several components. In Table 7 and 8, the same analysis is made as in Table 6, but for four respective two-star roads. There was a large difference in the number of crashes with a non-survival outcome, depending on the standard of road safety: 16 out of 66 on four-star roads compared with 78 cases out of 112 on two-star roads.

DISCUSSION

Road traffic crashes are a considerable public health problem and in order to achieve the target for road casualty reductions in Europe it is important to analyse cause of death in road crashes. The future road transport system, taking into consideration the infrastructure, vehicles and human beings, must be more compatible and more effective in limiting the consequences of road crashes when the crashes cannot be avoided. In order to achieve a more sustainable system, a preventive philosophy is necessary, where the infrastructure is based on the capabilities and limitations of human beings through good planning and road design. The Swedish Road Administration uses the model in their work to identify weaknesses in the road transport system. Integrated crash studies are rare and the model has never previously been evaluated. The model might be one way of evaluating the importance of the different components, to enable better prioritisation in the prevention work.

Limitations of the study

The data was limited to fatal crashes. If the model is to be a useful tool in traffic safety work, it is necessary to include serious injuries.

The estimation of crash severity in the cars was based on the Swedish Road Administration's data. There is a risk that the photos showing the deformation zone of the cars might be misleading (3D to 2D). However, in most cases written text was included that elucidated the data.

The analyses of the crashes were partly subjective, especially when it came to large deformations of the vehicle. The ideal situation was simulated, when all factors were altered to what is expected in a safe system. The ideal situation was simulated using factors that might have provided a safe outcome, if they were applicable to this particular case, in order to assess the probability of preventability and adaptation to the safe road transport system. To minimise errors of classification, a consensus group with significant experience from both real-life crashes and crash tests went through part of the material to estimate vehicle crash safety properties and the possibility of survival in another car or with other restraint systems.

Only excessive speed could be detected from this material. Probably more of the crashes than could be detected occurred at speeds over the speed limit. It is known that many drivers drive faster than the posted speed limit [9]. The speed limit has a major influence on the speed of impact.

Infrastructure in Sweden

In 1997 the Swedish government decided upon a road transport safety strategy called "Vision Zero", the aim of which is that no fatal or serious injuries should occur in the road transport system [10,11]. Therefore there have been major efforts on Swedish roads to create a safe road environment, e.g. central barriers to separate the traffic and minimise head-on collisions; guard-rails to prevent collisions with dangerous roadside areas, such as rocks, trees and poles; or the removal of roadside objects. However, one important step in creating a more sustainable road system is that the speed limits should be based on the safety level of the road. The concept of safe speed, one of the principles in this model, has been proposed to the Swedish government as the criterion for creating a new speed limit system.

The traffic situation in Sweden differs from other parts of Europe. The flow on the Swedish roads is much lower and the proportion of traffic on motorways is relatively low compared with for instance the UK or the Netherlands [5]. The network in Sweden consists of three main roads: motorways, two-lane roads 9-13 m wide, and two-lane roads 6-8 m wide. During recent years there has been a rapid growth of 2+1 roads with a central barrier in Sweden. This has been shown to be very effective in reducing the number of fatalities and serious injuries. Only two cases of fatalities on this type of road were represented in this study.

Safety model

The safety model used in this paper describes the simple interaction between a few components of the road transport system. While road crashes and crash outcome are complex and dependent on a large number of factors, the model only reflects a few of them. If, on the other hand the model can capture the majority of serious crashes in relation to outcome, by integrating the user, the vehicle and the road/speed, it is still a valuable attempt to both analyse as well as predict improvements in the system. Any further factors added to the model would have to contribute substantially in order to constitute any contribution to the model. While the model in the above sense seems simple, the NCAP and RAP rating systems are quite complex. It is also understood that the model does not give any guidance as to which method should be applied in order to generate contributions to fulfil the factors in the model. While it is clear that drivers should be sober, the model does not indicate at all how this could be achieved.

The safety criteria used in the model, to achieve a safe road transport system, cover more than 90% of the crashes. Only a few fatal crashes occurred despite the fact that all criteria were fulfilled. In these cases the criteria for safety road system does not work. Such examples are compatibility with passenger cars and heavy vehicles and small overlap collisions.

The road and the vehicle

In small overlap collisions the intrusion is the most critical parameter. Lindquist et al [12] have shown that the injury mechanisms are different in these crashes compared with full frontal collisions, and therefore a restraint system other than frontal airbags is needed to protect car occupants. The restraint system as well as front design of the vehicle should be constructed to manage this type of crash.

To improve the potential for injury prevention in head-on collisions with trucks, the truck could either be fitted with frontal underrun protection or enforced adoption of a lower speed limit on two-lane roads. More efforts are needed to solve the problem of head-on collisions on roads where the speed limit is 70 km/h.

Vehicle–animal crashes with both moose and deer are also a problem on Swedish roads. Fatal crashes with animals occurred on roads with speed limits of 70-, 90- and 110 km/h. In most cases the animal went through the windscreen and/or the roof collapsed. Modern cars have been shown to manage a collision with animals such as moose at 70 km/h [13]. Further studies are needed to evaluate the survivor potential in a collision at 90 km/h.

Furthermore, crash severity is high in a collision with narrow objects such as poles and trees, since the load is often concentrated to a small part of the car, and only a minor part of the energy absorption structure will be involved [14]. In such crashes it is hard to protect occupants from serious injuries in impact speeds above 30-50 km/h [15,16]. Therefore there is a shortcoming in the EuroRAP classification system, since there are no demands for a clear zone at 50 km/h. In Victoria, Australia, the guidelines for safety zone widths on single-carriageway roads in built-up areas state that they should be a minimum of three metres wide [17]. This needs to be evaluated. Speed should be in accordance with the type of road and compatible with the road environment. To stimulate development of safer vehicles, similar criteria to those for two-vehicle crashes tested in EuroNCAP should be used to develop a protection system for crashes between cars and roadside objects.

In addition to the criteria in EuroRAP for a safe car (at least four stars), this model has included equipment demands for side head-protection airbags and electronic stability control (ESC), since this provides a high preventive effect. McCartt and Kyrychenko [7] found that fatal injuries were reduced by 37% for head-protection airbags, and by 26% for torso-only side airbags, in side impacts. In our study this could probably have had an effect on the outcome in 17 out of 23 side impacts. In addition, more than a quarter of the crashes started with loss of control, and none of these cars were equipped with ESC.

Human beings

The use of seat belts is fundamental in creating a safe road transport system. All other vehicle-related systems, speed limits, road design, etc., are based on the restrained occupant. Not using seat belts is therefore a behaviour that takes the occupant outside the encompassing design of the road transport system. Smart seat belt reminders have been shown to increase seat belt use to nearly 99% [18,19], which shows that 100% usage is a natural target to make sure that other systems are used to their maximal potential.

Driving under the influence of alcohol is a cause of the crash on most occasions but in this study driving under the influence of alcohol has also been classified as a risk factor for fatal outcome, not only since the risk of a crash increases dramatically both for the occupant and the opposite party, but also because the risk of incorrect behaviour increases, such as driving in the wrong direction on a motorway and other violations of traffic laws.

In two cases, the fatal outcome was probably correlated to a lower biomechanical tolerance level than the criteria in the model. Age and fatal risk are strongly correlated with each other [20]. It might be impossible to have a 100% preventive effect for persons above 70-80 years of age with the criteria in question.

The most effective and efficient way of constructing a safe road transport system is to see how the three components can and must integrate together to minimise crash severity. Speed limits in relation to the infrastructure will be central in the design of such a system. Since the model is based on biomechanical human tolerances, there are several ways of reducing crash severity to improve survival, or better still, of reducing the probability of crash events occurring. This study indicates that the most effective approach to reduce the number of fatalities in Sweden is to make adjustments to roads or speed limits. If a crash takes place, in too many cases the safety level of the car or correct occupant behaviour would not have changed the fatal outcome. The analyses found that the crash severity far exceeded the limitations of human survival and the crashworthiness of the vehicle. The influence of the different components changed depending on the speed limit and type of collision. The occupants' behaviour contributed to a fatal outcome in 72% of all single-vehicle crashes compared with 54% of the total. All the three components of the transport system were weakest in single-vehicle collisions. A good safety level of the car was more crucial on roads with 50- and 70-km/h speed limits than on 90- and 110-km/h roads. This study indicates that many lives could have been saved if the vehicles with a lower standard of safety had been replaced. A modern car is designed to provide the occupants with necessary protection to ensure survival in collisions at up to 70 km/h. The primary role of the infrastructure is to assist in the reduction of the crash energy and to help the vehicle to maximise its inherent safety protection design. This study shows that in 40% of the accidents that occurred on roads with acceptable speed limits, the vehicle is the component that can contribute most to the reduction of fatalities.

To create a safe road transport system, there must be close cooperation between road designers and car manufacturers. Data on different crash severity depending on collision partner are needed in order to form a future road transport system that does not produce higher crash severity than the vehicle is able handle. The vehicle's crashworthiness must work in interaction with the road infrastructure. A safe road transport system also needs to be safe for all users, even the unprotected road users. This has not been taken into consideration in this study. However, further studies, with more data on crashes that cause severe injuries and injuries leading to disability, are needed to evaluate the model and to better understand relationships in the road transport system.

CONCLUSIONS

Both the model as well as where the highest potential could be found in a systems perspective, could be shown. In general, it was found that impact severity was higher than the expected crash protection of a modern and safe vehicle, even with a belted driver who was not speeding.

By applying an integrated model of a safe system, both the model and the possible potential are evaluated.

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APPENDIX

Human
n = 106
Vehicle Road
ok not ok not
27 79 28 78
Road Road Vehicle Vehicle
ok/not ok/not ok/not ok/not
8/19 20/59 8/20 19/59

Figure 1. The accidents there the human has fulfilled the requirements. The number of crashes divided into groups of acceptable/not acceptable road/vehicle.

Human
n = 135
Vehicle Road
ok not ok not
17 118 35 100
Road Road Vehicle Vehicle
ok/not ok/not ok/not ok/not
8/9 29/89 8/29 9/89

Figure 2. The accidents there the human has not fulfilled the requirements. The number of crashes divided into groups of acceptable/not acceptable road/vehicle.

Vehicle
n = 45
Human Road
ok not ok not
27 17 17 28
Road Road Human Human
ok/not ok/not ok/not ok/not
8/19 8/9 8/8 19/9

Figure 3. The accidents there the vehicle has fulfilled the requirements of four star rating by Euro NCAP. The number of crashes divided into groups of acceptable/not acceptable road/human behaviour.

Vehicle
n = 203
Human Road
ok not ok not
79 118 51 152
Road Road Human Human
ok/not ok/not ok/not ok/not
20/59 29/89 20/29 59/89

Figure 4. The accidents there the vehicle has not fulfilled the requirements of four star rating by Euro NCAP. The number of crashes divided into groups of acceptable/not acceptable road/human behaviour.

Road
n = 68
Human Vehicle
ok not ok not
28 37 17 51
Vehicle Vehicle Human Human
ok/not ok/not ok/not ok/not
8/20 8/29 8/8 20/29

Figure 5. The accidents there the road has fulfilled the requirements of four star rating by Euro RAP. The number of crashes divided into groups of acceptable/not acceptable vehicle/human behaviour.

Road
n = 180
Human Vehicle
ok not ok not
78 98 28 152
Vehicle Vehicle Human Human
ok/not ok/not ok/not ok/not
19/59 9/89 19/9 59/89

Figure 6. The accidents there the road <u>has not fulfilled</u> the requirements of four star rating by Euro RAP. The number of crashes divided into groups of acceptable/not acceptable vehicle/human behaviour.

Table A. The number of incidences where the factors did not meeting safety characteristics at various speed limits.

Factors	50 km/h	70 km/h	90 km/h	110 km/h
Human	16	36	62	21
Vehicle	18	64	97	24
Road	0	52	111	17

Table B. The number of occupants whose lives could have been saved on roads with the speed limitation of 50 km/h.

50 km/h	Fatalities		n= 22
By changing:	**Human**	**Vehicle**	**Road**
	10	9	3
Possible	1	1	1
in combination	1	1	1
Total	12	11	5

Table C. The number of occupants whose lives could have been saved on roads with the speed limitation of 70 km/h.

70 km/h	Fatalities		n=78
By changing:	**Human**	**Vehicle**	**Road**
	21	30	24
in combination	12	16	22
Total	33	46	46

Table D. The number of occupants whose lives could have been saved on roads with the speed limitation of 90 km/h.

90 km/h	Fatalities		n= 113
By changing:	**Human**	**Vehicle**	**Road**
	12	36	78
Possible	4	1	1
in combination	18	17	20
Total	34	54	99

Table E. The number of occupants whose lives could have been saved on roads with the speed limitation of 110 km/h.

110 km/h	Fatalities		n= 35
By changing:	**Human**	**Vehicle**	**Road**
	16	6	15
Possible		4	
in combination		3	3
Total	16	13	18

Table F. Single-vehicle collisions classified by the criteria for a safe road system.

Human	Vehicle	Road	N
not safe	not safe	not safe	59
not safe	not safe	OK	18
not safe	OK	not safe	4
not safe	OK	OK	3
OK	not safe	not safe	20
OK	not safe	OK	2
OK	OK	not safe	5
OK	OK	OK	2
not declare	not safe	not safe	2
not declare	not safe	OK	2
			117

Table G. The number of occupants that could be saved in single-vehicle collisions

Single-vehicle	Fatalities		n= 117
By changing:	**Human**	**Vehicle**	**Road**
	43	51	54
Possible	4	3	1
in combination	23	7	20
Total	70	61	75

Table H. Head-on collisions classified by the criteria for a safe road system.

Human	Vehicle	Road	N
not safe	not safe	not safe	24
not safe	not safe	OK	5
not safe	OK	not safe	5
not safe	OK	OK	5
OK	not safe	not safe	18
OK	not safe	OK	12
OK	OK	not safe	6
OK	OK	OK	4
not declare	not safe	not safe	1
			80

Table I. The number of occupants that could be saved in head-on collisions

Head-on Collision	Fatalities		n= 80
By changing:	**Human**	**Vehicle**	**Road**
	11	27	57
Possible	1	3	2
in combination	5	5	0
Total	17	35	59

Table J. Intersections collisions classified by use the criteria for a safe road system

Human	Vehicle	Road	N
not safe	not safe	not safe	6
not safe	not safe	OK	1
OK	not safe	not safe	14
OK	not safe	OK	3
OK	OK	not safe	7
OK	OK	OK	1
not declare	not safe	not safe	1
not declare	OK	OK	1
			34

Table K. The number of occupants that could be saved in side impacts at intersection

Intersection	Fatalities		n= 34
By changing:	**Human**	**Vehicle**	**Road**
	2	0	1
in combination	7	30	29
Total	9	30	30

A CRASH RISK ASSESSMENT MODEL FOR ROAD CURVES

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ABSTRACT

A comprehensive model to assess crash risks and reduce driver's exposure to risks on road curves is still unavailable. We aim to create a model that can assist a driver to negotiate road curves safely. The overall model uses situation awareness, ubiquitous data mining and driver behaviour modelling concepts to assess crash risks on road curves. However, only the risk assessment model, which is part of the overall model, is presented in the paper. Crash risks are assessed using the predictions and a risk assessment scale that is created based on driver behaviours on road curves. This paper identifies the contributing factors from which we assess crash risk level. Five risk levels are defined and the contributing factors for each crash risk level are used to determine risk. The contributing factors are identified from a set of insurance crash records using link analysis. The factors will be compared with the actual factors of the driving context in order to determine the risk level.

INTRODUCTION

The crash rates in road curves are about 1.5 to 4 times higher than in straight roads (Zegeer, Stewart, F. M. Council, Reinfurt, & Hamilton, 1992). Moreover, the crash severity for curve related crashes is higher than those occurring in straight roads (Glennon, Neuman, & Leisch, 1985). Hence, studies had been carried out to assess the crash risk. Crash risk assessments are conducted to determine future possible crash risks. There are different methods to assess risk on curves. Most of them are based on the number of fatalities or crash severity on curved roads. Another way to assess risk is to discover the contributing factors of a crash and determine the effect of each factor on risk. The contributing factors are related to vehicle, driver, and environment.

Related Studies

Risk can be also subjectively assessed. An interview based study by Higgins and Besinger, (Higgins, & Beesing, 2006) identified the "riskiest" driver behaviour as cell phone use and other "multi-tasking" while driving, aggressive driving behaviours such as speeding, running red lights, and failing to yield right-of-way to other vehicles. The following sub-sections discuss related objective risk studies grouped by vehicle, driver and environment.

Vehicle Related Studies Speed is the major contributing factor for road, including curve related crashes. Speeding had contributed 16% of the fatal crashes in Queensland, and is ranked as the fifth highest contributing factor to fatal crashes in 2003 (Queensland, 2005). Kloeden *et al.* (Kloeden, Ponte, & McLean, 1997) has shown that a small increase in speed lead to a rapid increase in crash risk. This is based on the fact that most drivers underestimate the required stopping distance. The crash and injury severity increases as the speed increases. Hence, several researchers have investigated the contributing factors and the way to estimate risk. The conservative way to estimate risk is to calculate the speed, stopping distance and impact speeds (Kloeden, Ponte, & McLean, 1997; RTA,2006). Impact speed is included in the calculation as studies have shown that as the impact speed increases, the likelihood to suffer fatal injury increases (Ashton, & Mackay, 1979). This estimation leads Koleden *et al*. (Kloeden, Ponte, & McLean, 1997) to show that the crash risk doubles with every 5km/h increase in a 60km/h limit zone. Furthermore, the risk of speeding in an urban area has equivalent risk to driving with illegal blood alcohol concentration.

Besides speeding, the age of a vehicle is another risk factor. Older vehicles have higher crash risk as they do not have advanced safety features. They also have safety defects such as faulty brakes, and worn out tyres. Blows et al. (Blows et al, 2003) has shown that crash injury risk increases as the age of the vehicle increases. Results have shown that vehicles manufactured before 1984 have three times the crash risk compared to those manufactured from 1994 onwards (Blows et al, 2003).

Driver Related Studies Inexperienced drivers are exposed to higher crash risk compared to other drivers. They have poor visual and perceptual skills, judgement, control, are unable to respond to risks, and unable to cope with distractions while driving (Government, 2005). This is based on the high crash rates inexperienced drivers have in the first six months of driving alone since they failed to recognize risk and have poor hazard perception. Furthermore, they do not handle the complex task of driving well (Government, 2005). Therefore, the crash risk increases when an inexperienced driver is driving on a curved road, as it requires more experience and skill to handle such situations.

Driver intoxication with alcohol is another risk related factor. Drinking can influence the ability to control the vehicle and perform tasks such as braking and steering. Additionally, alcohol impairs drivers' decision making, such as when they are not able to make judgements of the road geometry and condition to adjust the vehicle's dynamics accordingly (NHTSA, 2006). This increases the driver's exposure to crash risk when they negotiate a road curve. Thus, drink driving is one of the causes of crashes in road curves. In 2003, Queensland recorded 284 fatal crashes and 38% of the crashes were caused by alcohol or drugs (Queensland, 2005).

A driver raises his crash risk when he is fatigue (VicRoads, 2006). Fatigue can cause slow reaction, reduced concentration ability, and drivers take a longer interpretation time to understand the traffic situation. Drivers also have trouble to keep the vehicle within the lane, drifting off the road, change of speed and not reacting in time to avoid hazard situations. This leads to a high number of single vehicle crashes, run-off-road and hit roadside objects, and severe head-on collisions (Authority, 2005).

Fatigue is as unsafe as drink driving as research has shown that the driving ability of a fatigue driver who goes without sleep for 24 hours has the same driving ability of a driver with Blood Alcohol Concentration (BAC) of 0.1(VicRoads, 2006).

Environment Related Studies Environmental factors such as wet or slippery road surfaces, poor lighting, narrow shoulder width, slide resistance, and unprotected roadside environment, contribute to crashes in road curves. The crash risk in road curves is also influenced by the road design such as the degree of curve, length of curve, lane width, surface and side friction, sight distance, and super elevation. The following paragraphs discuss a few of the factors mentioned previously that influence crash risk.

Research has shown that a decrease in curve radii will increase the related risk rate. Blair (Turner, 2005) has defined the relative risk and curve risk and is presented in Figure 1.

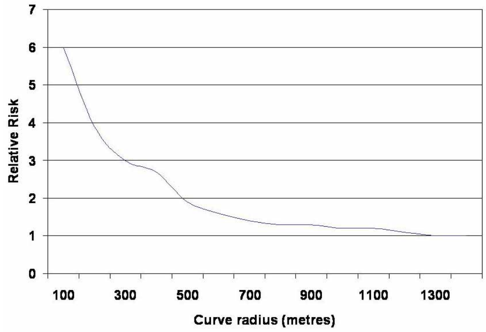

Figure 1. The relative risk for different curve radius (metres).

Sharp horizontal curves or curves with smaller radii are associated with large central angle and limited sight distance. Insufficient sight distance results in high crash rates in horizontal curve (Torbic et al., 2004) and increases the crash risk. The relative risk is approximately 1.1 when the sight distance is 2/3 of required and it increases to 1.42 when the sight distance is less than 2/3 of required (Turner, 2005).

The location of the curve is critical and will affect the crash risk level. The risk is higher when a curve is after a long straight road or after a sequence of gentle curves (Seneviratne & Islam, 1994). Other road features such as superelevation and side friction also contribute to crash rates. Superelevation will affect the travelling speed on curved road and in turn increase or decrease crash risk. Wet weather can contribute to the risk level when the superelevation is less than 2% (Dunlap, 1978).

To our knowledge, none of the existing risk assessment studies have integrated contributing factors of the situation (environment, vehicle, and driver) and past crash records. Past crash records used for our assessments are past crash claims from an insurance company. Risk is assessed based on the number of records and severity of each crash recorded. Even though FHWA had investigated crashes related to trees using the approach but there are no studies for curved roads yet.

The innovative aspect of the proposed approach is that it uses past crash records and information about the current situation that consists of environmental, vehicle dynamics and driver behaviour. Then the collected data is analysed in order to improve the accuracy of the real time risk assessment in a vehicle.

The rest of the paper is structured in the following manner. The overview of our conceptual framework is presented, followed by a description of the risk assessment methodology. Results of the crash history review is presented and discussed. Then we conclude with a summary of the findings and recommendations for future work.

CONCEPTUAL FRAMEWORK

Figure 2 illustrates the overall framework of our approach. Details are discussed in previous work (Chen et al, 2006). In summary, the framework consists of a training phase which involved crash history review, and simulation to study driving behaviour in curved roads. Then the review and simulation results are obtained and used to train a driver behaviour model. This is later used to assess crash risk in real-time. The risk assessment model is called Ubiquitous Situation Awareness Risk Prediction Model for Road Safety (UbiSARPS), which is designed to assess and determine crash risk on curved roads.

The focus of the paper is on the risk assessment model that is on the right side of Figure 3, and an overview of the analysis processes, that includes the grey out area, is also illustrated. Crash risk assessment of curved roads could help to determine future crash risks. Risk assessment involves the consideration of several factors that are related to road curves.

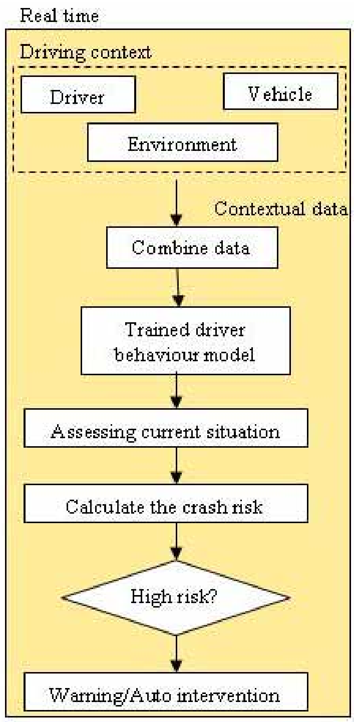

Figure 2. An overview of UbiSARPS.

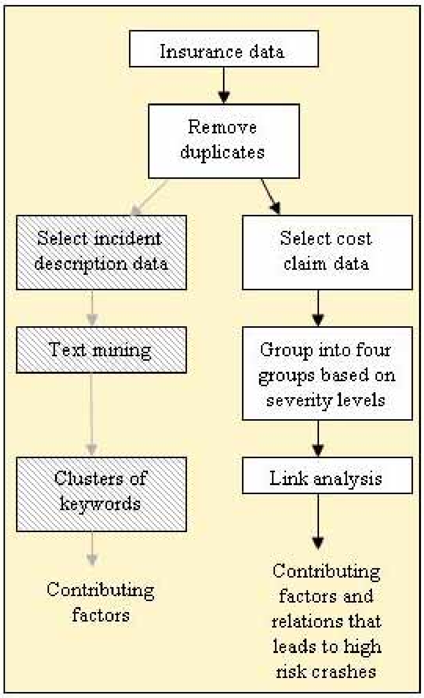

Figure 3. Overview of the crash review process which is part of the training phase.

The next section is a description of the review methodology.

CRASH REVIEW METHODOLOGY

Analysing past crash records is a critical step in assessing crash risk on curved roads. Crash risks are determined from contributing factors, crash severity, hazard locations, and patterns of crashes.

We mined a large amount of crash records from an insurance company in order to extract knowledge about contributing factors to crashes on curves. The records consist of 8035 insurance claims, related to property damage occurred in Queensland urban areas between the years 2003 and 2005 inclusive. Each record contains information about the crash such as the location of the crash, time, age of driver, years of experience, severity, and whether the driver was under the influence of alcohol. The records contain crash claims that cost more than AUD$2500.

In this paper, we classify the data into different vehicle damage severity groups and define a risk scale with five levels. Groups are classified based on the claim amount of each crash and corresponds to the risk scale level that we will define. The data are 'cleaned' before using for the analysis processes. The 'cleaning' process consists of removing duplicate records and replacing invalid or empty fields. The next section describes the risk scale levels.

Risk Scale Levels

A five-level risk scale is defined for assessing crash risk on road curves. A risk with level one indicates a low crash risk and the risk increases until level five which is an indication of high crash risk. Crash risk level is determined by assessing the contributing factors. A set of contributing factors are defined in each level and are used to determine the risk level of the current situation. The initial step to determine risk level is to use a set of selected contributing factors and compare with the defined contributing factors in each level. A close match to the defined contributing factors indicates the crash risk level.

With the insurance crash records, the five risk levels are based on the claim amount for curve related crashes. The records are divided into five groups and the first group is the records that cost less than AUD$2500. A previous (Chen, 2006) has presented the findings of the contribution factors on curved roads based on the claim descriptions. The remaining records are divided into quartiles which results in four equal groups of the records. The minimum claim amount to divide into quartiles is AUD$2502 and the maximum amount is AUD$63,314, and consists of 1041 records. Table 1 presents the distribution of the cost across different risk levels.

Table 1.
The cost distribution for each crash risk levels.

Level	Claim amount in AUD$
5	$9734-63,314
4	$5477-9733
3	$3479-5476
2	$2500-3748
1	Less than $2500

After defining the five levels, the next step is to define related contributing factors for each level. The contributing factors will be identified with the link analysis approach which is discussed in the Crash Records Analysis Process section.

The following section describes the preliminary analysis process on the crash records. A preliminary analysis was conducted to provide a background of the crash records used for the analysis process. Then the next step is to discover the contributing factors for each severity group.

Preliminary analysis

The aim of preliminary analysis is to determine the distribution of the contributing factors from the insurance crash records. This distribution provides an overview of the characteristics of the records used.

The initial step for the preliminary analysis is to determine and select the variables to observe. Selected variables are based on the contributing factors with the highest number of crashes that are identified by the Queensland Transport crash report. They are: *alcohol, inattention, inexperience, age, and wet roads*. The corresponding contributing factors from the insurance records are: *wet roads, inattention, inexperience, young drivers, and alcohol*.

The records used are cleaned and consist of all types of road crashes. The selected and cleaned records from the insurance company are imported into SPSS for analysis. A frequency count on the number of records is performed for each selected contributing factors and are consolidated and converted into a percentage. The consolidated results are used to discover the distribution of the contributing factors from the insurance company records. The contributing factors are arranged in a descending order in terms of the number of crashes and are presented in a chart. Figure 4 illustrates the distribution of the contributing factors from the insurance company crash records.

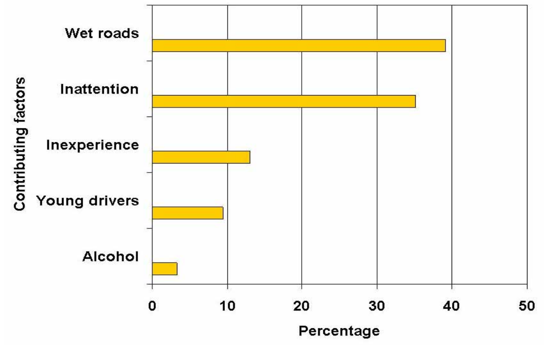

Figure 4. The distribution of the contributing factors from the insurance crash records.

The most significant contributing factor in the crash records is wet roads, followed by lose of control, inexperience, young drivers and alcohol.

These findings are different from Queensland Transport database which rank contributing factors as follows in Figure 5.

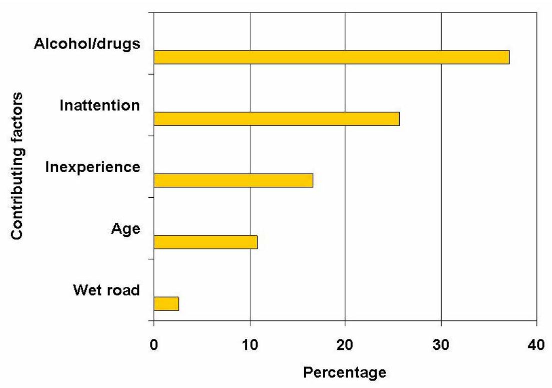

Figure 5. The distribution of the contributing factors defined in the Queensland Transport crash report (Queensland, 2005).

Crash Records Analysis Process

The aim of the analysis process is to determine the contributing factors for each crash of the five risk groups. The identified contributing factors will be exploited to define a risk scale.

Crash records are filtered and only curve-related crashes are analysed. Then the records are categorised into four groups based on the claimed amount. Each of the four categorized groups is examined using the link analysis method to identify the contributing factors in each group. Link analysis is a process to find the relationship between selected variables using nodes and links. A node represents a field attribute and a link represents an association between nodes where the variables from one node to another occurred together. For example, male drivers are involved with more tree related crashes than female drivers. This is concluded based on the number of links between the male node, and tree crash node. Figure 6 illustrates the nodes, links and relationships.

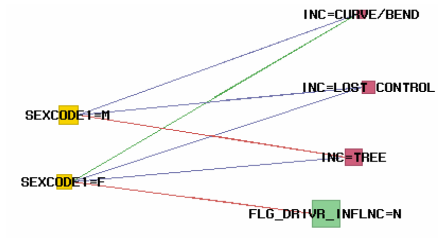

Figure 6. An example of nodes, links and their relationship.

The linkages are presented graphically; the size of the node indicates the number of records and different colours of the link indicates the number of related records. As seen in Figure 6, red lines have the most number of links compared to blue and followed by green lines. Therefore, an increase in size or change of colours signifies that nodes are highly associated with each other. This interpretation aids our analysis in identifying the significant contributing factors among the crash records. Then the identified contributing factors are listed and arranged in a chart format for each of the four groups.

Apparatus

In the preliminary analysis, a statistical tool called SPSS is used to remove duplicate records and to analyse the distribution of the contributing factors in insurance crash records. Later in the data analysis process, SPSS is used again to group the records into four groups that correspond to the vehicle damage severity levels. Then SAS is used to perform the link analysis process in order to identify contributing factors in the crash records.

CRASH RISK LEVELS AND RELATED CONTRIBUTING FACTORS

The expected result from the crash records analysis process is to obtain a different set of contributing factors for each crash risk level.

Risk Level One

The contributing factors for Level One are presented in previous work (Chen, 2006). hence, this paper presents the results from Level two to five.

Risk Level Two

Figure 7 illustrates the significant contributing factors for Level Two risk (claim cost = AUD$2500-3748). Significant factors are factors which are associated with a high number of crashes. The factors are expressed as the percentage of the total number of crashes for the first quartile group of records (n=261).

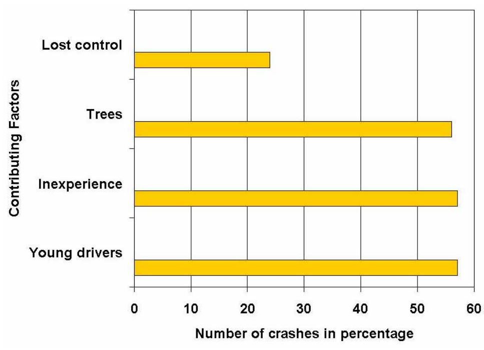

Figure 7. The list of contributing factors for Risk Level Two.

Figure 7 shows that young drivers of 22 years of age and drivers who have 9 years of driving experience are the significant factors in the list. The maximum age of drivers for this level risk is 43 years of age. Both genders are equally involved in the crashes, even though males have 8% more number of crashes than females. However, this is not a major issue. Hence, both genders face the same risk.

The next factor is trees where trees can be the roadside objects that the vehicle hit when it go off the road in order to avoid animals or through loss of control. Possible reasons for loss of driver control are: speeding, inattention, fatigue, inexperience, and misjudgement on curves. Hence, a driver will be assessed as Level Two risk if he or she is between 22 to 43 years of age, or with 9 years or less of driving experience or when there are trees or a curved road in the environment.

Risk Level Three

The total number of crash records used for Level Three analysis is 260. The claim cost is between AUD$3479 and AUD$5476. The list of contributing factors is expressed in percentage according to the total number of crashes and is illustrated in Figure 8. The contributing factors are similar to Risk Level Two, however, the detailed information of each factor are different.

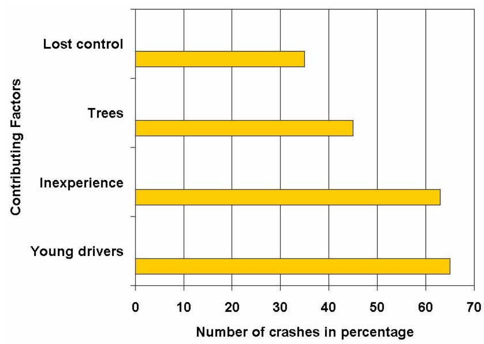

Figure 8. The list of contributing factors for Risk Level Three.

In Level Three, young drivers of 23 years of age or with 10 years or less of driving experience drivers are the leading contributing factors. This may be due to lack of skill to handle risk and the perception of risk is not well developed yet. This applies to underdeveloped both male and female drivers, as male drivers have 5% more number of crashes in comparison to female drivers. The maximum age is 43 years of age for level Three too. The remaining factors are trees, lost of control and curves. The tree factor is not significant compared to Level Two. However, the number of lost control crashes increase. A possible reason is due to speed as most drivers are over-confident and will drive more recklessly. Therefore, Level Three risk is identified when a driver with age ranges from 23 to 43 of age or with 10 or less years of driving experience and if he or she speeds.

Risk Level Four

This level of risk is considered moderately high and more contributing factors are identified. A total of 260 crash records and with claim cost between AUD$5477 and AUD$9733 are used for the analysis process. Figure 9 presents the list of factors.

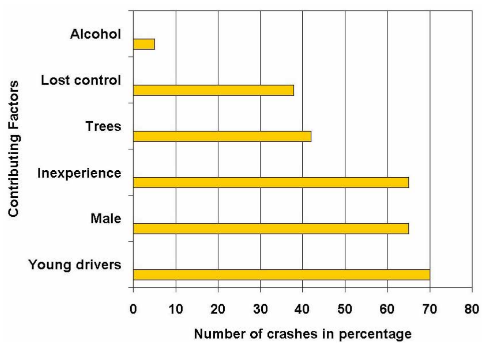

Figure 9. The list of contributing factors for Level Four.

The group of young drivers involved in Level Four of risk are 21 years of age with more male drivers are involved in the crashes. The maximum age is 41 years for this level. Another factor is the driving experience, where 9 or less years of driving increases the number of crashes. The remaining factors such as trees, lost of control and curves are similar factors to Level Two and Three. However, alcohol is an additional factor in Level Four. Alcohol can affect control and judgment when driving on the road. Risk increases when the driver drives in a curved road. Hence, when a male driver is between the age 21 and 41 and is alcohol intoxicated, the crash risk increases to level four.

Risk Level Five

Level Five is the maximum point of the risk scale and indicates the highest risk level. The crash claims cost for Level Five ranges from AUD$9734 to AUD$63,314 and 260 crash records are used. Figure 10 is the list of contributing factors for Level Five, expressed in percentage in terms of the total number of records used (n=260).

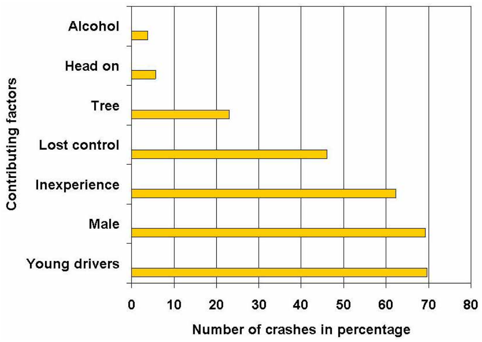

Figure 10. The list of contributing factors for Level Five.

Young drivers of 24 years of age and male drivers are the significant factor. The maximum age is 46 years of age. Drivers with 11 years of driving experience contribute to this level of risk. Then lost of control, trees, curves and alcohol are the other contributing factors. The additional factor is head-on type of crash. Head-on relates to possible causes such as lost of control, unintentional manoeuvre, fatigue, distraction, travels too fast in curves, and alcohol (NHTSA, 2006). Thus, the contributing factors to assess a driver with Level Five are when a driver is between 24 and 46 years of age or with 11 years of driving experience. Plus, other factors such as alcohol, speeding, fatigue, lost of control also increase the crash risk.

Table 2 summarizes the difference in the significant contributing factors for each risk level that was discussed in the previous sections. The comparison starts from Level Two and upwards to Level Five. Common factors are not listed in Table 2. From all the contributing factors in each level, the crash risk increases as alcohol consumption, and possible fatigue affects the driver performance in terms of alertness, reaction time, judgement and control over the vehicle.

Table 2.
Summary of the difference between the significant contributing factors for each risk levels.

Risk Levels	Contributing Factors
5	Fatigue, Speeding (Head-on related).
4	Alcohol, male drivers.
3	23 years of age drivers, 10 or less years of driving experience.
2	22 years of age drivers, 9 or less years of driving experience.
1	Presented in previous work (Chen, 2006).

CONCLUSION AND FUTURE WORK

Drivers are at risk when they start to drive their cars. The level of risk varies according to factors related to the environment, vehicle and driver. This paper analysed driver's related factors affecting crash risks.

The analysis of the insurance claim from an insurance database revealed that drivers are exposed to higher risk when they are young and/or with less than 10 years of driving experience. It also showed that crash risk decreases as young drivers obtain more driving experience (Government, 2005). Such findings are aligned with common knowledge about risk exposure of inexperienced drivers. Results also showed that drivers with 9 or less years of driving experience are exposed to a higher number of crashes on curves. A possible reason is that drivers have not developed their perception skill well and not able to handle risky situation as well as experienced drivers yet. Crash risk increases to level four or five when drivers consumed alcohol or are experiencing fatigue or driving in curve roads at high speed. The risk scale defined in this paper will be used to recommend advanced driving assistance interventions to drivers such as warnings or errors are automatically corrected by advanced mechanisms.

The records do not contain information about the curvature of the road, driver's speed at the time before the crash, driver's fatigue level or drug use. Thus, the information has to be obtained from sensors. The process of obtaining and analysing the sensor information will be carried out as part of the studies in the future.

The next step from here is to refine the risk scale with information from simulation as described in Figure 11.

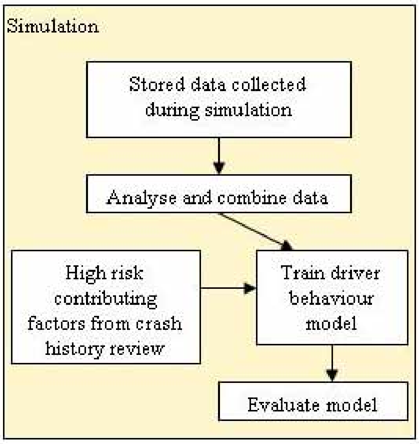

Figure 11. Overview of the simulation process.

A simulation session will be setup to collect information of driving behaviour in road curves. Then the information will be used to update and enhance the risk scale.

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THE TRACE PROJECT: AN INITIATIVE TO UPDATE ACCIDENT CAUSATION ISSUES AND EVALUATE THE SAFETY BENEFITS OF TECHNOLOGIES

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Paper Number 07-0400

ABSTRACT

The Integrated Safety programme and the eSafety initiative stress that the development of Intelligent Transport Systems in vehicles or on roads (and especially in the safety field) must be preceded and accompanied by a scientific accident analysis encompassing two main issues:

- The determination and the continuous up-dating of the etiology, i.e. causes, of road accidents (as well as the causes of injuries) and the assessment of whether the existing technologies or the technologies under current development address the real needs of road users inferred from accident and driver behavior analyses.

- The identification and the assessment (in terms of lives saved, injuries mitigation and accidents avoided), among possible safety technologies, of the most promising solutions that can assist the driver or any other road users in a normal road situation or in an emergency situation or, as a last resort, mitigate the violence of crashes and protect vehicle occupants, pedestrians, and two-wheelers in case of a crash or a rollover.

The general objective of the TRACE project (TRaffic Accident Causation in Europe) is to address these two issues by providing the scientific community, the stakeholders, the suppliers, the vehicle industry and the other Integrated Safety program participants with a global overview of the road accident causation issues in Europe, and possibly overseas, based on the analysis of any and all current available databases which include accident, injury, insurance, medical and exposure data (including driver behavior in normal driving conditions). The idea is to identify, characterise and quantify the nature of risk factors, groups at risk, specific conflict driving situations and accident situations; and to estimate the safety benefits of a selection of technology-based safety functions. Expected outcomes are essentially reports.

Beside this, TRACE proposes three different research angles for the definition and the characterization of accident causation factors, and to improve the methods actually used in accident analysis (diagnosis and evaluation, especially with regards to statistical techniques and human behaviour analysis).

Finally, TRACE intends to base the analyses on available, reliable and accessible existing and on-going databases (access to which is greatly facilitated by a series of partners highly experienced in safety analysis, coming from 8 different countries and having access to different kinds of databases, in-depth or regional or national statistics in their own country, and for some of them in additional countries).

The project is to last 2 years (January 2006 – December 2007) and involves 16 full partners and 6 sub contractors for a total of 386 men-months.

INTRODUCTION

Our planet shelters about 6 billion people, more than 22 million kilometres of roads, 470 million passenger cars and 145 million station wagons, vans and trucks[1]. One third of motorized vehicles move in the U.S.A. and another third in the European Union. According to the World Health Organization and other sources, the total number of road deaths, while not completely accurate, is estimated 1,2 million, with a further 50 million injured every year in traffic accidents. Two thirds of the casualties occur in developing countries. 70 % of casualties in these countries are vulnerable road users such as pedestrians, cyclists and motorcyclists.

[1] Estimated figures excluding the length of Chinese roads and Chinese vehicle fleet.

The European Union (E.U., 25 countries) is home to about 456 million inhabitants and about 270 million motorized vehicles. 2.000.000 personal injury road accidents and over 45 000 fatalities occur every year, which is now significantly higher than in the U.S.A. (42 000) which has a noticeably lower population, 290 million inhabitants and a smaller vehicle fleet (230 million motorized vehicles).

In most countries, economic losses due to road accidents represent 1 % or 2 % of GNP. In 1997, the European Transport Safety Council (ETSC) estimated the total cost of transport accidents in Europe at 166 billion Euros. 97 % of these costs, i.e. 162 billion Euros, were directly related to road transport.

Overall road safety has been increasing in industrialized countries for 30 years and this increase shows that political willingness and the application of countermeasures produce results. For example, the recent SUNFLOWER report, concludes that, between 1980 and 2000, in out of 3 of the most successful countries, fatality trends dramatically decreased, due to:

- Passive Safety measures: 15 % to 20 %
- Safety Belt wearing: 15 % to 20 %
- Alcohol countermeasures: 15 % to 20 %
- Specific Measures for vulnerable road users: 30 % to 40 %
- Actions targeting the Infrastructure: 5 % to 10 %
- Education – Training – Communication: 7 % to 18 %

Integrated Safety

However, Road Safety is still one of the main societal concerns today. It is not only a matter of concern for the European Commission and National Governments but also for the vehicle industry, insurance companies, driving schools, non-governmental organisations and more generally people who care about others. Especially, car manufacturers have made strong efforts and have dramatically improved their vehicles' passive (and also active) safety for the past 15 years. However, current road safety research has shown that an asymptote is about to be reached in most countries (even though France recently showed up an unprecedented success in fatalities prevention by the introduction of a voluntary enforcement policy for which automatic speed cameras are the most well-known aspect) and many experts agree that preventive (prevention of accidents) and active safety (recovery of an emergency situation) should now, particularly, be brought forward.

This is why the EUropean Council for Automotive Research (EUCAR) has launched in 2001 an initiative to develop a systemic approach to the problem of road safety: **Integrated Safety**. The idea is to revisit the Safety problem with a holistic System Approach. In 2006, 4 IP's and one STREP (AIDE, PREVENT, EASIS, APROSYS, GST) are on the way and are starting producing methodologies and results. Just a few of these research integrated projects or sub projects (i.e. Aprosys, Prevent-Intersafe) called for prior accident analysis in order to start further tasks (development of models, simulations, technologies, demonstrators, tests, etc.) on a thorough understanding of the real-world problems. Consequently, this knowledge is sometimes considered as a missing plinth.

eSafety

Simultaneously, an eSafety Forum was established by the European Commission DG Information Society in 2001 as a joint platform involving all road safety stakeholders. The Forum adopted twenty-eight recommendations towards the better use of Information and Communication Technologies (ICT) for improved road safety. But, even though former research in accident causation and impact assessment produced a tremendous amount of knowledge, the exact nature of the contribution that ICT can make to road safety could not be determined because consistent EU-wide accident causation analysis was not sufficiently available to gauge this impact. Consequently, the first of these recommendations sought to consolidate analyses from existing accident and risk exposure data sources for a better understanding of the causes and circumstances of road accidents and to determine the most promising and/or effective counter measures. The second recommendation called for the establishment of a common format for recording accident data to develop an information system covering all EU Member States.

When working groups were established to undertake the work required by the recommendations, one of the first to be established was an Accident Causation Analysis working group. The overall job of this working group was to establish the requirements for the results of the recommendations to be made available. The group intended to identify the remaining needs for a diagnosis of the safety issues and for an evaluation of the expected and observed effectiveness of the counter measures.

On the one hand, although neither in the EU nor in any of the member states there is anything like the major NHTSA accident database systems, i.e.

NASS (National Accident Sampling System) and FARS (Fatal Accident Reporting System), Europe does not start from scratch in this area of course. A number of data sources already exist but they fulfil varied objectives, are often at different levels, use different methodologies, are inconsistent and do not provide a "European" analysis of accident causation.

Simultaneously, The EU was and still is funding an important project, SafetyNet (The European Road Safety Observatory), which particularly aims at making consistent accident data collection protocols in several EU countries and at constituting an accident databank on injury and fatal accidents. But the project would provide neither accident data, nor accident analysis in the short term. Moreover this project does not aim at identifying relevant methodologies to evaluate the effectiveness and efficiency of safety systems based on technology.

To try to overcome these problems in the short term, the (Accident Analysis) Working Group has examined available data sources which were known to them. These sources are sometimes at EU level, sometimes Member State level sometimes company specific or complied by road safety institutions. Occasionally the sources cover a number of Member States. Some sources are high-level statistics while others are in-depth studies of small numbers of accidents. All these sources contain useful data so one of the first tasks of the working group has been to see how these varied sources could be better used to yield a more consistent European picture that would provide a safety diagnosis enabling the assessment of impact and thereby identify priorities for action.

The working group has collected information about a sample of twelve current databases that already exist in Europe or will be existing soon, such as CARE, MAIDS, GIDAS, EACS, CCIS, OTS, IRTAD, etc. Data exist outside Europe too of course but this has not been included since it is not always completely relevant for European experience. Some of these data sources are either private or commercial with significant access restrictions brought about by intellectual property right issues. Since there is little prospect of overcoming these restrictions there is no prospect of making disaggregated data publicly available. To overcome these problems the working group undertook some qualitative analysis of the data sources. This analysis assessed the essential characteristics of the data and secondly assessed the potential for the different sources to be used in conjunction with each other. Four criteria were used for this assessment:

- The degree of qualitative description of accidents in the data source; content, reliability, size/scope and relevance;

- The degree to which the source contains a statistical representativeness: content, size/scope, sub-samples, reliability and relevance;

- An evaluation of the sources;

- Whether or not the source contained case studies.

The analysis confirmed the hypothesis of the working group that although many information sources already exist they are not enough as they currently exist to provide Europe with the analysis it needs because the picture obtained was a mixed one. Some data sources were never designed for the purpose of coordinated analysis and therefore have little potential. Some others have their main focus on passive safety, biomechanics or traumatology and do not give much insight into the *causes* of the accidents they contain. Others have considerable potential.

Based on this qualitative analysis of existing sources the working group recommended to the eSafety Forum that existing sources can nevertheless help to give a better understanding on accident causation and to evaluate (at least partially) the effectiveness of some on-board safety functions, if shared analysis mechanisms are employed to interrogate the different data sources and share the results. This of course requires the formulation of a set of appropriate questions to establish what the analytical focus should be on and which can be used in the interrogation. To devise this list of questions a multi-stakeholder workshop was organised where participants shared and agreed items in a list of questions. Since the list was long and that resources to carry out the shared analysis were limited, the list was reordered by priority.

So far the work on this task had been done by a group of volunteers. The next stages of the task were assumed to be considerable and could only be done when resources are available to support the work. The necessary resources were expected to be made available at the end of 2004 and the work carried out over the next two years.

THE TRACE PROJECT

This dual context (The **Integrated Safety** program and the **eSafety** initiative) stressed that the development of Intelligent Transport Systems in vehicles or on roads (and especially in the safety field) must be preceded and accompanied by a scientific accident analysis encompassing two main issues:

- The **determination** and the **continuous up-dating** of the **etiology,** i.e. causes, of road accidents (as well as the causes of injuries) and the **assessment** of whether the existing **technologies** or the technologies under current development address the **real needs** of the road users inferred from the accident and driver behavior analyses.

- The **identification** and the **assessment** (in terms of saved lives, injuries mitigation and avoided accidents), among possible technology-based safety functions, of the **most promising solutions** that can assist the driver or any other road users in a normal road situation or in an emergency situation or, as a last resort, mitigate the violence of crashes and protect the vehicle occupants, the pedestrians, and the two-wheelers in case of a crash or a rollover.

These two main orientations (Diagnosis of the road safety problems and Evaluation of the most promising technological solutions) were the plinth of the TRACE (Traffic Accident Causation in Europe) proposal submitted to the European Commission in 2005. Actually, the European Commission has expressed two kinds of interest as regards accident analysis (cf. Strategic Objectives 2005-2006: 2.4.12: eSsafety – Co-operative systems for road Transport):

"In support of the eSafety initiative, and as a pre requisite for diagnosis and evaluation of the most promising active safety technologies:

- Research in consistent accident causation analysis to gain a detailed knowledge about the real backgrounds of European traffic accidents using existing data sources.

- Research to assess the potential impact and socio-economic cost/benefit, up to 2020, of stand-alone and co-operative intelligent vehicle safety systems in Europe".

TRACE addresses the first concern (accident causation) and the safety benefit part of the second one (impact assessment of technologies).

TRACE Objectives

In accordance to these concerns, the TRACE Consortium has identified the following objectives:

1. The definition of Accident Causation is not that clear. Numerous factors influence a country's transportation safety level. These factors are concerned with road safety policy, distribution and crashworthiness of the fleet, road network characteristics, human behaviour and attitudes, conditions of the trip, environment, etc. These issues have been studied for decades and considerable prevention efforts have been inferred from the analysis and comprehension of these factors. Nevertheless, further efforts are needed: all these factors have to be put forward and studied altogether in order to end up with a comprehensive and understandable definition of accident causation at the end of the project.

2. The second objective is to provide the scientific community, the stakeholders, the suppliers, the vehicle industry and the other Integrated Safety program participants with a global overview of the road accident causation issues in Europe, and possibly overseas, based on the analysis of any and all current and available databases which include accident, injury, insurance, medical and exposure data (including driver behavior in normal driving conditions). The idea is to identify, characterise and quantify the nature of risk factors, groups at risk, specific safety-related or risk-related societal issues, specific conflict driving situations and accident situations.

This objective will be achieved at the end of the project with the public dissemination of most of the final reports.

3. The third objective is to make this overview comprehensive, understandable and operational. Hence all aspects of safety are taken into account in order to achieve the following level of knowledge: when, where, how, why, to whom accidents happen? When, where, how, why, to whom injuries happen?

4. The fourth objective is to improve the multidisciplinary methodologies that are considered to be necessary to achieve this knowledge and especially methodologies in analysing the influence of human factors and also the statistical methodologies used in risk and evaluation analysis.

5. The fifth objective is to generate summary documents with vulgarised figures, statistics, results, or any kind of outcomes that can be used for the identification, validation of the relevance and the evaluation of expected[2] or observed effectiveness of safety functions based on

[2] The evaluation of the **potential** benefits concerns safety functions that are not yet implemented. The idea is to evaluate existing databases and accurately predict the expected effectiveness of such functions. The evaluation of the **observed** benefits concerns safety functions that are already implemented (e.g. Electronic Stability Programs or Emergency Brake Assist Systems) and need to be assessed.

technology that are already implemented in vehicles or could be put in vehicles in the future (i.e. in communication with the infrastructure or not, co-operating between vehicles, cooperating with the user, assisting or substituting the driver or not).

6. The sixth objective is to support, if needed and requested, participants of Integrated Projects and STREP's under the umbrella of the Integrated Safety Program, which would need accident causation inputs for the development of relevant technologies.

7. The seventh objective is to establish links with the other projects about road safety (especially SafetyNet, which own objective is to establish a Road Safety Observatory in Europe by the construction of several accident and exposure databases at a pan European level), and also the eImpact research project(s) that is dealing with the assessment of the potential impact and socioeconomic cost/benefit, up to 2020, of stand-alone and cooperative intelligent systems in Europe.

STRUCTURE OF THE PROJECT

Work Packages

TRACE is divided into 4 series of Workpackages:

- The first four workpackages propose three different research angles for the definition of accident causation, the quantification of the risk factors, and the evaluation of the effectiveness of safety functions. These are so-called operational workpackages.

  - **WP1**: Road Users

  - **WP2**: Types of driving situations and types of accident situations

  - **WP3**: Types of risk factors.

  - **WP4**: Evaluation. This fourth work package proposes to evaluate the effectiveness of safety functions in terms of expected (and observed) avoided accidents and saved lives.

    Evaluation is one of the core aspects of the project. We can split the safety systems into three concepts: the **safety functions**, i.e. the problems addressed (e.g. the reduction in braking distance); the **safety systems** (e.g. brake assist in case of braking distance reduction); and finally the **technologies** that address the safety system. Our ambition is to evaluate the effectiveness of a set of **safety functions** that are assumed to address some of the accident causation issues that we would have identified in the aforementioned work packages. This is needed both to complete the picture of accident causation and to assess what kind of systems can produce what can of results for what kind of problems.

Each WP is divided in tasks. For each task, the main objective is to identify the accident causation aspects through three kind of analysis:

  - A macroscopic (essentially) statistical analysis (aimed at describing the main problems),

  - A microscopic analysis (aimed at determining the accident mechanisms with the help of in-depth data), and,

  - A risk analysis (aimed at quantifying the risk factors in terms of risk, relative risk and, if possible, attributable risks).

- The other three work packages propose to support the operational work packages by providing them with enhanced methodologies with regards to, especially, human factors and statistical techniques. One work package is also devoted to the listing of existing and potential safety functions and technologies.

These are called the **Methodologies work packages** (WP5: Human factors; WP6: Safety Functions; WP7: Statistical Methods).

- The eighth work package (WP8: Data Supply) acts as a technical support to the operational WP's. WP8 brings together a wide range of existing data sources from across Europe to aid analyses taking place in other workpackages in TRACE. In addition, this WP provides information to help TRACE partners make best use of data. This WP serves an essential purpose, because the methodological WP will not have a sufficient range of data sources available to their partners or the resources necessary to collate a range of data wide enough to support their work. However, all sixteen partners participate in WP8, and they can potentially bring 39 European data sources, with additional data from other countries, which together provide information for TRACE at 3 levels: descriptive data, in-depth data and risk exposure data. Data is collated and reviewed before being packaged for despatch to other WP's where it is analysed. Thirty separate data packages will be prepared over the lifetime of TRACE.

- Finally, there is a **Management Workpackage** which aims at leading, managing and monitoring the whole project.

Additional issues

- This research addresses the current understanding of accident and injury causes, levels and trends through reliable exposure, accident and injury data systems. TRACE intends to base its safety diagnosis on available, reliable and accessible existing and on-going databases (access to which is greatly facilitated by a series of partners highly experienced in safety analysis, coming from 8 different countries and having access to different kinds of databases, in-depth or regional or national statistics in their own country, and for some of them in additional countries).

- TRACE is also putting its efforts into the development and improvement of methodologies, in particular those applicable to data analysis. Special care and attention is brought to methodologies which enable the linking of different databases and methodologies which make it possible to combine clinical analysis (or micro accidentology) and statistical analysis (or macro accidentology) into a predicted meso-accidentological analysis, combining in-depth accident analysis and accident epidemiology.

The same effort in developing and applying methodologies holds for human factors, risk analysis and applied epidemiological and statistical methodologies for safety impact assessment.

- A review of available knowledge and effective methodologies is systematically performed and reported by the WP's in order to start the work on the basis of a 'level-of-art' knowledge.

- The expected outcomes of the project are mainly reports**,** focussing on operational results, methodological aspects, and of course a large set of descriptive and analytic statistics about accident causation (identification and quantification of risk factors). Reports will also make extensive qualitative examinations of mechanisms which cause accidents from the perspective of the road users, the types of factors, and the accident scenarios (the 3 different angles proposed by TRACE).

Other expected outcomes are workshops, especially with the eImpact and SafetyNet projects, and two TRACE-related events: a mid-term seminar (internal assessment of the project after one-year duration) and a *End-of-Project* Conference with a higher expected number of attendees coming from outside the consortium in order to broadly disseminate the results achieved during the course of the project.

As it is anticipated that outcomes are expected in the short term, the duration of the project has been set to two years (24 months friom January 2006 to December 2007) in order to be in line with the expectations and also to keep the possibility to make some noticeable improvements in methodology needed for the exploitation of databases.

EXPECTED USE OF TRACE OUTCOMES

The fundamental objective of the TRACE project is to prosaically search for a dramatic reduction in road accidents and casualties by an increase in accident causation and injury causation knowledge leading through the identification of road users needs and the assessment of safety functions able to cover these needs. This general societal issue (in terms of life savings) can be split up into several issues impacted by TRACE.

1. The first expected outcome concerns the results drawn from accident analysis. The identification of complex accident causation schemes and the evaluation of the effectiveness (potential or observed, depending on the current existence of safety functions to be defined or validated) of safety functions will be of great help to stake holders in charge of selecting and prioritising the development of safety functions or in charge of evaluating the benefits of the functions that are already on the market. As this evaluation will have been carried out with information available from throughout Europe instead of information available locally, this is, again, an added value of working at a European level.

2. The second outcome concerns improvements or innovation in accident analysis methodologies.

Why are methodological improvements needed? For three complementary reasons:

- A good understanding of accident causation requires, among others, the use of in-depth accident investigations and not only national or international accident census based on the collection of police reports, because the information available in census is purely descriptive and quite poor. Despite the fact that the scientific literature about accident analysis is quite abundant, some improvements in the methods of analysing accidents could still be made from different research angles, which is one the basics of our project.

- It is well known that in-depth investigations can produce interesting results about accident mechanisms and accident factors. Unfortunately, these results are usually not statistically representative of national or international accident patterns and should not be used for the estimation of the prevalence of such accident patterns. TRACE intends to find a method which can combine in-depth accident data and national or international accident census in order to try to estimate the prevalence of accident factors, specified on the basis of in-depth data, in the total number of accidents.

- Evaluation of the effectiveness of safety functions (a priori or a posteriori) is more widespread in the United States of America than Europe where it remains more or less confidential. Consequently, and with special regards to the evaluation of the observed effectiveness, methodologies and data availability for these evaluations are not sufficiently covered by research. We are facing two important problems: the first one is the availability of data. It is indeed assumed that it is not easy to identify and select the involved vehicles with such or such device implemented from the accident files because the identification of the vehicle in the accident files does not show, in most cases, whether the vehicle was equipped or not. It is even more difficult to get exposure measures of fleets of vehicles equipped with the safety devices. These barriers must be investigated seriously. The second problem concerns the epidemiological methods used in such evaluation. Even though traditional methods (such as the so-called odds ratio methods used in the Daytime running lights studies or the above mentioned ESP studies for example[3]) are known, they have limits, have been questioned by some experts and should be highly revisited. TRACE offers an opportunity for such a re-visitation.

3. The third outcome concerns the establishment, within the STREP, of a parallel European forum for accident experts (SafetyNet can also be considered as a forum but is more focussing on data collection than data analysis). In that sense, TRACE would act as a network of excellence since many European accident experts are TRACE partners. This unique assembly of experts is providing a good opportunity to link the different research institutes together, to perform parallel identical analyses on different databases coming from different national sources (be they private, public, vehicle industry or international organisation) even more than now and to enhance European research in accidentology. This is, again, an additional benefit of running the project at a European level.

PARTNERS

The TRACE Consortium is composed with 16 partners (table 1) and five sub contractors (Accident Research Center, Monash University, Aus / HIT, Gr., Technical University of Graz, A / Ecole Normale de Cachan, F / Medial University Hannover, D).

Table 1. TRACE Partners

Participant Organisation Names	Participant Organisation short name
Laboratoire d'Accidentologie, de Biomécanique et d'études du comportement humain PSA-RENAULT	LAB (Coordinator),F
University of Birmingham	BASC, UK
Fundacion para la Investigacion y Desarollo en Automocion	CIDAUT, E
Idiada Automotive Technology S.A., E	IDIADA, E
Institut National de Recherche sur les Transports et leur Sécurité	INRETS, F
Institut für angewandte Verkehrs- und Tourismusforschung e.V.	IVT, D
University of Patras – Laboratory for Manufacturing Systems and automation	LMS, Gr
Lundwig-Maximilians Universitaet Muenchen (Munich University)	LMU, D
Loughborough University	VSRC, UK
Allianz Center for Technology	AZT, D
Bundesanstalt für Strassenwesen	BAST, D
ELASIS S.C.p.A	ELASIS, I
Netherlands Organisation for Applied Scientific Research	TNO, NL
Volkswagen AG	VOLKSWAGEN, D
Institut for Mathematical Stochastics, (Technische Universität Braunschweig)	TUBS, D
Centrum Dropravniho Vyzkumu	CDV, CZ

The highest number of partners (6 out of 16) come from Germany. After that France, Spain and UK are represented by 2 partners, then Greece, Italy, The Netherlands and the Czech Republic with 1 partner. In total 12 partners are from car-producing countries, which might be expected for a project on traffic eSafety.

The geographic distribution of the consortium covers different parts of Europe in order to give

[3] See for example *The safety effects of Daytime Running Lights* (1997) by Matthijs Koornstra, Frits Bijleveld and Marjan Hagenzieker. Swov.

insight into the traffic safety situation throughout Europe. Central Europe is well represented by Germany, the United Kingdom and The Netherlands. France, Italy, Spain and Greece cover the southern part of Europe. The eastern part of Europe is represented by the Czech Republic.

Actually, France (22%), Germany (22%), United Kingdom (17%) and Spain (17%), and are the largest contributors in terms of resources (i.e., man – months).

Within the project, the car industry is represented as full partners by 4 major European car manufacturers: LAB (representing Renault and PSA), ELASIS for FIAT, and VOLKSWAGEN. Together they are responsible for almost 50 % of the market share of cars sold in Europe. The car manufacturers participating in this project have a perfect understanding of the latest developments in car safety and important new trends. Also, they have the capability to deliver accident analysis and databases as they are collecting themselves accident data and conduct their own accident research.

The second group of participants are the research institutes throughout Europe. In this category important traffic safety research institutes from 5 different EU countries are represented (France, Germany, Spain, The Netherlands, Czech Republic). Since traffic safety is more and more seen as a European (or even worldwide) matter, all these institutes have very broad contacts throughout Europe, but often also with associations with the national authorities on road safety.

Also one organisation of insurance companies is involved, which can provide interesting, unique and very useful insight based on the special knowledge they have on traffic accidents. The category of research institutes covers a wide range of research areas, from the vehicle and infrastructure aspects to more specific aspects of traffic accidents and accidentology.

The third group is formed by 6 universities from 3 different countries in Europe (United Kingdom, Germany, Greece). For an innovative research project, it is very important to have the support and involvement of university groups that move on the front line of innovations and research. Most of the universities participating in this project are technical institutes of which a department is involved directly in transportation research. Other universities include medical universities or transport-related laboratories with epidemiology expertise.

MANAGEMENT

The scientific activities of the TRACE STREP Project are all intended to strive towards an overall common goal, and each activity is defined as a necessary contribution towards this goal. The size of TRACE does not allow for only one organisational level, which should be in control of every detail of TRACE. On the other hand, a heavy and hierarchical organisation can often be too costly and too inflexible for research and development processes. Considering these aspects, TRACE has a simple but effective management structure where responsibilities are distributed vertically between the steering committee and workpackages and horizontally, across workpackages.

The monitoring, control and steering of TRACE are executed by the Coordinator and the Steering Committee. The Steering Committee consists of representatives of major partners of TRACE (i.e. WP leaders). They monitor the progress of TRACE, consolidate its activities and propose decisions.

The Coordinator of TRACE chairs the Steering Committee and acts as the speaker of TRACE.

A General Assembly of TRACE meets thrice in the project (beginning of the project, end of the project and one meeting in-between) and aims at reviewing all work done within all WP's up to the date meeting. All partners, observers and sub contractors are invited.

A scientific committee (also so-called *Wise Guys* committee) has been considered at the beginning of the project. But the project runs out of time and the steering committee has decided to do another way. The role of this committee would have be to give external advices and comments on the reports delivered by the Consortium. Actually, all reports will be commented in order to increase their quality by experienced external experts in each WP.

CONCLUSION

TRACE has started in January 2006 and will be soon beginning releasing the expected 40 reports. The work has followed and will keep on following this schedule:

1. Make an **analytical overview** (contents, quality, consistency, pertinence, applicability, representativity, extensive/intensive, etc.) **of current safety databases** available in Europe (accident databases, exposure databases, driver behaviour databases, insurance, medical databases,

etc.) and select those which are accessible, high-quality rated and relevant for the analysis[4].

2. Make an **analytical list** of the known safety functions, underlining their objective and they work.

3. Perform a **systematic and comprehensive literature review of methodologies** in accident analysis, human factors and evaluation of the effectiveness of safety measures.

4. Use available accident data or available knowledge in order to set an up-to-date descriptive **diagnosis of the accident causation issues**, hopefully in Europe but at least in the countries where the data (and especially but not only accident data) is available.

If available, exposure databases are put in perspective in order to estimate risks and relative risks of being involved in road accidents for different categories of road users on different road networks and environment conditions. Traditional methods for alternative exposure measurements (such as induced exposure or quasi induced exposure) are also considered.

In addition, large or small in-depth databases, oriented to primary or secondary safety (such as CCIS, GIDAS, LAB, EACS, MAIDS, etc.) are exploited, if available, in order to identify and assess the accident mechanisms for vehicle occupants, pedal cyclists, pedestrians, powered two-wheelers.

Most of these databases belong to TRACE participants and access to them should not be a problem except in a few cases where an official request for access are to be made to the owners.

Also, we are establishing and applying a sociological and socio-psychological approach, aimed to analyze the relevance of different socio-cultural frameworks for accident causation factors. Within this dimension, we address issues such as gender and age (or 'generation'), as well as contextual issues like education or the paradigm of our 'automobile culture'. In this sociological approach, a special emphasis is made on the multidimensional topic of 'risk' in its socio-cultural context.

As a whole, TRACE intends to take a picture (as comprehensive as possible) of the accident causation problems on European roads by combining explicitly in-depth accident analysis, road epidemiology, and human factors analysis.

5. Use all these analyses in order to **infer drivers' needs** and subsequently **recommend safety functions** that would be promising for the avoidance or the mitigation of accidents and their severity

6. Select amongst the list of functions that will have been defined beforehand, some relevant functions that are **not currently on the market** or currently undeveloped, and develop specific methodologies capable of estimating the **expected effectiveness** of this set of safety functions. Then, estimate this potential in terms of accident savings and life savings.

7. Select amongst the list of functions that would have been defined beforehand, some relevant functions that are **already on the market** (such as ABS, Brake Emergency Assist, ESP, Navigation systems, etc.) and develop specific methodologies capable of estimating the **observed effectiveness** of this set of safety functions. Then, estimate this potential in accident savings and life savings.

These two aspects of evaluation of the effectiveness of safety functions are crucial in TRACE. They will serve as an assessment of previous choices (for existing safety functions) and as a support for future decisions since the methodology should be able to prioritise, amongst the most promising safety systems, those with the highest potential influence on safety.

8. **Disseminate** the results to the scientific community, stakeholders, vehicle industry, suppliers, and research labs either by reports or directly on the Web. No industrial product is foreseen.

All results will be available for the duration of the project (2 years) to the partners within each of the Work Packages. All reports will then be fully public at the end of the project.

As a summary, these TRACE activities could be well resumed with these four keywords:

- **Diagnosis** of the accident causation issues (with the help of clinical, epidemiological and psycho sociological methods)

- Inference of road users' needs

- Identification of safety functions potentially effective in tackling the problems

[4] A provisional assessment of these databases is provided in Annex 1 of this proposal.

- **Evaluation** of the effectiveness of the functions (in terms of reduction of road toll)

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Further information can be found in the public area of the TRACE web site:

www.TRACE-project.org

DEFINITION OF A PRE-CRASH SCENARIO TYPOLOGY FOR VEHICLE SAFETY RESEARCH

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ABSTRACT

This paper defines a new pre-crash scenario typology for vehicle safety research based on the 2004 General Estimates System (GES) crash database. The purpose of this typology is to establish a common foundation for public and private organizations to develop and estimate potential safety benefits of effective crash countermeasure systems. Pre-crash scenarios portray vehicle movements and critical events immediately prior to the crash. This new typology consists of a set of 36 pre-crash scenarios representing 99.4% of all police-reported crashes that involve at least one light vehicle (i.e., passenger car, sports utility vehicle, van, mini-van, and light pickup truck). Light-vehicle crashes accounted for about 5,942,000 police-reported crashes in the United States based on 2004 GES statistics. This typology is nationally representative and can be annually updated using national crash databases. This paper quantifies the severity of the scenarios in terms of annual crash frequency, economic costs, and functional years lost. Characteristics of the driving environment, driver, and vehicle are also described.

INTRODUCTION

A number of crash typologies have been developed over the years in support of vehicle safety research. Crash typologies provide an understanding of distinct crash types and scenarios and explain why they occur. They serve as a tool to identify intervention opportunities, set research priorities and direction in technology development, and evaluate the effectiveness of selected crash countermeasure systems. Recently, two crash typologies have been widely used for crash avoidance research in support of the Intelligent Vehicle Initiative (IVI) within the United States Department of Transportation's (U.S. DOT) Intelligent Transportation Systems program: 44-crashes and pre-crash scenarios.

The "44-crashes" typology has been developed by General Motors and adopted by automakers for the design, development, and benefits assessment of potential crash countermeasure technologies [1,2]. This typology identified very specific crash scenarios representing all collisions in the United States and investigated the causes associated with each crash scenario using the 1991 General Estimates System (GES) crash database and samples of 1990-1991 police-reported crashes from the states of Michigan and North Carolina. Shortcomings of this typology include the limited study of state crash data and the amount of effort required to replicate the results using recent crash data.

The U.S. DOT has devised the "pre-crash scenarios" typology based primarily on pre-crash variables in the National Automotive Sampling System crash databases including the GES and Crashworthiness Data System (CDS) [3]. This typology has been utilized to identify intervention opportunities, develop performance guidelines and objective test procedures, and estimate the safety benefits for IVI crash countermeasure systems. Single-vehicle and two-vehicle crashes of common crash types were analyzed to produce the list of representative pre-crash scenarios. Multi-vehicle (> 2 vehicles) crashes were not included in the analysis. Some low-frequency crash types were also excluded such as vehicle failure, non-collision incidents, and evasive action scenarios. The "pre-crash scenarios" typology did not represent 100% of all police-reported crashes.

This paper defines a new typology of pre-crash scenarios for vehicle safety research by combining crash information from both typologies mentioned above. This new typology consists of pre-crash scenarios that depict vehicle movements and dynamics as well as the critical event occurring immediately prior to crashes involving at least one light vehicle (i.e., passenger car, sports utility vehicle, van, mini-van, and light pickup truck). This typology will establish a common foundation for public and private researchers to determine which traffic safety issues should be of first priority to investigate and to develop concomitant crash countermeasure systems. Its main objectives are to:

- Identify all common pre-crash scenarios of all crashes involving at least one light vehicle.
- Quantify the severity of each pre-crash scenario in terms of the frequency of occurrence, economic costs, and functional years lost.

- Portray each scenario by crash contributing factors and circumstances in terms of the driving environment, driver, and vehicle.
- Provide representative crash statistics that can be annually updated using national crash databases.

Next, this paper describes the methodology to identify pre-crash scenarios using GES variables. This is followed by listing the pre-crash scenarios of the new typology. Afterward, each pre-crash scenario is characterized by crash severity, contributing factors, and circumstances. Finally, this paper discusses the national representation and mapping of the new typology to the "44-crashes" typology.

SCENARIO IDENTIFICATION METHODOLOGY

The new crash typology is primarily structured with dynamically-distinct pre-crash scenarios that describe vehicle movements and critical events leading to the crash. The GES Vehicle File contains the Accident Type, Movement Prior to Critical Event, and Critical Event variables that allow the identification of such scenarios [4]. The Accident Type variable categorizes the pre-crash situation. The Movement Prior to Critical Event variable records the attribute that best describes vehicle activity prior to the driver's realization of an impending critical event or just prior to impact if the driver took no action or had no time to attempt any evasive maneuver. The Critical Event variable identifies the circumstances that made the crash imminent. The new typology is derived from separate analyses conducted on single-vehicle, two-vehicle, and multi-vehicle crashes. The GES Event File identifies the first event in a crash, which helps to distinguish pre-crash scenarios in two-vehicle and multi-vehicle crashes.

A coding scheme based on GES variables and codes was devised to identify common pre-crash scenarios representing 100% of all light-vehicle crashes [5]. A total of 46 pre-crash scenarios were initially coded and prioritized in a selected order as listed in Table 1. The new pre-crash scenario typology was then created by querying the 2004 GES and deducting the scenarios in the same order using the process of elimination, and thus avoiding double counting of crashes in each of these scenarios. The list of selected scenarios was prioritized by starting with scenarios associated with crash contributing factors such as vehicle control loss and driver violation of red light/stop sign. Such scenarios result in different crash types. For example, loss of vehicle control due to excessive speed could lead to a vehicle running off the road, rear-ending another vehicle in front of it, or encroaching into another lane and side-swiping an adjacent vehicle. From a crash avoidance perspective, the problem of vehicle control loss is identical in all three cases. A potential crash countermeasure function would detect the excessive speed or the imminent loss of control regardless of what crash type these conditions might lead to. Therefore, scenarios based on crash contributing factors supersede scenarios that represent dynamically-distinct driving situations based on vehicle movements and dynamic states.

PRE-CRASH SCENARIO TYPOLOGY

The new pre-crash scenario typology of all light-vehicle crashes was derived by integrating lists of pre-crash scenarios from single-vehicle, two-vehicle, and multi-vehicle crashes based on 2004 GES statistics. Approximately 5,942,000 police-reported crashes involved at least one light vehicle, which accounted for 96.3% of all crashes in 2004. A total of 10,695,000 vehicles and 15,027,000 people were involved in these light-vehicle crashes resulting in 2,737,000 injured people.

Table 2 ranks pre-crash scenarios of all light-vehicle crashes in descending order in terms of the frequency of occurrence. A total of 36 pre-crash scenarios represent 99.4% of all light-vehicle crashes or 95.7% of all vehicle-type crashes. Further research is needed to identify how many crashes involving medium/heavy vehicles only are represented by this new typology. The top scenario with an individual relative frequency over 10% – lead vehicle stopped – accounts for 16% of all light-vehicle crashes. The following six scenarios with an individual relative frequency between 5 and 10% represent about 40% of all these crashes. The remaining 29 pre-crash scenarios correspond to 43% of all light-vehicle crashes. There are "other" scenarios that only account for 0.6% of all light-vehicle crashes including on-road rollover (0.06%), hit and run (0.09%), no driver present (0.07%), and other non-specific or no-details scenarios.

DESCRIPTION OF SCENARIOS

This section provides a detailed description for each of the 36 scenarios based on the same order as listed in Table 2. The severity of each scenario is quantified in terms of economic costs, functional years lost, number of vehicles involved, number of people involved, and percentage of people who suffered high-level injuries based on the Abbreviated Injury Scale greater than or equal to 3 (AIS 3+): serious, severe, critical, or fatal. The GES does not provide detailed information regarding injury severity based on the AIS coding scheme. Instead, the GES records injury severity by crash victim on the KABCO scale from police crash reports. Police reports in almost every state use KABCO to classify crash victims as K – killed, A – incapacitating injury, B – non-incapacitating injury, C – possible injury, O – no apparent injury, or ISU – Injury Severity Unknown. The KABCO coding scheme allows nonmedically trained persons to make on-scene injury assessments without a hands-on examination. However, KABCO ratings are imprecise and inconsistently coded between states and over time. To estimate injuries based on the MAIS coding structure, a translator derived from 1982–1986 NASS data was applied to the GES police-reported injury profile [6]. The following matrix equation shows the multiplicative factors used to convert injury severity from KABCO to MAIS designations:

$$\begin{bmatrix} MAIS0 \\ MAIS1 \\ MAIS2 \\ MAIS3 \\ MAIS4 \\ MAIS5 \\ MAIS6 \end{bmatrix} = \begin{bmatrix} 0 & 0.01516 & 0.04938 & 0.19919 & 0.92423 & 0.07523 \\ 0 & 0.49183 & 0.79229 & 0.71729 & 0.07342 & 0.70581 \\ 0 & 0.27920 & 0.12487 & 0.06761 & 0.00206 & 0.15708 \\ 0 & 0.16713 & 0.03009 & 0.01509 & 0.00029 & 0.04343 \\ 0 & 0.02907 & 0.00267 & 0.00064 & 0.00001 & 0.01712 \\ 0 & 0.01762 & 0.00069 & 0.00018 & 0.00000 & 0.00134 \\ 1 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} K \\ A \\ B \\ C \\ O \\ ISU \end{bmatrix}$$

It should be noted that K injuries in KABCO are converted only to fatalities and non-K injuries in KABCO are converted to MAIS 0-5 injuries. The National Highway Traffic Safety Administration recommends that fatal crashes and fatalities be extracted from the Fatality Analysis Reporting System (FARS), not GES, since it contains records on all fatal traffic crashes and thus provides a more accurate representation of fatal crashes and fatalities than the sample contained in the GES. This paper, however, counts fatalities from the GES because FARS does not contain the Accident Type and Critical Event variables needed to identify the pre-crash scenarios of the new typology.

Table 3 provides severity information for each scenario. Economic costs of crashes include lost productivity, medical costs, legal and court costs, emergency service costs, insurance administration costs, travel delay, property damage, and workplace losses [7]. Functional years lost is a non-monetary measure that sums the years of life lost to fatal injury and the years of functional capacity lost to nonfatal injury [8]. The economic costs in Table 3 are expressed in year 2000 dollar values.

Typical scenarios are described below by driving environment, driver, and vehicle factors that are most frequently reported in GES crash files. The description also lists over-represented factors based on a simple comparison of percentages between factors in each scenario and concomitant statistics from all light-vehicle crashes and driver exposure data. For example, darkness will be over-represented in a pre-crash scenario if 40% of the crashes occur in the dark that accounts for only 25% of the national distance traveled. It is noteworthy that over-represented factors may not be necessarily the most frequent.

1. Lead Vehicle Stopped: Vehicle is going straight in an urban area, in daylight, under clear weather, at an intersection-related junction with a posted speed limit of 56 km/h; and then closes in on a stopped lead vehicle. Vehicle may also be decelerating or starting in traffic lane and closes in on a stopped lead vehicle. In 50% of these crashes, the lead vehicle first decelerates to a stop and is then struck by the following vehicle. This typically happens in the presence of a traffic control device or the lead vehicle is slowing down to make a turn. This particular scenario is closely related to, but distinct from, the lead-vehicle-decelerating scenario (scenario 4). Rural area, intersection-related junction, inattention, speeding, and younger driver (≤ 24 years old) are over-represented.

2. Control Loss without Prior Vehicle Action: Vehicle is going straight or negotiating a curve in a rural area, in daylight, under adverse weather conditions, with a posted speed limit of 88 km/h; and then loses control due to slippery roads and runs off the road. Vehicle action refers to a vehicle decelerating, accelerating, starting, passing, parking, turning, backing up, changing lanes, merging, and making a successful corrective action to a previous critical event. Dark, adverse weather, slippery road, rural area, non-junction, high-speed road, speeding, younger driver, and rollover are over-represented.

3. Vehicle(s) Turning at Non-Signalized Junctions: Vehicle stops at a stop sign in a rural area, in daylight, under clear weather, at an intersection with a posted speed limit of 56 km/h; and then proceeds to turn left or right against lateral-crossing traffic. Rural area, intersection and driveway/alley locations, low-speed road, vision obscured, inattention, female, and younger and older (≥ 65 years old) drivers are over-represented.

4. Lead Vehicle Decelerating: Vehicle is going straight while following another lead vehicle in a rural area, in daylight, under clear weather, at a non-junction with a posted speed limit of 88 km/h; and then the lead vehicle suddenly decelerates. Vehicle may also be decelerating in traffic lane and then closes in on a decelerating lead vehicle. Daylight, adverse weather, rural area, intersection-related junction, high-speed road, inattention, speeding, and younger driver are over-represented.

5. Road Edge Departure without Prior Vehicle Maneuver: Vehicle is going straight or negotiating a curve in a rural area at night, under clear weather, with a posted speed limit of 88 km/h; and then departs the edge of the road at a non-junction area. Vehicle maneuver denotes passing, parking, turning, changing lanes, merging, and successful corrective action to a previous critical event. Dark, rural area, non-junction, alcohol, inattention, speeding, drowsiness, younger driver, and rollover are over-represented.

6. Vehicle(s) Changing Lanes–Same Direction: Vehicle is changing lanes, passing, or merging in an urban area, in daylight, under clear weather, at a non-junction with a posted speed limit of 88 km/h; and then encroaches into another vehicle traveling in the same direction. Non-junction area, high-speed road, inattention, and younger driver are over-represented.

7. Animal Crash without Prior Vehicle Maneuver: Vehicle is going straight or negotiating a curve in a rural area at night, under clear weather, with a posted speed limit greater of 88 km/h; and then encounters an animal at a non-junction location. Dark, rural area, non-junction, and high-speed roads are over-represented.

8. Straight Crossing Paths at Non-Signalized Junctions: Vehicle stops at a stop sign in an urban area, in daylight, under clear weather, at an intersection with a posted speed limit of 40 km/h; and then proceeds against lateral-crossing traffic. Vehicle may also be going straight through an uncontrolled junction and then cuts across the path of another straight-crossing vehicle from a lateral direction. Moreover, both vehicles may first stop and then proceed on straight crossing paths. Rural area, low-speed road, vision obscured, female, and younger and older drivers are over-represented.

9. Running Red Light: Vehicle is going straight in an urban area, in daylight, under clear weather, with a posted speed limit of 56 km/h; and then runs a red light while crossing straight or turning left at an intersection and collides with another straight-crossing vehicle from a lateral direction. Urban area, inattention, female, and younger and older drivers are over-represented.

10. Vehicle(s) Turning–Same Direction: Vehicle is turning left or right at an intersection in an urban area, in daylight, under clear weather, with a posted speed limit of 56 km/h; and then cuts across the path of another vehicle initially going straight in the same direction. Clear weather, dry road, low-speed road, and younger driver are over-represented.

11. Left Turn across Path from Opposite Directions (LTAP/OD) at Signalized Junctions: Vehicle is turning left in an urban area, in daylight, under clear weather, at a signalized intersection with a posted speed limit of 56 km/h; and then cuts across the path of another vehicle crossing straight from an opposite direction. Vehicle may also be turning left across the path of another vehicle that is also turning left from the opposite direction. Intersection, low-speed road, vision obscured, inattention, female, and younger driver are over-represented.

12. Lead Vehicle Moving at Lower Constant Speed: Vehicle is going straight or decelerating in traffic lane in an urban area, in daylight, under clear weather, at a non-junction with a posted speed limit of 88 km/h; and then closes in on a lead vehicle moving at a lower constant speed. Non-junction location, high-speed road, inattention, speeding, and younger driver are over-represented.

13. LTAP/OD at Non-Signalized Junctions: Vehicle is turning left, in daylight, under clear weather, at an intersection without traffic controls, with a posted speed limit of 56 km/h; and then cuts across the path of another vehicle traveling from the opposite direction. Two vehicles may also be traveling in opposite directions and then both vehicles may turn left across their paths. Rural area, intersection and driveway/alley locations, low-speed road, vision obscured, inattention, and younger and older drivers are over-represented.

14. Backing Up into Another Vehicle: Vehicle is backing up or leaving a parked position (backing up) in an urban area, in daylight, under clear weather, at a driveway/alley location, with a posted speed limit of 40 km/h; and then collides with another vehicle. Daylight, driveway/alley and intersection-related locations, low-speed road, vision obscured, inattention, and younger driver are over-represented.

15. Vehicle(s) Not Making a Maneuver–Opposite Direction: Vehicle is going straight or negotiating a curve in a rural area, in daylight, under clear weather, at a non-junction with a posted speed limit of 88 km/h; and then drifts and encroaches into another vehicle traveling in the opposite direction. Dark, adverse weather, wet/slippery road surface, non-level road, rural area, non-junction, alcohol, male, and younger driver are over-represented.

16. Control Loss with Prior Vehicle Action: Vehicle is turning left or right at an intersection-related area, in daylight, under clear weather, with a posted speed limit of 72 km/h; and then loses control due to wet/slippery roads and runs off the road. Vehicle may also be decelerating in the traffic lane or changing lanes and then loses control. Dark, adverse weather, wet/slippery road, intersection-related, speeding, younger driver, and rollover are over-represented.

17. Vehicle(s) Drifting–Same Direction: Vehicle is going straight in an urban area, in daylight, under clear weather, at a non-junction with a posted speed limit of 88 km/h; and then drifts into an adjacent vehicle traveling in the same direction. Vehicle may also drift into another vehicle stopped in traffic lane. High-speed road, speeding, and younger driver are over-represented.

18. Following Vehicle Making a Maneuver: Vehicle is changing lanes or passing in an urban area, in daylight, under clear weather, at a non-junction with a posted speed limit of 88 km/h; and then closes in on a lead vehicle. Vehicle may also be turning right and then closes in on a lead vehicle. Intersection-related location, inattention, speeding, and younger driver are over-represented.

19. Road Edge Departure with Prior Vehicle Maneuver: Vehicle is turning left or right at an intersection-related location, in a rural area at night, under clear weather, with a posted speed limit of 40 km/h; and then departs the edge of the road. Vehicle may also attempt to change lanes, pass, or enter/leave a parking position and departs the edge of the road. Dark, intersection-related, low-speed road, alcohol, inattention, and younger driver are over-represented.

20. Road Edge Departure While Backing Up: Vehicle is backing up or leaving/entering a parked position (backing up) in an urban area, in daylight, under clear weather, with a posted speed limit of 40 km/h; and then departs the road edge on the shoulder/parking lane in a driveway/alley location. Driveway/alley location, low-speed road, alcohol, inattention, and younger driver are over-represented.

21. Object Crash without Prior Vehicle Maneuver: Vehicle is going straight or negotiating a curve in a rural area, at night, under clear weather, at a non-junction location with a posted speed limit of 88 km/h; and then collides with an object on the road. First harmful events occur on the road, on shoulder/parking lane, or off the road. Dark, rural area, non-junction, high-speed road, alcohol, younger driver, rollover, and hit and run are over-represented.

22. Evasive Action without Prior Vehicle Maneuver: Vehicle is going straight in an urban area, in daylight, under clear weather, at a non-junction location with a posted speed limit of 56 km/h; and then takes an evasive action to avoid an obstacle. First harmful events occur on the road, off the road, or shoulder/parking lane. Driveway/alley and younger driver are over-represented.

23. Vehicle(s) Parking–Same Direction: Vehicle is leaving a parked position or making a U-turn in an urban area, in daylight, under clear weather, with a posted speed limit of 40 km/h; and then encounters another vehicle traveling in the same direction at a non-junction area. Adverse weather, non-junction area, low-speed road, inattention, and younger driver are over-represented.

24. Running Stop Sign: Vehicle is going straight in a rural area, in daylight, under clear weather, with a posted speed limit of 56 km/h; and then runs a stop sign at an intersection. Vehicle may also run a stop sign while turning either left or right. Low posted speed limit (≤ 56 km/h), inattention, and younger and older drivers are over-represented.

25. Non-Collision Incident: Vehicle is going straight in a rural area, in daylight, under clear weather, at a non-junction location with a posted speed limit of 88 km/h; and then a fire starts on board the vehicle. First harmful events encompass fire or explosion, pavement surface irregularities such as potholes, person injured in vehicle or fell from vehicle, thrown or falling object, and other non-collision events. Clear weather, dry road, rural area, non-junction, high-speed road, and vehicle contributing factors are over-represented.

26. Vehicle Failure: Vehicle is going straight or negotiating a curve in a rural area, in daylight, under clear weather, on a dry road with a posted speed limit of 88 km/h; and then loses control due to catastrophic component failure at a non-junction and runs off the road. Failure of tires, brakes, power train, steering system, and wheels contributed to about 95% of these crashes, with tires alone accounting for 62% of vehicle failure crashes. Rural area, non-junction, high-speed road, younger driver, and rollover are over-represented.

27. Pedestrian Crash without Prior Vehicle Maneuver: Vehicle is going straight in an urban area, in daylight, under clear weather, with a posted speed limit of 40 km/h; and then encounters a pedestrian at a non-junction location. Vehicle may also be starting in traffic lane or negotiating a curve. The pedestrian is running onto the road in 36% of overall scenario crashes. Dark, adverse weather, non-junction area, low-speed road, vision obscured, and younger driver are over-represented.

28. Vehicle Turning Right at Signalized Junctions: Vehicle is turning right in an urban area, in daylight, under clear weather, at a signalized intersection with a posted speed limit of 56 km/h; and then turns into the same direction of another vehicle crossing straight initially from a lateral direction. Vehicle may also be turning right at a signalized intersection and then turns into the opposite direction of another vehicle traveling or stopped initially from a lateral direction. Adverse weather, intersection and intersection-related locations, low-speed road, vision obscured, and younger and older drivers are over-represented.

29. Object Crash with Prior Vehicle Maneuver: Vehicle is leaving a parked position at night, in an urban area, under clear weather, at a non-junction location with a posted speed limit of 40 km/h; and then collides with an object on road shoulder or parking lane. Vehicle may also be turning right and collides with an object. Commonly-cited first harmful events are parked motor vehicle and post, pole, or support. Dark, wet/slippery road, urban area, non-junction, low-speed road, alcohol, younger driver, and hit and run are over-represented.

30. Pedalcyclist Crash without Prior Vehicle Maneuver: Vehicle is going straight or starting in traffic lane in an urban area, in daylight, under clear weather, with a posted speed limit of 40 km/h; and then encounters a pedalcyclist at an intersection. Clear weather, dry road, intersection, low-speed road, vision obscured, and female driver are over-represented.

31. Animal Crash with Prior Vehicle Maneuver: Vehicle is leaving a parked position or passing another vehicle in a rural area at night, under clear weather; and then encounters an animal at a non-junction area. Dark, wet/slippery road, rural area, non-junction, and high-speed road are over-represented.

32. Pedalcyclist Crash with Prior Vehicle Maneuver: Vehicle is turning right or left in an urban area, in daylight, under clear weather, with a posted speed limit of 40 km/h; and then encounters a pedalcyclist at an intersection. Clear weather, dry road, intersection and intersection-related locations, low-speed road, vision obscured, inattention, and younger driver are over-represented.

33. Pedestrian Crash with Prior Vehicle Maneuver: Vehicle is turning left or right in an urban area, in daylight, under clear weather, with a posted speed limit of 56 km/h; and then encounters a pedestrian in the crosswalk at a signaled intersection. Urban area, intersection and intersection-related locations, low-speed road, vision obscured, and inattention are over-represented.

34. Lead Vehicle Accelerating: Vehicle is going straight or starting in traffic lane in an urban area, in daylight, under clear weather, at intersection-related location with a posted speed limit of 72 km/h; and then closes in on an accelerating lead vehicle. Dry road, intersection-related, high-speed road, traffic signal, inattention, speeding, female, and younger driver are over-represented.

35. Vehicle(s) Making a Maneuver–Opposite Direction: Vehicle is passing another vehicle in a rural area, in daylight, under clear weather, at a non-junction with a posted speed limit of 88 km/h; and encroaches into another vehicle traveling in the opposite direction. Vehicle may also be changing lanes or in the middle of a corrective maneuver and encroaches into another vehicle traveling in the opposite direction. Dark, adverse weather, rural area, non-junction, high-speed road, alcohol, vision obscured, inattention, speeding, male, and young driver are over-represented.

36. Evasive Action with Prior Vehicle Maneuver: Vehicle is turning left at an intersection-related location, in an urban area, in daylight, under clear weather, with a posted speed limit of 56 km/h; and then takes an evasive action to avoid an obstacle. Vehicle may also be passing, turning right, or changing lanes and then takes an evasive action to avoid an obstacle. Dark, urban area, intersection-related location, and younger driver are over-represented.

VALIDATION OF NEW TYPOLOGY

A sample of 236 crash police reports were carefully reviewed to ensure that each crash can be assigned to each of the 36 pre-crash scenarios in the new typology. These reports were obtained from the department of motor vehicles in the state of Massachusetts. The dates of these reports spanned from September 2004 through March 2005, which covered some severe winter months with a substantial amount of snowfall. All crashes were successfully mapped to this new pre-crash scenario typology, except for one crash (categorized as "other") in which a car being towed by a truck sideswiped six parallel parked cars. The two most frequent scenarios in the sample corresponded to the top two most frequent scenarios in the United States as listed in Table 2.

The "44-crashes" typology was also mapped to this new pre-crash scenario typology. Most of the 44 crashes are represented either directly or indirectly by the different variations of pre-crash scenarios in the new typology. For instance, one of the 44 crashes addresses emergency vehicles as they pass through signalized intersections on red. This crash is assigned to "running red light" scenario in the new typology even though the analysis of light-vehicle crashes in this report excludes emergency vehicles. However, the GES contains the needed variables to explicitly describe emergency-vehicle crashes that involve police cars, ambulances, or firefighting vehicles. Other crashes in the "44-crashes" typology represent tailgate, pedal miss, and stutter stop rear-end crash scenarios. These scenarios are indirectly classified in the new typology under lead vehicle decelerating, stopped, or accelerating due to the lack of GES variables and codes that refer to these particular events (e.g., tailgate, etc).

CONCLUSIONS

This paper identified and described a novel typology of pre-crash scenarios, which serves as a foundation for vehicle safety research. This typology consists of 37 pre-crash scenarios (including "other") that accounted for approximately 5,942,000 police-reported crashes involving all light vehicles based on 2004 GES statistics. These crashes resulted in estimated economic costs of $119,846,000,000 and 2,769,000 functional years lost. These statistics do not incorporate data from non-police-reported crashes. Excluding the "other" scenario, this new pre-crash scenario typology represents about 99.4% of all light-vehicle crashes.

Ranking the pre-crash scenarios by crash frequency, economic costs, and functional years lost, the following seven dominant scenarios emerged from a combination of these three measures:

- Control loss without prior vehicle action
- Lead vehicle stopped
- Road edge departure without prior vehicle maneuver
- Vehicle(s) turning at non-signalized junctions
- Straight crossing paths at non-signalized junctions
- Lead vehicle decelerating
- Vehicle(s) not making a maneuver - opposite direction

Crash statistics of this new typology should be updated on an annual basis using the GES or CDS so as to ensure the consistency of its scenario ranking and national representativeness of all light-vehicle crashes over time. It is recommended that the crash severity of the updated typology be quantified using values of economic costs and functional years lost from more recent years. Such updates also serve to identify trends in crash statistics and assess effectiveness of new automotive safety technologies in the vehicle fleet such as electronic stability control systems. Some safety systems can affect these crash scenarios by avoiding the crash altogether, others can reduce the harmful effects of the crash. The next challenge is to use these scenarios as a basis for coordinated benefits evaluations for integrated safety systems that can provide improvements in both crash avoidance and crashworthiness without double counting or otherwise over- or under-estimating safety benefits.

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Table 1. Ordered List of Pre-Crash Scenarios

No	Scenario
1	No Driver Present
2	Vehicle Failure
3	Control Loss with Prior Vehicle Action
4	Control Loss without Prior Vehicle Action
5	Running Red Light
6	Running Stop Sign
7	Road Edge Departure with Prior Vehicle Maneuver
8	Road Edge Departure without Prior Vehicle Maneuver
9	Road Edge Departure While Backing Up
10	Animal Crash with Prior Vehicle Maneuver
11	Animal Crash without Prior Vehicle Maneuver
12	Pedestrian Crash with Prior Vehicle Maneuver
13	Pedestrian Crash without Prior Vehicle Maneuver
14	Pedalcyclist Crash with Prior Vehicle Maneuver
15	Pedalcyclist Crash without Prior Vehicle Maneuver
16	Backing Up into Another Vehicle
17	Vehicle(s) Turning – Same Direction
18	Vehicle(s) Parking – Same Direction
19	Vehicle(s) Changing Lanes – Same Direction
20	Vehicle(s) Drifting – Same Direction
21	Vehicle(s) Making a Maneuver – Opposite Direction
22	Vehicle(s) Not Making a Maneuver – Opposite Direction
23	Following Vehicle Making a Maneuver
24	Lead Vehicle Accelerating
25	Lead Vehicle Moving at Lower Constant Speed
26	Lead Vehicle Decelerating
27	Lead Vehicle Stopped
28	LTAP/OD* at Signalized Junctions
29	Vehicle Turning Right at Signalized Junctions
30	LTAP/OD at Non-Signalized Junctions
31	Straight Crossing Paths at Non-Signalized Junctions
32	Vehicle(s) Turning at Non-Signalized Junctions
33	Evasive Action with Prior Vehicle Maneuver
34	Evasive Action without Prior Vehicle Maneuver
35	Rollover
36	Non-Collision Incident
37	Object Crash with Prior Vehicle Maneuver
38	Object Crash without Prior Vehicle Maneuver
39	Hit and run
40	Other - Rear-End
41	Other - Sideswipe
42	Other - Opposite Direction
43	Other - Turn Across Path
44	Other - Turn Into Path
45	Other - Straight Paths
46	Other

LTAP/OD: Left Turn Across Path/Opposite Direction

Table 2. Pre-Crash Scenarios of All Light-Vehicle Crashes

No	Scenario	Frequency	Rel. Freq.
1	Lead Vehicle Stopped	975,000	16.41%
2	Control Loss without Prior Vehicle Action	529,000	8.90%
3	Vehicle(s) Turning at Non-Signalized Junctions	435,000	7.32%
4	Lead Vehicle Decelerating	428,000	7.20%
5	Road Edge Departure without Prior Vehicle Maneuver	334,000	5.62%
6	Vehicle(s) Changing Lanes – Same Direction	338,000	5.69%
7	Animal Crash without Prior Vehicle Maneuver	305,000	5.13%
8	Straight Crossing Paths at Non-Signalized Junctions	264,000	4.44%
9	Running Red Light	254,000	4.27%
10	Vehicle(s) Turning – Same Direction	222,000	3.73%
11	LTAP/OD at Signalized Junctions	220,000	3.71%
12	Lead Vehicle Moving at Lower Constant Speed	210,000	3.53%
13	LTAP/OD at Non-Signalized Junctions	190,000	3.19%
14	Backing Up into Another Vehicle	131,000	2.20%
15	Vehicle(s) Not Making a Maneuver – Opposite Direction	124,000	2.08%
16	Control Loss with Prior Vehicle Action	103,000	1.73%
17	Vehicle(s) Drifting – Same Direction	98,000	1.65%
18	Following Vehicle Making a Maneuver	85,000	1.44%
19	Road Edge Departure with Prior Vehicle Maneuver	68,000	1.14%
20	Road Edge Departure While Backing Up	66,000	1.11%
21	Object Crash without Prior Vehicle Maneuver	55,000	0.92%
22	Evasive Action without Prior Vehicle Maneuver	56,000	0.95%
23	Vehicle(s) Parking – Same Direction	48,000	0.81%
24	Running Stop Sign	48,000	0.81%
25	Non-Collision Incident	46,000	0.77%
26	Vehicle Failure	42,000	0.71%
27	Pedestrian Crash without Prior Vehicle Maneuver	39,000	0.66%
28	Vehicle Turning Right at Signalized Junctions	35,000	0.59%
29	Object Crash with Prior Vehicle Maneuver	30,000	0.51%
30	Pedalcyclist Crash without Prior Vehicle Maneuver	24,000	0.41%
31	Animal Crash with Prior Vehicle Maneuver	23,000	0.39%
32	Pedalcyclist Crash with Prior Vehicle Maneuver	18,000	0.31%
33	Pedestrian Crash with Prior Vehicle Maneuver	17,000	0.29%
34	Lead Vehicle Accelerating	19,000	0.32%
35	Vehicle(s) Making a Maneuver – Opposite Direction	15,000	0.26%
36	Evasive Action with Prior Vehicle Maneuver	13,000	0.22%
37	Other	36,000	0.60%

Table 3. Severity Statistics of Light-Vehicle Pre-Crash Scenarios

Scenario	Economic Cost ($M)*	Functional Years Lost	Vehicles Involved	People Involved	People AIS 3+
Lead Vehicle Stopped	15,388	240,000	2,162,000	3,032,000	0.50%
Control Loss without Prior Vehicle Action	15,796	478,000	596,000	825,000	2.67%
Vehicle(s) Turning at Non-Signalized Junctions	7,343	138,000	872,000	1,212,000	0.71%
Lead Vehicle Decelerating	6,390	100,000	936,000	1,283,000	0.49%
Road Edge Departure without Prior Vehicle Maneuver	9,005	270,000	338,000	456,000	2.79%
Vehicle(s) Changing Lanes – Same Direction	4,247	71,000	635,000	884,000	0.42%
Animal Crash without Prior Vehicle Maneuver	1,632	24,000	311,000	414,000	0.38%
Straight Crossing Paths at Non-Signalized Junctions	7,290	174,000	535,000	765,000	1.21%
Running Red Light	6,627	135,000	528,000	740,000	1.81%
Vehicle(s) Turning – Same Direction	2,810	47,000	446,000	641,000	0.44%
LTAP/OD at Signalized Junctions	5,749	121,000	457,000	664,000	1.16%
Lead Vehicle Moving at Lower Constant Speed	3,910	78,000	445,000	612,000	0.71%
LTAP/OD at Non-Signalized Junctions	5,137	113,000	389,000	558,000	1.24%
Backing Up into Another Vehicle	947	9,000	261,000	363,000	0.13%
Vehicle(s) Not Making a Maneuver – Opposite Direction	6,407	206,000	232,000	330,000	2.58%
Control Loss with Prior Vehicle Action	1,970	49,000	135,000	192,000	1.43%
Vehicle(s) Drifting – Same Direction	1,383	37,000	235,000	330,000	0.58%
Following Vehicle Making a Maneuver	1,212	18,000	180,000	249,000	0.50%
Road Edge Departure with Prior Vehicle Maneuver	1,144	34,000	70,000	98,000	1.42%
Road Edge Departure While Backing Up	350	6,000	66,000	95,000	0.27%
Object Crash without Prior Vehicle Maneuver	687	19,000	55,000	76,000	1.12%
Evasive Action without Prior Vehicle Maneuver	1,349	36,000	99,000	137,000	1.23%
Vehicle(s) Parking – Same Direction	623	11,000	95,000	125,000	0.45%
Running Stop Sign	1,310	28,000	93,000	133,000	1.33%
Non-Collision Incident	592	13,000	82,000	112,000	0.56%
Vehicle Failure	1,051	26,000	53,000	89,000	1.78%
Pedestrian Crash without Prior Vehicle Maneuver	4,022	144,000	42,000	98,000	5.74%
Vehicle Turning Right at Signalized Junctions	355	4,000	71,000	98,000	0.27%
Object Crash with Prior Vehicle Maneuver	155	3,000	30,000	34,000	0.35%
Pedalcyclist Crash without Prior Vehicle Maneuver	1,301	39,000	25,000	58,000	3.27%
Animal Crash with Prior Vehicle Maneuver	120	2,000	24,000	27,000	0.36%
Pedalcyclist Crash with Prior Vehicle Maneuver	523	11,000	19,000	48,000	1.65%
Pedestrian Crash with Prior Vehicle Maneuver	843	24,000	18,000	41,000	2.87%
Lead Vehicle Accelerating	273	4,000	40,000	54,000	0.55%
Vehicle(s) Making a Maneuver – Opposite Direction	943	32,000	30,000	40,000	3.16%
Evasive Action with Prior Vehicle Maneuver	198	4,000	25,000	36,000	0.64%
Other	764	21,000	65,000	78,000	1.16%
Total	119,846	2,769,000	10,695,000	15,027,000	0.97%

*: Expressed in year 2000 dollar value

COLLISION WARNING WITH AUTO BRAKE - A REAL-LIFE SAFETY PERSPECTIVE

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ABSTRACT

Automotive safety has gained an increasing amount of interest from the general public, governments, and the car industry. This is more than justified by traffic accident statistics, as each year around 1.2 million people die due to road traffic accidents. For these reasons safety remains a core value of Volvo Cars. This paper presents some of the latest active safety developments within Volvo Cars.
Rear-end collisions are common accident scenarios and a common cause of these accidents is driver distraction and thus not reacting in time. No vehicle system is a substitute for the most important safety feature in any vehicle: the driver. However, Volvo is harnessing innovative technologies to help alert drivers to avoid potential collisions and reduce the potential impact speed when a collision cannot be avoided.
One of those systems is Collision Warning with Auto Brake where the area in front of the vehicle is continuously monitored with the help of a long-range radar and a forward-sensing wide-angle camera fitted in front of the interior rear-view mirror. A warning and brake support will be provided for collisions with other vehicles, both moving and stationary. Additionally, if the driver does not intervene in spite of the warning and the possible collision is judged to be unavoidable; intervention braking is automatically applied to slow down the car. This aims at reducing impact speeds and thus the risk for consequences.
This system has been verified using innovative CAE methods and practical tests. Finally, it is discussed how the benefit of such systems can be judged from real-life safety perspective using traffic accident statistics.

INTRODUCTION

Over the years, automotive safety has gained an increasing amount of interest from the general public, governments, and the car industry. Traffic accident statistics more than justify this focus, as each year around 1.2 million people die due to road traffic accidents [1].
Safety is and remains a core value of Volvo Cars, and it has a long tradition. A successful way to attain continuous improvements in safety development is a working process based on real world situations and the feed-back of this information into the product development. This working method has been found very effective in passive safety development [2]. The present study applies this working process into development of new active safety systems. Active safety systems require a wider scope of the study and performance goals, thereby expanding to accident occurrence beside injury protection and opponent vehicle beside host vehicle. The aim of this paper is to present some of the latest active safety developments within Volvo Cars and to put them into context of the working process [2].

REAR-END COLLISIONS

This section will put the area of rear-end collisions in the context of real-world situations. Accident data will be used as the basis for the problem definition as well as for the calculation of benefit. A brake-down of the problem definition is used to guide the evaluation and performance prediction process. For this purpose, three different sets of accident data will be used.

Statistical accident data bases

Three databases from three different countries are used as the basis for the problem definition.

Figure 1. Volvo's Traffic Accident Research.

Volvo's statistical accident database contains Volvo vehicles in Sweden in which the repair cost due to an accident exceeds a specified level, currently SEK 45000. The database, which contains information about the crash, the vehicles and the

occupants including injuries if any, is further described in [2].
The GIDAS database (German In-Depth Accident Study) is the second European database used in this study. Traffic accidents within Hanover and Dresden and the rural areas surrounding these cities are investigated according to a statistical sampling process [3].
As a complement to the European data, NASS/CDS (National Automotive Sampling System Crashworthiness Data System) is also used [4]. CDS provides in-depth crash investigations of a representative sample of police-reported tow-away crashes throughout the United States. Data is weighted to provide a nationwide estimate of all types of crashes and injuries.

Problem definition

Compared to the evaluation of passive safety systems, active safety systems require a wider scoop of the study and performance goals. It includes accident occurrence together with injury protection for opponent vehicles as well as for the host vehicle, as illustrated in Figure 2.

	Minor-Severe Accidents	**Occupant injuries**
Host vehicle	reduction ↘	reduction ↘
Opponent vehicle	reduction ↘	reduction ↘

Figure 2. Problem definition active safety.

Najm *et al.* [5], focusing on light vehicle crashes in the NASS/GES database, show that rear-end collisions are most frequent among all crash types accounting for 29% of all crashes. In the present study, the numbers of occurrences are clustered in impacts instead of collisions. Note that a collision is an event where possibly several vehicles can be involved and an impact is a consequence for a single vehicle. The aspects of self protection are accident reduction and occupant injury reduction from the host perspective. Partner protection is thus accident reduction and occupant injury reduction from the opponent perspective. Below, these will be dealt with separately.

<u>Self protection</u>
The distribution of impact configurations is shown in Figure 3. Approximately 50% of all impacts are to the front of the vehicle. Frontal impacts into an opponent motor vehicle's rear end account for 6-9% of the total share. Even though different selection criteria for the different data sets are used, the distributions are quite similar.

The occupant injury share from this type of impact situations can be seen in Figure 4 of all MAIS2+ injuries. In the three datasets used, frontal impacts into an opponent motor vehicle's rear end account for up to 5% of the total share of MAIS2+ injuries. The relatively small share is mainly due to the relatively low impact severity level in comparison to the other frontal impact situations.

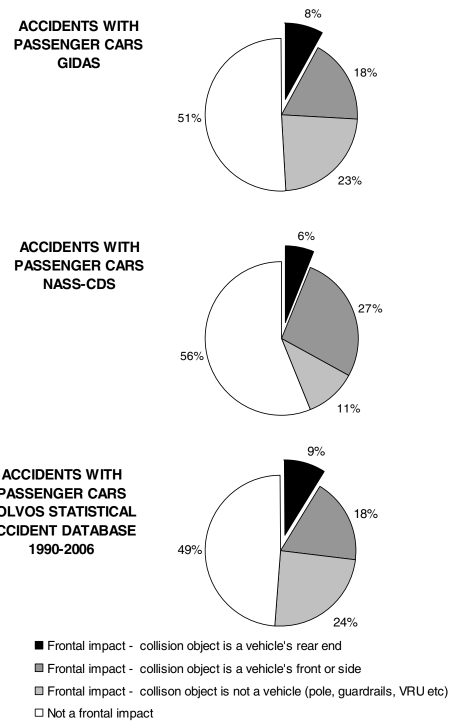

Figure 3. Distribution of impact configuration from a host perspective.

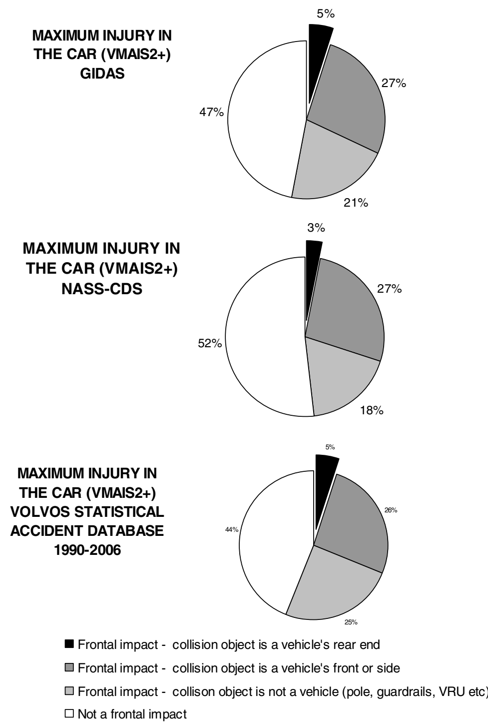

Figure 4. Distribution of MAIS 2+ injuries from a host perspective.

However, excluded in Figure 4 are all AIS1 injuries, such as *e.g.* AIS1 neck injuries. These injuries are frequent, can occur even at low impact severity and are the most common injury type of all in a frontal impact according to Volvo's statistical data base [6].

Partner protection

If considering impact situations from a partner protection perspective, the majority of impacts to the rear of the car is due to another passenger vehicle running into them. As can be seen in Figure 5, 12% in GIDAS, 6% in the Volvo data and 4% in NASS/CDS of the totals, were vehicles impacted from the rear by another passenger vehicle. These differences probably reflect the differences in collection criteria for the different data sets. NASS/CDS only covers tow-away situations; the Volvo data is collected based on a repair cost limit, including also situations without tow-away. In GIDAS even low-impact severity events are included and by that the most comparable set to the data in NASS/GES as used by [5].
Occupants in the opponent vehicles are also exposed for possible occupant injuries. In the vehicle impacted from the rear, the most common injury type is AIS 1 neck injuries, often referred to as whiplash injuries [7]. These injuries are very frequent and can occur even at low impact severity.

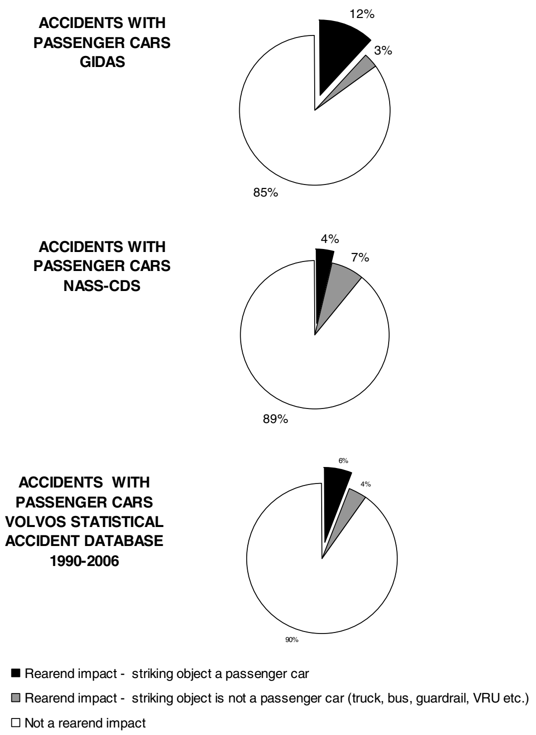

Figure 5. Distribution of impact configuration from an opponent perspective.

Accident occurrence

For intervention and development of active safety systems it is also important to understand the parameters influencing the accident type and traffic situation of interest and further consider reasons behind accident occurrence. It is not only important to understand what happened in an accident, but also to understand why an accident happened in the first place
Driver inattention and thus not reacting in time is a major cause of rear-end accidents. In the 100-Car Naturalistic Driving Study, the first study of its kind where detailed information on a large number of near-crash events is collected, nearly 80 percent of all crashes and 65 percent of all near-crashes involved driver inattention just prior to the onset of the conflict [8]. Inattention was a contributing factor for 93 percent of rear-end-striking crashes. The problem definition points out the importance of the area as well as the focus in the development process. In the next section Collision Warning with Auto Brake is introduced. A detailed description of the system, as well as brief summary of the difference between the first and second generation, will be presented.

COLLISION WARNING WITH AUTO BRAKE

Collision Warning with Auto Brake is an active safety system that helps the driver to avoid or mitigate rear-end collisions. It uses forward-looking sensors to detect obstacles ahead of the vehicle. When a high risk for a rear-end collision is detected the system helps the driver by providing a warning and brake support. If the driver does not react in time and a collision is judged to be unavoidable, the system will automatically brake the vehicle. This may not avoid the accident, but the consequences can be reduced.
This system is introduced in two steps. The first generation, called Collision Warning with Brake Support, is currently on the market in the new Volvo S80 allowing activation on vehicles that are moving or have been detected as moving. The second generation, called Collision Warning with Auto Brake, will be introduced in the near future. The latter system includes the functionality of the prior system but will also activate for stationary opponent vehicles in certain scenarios and will provide auto brake. The differences and the motivation for the two generations are explained in Coelingh *et al.* [9].

Sensor System

Information about the traffic situation in front of the host vehicle is obtained from two sensors:

- A 77-GHz mechanically-scanning forward-looking radar, mounted in the vehicles grille, which measures target information such as range, range rate and angle in front of the vehicle in a 15 degree field-of-view.

- A 640*480 pixel black and white progressive scan CMOS camera, mounted behind the windscreen, which is used for classifying the objects, *e.g.* as vehicles, in a 48-degree field-of-view. Since the camera is used for reporting both vision objects and lane markings, the field of view was chosen to work for both.

The combination of these two independent and complementary sensors provides high-confidence in lead-vehicle detection. This is important as the system should not be activated for stationary objects that are part of the normal driving environment, *e.g.* manhole covers. With only a radar sensor one cannot distinguish between reflections from a vehicle and reflections from any other object. However, the additional object classification of the camera is used to distinguish between vehicles and non-vehicles therefore the risk for false activations can be significantly decreased.

Collision Warning

The Collision Warning (CW) function is targeting to avoid or mitigate collisions by means of warning the driver ahead of a possible collision. The system requires high usability, low number of nuisance alarms and an efficient Human Machine Interface (HMI). The Collision Warning system should provide a relative late warning in order to reduce nuisance alarms and to reduce the possible misuse where an early warning system may build a trust that is falsely interpreted by the driver to allow for execution of non-driving tasks. The activation of the Collision Warning will therefore approximately occur when the driving situation is considered to be unpleasant. However, it shall allow the driver to brake to avoid or mitigate an accident provided the following distance was initially longer than the warning distance (refer next paragraph).

Threat Assessment

The aim of the threat assessment is to understand if the information from the forward sensing system shows that there is a risk for collision. The first step is to approve a lead vehicle as staying in the forward path within a given time to collision utilizing intra-vehicle and yaw-rate information. Given an approved lead vehicle a second step calculates a total warning distance, *i.e.* the predicted distance required for avoiding a collision. The total warning distance base calculation is derived from a sum of three distinct distance calculations. The first is the driver reaction distance which is obtained from the predicted driver reaction time multiplied by vehicle speed. The second is the system reaction distance which is obtained from the system reaction time multiplied by vehicle speed. The third is the braking distance to avoid impact using the current physical states of the lead vehicle and the host vehicle using the constant acceleration model for the behavior of the host and the target vehicle closely mimicking the CAMP late warning algorithm [10]. The sum of above provides a total warning distance. If the distance to the forward vehicle becomes lower than the total warning distance a warning is to be issued.

Furthermore, in order to further reduce nuisance alerts, a predicted driver reaction time modulated by driver action is used. As an example the predicted reaction time is normal when the driver has the foot on the pedals and is following the lead vehicle in a common way. In the event the driver is releasing the throttle or starting to brake, the predicted reaction time is reduced since the system predicts that the driver is aware of a potential danger ahead. Another action performing similar reduction is negotiating a curve. The reduction of the driver reaction time leads to a lower warning distance and consequently less risk of alerting a driver in a normal driving situation.

Collision Warning HMI

An efficient HMI for a warning system is characterized by a low driver reaction time, as this is crucial for improving the possibility for the driver to mitigate or even avoid a collision. Moreover, an efficient HMI puts requirements on low false and nuisance alarm rates, since there is a risk for overexposure that may lead to drivers deactivating the system. A number of studies have been executed related to efficient visual warning interfaces. The selected warning interface is a dual modality warning incorporating visual and audible channels. The visual warning is a flashing red horizontal line located in the lower part of the windshield in the forward direction of the driver, refer Figure 6. The sound consists of tone burst with harmonics content. When the audible warning is active the sound system is muted.

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Figure 6. Collision Warning head-up display.

The Collision Warning can be turned off by a main switch. The system includes a warning distance setting using three levels. The levels have been defined by balancing driver behavior in late brake situations versus normal driving behavior. The warning distance settings are differentiated by the deceleration level used in the different settings, *i.e.*

the predicted brake ability by the driver. They also reduce warnings in normal driving situations to different levels.

Auto Brake

Although it is expected that a large share of drivers unaware of a hazardous traffic situation, will be able to escape this situation due to the received collision warning, there are cases when drivers are not able to react in time to the warning. In that case it is beneficial to the driver to get support in the upcoming collision event. This can be achieved by reducing the collision energy by optimizing driver-initiated braking or through automatically putting on the brakes prior to the collision event, see also [11] and [12].

When providing autonomous interventions that override or complement the driver's actions, one has to ensure that customer satisfaction is not negatively affected by false interventions. Customer acceptance is crucial in order to increase take rates and thus to increase the overall real-life safety benefit of the system. It is therefore necessary to implement a decision making strategy that reduces the amount of false interventions while not missing collision events where the driver needs support.

Therefore, an intervention decision should be based on two main information categories: traffic situation data and driver actions. The traffic situation data is used to quantify the risk for a collision event, in other words a threat assessment is performed. This assessment will never be perfect as sensor information is usually a subset of the totally available information and mostly affected by latencies. So, a collision may appear to be unavoidable but is in reality avoidable. Hence, a driver that takes distinct steering and/or braking action is judged to be in control of the situation and should be trusted. The driver override function is to detect these distinct driver actions.

As soon as the support system has performed the threat assessment and driver override detection, the outcome can be weighted by the brake intervention strategy and a decision on an autonomous brake intervention can be taken.

Threat Assessment

The aim of the threat assessment is to fuse sensor information from the vehicle environment to a collision risk. The collision risk is a probability for a collision to take place, given that the currently observed physical states will be governed by a model for the traffic scenario until the collision instant. The current implementation of the threat assessment makes use of a constant acceleration model for the behavior of the host and target vehicles.

When it comes to the quantification of the collision risk, the motion of the host vehicle in relation to the target vehicles is analyzed. A possible collision event is said to be imminent as soon as neither steering nor brake action would lead to an avoidance of the collision. In terms of accelerations this means as soon as the maximum achievable lateral and longitudinal acceleration due to steering and braking action is less than the needed respective accelerations, a collision is imminent. The ratio of the needed acceleration and maximum achievable acceleration for braking and steering actions is denoted braking threat number (BTN) and steering threat number (STN), respectively, and has been introduced in [13] as quantifier for the collision risk. In [14] this concept is extended to a more generally valid approach.

A derivation of the BTN and STN can be found in [13]. Principally, the idea is to treat the longitudinal and lateral dimension as being independent. Then the BTN can be estimated from the host acceleration, range, range rate and range acceleration measurements. In case of the STN, the derivation requires two steps. First, the time until the possible collision instant is computed and second, the needed lateral acceleration that would lead to a lateral displacement for avoiding the target at the collision instant is estimated. Thus, measurements for lateral offset between host and target at the collision instant is needed, as well as measurements for host and target widths. Both BTN and STN are used in the decision process.

Threat assessment is based on a pure physical interpretation of traffic situation data that is reported by a sensor system. Although this information could suffice to determine if a possible collision event requires immediate braking action, a driver might be fully aware of the situation but has more information available than the sensor system can report. It is therefore necessary to consider driver actions in order to determine if the driver is overriding the support system.

Driver Override

The objective of the driver override function is to inhibit a brake intervention when the driver has the situation under control. However, this is difficult or even impossible to measure and therefore driver inputs as steering and braking activities are considered instead, as these are the natural countermeasures in a collision event. Furthermore, the release of the accelerator pedal is considered, as this indicates that any further acceleration is undesired, and it can be assumed that the driver is thereby acknowledging a collision risk.

Since the level of action that is required to activate a steering or brake override depends on the driver and on the traffic situation, the decision threshold is empirically determined through extensive testing in real life traffic situations with a large number of drivers.

Brake Intervention

When both collision risk and driver override flags are available a decision on a brake intervention can be made. Since there are two numbers available that quantify the collision risk, these number need to be fused. Clearly, several methodologies can be employed. Most straight forward approaches are the usage of the min or max operator yielding a conservative or progressive approach, respectively. A more thorough discussion of the decision concepts for collision avoidance is given in [11] Still, it can be reasoned what role the BTN has when it come to autonomous brake intervention. When the STN reaches or exceeds one, the driver is no longer able to steer away. In other words, the only option that remains for the driver is to brake. Additionally, it can be shown that the BTN is larger than the STN in many traffic scenarios. Usually, in the remaining situations the BTN has rather large values but still below one. This suggests that the STN alone can be used to trigger autonomous braking, yielding a mixture between the conservative and the progressive approach.
When a progressive intervention strategy is used for a support system the false intervention rate is usually increased. In order to achieve a progressive intervention approach with a low false intervention rate, the override flags play a key role. Making use of flag timing in relation to collision risk enables an inhibit strategy that reduces the false intervention rate. Naturally, the trimming of the inhibit strategy is based on physical interpretation of traffic situations and testing results with either artificially generated traffic situations or real-life traffic situations.
In the first stage there are two intervention types: pre-charge and increased sensitivity for Emergency Brake Assist. In a scenario where the rear-end collision risk is judged to be credible, meaning that the BTN and STN are increased but have not yet reached one, these intervention types are activated simultaneously. The pre-charge prepares the brake system for upcoming brake activation in order to reduce latencies. Furthermore, an increased level of pre-charge is applied upon indication that the driver has released the throttle pedal in response to the threat of collision. The brake system continuously monitors the brake pressure and brake pressure gradient of driver-initiated brake applies. When both exceed a certain threshold, full braking is applied automatically until the brake pedal is released (EBA), refer [15]. When a rear-end collision is judged to be credible, this threshold will be lowered, such that the driver can obtain full braking faster and with less effort. At low relative velocities, this brake boosting function can help to avoid a collision, alternatively it will mitigate it, *i.e.* reduce impact speed.
In the second stage, the above described idea is expanded by adding the autonomous braking to the intervention types. Again, the same sequence as above is valid, but as soon as the imminence of the collision is reached and the target object is confirmed as a vehicle, the auto brake command is issued and the host vehicle is slowed down at a deceleration of 0.5g. Moreover, the engine torque is automatically reduced to a level comparable to a full release of the accelerator pedal.
As a precaution, the autonomous intervention length in time is bounded to 1.0 seconds. According to first principals the collision has to occur within that time frame, and thus a longer intervention is not needed. In the rare case of a false intervention the intervention length and thus the inconvenience for the driver is limited.
By using the principles described above, auto brake can reduce the impact speed with up to 15 km/h, depending on the driving scenario.

SYSTEM PERFORMANCE

In the verification of the complete Collision Warning with Auto Brake system, validating both the function performance and the chosen concept are of importance. Minimum requirements for true positive and false positive performance need to be fulfilled and verified with a certain confidence level. The objectives of the tests are:

- to verify that the system provides an intervention in driving scenarios that constitute a high risk for a rear-end accident (true positives) and does not fail to intervene in these collision scenarios (false negatives);
- to verify that the system does not disturb the driver with false activations, under normal driving conditions (false positives).

The true positives are verified in a set of rear-end accident scenarios that have been defined based on real-world accident statistics. These vary in terms of absolute speed and acceleration of host and target vehicle, lateral off-set between host and target, driver behavior *etc*. For all scenarios acceptance criteria for the collision warning activations have been defined.
The false negatives are verified during extensive testing on public road. Normal driving conditions have been formally defined using a real-world user profile. This profile represents the driving conditions in terms of road type, lighting and weather conditions, driver population *etc*.

Verification Methods

The Collision Warning with Auto Brake system has been verified in the selected real world scenarios using different verification methods. In a specially developed simulation environment, Volvo Cars Traffic Simulator (VCTS) realistic Simulink models for traffic environment, driver, vehicle dynamics, sensors, actuators *etc*. are incorporated. The Collision Warning systems can either be represented by Simulink models (off-line simulation) or by the embedded control unit (hardware-in-the-loop simulation).

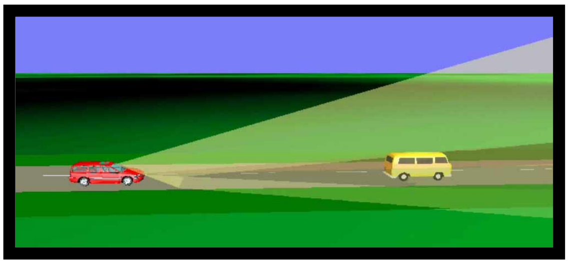

Figure 7. Volvo Cars Traffic Simulator.

The advantage of VCTS is the possibility to batch-analyze the collision warning systems in a large number of collision and non-collision scenarios, in a repeatable way. Acceptance criteria have been defined based on ground-truth data from the simulation environment.
In order to physically test the collision warning system in different collision scenarios, without any risk for personal injuries and property damage, special test equipment has been developed. Target vehicles are represented by large inflated balloons that allow for collisions with the host vehicle.

Figure 8. Physical test environment.

The balloon can be attached to a horizontal beam connected to another rig vehicle, such that it also can represent a moving target in different scenarios.

REAL-LIFE SAFETY EVALUATION

Predicting the real-life safety benefit of active safety systems covers the broad variety from the driver-car interaction to issues such as socio-economic impact by reducing accidents and occupant injuries. This area is complex and today impossible to cover completely. Even the more limited focus of a car manufacturer is wide. As illustrated in Figure 2; host as well as opponent vehicle, accident as well as occupant injuries are involved.

For the systems in the present study, diverse issues such as speed reduction and driver interacting (*e.g.* warning) are key items and need to be understood and handled separately.

In Lindman and Tivesten [16] a method for estimating the benefit of autonomous braking systems using accident data was presented. It specifically presents a method to estimate the effectiveness of reducing speed prior to impact. The method used for estimating effectiveness of reducing speed prior to impact [16] makes it possible to use any occupant injury risk estimation. Presuming 100% market penetration and system performance as well as optimum friction circumstances *etc*, approximately 50% of the 6-9% of frontal impacts where the collision object is the rear of a vehicle will be avoided, *i.e.* collisions at low speed. For many accident situations the impact speed and hence the consequences will be reduced. The most frequent occupant injuries in rear-end collisions are AIS1 neck injuries, both in the host as well as in the opponent car. AIS1 neck injuries in frontal impacts account for the majority of all AIS1 neck injuries although rear-end impacts account for the highest risk of acquiring this type of injury [7]. Even in these first stages of the development phase for autonomous driver support systems, the risks of AIS1 neck injuries can be considerably reduced both in the host and opponent vehicles just by avoiding a portion of host vehicle frontal impacts using a speed reduction system.

Understanding and quantifying driver-interacting aspects are more difficult than speed reduction calculation. The complete picture is only given in real world situations where, today, only limited data is available. In Najm *et al.* [17] 66 subjects participated in a FOT for a period of four weeks for the purpose of evaluate a combination of forward crash warning and adaptive cruise control. The study indicates that the system might prevent 3%-17% of all rear-end-crashes, expressed as a "conservative estimate".

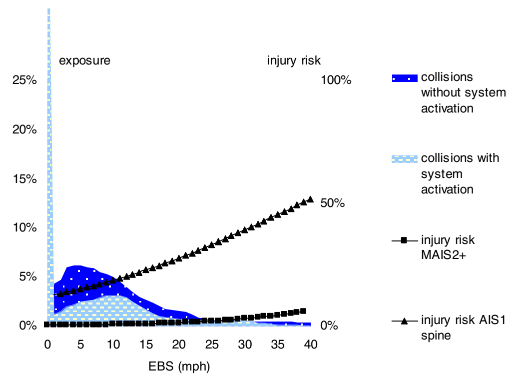

Figure 9. Exposure shift due to auto brake [16].

The total benefit prediction is a combination of host and opponent vehicle protection. For the systems presented in the present study, Figure 9 illustrates the exposure shift with and without speed reduction and injury risk (MAIS2+ and AIS1 neck injuries) for the host vehicle with respect to accidents and occupant injuries based on Volvo passenger cars. A general assessment of injury reduction due to this system related to partner protection can also be performed, however then based on a diverse sample of cars, *i.e.* not only Volvo cars.
The benefit of a system is a sum of the four boxes in Figure 2 combining effects on driver interaction as well as speed reduction. By adding together the different known aspects a total estimation can be made.

SUMMARY AND DISCUSSIONS

A break-down of the problem definition was used to guide the evaluation and performance prediction process as well as the system development. In this particular case it was discussed that rear-end collisions are relatively frequent and expose the occupants in the host as well as in the opponent vehicle to possible occupant injuries. The challenge is to aim for reduction of accident occurrence and if not possible impact severity reduction for reducing likelihood of occupant injury.

Collision Warning with Auto Brake is the second generation of Volvo Cars' collision avoidance and mitigation system. Currently rear-end collisions are addressed and the amount of auto brake is limited. Different test methods were used to verify and validate the systems performance. The results show that warning and auto brake are activated according specification during the selected set of collision situations. Furthermore, on road evaluation shows that risk of disturbing the driver under normal driving conditions is acceptably low. However, it can never be guaranteed that the system will always activate during a collision and that there will never be a false activation, but verification showed that the Collision Warning function performs well in terms of balancing nuisance and false activations versus correct activations.

This study presents some initial steps in assessing the performance of the system from a real-life safety perspective:

1. Determine the speed reduction that is achieved by the system in all collision scenarios.
2. Determine how the driver population reacts to warnings in the set of collision scenarios; refer [10] and [18]. Among the four different setting evaluated in [18] the Collision Warning head-up display of Figure 6 showed favorable results. The average brake reaction times were significantly faster for the selected head-up display warnings (approximately 200 ms), as compared to alternative solutions. The same result was found for the median, minimum and maximum reaction times. The selected display also performed best related to low amount of missed warnings. Based on these results, the warning concept is promising, although more aspects of driver interaction are involved.
3. Determine how many drivers avoid a collision because of a warning and brake support or how much speed reduction is achieved by driver braking upon a warning. This is an extensive area for research and it is dealt with in a large number of scientific studies. The knowledge needed requires testing in realistic situations and it needs to be balanced with experiences from studies dealing with passenger car driver's behavior. *E.g.* Ljung *et al.* [19] show that reactions to a warning system's HMI depend on previous exposures to warnings.

These threes steps address the true positive performance and the majority of the challenges are found in the area of collision warning. Other aspects, which also need more focus, are driver acceptance of nuisance and false activations and system adaptation. These areas of performance evaluation will gain from using information collected in naturalistic driving studies and field operational tests with relevant selection of subjects. During the development of Collision Warning with Brake Support, field studies were done based on a real-world user profile. Another type of field operation test, with a different system, was performed by Najm *et al.* [17] and it addresses the issue of driver acceptance. The study by Najm *et al.* indicates the importance of finding a good balance of nuisance and false activations versus correct activations. System adaptation over time is an aspect that requires solid field data and is further discussed in [20], although not dealing with the particular system discussed here.

Future field follow-up of this system will not only give feedback regarding the performance of the system but also be the basis for future system development. Then enhanced data can be collected to give feed-back on collision avoidance as well as speed reductions. This needs to take into account issues such as speed reduction, driver reaction, system adaptation and customer acceptance, which all are important aspects in the total benefit estimation. This information will improve the prediction done in this study, although, the evaluation methods presented in this study show a good start for prognosis of real-world performance. As a result, the enhanced knowledge can be used to further develop system performance, possibly expanded to cover other situations as well.

CONCLUSIONS

This study presents a second generation of a collision avoidance and mitigation system, Collision Warning and Auto Brake, aiming at reducing the occurrences of as well as consequences of a rear end collision. The total safety benefit is difficult to predict in absolute numbers. The evaluation methods presented in this study show good prognosis for real-world performance by addressing occupant protection and accident avoidance both in host and opponent vehicle.

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CHARACTERISTICS OF ROLLOVER CRASHES

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Paper Number 07-0479

ABSTRACT

Rollover crashes are investigated to identify ways in which active and passive safety solutions might be applied most effectively. Results of at-scene investigations of rural crashes by a research team and police reports of all crashes are reviewed. 236 crashes to which an ambulance was called, including 64 rollover cases, were investigated in the at-scene study, conducted on rural roads in South Australia. During a similar period police reports were compiled on 163,578 crashes, including 2,653 rollover cases. Injuries were sustained in 50% of the rollover cases but in only 18% of all other reported crashes (crashes resulting in a casualty or property damage of more than $1,000 were required to be reported). About half of the single vehicle rollover crashes in both studies occurred on straight roads; in the at-scene study after the vehicle drifted onto the unsealed shoulder. In almost every such case the vehicle yawed out of control before rolling. This is illustrated by photographs of the yaw marks and the final position of the vehicles, together with scale plans of these vehicle motions. The percentage of crashes which resulted in rollover increased with the posted speed limit: 5% at 80 km/h to 31% at 110 km/h. Vehicle factors relevant to crash and injury causation are also addressed. Combining information from these two studies overcomes to some extent their individual limitations, of small sample size in one instance and less detailed data in the other. These studies illustrate, among other matters, the type and frequency of situations in which stability control can be expected to prevent rollover crashes in a region where the roads are rarely wet, together with the importance of limiting travelling speed.

INTRODUCTION

This paper is based on information on crashes reported to or investigated by the police in South Australia, together with data from an in-depth study of 236 crashes to which an ambulance was called on rural roads within 100 km of the city of Adelaide. South Australia covers an area of over one million square kilometres (Texas is almost 700,000) and has a population of 1.12 million, of whom 73 per cent live in the Adelaide metropolitan area.

METHOD

The in-depth study was conducted by the Road Accident Research Unit (now renamed the Centre for Automotive Safety Research, CASR) between March 1998 and February 2000. Unit personnel attempted, usually successfully, to reach the scene of the crash before the vehicles were moved. Vehicle positions and damage were recorded and the site was mapped and photographed. Participants and witnesses were interviewed in most cases, initially at the scene in some cases and later in follow up interviews. In some fatal cases, where the vehicle positions had been marked by the Police Major Crash Investigation Unit, the CASR investigating team examined the crash scene within 24 hours. This had the effect of increasing the proportion of fatal crashes in the sample.

The sample of crashes investigated is not fully representative of all crashes occurring in the study area because the investigating teams were on call more frequently during daylight hours from Monday to Friday than on weekends. Similarly, night time crashes were under represented, apart from Thursday and Friday nights. However, characteristics associated with single vehicle rollover crashes can reasonably be compared with corresponding characteristics associated with other types of crash in this sample.

Some comparisons are made with data on all crashes reported to the police in South Australia which are held in the Traffic Accident Reporting System (TARS). These comparisons are influenced by the inclusion of crashes in the metropolitan area of Adelaide in the State-wide TARS data and by differences due to the study area including most of the populated hill country in the State.

RESULTS

Rollover Alone and After a Collision

Sixty four of the 236 crashes resulted in a vehicle rolling over. There were 19 cases in which a vehicle rolled without any prior collision. Another 21 of these rollovers occurred following a collision with another vehicle and in the remaining 24 single vehicle rollover crashes the vehicle rolled after a collision with a tree or an embankment (Table 1). However, it should be noted that in many of these single vehicle rollovers after a collision with a fixed object it is probable that the vehicle would have rolled over in any event had the collision not occurred.

Table 1.
Rollover crashes and prior collisions

Prior Collisions	Number of Crashes
No prior collision	19
Collision with fixed object	24
Collision with other vehicle	21
Total	64

Road and Traffic Factors

Almost half (49%) of the single vehicle rollover crashes occurred on straight sections of road, with about two thirds of the remainder on right hand curves (Table 2). (Note that traffic keeps to the left in Australia.) The percentage on straight roads was slightly higher (57%) in the State-wide police data (TARS) cases which may be due partly to chance variation but also to the topography of the in-depth study area which, as noted above, covered a much higher proportion of hill terrain than the whole State, which is mainly flat and hence with mostly straight roads. The vehicle movements on straight roads that typically resulted in rollover are described later in this paper.

Table 2.
Road alignment in single vehicle rollover crashes compared to all other crash types

Road Alignment	Rollover	Other	Column % Rollover	Column % Other
Straight	21	117	48.8	60.6
Right curve	13	45	30.2	23.3
Left curve	9	31	20.9	16.1
Total	43	193	100.0	100.0

* Note: Traffic keeps to the left in Australia.

The default open road speed limit in South Australia is 100 km/h, with most major highways zoned at 110 km/h. Consequently, it is not surprising that 81 per cent of these 43 single vehicle rollover crashes occurred on roads having a speed limit of at least 100 km/h (Table 3). However, eight of the single vehicle rollover crashes on 100 km/h roads occurred on bends having a posted advisory speed ranging from 25 to 80 km/h. Two of the 16 crashes on 110 km/h roads occurred on bends where an advisory speed was posted (65 and 75 km/h).

As noted, 81 per cent of these single vehicle rollover crashes occurred on 100 or 110 km/h roads. This is very close to the State-wide figure of 84 per cent for single vehicle rollover crashes. Single vehicle rollover crashes increase as a percentage of all crashes at the higher speed limits, both in the in-depth study data and the State-wide TARS data, to the extent that 30 per cent of all crashes on 110 km/h speed limit roads are single vehicle rollovers, compared with less than 20 per cent on 100 km/h roads (Table 3).

The two crashes which occurred on 60 km/h roads, in rural towns, were unusual in that one involved a rigid truck on which the load shifted when cornering and the other an elderly driver whose car ran up onto an embankment for no apparent reason and rolled over.

Some of these crashes were included in a case control study of travelling speed and the risk of crash involvement and so the travelling speed of the vehicle which rolled over had been estimated. (Kloeden et al, 2001) There were two crashes on 100 km/h speed limit roads where the cars were estimated from crash reconstruction to have been exceeding the limit by a wide margin (travelling speeds of 150 and 170 km/h). However there were also cases in which the estimated travelling speed was much less than the posted speed limit, as low as 65 km/h in one crash on a 100 km/h road.

Table 3.
Speed limit by percentage of single vehicle rollover crashes: in-depth study and state-wide

Speed Limit	Rollover Crashes	Other Crashes	% Rollover	% Rollover TARS*
60 km/h	2	32	5.9	0.7
70 km/h	2	4	33.3	1.7
80 km/h	2	32	5.9	4.9
90 km/h	2	7	2.2	7.7
100 km/h	19	81	19.0	18.9
110 km/h	16	37	30.2	30.6
Total	43	193	18.2	6.1

* Note: Crashes resulting in a fatality or injury requiring at least treatment at a hospital in South Australia 1999-2003

Type of Vehicle

A car or car derivative (station wagons and some utilities) accounted for almost three fifths of the vehicles which rolled over in the 64 crashes. (Table 4) What is more interesting, given the relative numbers of vehicles on the roads, is the high percentage (24.6%) of SUV vehicles, and the fact that three of these SUV vehicles were towing trailers. It is relevant to note here that the mean age of the vehicle fleet in Australia is about 11 years and SUVs have become an increasing proportion of that fleet, at least until very recently.

The percentage of semi trailers in Table 4 (10.8%) may be accounted for in part by the comparatively high exposure of these vehicles in terms of distance travelled but the crash circumstances demonstrated their well-recognised deficit in lateral stability compared to other types of vehicle.

Table 4.
Type of vehicle in all crashes resulting in a rollover

Type of Vehicle	Number of Vehicles	% of Vehicles
Car or car derivative	38	58.5
Semi trailer	7	10.8
Light van	1	1.5
Rigid truck	3	4.6
SUV (three towing a trailer)	16	24.6
Total	65	100.0

Note: Two vehicles rolled in one crash (semi trailer & SUV)

The percentage of cars among those vehicles that rolled following a collision with another vehicle (45.5%) was lower than it was among vehicles involved in single vehicle rollovers (65.1%) (Tables 5 and 6). This could indicate that a car is more stable than an SUV in a collision but the number of cases is small and this observed difference is not statistically significant.

Table 5.
Type of vehicle rolling over after colliding with another vehicle

Type of Vehicle	Number of Vehicles	% of Vehicles
Car or car derivative	10	45.5
Semi trailer	3	13.6
Rigid truck	2	9.1
SUV (one towing a trailer)	7	31.8
Total	22	100.0

Note: Two vehicles rolled in one crash (semi trailer & SUV)

Two thirds of the crashes in which a vehicle rolled over involved only that vehicle and almost two thirds (65.1%) of the vehicles in these single vehicle rollovers were cars (Table 6).

Table 6.
Type of vehicle in single vehicle rollover crashes

Type of Vehicle	Number of Vehicles	% of Vehicles
Car or car derivative	28	65.1
Semi trailer	4	9.3
Light van	1	2.3
Rigid truck	1	2.3
SUV (two towing a trailer)	9	20.9
Total	43	100.0

The relative involvement of cars compared to other vehicles (mostly SUVs) differed markedly however depending on whether or not the vehicle struck a fixed object, usually a tree, before rolling over. In the cases involving no prior impact, 42.1 per cent of the vehicles were cars whereas the corresponding percentage for cars in rollover crashes with a prior impact was 83.3 per cent (Tables 7 and 8, respectively). The crash circumstances indicated that a rollover would still have occurred in many of these cases had there been no collision with a fixed object.

Table 7.
Type of vehicle in single vehicle rollover crashes without a prior collision with a fixed object

Type of Vehicle	Number of Vehicles	% of Vehicles
Car or car derivative	8	42.1
Semi trailer	3	15.8
Rigid truck	1	5.3
SUV (two towing a trailer)	7	36.8
Total	19	100.0

Table 8.
Type of vehicle in single vehicle rollover crashes with a prior collision with a fixed object

Type of Vehicle	Number of Vehicles	% of Vehicles
Car or car derivative	20	83.3
Semi trailer	1	4.2
Light van	1	4.2
SUV	5	26.3
SUV	2	10.5
Total	24	100.0

The numbers of cases involving SUV vehicles in Tables 7 and 8 are too small to provide a reliable comparison with the corresponding data for cars presented in the previous paragraph but the percentages are consistent with SUV vehicles rolling over before they have travelled out of control far enough to collide with a fixed object. The percentage of each of the above types of vehicle involved in a single vehicle rollover is compared with all vehicles of that type involved in the crashes investigated in the in-depth study in Table 9. The two types of vehicle that have by far the highest rate of single vehicle rollover, given involvement in a crash, are SUVs and semi trailers. This is consistent with the corresponding State-wide TARS data, as far as the types of vehicle can be compared. Once again, the higher percentage of all types of vehicle involved in single vehicle rollovers in the in-depth study is probably mainly a reflection of differences in topography.

Table 9.
Types of vehicle in single vehicle rollover crashes compared to vehicles in all other crash types: In-depth and TARS data

Type of Vehicle	Rollover	Other	% Rollover	% Rollover TARS[1]
Car	28	247	10.2	3.6
SUV	9[2]	25[3]	26.5	10.7
Semi trailer	4	13	23.5	-
Rigid truck	1	14	6.7	-
Van	1	15	6.3	4.5
Total	43	314	12.0	4.15
All trucks	5[4]	27[4]	15.6[4]	9.5

Notes: [1] See note to Table 3; [2] Two towing a trailer; [3] One towing a trailer; [4] Included above

Driver Characteristics

The age distribution of the drivers involved in single vehicle rollover crashes was very similar to that for all other drivers in this sample of crashes. There were eight drivers under 20 years of age and they were all on Provisional licences. They represented 18.6 per cent of all of these 43 drivers, slightly more than the 14.4 per cent of those drivers in this age group involved in the other types of crash in this study sample. Overall, however the percentage of drivers under 30 years of age was almost exactly the same in both groups of drivers (37.2% for those in single vehicle rollovers and 37.7% for the remainder). This is consistent with the results from the TARS data, which showed little difference in the age distribution of these two groups of drivers apart from an apparent over representation of drivers in the 16 to 18 year age range.

There were more male than female drivers involved in single vehicle rollover crashes but the difference was small (55.8% were male) and less than for the other types of crash in the in-depth study sample (62.6%). There was some statistically insignificant difference (p=0.389, Chi square=0.74) in the percentage of male drivers in this sample who were involved in single vehicle rollover crashes compared with other types of crash (10.9%) and the corresponding percentage for female drivers (14.0%). (Table 10) The corresponding percentages for State-wide single vehicle crash data were males 4.2 and females 4.1.

Table 10.
Sex of drivers involved in single vehicle rollover crashes compared to all other crash types

Sex of Driver	Rollover	Other	% Rollover
Male	24	196	10.9
Female	19	117	14.0
Total	43	313	12.1

Drivers operating on a Provisional licence had a higher rate of involvement in single vehicle crashes than in other types of crash but not to a statistically significant degree (Table 11). However, a slightly larger difference was observed in the TARS data and it was statistically significant, as would be expected with the much larger number of cases.

Table 11.
Licence status of drivers involved in single vehicle rollover crashes compared to all other crash types and TARS data

Licence Status	Rollover	Other	% Rollover	% Roll TARS
Learner	-	-	-	8.2
Provisional	8	45	15.1	5.0
Full	35	275	11.3	3.1
Unlicensed	-	-	-	8.6
Total	43	313[1]	12.1	4.1

Note: [1] Excludes 3 Learners and 8 unlicensed drivers

Blood alcohol levels were obtained for 36 of the 43 drivers. Twenty eight were sober (78% of the known BAC cases), probably reflecting the bias towards daytime crashes in the sample (but see the following case description), two were below the legal blood alcohol limit of 0.05 g/100mL, another two were above the limit but below 0.10 and four were above 0.116, with the highest being 0.256.

The crash involving the driver who had a blood alcohol level of 0.256 occurred at 4.30 pm on a Saturday. The driver allowed the car to drift across onto the left unsealed shoulder for some considerable distance before overcorrecting to the right. The car, a 1978 HZ Holden Kingswood, then yawed across the road and rolled three quarters of a turn on striking a low bank. (Figures 1, 2 and 3) The uninjured 49 year old male driver was probably wearing a seat belt.

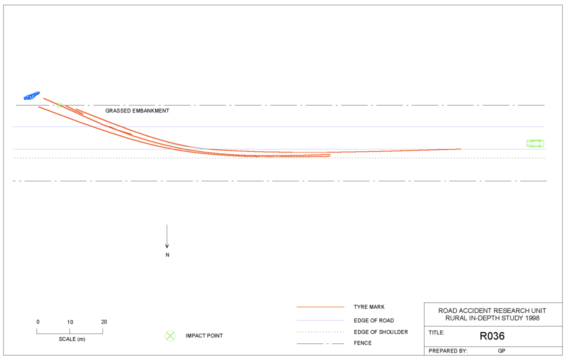

Figure 1. Site diagram showing tyre marks from initial off road excursion and overcorrection back to the right.

Figure 2. Yaw marks leading to the point of rollover.

Figure 3. Car rolled to the left 3/4 of a turn. Shown here after being rolled back onto its wheels.

Injury Severity

Injury severity is expressed here in terms of the level of treatment required or, for fatal cases, the outcome. The distribution of the maximum injury severity in each of these single vehicle rollover crashes is shown in Table 12. (AIS ratings of injuries are available but are not included in this paper.)

The percentage of fatal crashes is larger than would be expected in a representative sample of all crashes to which an ambulance is called for the reason noted earlier in this paper.

Table 12.
Maximum injury severity in single vehicle rollover crashes

Maximum Injury Severity	Number of Crashes	% of Crashes
Property damage only*	9	20.9
Treatment at hospital	18	27.9
Admission to hospital	14	32.6
Fatal	8	18.6
Total	43	100.0

* Note: Includes some cases involving injuries treated by private doctor

The comparison of the distribution of injury severities between single vehicle rollover crashes and other crashes shown in Table 13 provides a more meaningful assessment of the importance of single vehicle rollover crashes.

Bearing in mind that the criterion for entry into this sample of crashes of all types was that an ambulance be called, it is notable that over one third of all of the occupants involved did not require ambulance transport (36.3% of the 571 occupants). However less than 20 per cent of the occupants in single vehicle rollover crashes were in that category compared with 38 per cent of vehicle occupants in other types of crash ($p=0.004$, Chi square=8.12). This difference was accounted for mainly by a higher percentage of the rollover cases requiring treatment at hospital, but not admission, and a higher percentage who were fatally injured.

In other words, occupants in a single vehicle rollover were more likely than occupants of vehicles in other types of crash to be injured to a degree requiring transport to hospital by ambulance but no more likely to be admitted to hospital. The higher percentage of rollover cases resulting in a fatal injury was within the bounds of chance variation, and partially due to the method of inclusion of such cases.

Table 13.
Injury severity of occupants in single vehicle rollover crashes compared to occupants involved in all other crash types

Injury Severity	Rollover	Other	Column % Rollover	Column % Other
Property damage only*	12	195	19.7	38.2
Treatment at hospital	22	127	36.1	24.9
Admission to hospital	18	138	29.5	27.1
Fatal	9*	50	14.8	9.8
Total	61	510	100.0	100.0

* Note: Includes some cases involving injuries treated by private doctor and two occupants of one car were fatally injured

There was no meaningful difference in the maximum injury severity distributions between single vehicle rollover crashes with and without a collision with a fixed object but the number of cases was small in each group.

Seat Belt Use, Injury Severity and Ejection

Eighty per cent of the most severely injured occupants (the most severely injured in each of the single vehicle rollover crashes) were wearing a seat belt in the crash, based on the 40 out of 43 crashes for which this information was available. There appears to be a clear negative association between belt use and injury severity, as listed in Table 14. However, the very small number of "belt not worn" cases means that comparing "admission to hospital and fatal" with "treatment and no injury" cases with respect to belt use fails to yield a statistically different difference.

Table 14.
Maximum injury severity of occupants in single vehicle rollover crashes by seat belt use

Maximum Injury Severity	Belt Worn	Belt Not Worn	Belt Use Unknown	% Worn (Known)
Property damage only*	9	-	-	100.0
Treatment at hospital	11	1	-	91.7
Admission to hospital	19	4	1	69.2
Fatal	3	3	2	50.0
Total	32	8	3	80.0

* Note: Includes some cases involving injuries treated by private doctor

Similarly, four of the eight most severely injured occupants per vehicle who were not wearing a seat belt were ejected in the crash, compared with none of the 31 who were wearing a seat belt (Table 15).

Table 15.
Occupant ejection from the vehicle in single vehicle rollover crashes by seat belt use

Ejection	Belt Worn	Belt Not Worn	Belt Use Unknown	% Worn (Known)
Yes	-	4	1	0.0
No	31	4	-	88.6
Unknown	1	-	2	-
Total	32	8	3	80.0

Finally, the five ejected occupants included three of the seven fatalities for whom ejection status could be determined (Table 16).

Table 16.
Maximum injury severity of occupants in single vehicle rollover crashes by ejection from the vehicle

Maximum Injury Severity	Ejected	Not Ejected	Ejection Unknown	% Ejected (Known)
Property damage only*	-	9	-	0.0
Treatment at hospital	1	10	1	9.1
Admission to hospital	1	12	1	7.7
Fatal	3	4	1	42.9
Total	5	35	3	12.5

* Note: Includes some cases involving injuries treated by private doctor

Vehicle Movements Preceding Rollover

Most of the cars involved in single vehicle rollovers in this sample of crashes were travelling on a straight road (Table 17). Two crashes were not relevant to this consideration of vehicle movements preceding rollover. One simply involved a car running off the road and along an embankment for no apparent reason. The elderly driver ceased driving following that crash. Another crash was thought probably to have been intentional.

Table 17.
Cars in single vehicle rollover casualty crashes by road alignment and initial and final off road excursion

Road Alignment	Initial Off Road Excursion on:		Final Off Road Excursion on:	
	Left	Right	Left	Right
Straight	12 (4)[1]	2 (1)	5	4
Right curve	6 (2)	2 (2)	3	1
Left curve	3 (2)	1	1	1
Total[2]	21(8)	5 (3)	9	6

Notes:
[1] Number in parentheses indicates that the initial off road excursion was also the final one
[2] Two cases have been omitted (see text)

In almost every case the car that rolled over yawed out of control before rolling. The typical vehicle movement that precipitated the loss of control was running gradually across to the left until the left hand wheels ran onto the unsealed gravel shoulder. The driver then swerved back to the right and overcorrected to the left, as shown in one such crash. (Figures 4, 5 and 6) The 17 year old female driver had held a licence for less than a year. She was wearing a seat belt and sustained only a minor laceration (AIS 1) to her head. The car was a 1975 Datsun 120Y which had low pressures in the rear tyres. While this may have increased the difficulty in controlling the car, the vehicle motions following the initial off road excursion were very similar to those in other crashes where tyre pressures were at the recommended levels.

There were more single car rollovers on right hand rather than left hand curves, but together they still accounted for fewer crashes than the single car rollovers on straight sections of road (Table 17).

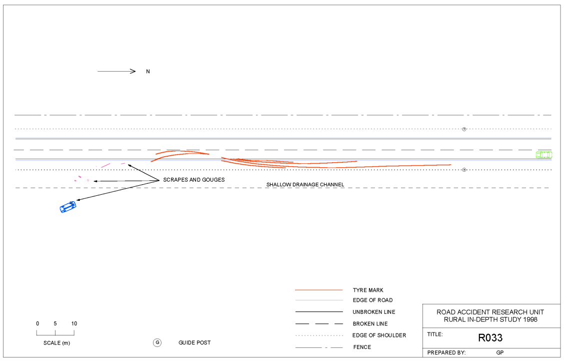

Figure 4. Site diagram showing tyre marks in initial off road excursion and followed by yaw marks to the right and back to the left.

Figure 5. Yaw marks at the point of rollover and final location of car (rolled back onto its wheels).

Figure 6. Roof damage following rollover.

SUVs in Single Vehicle Rollovers

There were nine single vehicle rollovers involving a SUV. In one of these the vehicle rolled on a winding downhill section of a divided highway but, despite multiple rolls, remained on the two lanes for traffic in its direction of travel. There were also two cases in which the initial loss of control was either precipitated by, or strongly influenced by, a trailer which was being towed by the SUV. One of these two crashes occurred on a straight road when the trailer began to oscillate behind the short wheelbase SUV and the other on a gradual left hand curve during an overtaking manoeuvre.

The number of cases involving SUVs is too small to provide a reliable basis for comparison with single vehicle rollovers involving cars but in five of the eight SUV cases the initial was also the final excursion (Table 18), as illustrated in Figures 7, 8 and 9. We were not able to determine why the vehicle went out of control in this crash, which occurred on a wet road. The unrestrained 51 year old driver, who remained inside the vehicle, sustained multiple fractures, including neck of femur and four ribs.

Table 18.
SUVs in single vehicle rollover casualty crashes by road alignment and initial and final off road excursion

Road Alignment	Initial Off Road Excursion on:		Final Off Road Excursion on:	
	Left	Right	Left	Right
Straight	2 (1)[1]	1 (1)	1	-
Right curve	1 (1)	-	-	-
Left curve[2]	3 (2)	1	1	1
Total	6 (4)	2 (1)	2	1

Notes: [1] Number in parentheses indicates that the initial was also the final off road excursion
[2] There was one case, not listed here, in which the vehicle rolled on a winding road without leaving the paved roadway

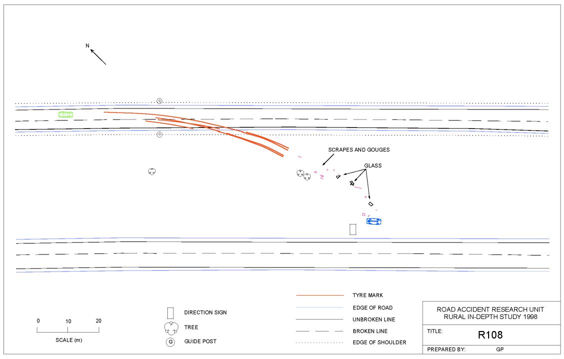

Figure 7. Site diagram showing yaw marks and final position of vehicle.

Figure 8. Yaw marks after leaving the sealed road surface.

Figure 9. 1988 Toyota Land Cruiser in final position (doors cut away by emergency service).

DISCUSSION

The United States New Car Assessment Program (NCAP) rollover resistance rating is primarily based on the Static Stability Factor (measured as a function of the track of the vehicle in relation to the height of its centre of gravity) for the following reason:

> "About 95% of rollovers are tripped - meaning the vehicle struck something low, such as a curb or shallow ditch, causing it to tip over. The Static Stability Factor (SSF) is specifically designed to measure this more common type of rollover and thus plays a significantly larger role in a vehicle's star rating" .... "than the results of the dynamic maneuvering test." (www.safercar.gov)

However, the "dynamic maneuvering test" measures whether a vehicle tips up in a "fishhook" or Road Edge Recovery manoeuvre which, as its name indicates, is very similar to the motion which results from a driver allowing a vehicle to run off onto the unsealed shoulder and swerve abruptly back onto the road, often then overcorrecting back to the left, as was commonly the case in the rollover crashes reviewed here, which occurred mainly on straight roads in the State-wide data.

Furthermore, electronic stability control would appear to have the potential to prevent the loss of control consequent on most of the road edge recovery manoeuvres seen in this study. Eighty per cent of the single car rollover crashes in this in-depth study sample were initiated by the car running at least partially onto the left unsealed shoulder.

Vehicle-based lane deviation detectors may reduce the frequency of such initial off road excursions, at least in those cases where edge lines are provided on the roadway. Similarly, countermeasures such as audio-tactile edge lining and sealing the shoulder could be expected to reduce the frequency of out of lane excursions and the loss of control in those excursions that do occur.

The risk of a casualty crash being a single vehicle rollover increases markedly at higher travelling speeds, as indicated by the speed limit of the road on which the crash occurred. This adds strong support to the case for reductions in the higher speed limits in rural areas in Australia and elsewhere.

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