UNPRECEDENTED VEHICLE AND TRAFFIC SAFETY INTEGRATING V2X COMMUNICATION

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ABSTRACT

Networking of active and passive safety systems is the fundamental basis for comprehensive vehicle safety. Situation-relevant information relating to driver reactions, vehicle behavior and nearfield traffic environment are fed into a crash probability calculator, which continually assesses the current crash risk and intervenes when necessary with appropriate measures to avoid a crash and reduce potential injuries. Know-how in the fields of active and passive safety, beam and image vehicle surrounding sensors, and innovative driver assistance systems provide effective protection not only for vehicle occupants but also for other, vulnerable road users. This functionality up till now only relates to the ego- vehicle itself. The next logical step is to integrate V2X communication. The integration of this embedded, in-vehicle wireless communication system allows Car-to-Car (C2C) and Car-to-Infrastructure (C2I) functionality for, e.g. time critical hazard warning. This comprehensive focus on creating cars that avoid crashes, prevent injuries and provide immediate assistance information should a crash prove unavoidable is an integral element of cascaded ContiGuard® protection measures.

INTRODUCTION

Besides the CO_2 discussion, which currently dominates vehicle specifications, the improvement of driving and traffic safety is the second global trend alongside the enhancement of individual mobility in emerging economies and the trend towards comprehensive information networking on the way to the „always on" information society (Figure 1).

In vehicle safety systems it is still common practice to develop passive systems – which help mitigate crash-related injuries – as autonomous units, in a separate process from the development of active safety systems that help avoid crashes. The first decisive improvements in vehicle safety came in the mid-1960s with the introduction of the safety passenger cell, the three-point seat belt, and the optimized crumple zone – all focused on passive safety. With increasing numbers of ABS systems as standard equipment in the late 1980s, the foundations for active electronic safety systems (preventing the accident from happening) were laid.

Figure 1. Automotive Megatrends

Just how effective the networking of active vehicle safety systems can be, was first demonstrated in a primary phase in 2000, through the Reduced Stopping Distance (RSD) project. In what was called the "30-meter car", the tires, air springs, variable dampers and electro-hydraulic brakes were linked to form an optimized overall system. As a result, the car's braking distance from an initial speed of 100 kph was cut from 39 meters to 30 meters, and the total stopping distance was reduced by up to 13 meters, compared in each case with a standard production model car.

Since then, important electronically controlled systems in both the active and passive safety areas have become standard specification in a broad-based vehicle population, systems such as ABS, ESC, belt tensioners, and airbags. These are, however, designed as stand-alone systems (Figure 2). Active and passive safety developments have until now remained two separate domains.

Figure 2. Fundamentals of Safety

In order to attain optimum protection, however, these systems must be networked by collecting information on vehicle behavior, vehicle environment, and driver reactions, merging the data, evaluating it, and translating it into coordinated protection measures.

Today, for example, Continental's know-how in the fields of active and passive safety, beam and image sensors, innovative driver assistance systems, and tire technology is being channeled into the company-wide ContiGuard® integrated safety concept, in order to achieve a decisive step closer to vision zero, the vision of a traffic without fatalities and severe accidents.

INTEGRATING ACTIVE AND PASSIVE SAFETY

ContiGuard® brings together the vehicle's active and passive safety systems to form a network. The basic principle is the networking of the driving dynamics data supplied by the Electronic Stability Control ESC with signals describing the driver's behavior and surrounding sensors.

The key integration component is the crash probability calculator, which constantly processes and evaluates incoming data. For any given situation, the calculator computes a hazard potential that reflects the current crash probability.

Should the hazard potential exceed defined limits, the crash probability calculator initiates a function and time staged protection strategy (Figure 3). If, for example, two vehicles are driving nose to tail, various levels of crash probability and pre-crash protection measures can be determined from their relative speeds and the distance between them. Beginning with an acoustic, visual or haptic warning, these can extend from prophylactic (reversible) seatbelt pre-tensioning, adjustment of seat (anti-submarining), backrests and head restraints, to closing the windows and sunroof.

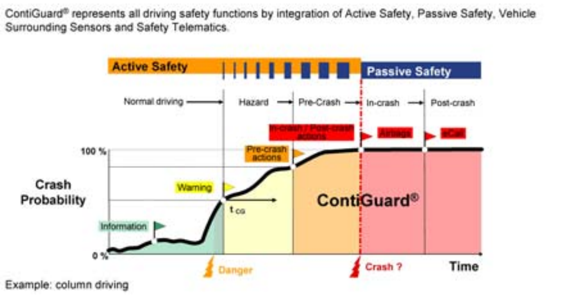

Figure 3. ContiGuard® – Continentals Comprehensive Driving Safety System

Simultaneously, the brake system is preconditioned by boosting the system pressure from pre-fill all the way to limited automatic pre-braking and extended brake assist function.

The full range of measures described above is only available if the vehicle is equipped with a full-power brake system including Electronic Stability Control (ESC) designed to accept external control signals and distance monitoring sensors such as those featured in Adaptive Cruise Control (ACC) systems.

Sophisticated anti-lock brake systems with brake assist functions and adaptive cruise control systems give the driver greater and more comfortable control over the forward dynamics of the vehicle. Modern stability management systems such as ESC can now prevent many skid-related crashes. In addition, electronic control units for airbags, seat belts and rollover protection have significantly improved occupant protection over the last few years.

Advanced surrounding sensors will play a key role in the development of the car of the future designed to prevent crashes and mitigate injuries. New to the market is the development of a pre-crash Closing Velocity (CV) sensor. This highly dynamic sensor, which features a wide short-distance detection range, is ideal for detecting relevant objects very close to the vehicle and enables robust predictions of the severity and direction of an impending crash. This information enables the crash probability calculator to e.g. activate the multi-stage Smart Airbags appropriately or to apply the brakes autonomously. Apart from improving occupant protection, the CV sensor in combination with additional contact sensors mounted on the front end of the vehicle can also serve to enhance pedestrian protection (Figure 4).

Figure 4. Emergency Brake Assist - City (EBA-City)

Additionally radar based beam sensors are being further developed to cover a wider object detection range. The ARS300 sensor has the potential to cover both the mid-range and far-range environment, so that active safety systems (preconditioning of the brake system, extended Brake Assist, …) and passive safety systems (reversible occupant positioning and retention, vehicle interior preconditioning, Smart Airbags, …) can be realized.

Another step towards greater safety will occur with the sensor fusion of the before mentioned radar-based beam sensors with image-processing camera systems which are already available in the market e.g. to detect the driving lane ahead as in Lane Departure Warning (LDW). Networking these technologies will, for the first time, not only detect objects on the road but also classify them. The appropriate safety systems for a given situation can then be activated even more effectively, providing optimum protection for vehicle occupants and other road users.

TELEMATIC COMMUNICATION

The "seeing" car of the future will feature onboard intelligence, data interchange with other vehicles, and telematics information, allowing it to actively avoid a large proportion of potential crashes.

With comprehensive vehicle safety and traffic management becoming more and more critical aspects of global mobility, the essential cornerstone Telematics will play an important role in efforts to integrate embedded, in-vehicle wireless communication systems into ContiGuard®, which focuses on creating cars that avoid crashes, prevent injuries and provide immediate assistance if a crash proves unavoidable.

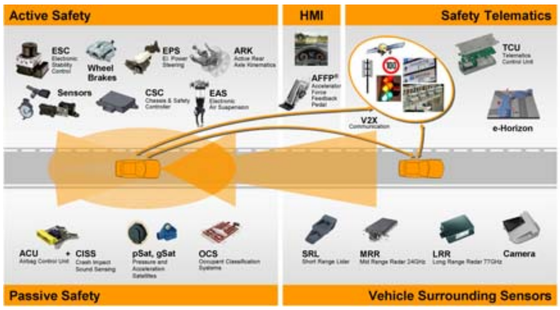

Figure 5. The Five Cornerstones of Comprehensive Vehicle Safety

Figure 5 shows the five cornerstones and elements of the modular comprehensive ContiGuard® safety toolbox.

Safety Telematics – eCall

Today, Continental's Safety Telematics systems help to make cars safer and provide a "wireless life-line" to emergency assistance the critical seconds after a crash occurs. In case of an accident, the eCall Telematics Control Unit (TCU) in the car will transmit an emergency call that is automatically directed to the nearest emergency service. eCall can be triggered in two ways. Manually operated, the voice call enables the vehicle occupants to communicate with the trained eCall operator. At the same time, a minimum set of data will be sent to the eCall operator receiving the voice call.

In case of a severe accident the information on deployment of e.g. airbags or in-vehicle sensors will initiate an automatic emergency call (Figure 6).

Figure 6. eCall – Rescue Chain

When activated, the in vehicle eCall device will establish an emergency call carrying both voice and data directly to the nearest emergency services (normally the nearest 112 Public Safety Answering Point, PSAP).

The life-saving feature of eCall is the accurate information it provides on the location of the accident site: the emergency services are notified immediately, and they know exactly where to go. This results in a drastic reduction in the rescue time.

Estimations for eCall carried within the E-MERGE project and the SEiSS study indicate that in the European Union up to 2.500 lives would be saved per year, with up to 15 % reduction in the severity of injuries.

Integrating V2X Communication

Under development is Dedicated Short Range Communication (DSRC) for vehicles, which allows receiving of traffic and warning information directly from other cars, even those not visible to today's surrounding sensors. Examples for DSRC applications are shown in the following. (Fig. 7 to 10)

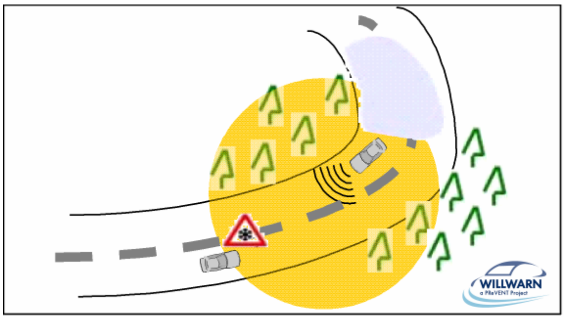

Figure 7. Hazard Warning

<u>Hazard Warning</u> - The driver is warned if his vehicle approaches a potentially hazardous situation on the road ahead. Hazards can be construction zones, breakdown situations, accidents, end of traffic jams, imminent forward collision, black ice, etc.

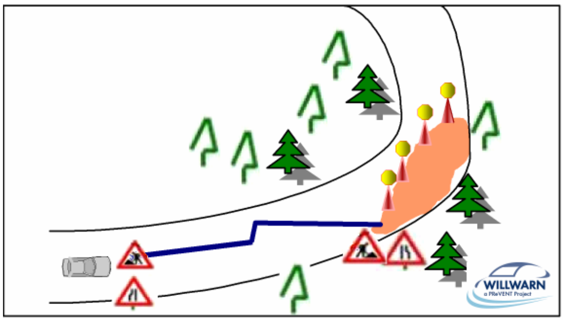

Figure 8. In Vehicle Signing

<u>In Vehicle Signing</u> - Display or announcement of localized traffic sign information such as speed limits, temporary right of way changes, traffic routing, etc. It is of particular relevance for, but not limited to, dynamic information.

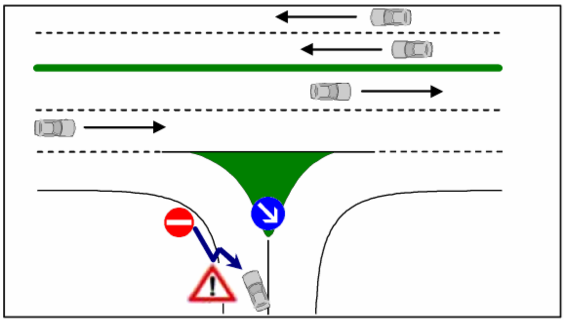

Figure 9. Traffic Rule Violation Warning

<u>Traffic Rule Violation Warning</u> - The driver is warned if he is about to violate a traffic rule. This includes traffic signal violations, stop sign violations, right-of-way violation and cross-traffic collision avoidance, etc. It is of particular relevance for, but not limited to, dynamic traffic sign information.

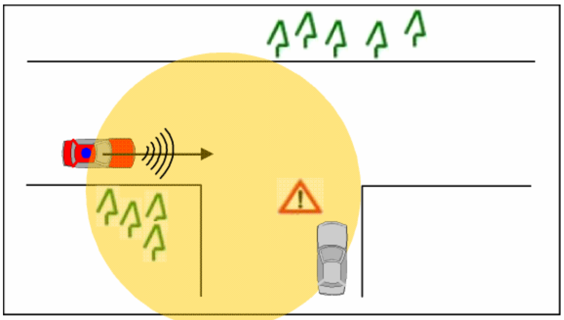

Figure 10. Emergency Vehicle Warning

<u>Emergency Vehicle Warning</u> - The driver is warned of approaching emergency vehicles which claim the right of way.

Shadowing by other vehicles, as with beam or image sensors, will be less of a problem and therefore further increase the range achieved in typical driving situations. In addition, information from the infrastructure can be provided, such as traffic light status, position of road works, local weather information, etc. DSRC will reduce the driving risk by providing local hazard warnings and bring active safety to a new dimension.

Combining DSRC and surrounding sensors will lead to cascaded information and actions resulting in a system capable of providing a safe driving state, helping to prevent crashes and in case needed, reduce the severity of a crash. Therefore, the information from DSRC is taken into account first, validated via surrounding sensors and accordingly supported by actions such as provided by ESC systems.

Connectivity

On the comfort side this next generation of telematics systems will soon offer the motorist even greater freedom at the wheel. Any portable device connected to the vehicle by Bluetooth or USB can be operated either by voice command or from the controls in the steering wheel or instrument panel. In addition, new telematics systems use wireless connectivity to load address books from the cell phone into the car; they can read out incoming short messages and support personalized ring tones and stored speed dialing numbers. An optional, integral telephone module allows both internet access and service and assistance functions, including automatic emergency calls.

CONCLUSION

Today's vehicles have already reached a high safety standard thanks to current, state of the art technologies such as Airbags and the Electronic Stability Control System ESC. Networked active and passive safety is in the market and is already being equipped to premium class vehicles and in the future be enhanced by telematics – in this case by eCall. But telematics also offers possibilities for safety related vehicle communication in the future, namely V2X. The information cascade for safety systems improves the range of, for example, ContiGuard®.

Cascading starts with DSRC, is validated by surrounding beam and/or image sensors and the performed actions are supported by electronically controlled safety systems e.g. ESC and/or intelligent restraint systems.

Connected Safety Telematics offers comprehensive traffic safety and can be combined with service providers with the aim to provide intelligent mobility.

Furthermore, Continental will participate within a four-year, practical field test for Safe Intelligent Mobility (SIM-TD). The purpose of this project, which will be staged in the Rhine-Main region around Frankfort in Germany, is to equip and network vehicles and the transport infrastructure with communication units. By means of car communication units (CCU) and road side units (RSU), relevant information can improve traffic efficiency and road safety by utilizing innovative telematics technology: hazard warnings can be exchanged directly between the participating vehicles, for example. These automatically detect critical road conditions by means of the on-board sensors. The same applies in the case of accidents. The real-time information is supplied to nearby vehicles, warning them, for example, about accidents, icy roads or traffic jams which normally cannot be detected in time by approaching vehicles.

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USING DEDICATED SHORT RANGE COMMUNICATIONS FOR VEHICLE SAFETY APPLICATIONS – THE NEXT GENERATION OF COLLISION AVOIDANCE

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ABSTRACT

This paper provides the status of the Vehicle Safety Communications-Applications (VSC-A) research project, which was designed to determine if dedicated short range communications (DSRC) paired with accurate vehicle positioning can improve upon autonomous vehicle-based safety systems or enable new communication-based safety applications. This three-year project is a collaborative effort between government and industry to develop the underlying pre-competitive elements needed to enable the deployment of vehicle-to-vehicle (V2V) communication-based crash avoidance applications. The effort includes the development of core software and hardware modules and prototype applications. These use DSRC in conjunction with enhancements to vehicle positioning systems to demonstrate crash avoidance capabilities, which are interoperable between different vehicle manufacturers. To support the development of interoperable systems, the partners have participated in standards and security protocol development activities. The core modules and prototype applications are implemented on a five-vehicle testbed fleet, which will be used to conduct objective tests that are then used to validate minimum performance specifications established as part of this project. These tests will in turn support a safety benefits estimation process to determine the potential for preventing or mitigating crashes and associated fatalities, injuries, and property damage.

BACKGROUND

In 1999[1], the US Federal Communications Commission (FCC) allocated wireless spectrum in the 5.9 GHz frequency range for use by DSRC systems supporting Intelligent Transportation Systems. One of the goals in establishing this DSRC capability was to improve traveler safety by supporting the development of vehicle safety applications. In 2006[2], the FCC further refined the rules for DSRC to explicitly consider "vehicle-to-vehicle collision avoidance and mitigation," reflecting the results of research experience. As a result, DSRC is enabling the development of these next-generation communications-based vehicle safety systems in the VSC-A initiative.

The VSC-A project builds upon the results of the first Vehicle Safety Communications (VSC) project(1), conducted from 2002 to 2005 through collaboration between the National Highway Traffic Safety Administration (NHTSA) and automakers in the Crash Avoidance Metrics Partnership[3] (CAMP) Vehicle Safety Communications Consortium consisting of seven automotive original equipment manufacturers (OEMs). Working together, they investigated the potential of V2V and vehicle-to-infrastructure communications as a means of improving crash prevention performance.

Building upon the success of the VSC project, the CAMP Vehicle Safety Communications 2 Consortium (Ford, General Motors, Honda, Mercedes-Benz, and Toyota) and NHTSA are now engaged in the final year of a 3-year cooperative agreement to conduct enabling research to support

[1] FCC Report and Order 99-305, adopted October 21, 1999.

[2] FCC Memorandum Opinion and Order 06-100, adopted July 20, 2006.

[3] The Ford Motor Company and General Motors Corporation formed the Crash Avoidance Metrics Partnership (CAMP) in 1995. The objective of the partnership is to accelerate the implementation of crash avoidance countermeasures to improve traffic safety by defining and developing necessary pre-competitive enabling elements of future systems. CAMP provides a flexible mechanism to facilitate interaction among additional participants as well, such as the US DOT and other OEMs, in order to execute cooperative research projects.

pre-competitive system development and demonstrate the performance of V2V communications-based safety applications. The VSC-A project aims to develop and test the system components that are required before automotive OEMs can develop and deploy production systems.

CRASH SCENARIO IDENTIFICATION

Figure 1 gives the distribution of the 6.2 million crashes reported in 2004 via NHTSA's General Estimate System (GES) (2). Classification of crashes is by the GES variable "Manner of Collision." While radars have a limited FOV (field of view) for detecting potential collisions, V2V communications and GPS receivers enable a 360 degree FOV. Thus, rear-end, head-on, angle, and sideswipe crashes are all relevant to V2V applications. Angle and sideswipe crashes would also include intersection related crashes. Crashes classified as "not collision with motor vehicle in transport" represents road departure crashes that are not relevant to the VSC applications. Based on this classification, the V2V applications discussed above are applicable to approximately 66% or 4 million crashes annually.

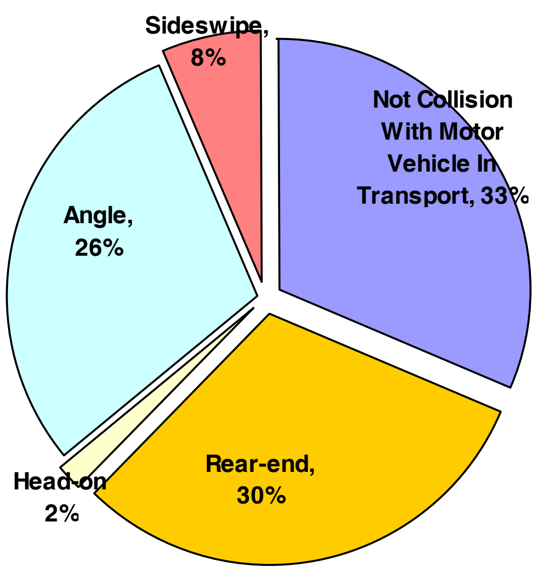

Figure 1, Crash problem classified by manner of collision, 2004 GES.

To focus the development efforts, the U.S. DOT provided the VSC-A team with crash scenarios to serve as a starting point for analysis and as a reference for the selection of the set of safety applications for study under the VSC-A project. The U.S. DOT, with support from the U.S. DOT's Volpe national transportation Systems Center and Noblis, evaluated eight pre-crash scenarios in order to provide high potential benefit crash imminent safety scenarios for study. The crash scenarios chosen were based on:

- Crash rankings by frequency;
- Crash rankings by cost;
- Crash rankings by functional years lost[4]; and
- A composite crash rankings (based on the above three ranks)

The 2004 GES crash database is the basis for the set of crash scenarios. The evaluation also indicated which system type (autonomous, V2V, or both) addresses, or could address, the different crash scenarios presented.

From the composite ranking of crash imminent scenarios , the top five crash scenarios, ranked based on crash frequency, crash cost, and functional years lost, that could be addressed by V2V safety applications, were selected. This ranking allowed the team to focus on the most frequent, highest cost, and most damaging crashes, while keeping the program scope to a manageable level. Table 1 contains the final set of crash imminent scenarios, as agreed between the VSC-A team and U.S. DOT, to be targeted under the VSC-A project

	Crash Imminent Scenario	High Freq	High Cost	High Years

[4] 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 (3)

1	Lead Vehicle Stopped	✓	✓	✓
2	Control Loss Without Prior Vehicle Action[5]	✓	✓	✓
3	Vehicle(s) Turning at Non-Signalized Junctions	✓	✓	
4	Straight Crossing Paths at Non-Signalized Junctions			✓
5	Lead Vehicle Decelerating	✓	✓	
6	Vehicle(s) Not Making a Maneuver – Opposite Direction			✓
7	Vehicle(s) Changing Lanes – Same Direction	✓		
8	LTAP/OD at Non-Signalized Junctions			

A "✓" Denotes a Top Five Ranking in each category

Table 1 Crash Imminent Scenarios

VSC-A OBJECTIVES

To address the goal of the VSC-A program, the program has the following objectives, broken out into two parts: 1) Technology development and 2) Benefits assessment activities:

Technology development objectives:

1. Develop scalable, common vehicle safety communication architecture, protocols, and messaging framework (interfaces) necessary to achieve interoperability and cohesiveness among different vehicle manufacturers. Standardize this messaging framework and the communication protocols (including message sets) to facilitate future deployment.

2. 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.

3. Define a set of DSRC + Positioning-based vehicle safety applications and application specifications including minimum system performance requirements.

Benefit assessment activities objectives:

1. Assess how previously identified crash-imminent safety scenarios in autonomous systems could be addressed and improved by DSRC + Positioning systems.

2. Develop a well understood and agreed upon benefits, with respect to market penetration, analysis, and potential deployment models, and crash reduction and mitigation for a selected set of communication-based vehicle safety applications.

3. Develop and verify a set of objective test procedures for the vehicle safety communications applications.

VSC-A PROGRAM

To achieve the goals outlined in the introduction, the VSC-A program is organized as follows:

- Technology Development
- Performance Specifications Development
- Safety Benefits Estimation

Technology Development

The U.S. DOT has conducted extensive research on the effectiveness of autonomous vehicle-based collision countermeasures for rear-end, road departure, and lane change crashes(4, 5, 6, 7, 8). Field operational tests of rear-end and road departure collision warning systems have shown measurable benefits in reduction of crashes. However, the systems have inherent shortcomings that reduce their effectiveness and limit driver acceptance. These shortcomings include misidentification of stopped vehicles and other in-path obstacles for rear-end collision warning systems, as well as map errors , misidentified lane markings, and limited availability for road departure crash warning systems.

A VSC-A equipped vehicle uses DSRC, in conjunction with vehicle positioning information, to broadcast its location, travel path, and status (e.g. braking, etc.). By using wireless communications, VSC-A has the potential to prevent vehicle crashes in

[5] The control loss cases being addressed by vehicle to vehicle communications are those in which a vehicle that begins to experience control loss (e.g. slippery conditions- detected using ABS or stability control) broadcasts a message to other vehicles. The first (transmitting) vehicle does not need to crash for this warning to be transmitted.

situations where an autonomous vehicle safety system may have difficulties. For example, if a braking vehicle on a curve falls outside the coverage area of an autonomous radar-based system, a wireless message could still relay information to a following vehicle so that it would recognize the need to stop. As part of this project, CAMP has investigated specific scenarios in which communications-based safety systems may be more effective than autonomous systems.

V2V wireless communications, paired with accurate vehicle positioning, may truly overcome these shortcomings and thus enable improved safety system effectiveness by complementing or, in some instances, providing alternative approaches to autonomous safety equipment.

To access the performance of the scenarios identified above a test program was proposed. Implementing this test program requires that CAMP build a fleet of test vehicles. The testbed fleet consists of five different vehicles (a 2007 Ford Flex, a 2005 GM Cadillac STS Sedan, a 2006 Honda Acura RL, a 2006 Mercedes-Benz ML 350, and a 2006 Toyota Prius). Each participating OEM will build a vehicle, and each is equipped with identical VSC-A system components. The major technology components developed and installed in each vehicle include:

- A DSRC Radio – the DSRC radio transmits and receives messages to/from other vehicles
- A Global Positioning Satellite (GPS) Receiver – the GPS receiver provides real-time location information for the host vehicle
- An Interface for each Specific Vehicle – the interface provides a common connection to permit access to information on the internal vehicle bus of the host vehicle
- On-Board Equipment – this hosts the system core software modules and the prototype applications

The system core modules provide the supporting capabilities that enable the applications to function. They include path history, host vehicle path prediction, target classification, wireless message handler, and threat arbitration. These modules receive messages from other vehicles, store and process relevant information to determine threats, and monitor host-vehicle location and actions and transmit messages to other vehicles, enabling them to do the same.

DSRC + Positioning

This stage of the program is concerned with the development of accurate, and affordable, vehicle positioning. DSRC provides the wireless communications system supporting V2V communications for the safety applications. Under VSC-A, an equipped vehicle will be able to keep track of surrounding vehicles and the potential threat they pose by receiving periodic wireless messages. For a vehicle to determine the potential threats posed by other vehicles, it needs to know the relative position of surrounding vehicles and other relevant information such as braking status from those vehicles. The relative position can be determined using knowledge of a vehicle's own position in conjunction with the other vehicle's broadcasted position information. The core modules developed for the VSC-A testbed support the necessary processing and tracking for both transmission of messages to other vehicles and receipt and processing of other vehicles' messages.

The positioning information necessary to support the applications requires sufficient precision to support lane-level positioning so that other vehicles posing a potential threat could be classified by lane.

The VSC-A team investigated existing GPS-based systems used in high accuracy relative-positioning applications. Based on results from the CICAS-V[6](9) lane-level positioning system implementation, and results from an expert workshop on existing technologies, appropriate relative positioning methods were identified for further evaluation(10). The interface definition of the relative positioning system was defined so that different relative positioning implementations can be used in the testbed without changing the over-the-air message format.

Interoperability / Standards

Without standardization, different vehicles cannot communicate properly with other vehicles, and an interoperable solution involving different manufacturers would be impossible. To this end, CAMP is focused on the development of scalable, common communications architecture. Thus, an important goal of the VSC-A project is the standardization of the message sets, message composition approach, and communication protocols

[6] CICAS-V stands for Cooperative Intersection Collision Avoidance System - Violation

for DSRC-based vehicle safety. To achieve this goal, the VSC-A standards working group developed a standards support plan in February 2007 (10). This plan outlines the current standards landscape. The plan also provides a guideline by which the VSC-A standards working group will coordinate their interactions between the various task activities and results and the identified relevant Standard Development Organizations activities.

As part of the short-term standards support activities highlighted in the plan, the VSC-A team has substantially increased OEM participation under the Society of Automotive Engineers (SAE) DSRC Technical Committee. The following standards were impacted as a result:

- SAE J2735, which specifies message sets, data frames and elements to permit interoperability at the application layer. This supports development of different applications that can rely upon the same standard message set elements.

- Institute of Electrical and Electronic Engineers (IEEE) 802.11p standard, which is similar to 802.11g used for home wireless networks, covers the lower layer communications standards that enable low-latency wireless communications critical for vehicle-based safety communications.

- The IEEE 1609.x Family of Standards for Wireless Access in Vehicular Environments (WAVE) defines the architecture, communications model, management structure, security mechanisms, and physical access for wireless communications in the vehicular environment. WAVE is a mode of operations for use by 802.11p compliant devices that enable low latency communication exchanges.

The VSC-A team will continue active participation to guide these developing standards based on the output of the work being performed under the VSC-A project.

<u>Security</u>

In order for communications-based vehicle safety systems to be deployed, the systems must implement security protocols and capabilities ensuring that drivers are given warnings based only on authentic threats, and that drivers' privacy is protected. Within the VSC-A project, the security task is focused primarily on message authentication while preserving driver/owner privacy, controlling bandwidth overhead, processing requirements, and latency.

Working with a consulting security expert, a VSC-A threat model document was developed which considers privacy vs. revocation, certificate distribution and revocation, and computational and bandwidth requirements. Threats to privacy were identified as a major priority. Several candidate security protocols for broadcast authentication and privacy protection were also developed and subjected to a preliminary evaluation. In addition, development includes the definition of over-the-air security message formats and initial efforts to interface the security module with the rest of the testbed system.

<u>Prototype Applications</u>

The VSC-A project is prototyping six distinct applications intended to address different crash scenarios (see Table 1). However, the project does not focus on production-ready applications, only prototype applications to demonstrate and evaluate system capabilities. The applications, and a brief description of each, follow:

A. Emergency Electronic Brake Light (EEBL) - The EEBL application enables a host vehicle to broadcast a self-generated emergency brake event to surrounding remote vehicles. Upon receiving such event information, the remote vehicle determines the relevance of the event and, if necessary, warns the driver. This application is particularly useful when the driver's line of sight is obstructed by other vehicles or bad weather conditions - fog, heavy rain, for example.

B. Forward-collision warning (FCW) - The FCW application warns the driver of the host vehicle of an impending rear-end collision with a remote vehicle ahead in traffic in the same lane and direction of travel. FCW is intended to help drivers avoid or mitigate rear-end vehicle collisions in the forward path of travel.

C. Intersection-Movement Assist (IMA) - The IMA application is intended to warn the driver of a host vehicle when it is not safe to enter an intersection due to high collision probability with other remote vehicles.

D. Blind-Spot Warning (BSW) + Lane-Change Warning (LCW) - During a lane-change attempt, the BSW + LCW application warns the driver of the host vehicle if the zone into which the host vehicle intends to switch is, or will soon be, occupied by another vehicle traveling in the same direction. Moreover, when a lane change is not being attempted, the application informs the driver of the host vehicle when a vehicle in an adjacent lane is positioned in a host vehicle's blind-spot zone.

E. Do-not-pass warning (DNPW) - When the host-vehicle driver attempts to pass a slower vehicle, the DNPW application issues a warning when the passing zone is occupied by a vehicle traveling in the opposite direction. In addition, even when a passing maneuver is not being attempted, the application informs the host-vehicle driver of the host vehicle that the passing zone is occupied .

F. Control-loss warning (CLW) - The CLW application enables a host vehicle to broadcast a self-generated control loss event to surrounding remote vehicles. Upon receiving such event information, the remote vehicle determines the relevance of the event and, if necessary, provides a warning to the driver.

These applications have been prototyped in the testbed and the OEMs have begun testing their performance under a variety of controlled conditions. Table 2 shows the relationship between the crash types and applications.

		SAFETY APPLICATIONS					
		A	B	C	D	E	F
CRASH TYPES	**Lead Vehicle Stopped**	✓	✓				
	Lead Vehicle Decelerating	✓	✓				
	Vehicle(s) Turning at Non-Signalized Junctions			✓			
	Straight Crossing Paths at Non-Signalized Junctions			✓			
	Vehicle(s) changing lanes – same direction				✓		
	Vehicle(s) Not Making a Maneuver – Opposite Direction					✓	
	Control Loss Without Prior Vehicle Action						✓

Table 2: Crash Types vs. Safety Applications

Performance Specifications Development
The VSC-A project also includes the development of performance specifications for each of the prototype applications. These specifications represent the minimum performance that an application must satisfy in order to achieve basic crash avoidance capability. It is expected that application developers will go beyond these minimum specifications when production systems are developed. However, a common basis established by minimum performance criteria can be used to test application performance across different vehicles and application developers.

The project also includes the development and execution of objective tests. These tests will verify system performance at the prototype stage. The tests will include specific procedures based on the minimum performance specifications developed and will result in objective measures of how well the prototype satisfies the criteria under specific test conditions. Since the VSC-A system is not yet at the stage of a field operational test, the objective test plan will attempt to capture how well the prototype applications and underlying core modules developed in this project achieve the crash avoidance capabilities in a variety of scenarios. These scenarios are selected based on the particular application, and since the tests are intended to capture prototype performance, they will not include evaluation of the driver-vehicle interface performance.

Safety Benefits Estimation
The Volpe Center is leading the effort to estimate safety benefits associated with deployment of safety applications within the VSC-A project. To determine the safety benefits of this new technology the Center will implement a benefits equation for the estimation of number of crashes prevented by the V2V countermeasure, and provide extensions for estimation of impact on level of injury. Although there are many formulations, they all are based on the fundamental definition of benefits (11):

$$B = N_{WO} - N_W \qquad (1)$$

Where,

B = benefits, (which can be the number of crashes, number of fatalities, "harm," or other such measures).

N_{wo} = value of this measure, (for example, number of crashes) that occurs *__without__* the system.

N_w = value of the measure *with* the system fully deployed.

The value of N_{wo} is usually known from crash data files, but N_w is not known for pre-production. Thus, it is necessary to estimate the effectiveness of a countermeasure and combine it with the known value of N_{wo}, as shown in the following equation:

$$B = N_{WO} \times SE \quad (2)$$

Where,

SE = effectiveness of the system, and

N_{wo} = baseline number of crashes.

An extension of this idea is that the overall benefits consist of the sum of benefits across a number of specific scenarios:

$$B = \sum_i N_{WO_i} \times E_i \quad (3)$$

Where,

"i" = individual scenarios.

E_i = effectiveness of the system in reducing the number of crashes in a specific crash-related scenario

N_{woi} = baseline number of crashes in individual scenario "i"

B_i = the benefits in each of the individual scenarios.

This safety benefits estimation effort will incorporate the results from objective tests conducted in the coming year and use NHTSA crash databases to determine the crashes scenarios likely to be avoided by each VSC-A application. In support of this process, Noblis is developing a market penetration model to capture the impact of deployment of the system over time. The results of the safety benefits estimation will utilize the best available information to guide further development and deployment.

FUTURE ACTIVITIES

During the final year of the project, objective tests will be run to evaluate the prototype's performance, support estimation of safety benefits, and guide future development.

SUMMARY

This paper provided the status of research on the use of V2V communications and relative positioning for crash avoidance applications. The VSC-A project has made considerable progress in developing the key components necessary for interoperable crash avoidance applications. Project activities have focused on two major areas:

Technology development objectives:

1. Develop scalable, common vehicle safety communication architecture, protocols, and messaging framework (interfaces) necessary to achieve interoperability and cohesiveness among different vehicle manufacturers.

2. Develop accurate and affordable vehicle-positioning technology

3. Define set of DSRC + Positioning-based vehicle safety applications and application specifications.

Benefit assessment objectives:

1. Assess how previously identified crash-imminent safety scenarios in autonomous systems could be addressed and improved by DSRC + Positioning systems.

2. Develop a well understood and agreed upon benefits, with respect to market penetration, analysis, for a selected set of communication-based vehicle safety applications.

3. Develop and verify a set of objective test procedures.

Coordination and support with other programs / organizations has also taken place.

The system concept and prototype described in this paper has already experienced substantial development in the form of testbed fleet with functioning system core modules and six prototype applications.

ACKNOWLEDGEMENTS
Our special thanks to Farid Ahmed-Zaid of Ford Motor Company, the project's Principal Investigator, for his insight and support of this work.

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COOPERATIVE INTERSECTION COLLISION AVOIDANCE SYSTEM FOR VIOLATIONS (CICAS-V) FOR AVOIDANCE OF VIOLATION-BASED INTERSECTION CRASHES

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ABSTRACT

Intersection crashes account for 1.72 million crashes per year in the United States. In 2004 stop-sign and traffic signal violations accounted for approximately 302,000 crashes resulting in 163,000 functional life-years lost and $7.9 billion of economic loss [1]. The objective of the Cooperative Intersection Collision Avoidance System for Violations (CICAS-V) project was to design, develop, and test a prototype system to prevent crashes by predicting stop-sign and signal-controlled intersection violations and warning the violating driver. The intersection portion of the system consists of a signal controller capable of exporting signal phase and timing information, a local global positioning system (GPS), and Roadside Equipment (RSE) that includes computing, memory, and Dedicated Short Range Communication (DSRC) radio. The vehicle portion of the system includes on-board equipment for computing and 5.9 GHz DSRC radio connected to the vehicle controller area network (CAN), positioning, and the Driver-Vehicle Interface (DVI). The intersection sends the signal phase and timing, positioning corrections, and a small map (< 1 kb) to the vehicle. The vehicle receives this information and, based on speed and distance to the stop location, predicts whether or not the driver will violate. If a violation is predicted, the driver is warned via a visual/auditory/haptic brake pulse DVI. The system was installed in the vehicles of five Original Equipment Manufacturers (OEMs): Daimler, Ford, General Motors, Honda, and Toyota. Intersections were equipped in California, Michigan, and Virginia. Tests of the system included both on-road and test-track evaluations. System performance was excellent and recommendations were made for continuing with a large field operational test (FOT). The system can be installed at any intersection with sufficient positioning coverage and in any vehicle with an electronic stability system. This system constitutes the first FOT-ready Vehicle Infrastructure Integration safety application

INTRODUCTION

Intersection crashes account for 1.72 million crashes per year in the United States. In 2004 stop sign and traffic signal violations accounted for approximately 302,000 crashes resulting in 163,000 functional life years lost and $7.9 billion of economic loss (National Highway Traffic Safety Administration, 2006). The objective of the Cooperative Intersection Collision Avoidance System for Violations (CICAS-V) project was to design, develop, and test a prototype system to prevent crashes by predicting stop-sign and signal-controlled intersection violations and warning the violating driver.

The developed system includes both intersection and vehicle equipment communicating via 5.9 GHz Dedicated Short Range Communication (DSRC). The intersection equipment consists of Road-Side Equipment (RSE), containing a computing system, DSRC radio and a global positioning system (GPS) unit. In signalized intersections, the RSE is connected to the traffic signal controller from which it obtains signal phase and timing information in real-time. The vehicle equipment includes On-Board Equipment (OBE), containing a computing system and a DSRC radio, as well as a GPS unit and a driver-vehicle interface (DVI) to present a timely and salient warning to the driver for whom a violation of a Traffic Control Device (TCD) is predicted.

The system was installed in the vehicles of five Original Equipment Manufacturers (OEMs): Daimler, Ford, General Motors, Honda, and Toyota. The system installed in the GM vehicle contained the full prototype, including the haptic brake pulse in the Driver Vehicle Interface (DVI). The vehicles of the other OEMs had the CICAS-V without the brake pulse. Several intersections in California, Michigan and Virginia, managed through signal controllers from different manufacturers, were instrumented with the CICAS-V equipment and used for testing throughout project execution. The full prototype, i.e. including the full DVI, supported the pilot Field Operational Test (FOT) that concluded phase 1 of the project. Based on the very positive results from this pilot FOT, recommendations were made for continuing with a large scale FOT. The CICAS-V project is a joint effort of the U.S. Department of Transportation (USDOT) and the Vehicle Safety Communications II (VSC-2) Consortium at the Crash Avoidance Metrics Partnership (CAMP).

CONCEPT OF OPERATIONS

The Concept of Operations (ConOps) formed the basis of the system engineering activities and system development. For a signalized intersection, the basic concept of CICAS-V is illustrated at a high level in **Figure 1**. It shows a CICAS-V equipped vehicle approaching a CICAS-V equipped intersection and receiving an over-the-air messages from the local RSE. The information carried in such a message includes:

- Signal Phase and Timing (SPaT) – real-time information of traffic light status
- Geometric Intersection Description (GID) – a digital map of the intersection
- GPS differential corrections (if accurate positioning information is required)
- GIDs of stop-controlled intersections in the vicinity of the RSE (optional)

The driver is issued a warning if the equipment in the vehicle determines that, given current operating conditions, the driver is predicted to violate the signal in a manner which is likely to result in the vehicle entering the intersection. This warning will raise the driver's attention, so that the driver can determine the safest course of action, possibly bringing the vehicle to a safe stop before it enters the intersection crash box. While the system may not prevent all crashes through such warnings, it is expected that, with an effective warning, the number of traffic control device violations will decrease, and result in a significant decrease in the number and severity of crashes at controlled intersections.

The vehicle OBE determines the probability of a violation by continuously reassessing the current distance from the stop bar for the actual lane of travel, the speed of the vehicle, and the current signal phase. If the phase is amber, then the vehicle OBE determines from the time left in phase whether it will pass the stop bar before the onset of the red phase. If the vehicle will cross the stop bar after the light has turned red, given the dynamic conditions of the vehicle, an alert is issued to the driver.

For stop-controlled intersections the vehicle only needs to assess the distance from the stop bar, based on the current vehicle and stop bar locations, and the vehicle operating conditions.

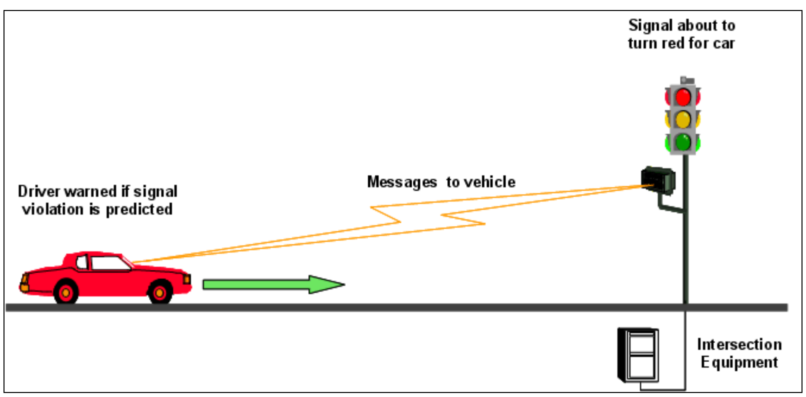

Figure 1: Basic concept of the CICAS-V system at a signalized intersection.

REQUIRED POSITIONING ACCURACY

For the CICAS-V ConOps to work, it is necessary for the vehicle to position itself with sufficient accuracy along the approach to the intersection. Researchers commonly refer to two levels of positioning accuracy: WhichRoad and WhichLane.

WhichRoad accuracy requires that the combined error of GID and positioning does not exceed 5 m. This level of accuracy is required for CICAS-V at most stop-sign controlled intersections and at signalized intersections with no dedicated turn lanes with their own movement independent of the signal indication of the through movement.
WhichLane accuracy requires that the combined error of GID and positioning does not exceed 1.5 m

(approx ½ lane width) and is necessary for CICAS-V at (mainly signalized) intersections with protected left or right turns where the turn phase differs from the phase for the straight crossing direction.

Throughout the project, it was assumed that, by using GPS differential corrections, it would be possible to achieve a positioning accuracy better than 1 m. To contain the combined GID and positioning error within the required limit, it was thus determined that the accuracy of the GID had to be better then 0.5 m.

GEOMETRIC INTERSECTION DESCRIPTION

The vehicle OBE needs to have a map of the intersection with the necessary accuracy determined by the intersection type. Throughout project execution, no distinctions were made with regard to the GID accuracy for the intersections and all GIDs had the same lane-level accuracy.

The GID has to have the following properties:

- Sufficiently accurate (30 cm for WhichLane) road/lane geometry for all lanes/approach roads;
- Intersection identification, including whether the intersection is stop-sign controlled or signalized;
- Stop bar locations for all lanes;
- An intersection reference point;
- Lane widths for all the lanes;
- Correspondence between lane and traffic signal applying to the lane.

The ConOps did not assume that the vehicle would already have an intersection map stored onboard, thus the requirement that such a map be transmitted from RSE at the intersection to the vehicle through 5.9 GHz DSRC. This imposed a constraint on the size of the GID to be transmitted over the air. The ConOps did not determine how GIDs for stop sign intersections are distributed to the vehicle. An alternative is that they are distributed by nearby RSE.

In order to increase reception probability, the GID needed to fit within a single DSRC Wave Short Message (WSM) packet. The WSM maximum packet size is 1.4 Kbytes as specified in the IEEE 802.11p proposed standard [2,3]. Furthermore, about 400 bytes of this packet are assumed to be used for security payload and are not available for the actual message content. Those constraints led to the design of a small map of about 1 Kbyte to store the GID. The GID specifications developed by the CICAS-V project have been entered in the Society of Automotive Engineers (SAE) J2735 standards process to become a future automotive standard.

In order to minimize the size of the GID, the following design choices were made:

- All geometry points are Cartesian offsets from an intersection reference point that is given in (Latitude, Longitude, and Altitude) coordinates in the WGS 84 system. This means that all the points that are used to describe the geometry are described as distance in decimeters from the intersection reference point (x [decimeters], y [decimeters], z [decimeters]);
- All roads/lanes are described as an ordered set of geometry points together with the lane width at each point;
- The lane geometry is described by specifying the centerline of the lane;
- The stop bar location for each lane is the first geometry point for the lane;
- Lane geometries are represented out to a distance of 300 m from the intersection reference point for approaching lanes (note that GIDs might overlap in some cases);
- Outgoing lanes are optional but can be included, if necessary.

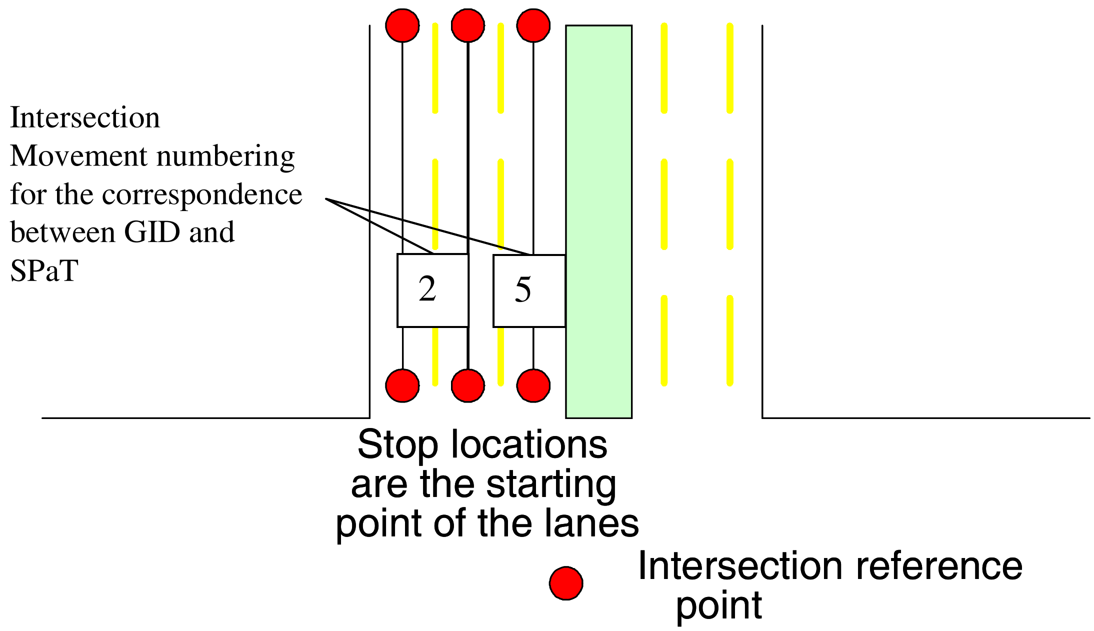

Figure 2: GID elements

The basic element of the GID (**Figure 2**) is a point or "node." Two types of GID nodes are defined: (a) the Intersection Reference Point (IRP), expressed as Latitude, Longitude, and Altitude; and (b) the Nodes that describe the lanes, given as offsets in Cartesian coordinates from the IRP. The set of nodes that describe a lane are collected in the "Node List."

Two kinds of lanes are defined:

- Reference Lane
- Computed Lane

A reference lane is a lane that is fully specified by a list of points. A computed lane is a lane that can be derived from a reference lane by a simple parallel shift of the reference lane. This method reduces the size of the GID message for cases in which several parallel lanes can be grouped into one approach. An approach is defined as all lanes of traffic governed by a single, independent signal phase cycle, moving towards an intersection from one direction. This corresponds to the term "Movement" used by Traffic Engineers.

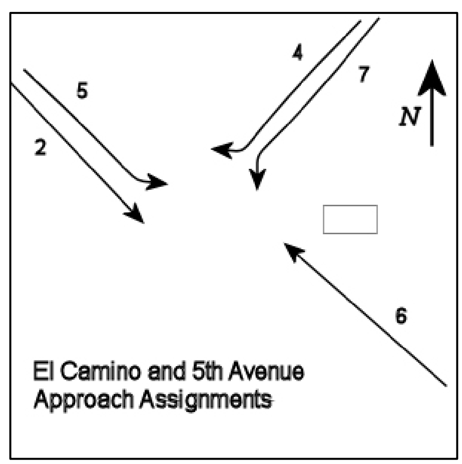

Figure 3: Approaches for the intersection at 5th Ave. and El Camino Real in Atherton, California.

Figure 3 shows the seven approaches to the intersection of 5th Ave. and El Camino Real in Atherton, California. Approach 6 consists of three lanes for which the rightmost lane is wider than the other two due to parking possibilities. Approach 2 contains three lanes and approach 5 contains two lanes. For approach 2 the GID specifies the leftmost through lane as a reference lane and the other two lanes in the approach are represented as computed lanes. The same is true for approach 6 for which the leftmost lane is again specified through a node list and the other two lanes can be specified by the offset from the reference lane.

It should be noted that the computed lane is not a mandatory feature of the GID but a device to minimize the size. In the GID, all lanes can be specified through node lists (as reference lanes) if the size of the GID permits.

The resulting GID is a very compact map of the intersection. For instance, the size of the GID for 5th Ave. and El Camino Real is 352 bytes, while the size of the GID for the most complicated intersection in the project, Franklin and Peppers Ferry in Christiansburg, VA, is 869 bytes.

No commercial maps available today can describe the intersection geometry to the required accuracy level, and some of the required GID attributes such as stop location are similarly missing, therefore, the CICAS-V project had to generate the GIDs.

After looking at several alternatives, aerial surveying was selected as the method to map the intersections. The company chosen to map the intersections was HJW GeoSpatial, Inc. (HJW) in Oakland, California. The CICAS-V project developed specifications for the GID that were transmitted to HJW and HJW then took a high-resolution aerial photograph of the intersections. The resulting image had to be ortho-rectified. Also for this purpose a number of points on the picture were mapped by a surveyor on site. The company took the lane markings on the image to determine the location of the centerline for each lane and delivered the geometry of the lanes as a set of points, as specified. Those points were subsequently converted into the GID message, using a compiler that was specifically developed for CICAS-V.

Figure 4: Aerial view of the Intersection at 5th Ave. and El Camino Real in Atherton, California.

In mapping the intersection, work was conducted to specify the "North" direction accurately as the Geographic North in the WGS 84 Coordinate System. Using the "North" direction in the State Plane Coordinate System or the UTM Coordinate System, which are both used widely to specify geography, will lead to a rotation of the GID with respect to the Ground Truth by an angle that is location dependent. The farther the location of the intersection is away from the central meridian, the larger the angle between UTM north and geographic north. For the mapping of the intersection, this can amount to several meters of discrepancy between the position on the GID and the GPS position that the vehicle receives from the positioning system.

SIGNAL PHASE AND TIMING

The intersection sends controller Signal Phase and Timing (SPaT) information to the vehicle 10 times per second and the vehicle will select the correct signal indication, based on its approach. The SPaT message contains the signal phase indication of the current phase, the time until the next signal phase change and information to correlate the signal indication with the approach for all the approaches in the GID.

As for GIDs, SPaT information is best included in a single DSRC WSM packet. This packet is generated by extracting the data in real-time from the traffic signal controller and formatting it into the SPaT message. Depending on the traffic signal controller hardware and the signal controller protocol, SPaT information is exported directly or some inference via a state machine running on the RSE is necessary to determine the correct phase.

GPS CORRECTIONS

The overarching goal of the CICAS-V positioning and GPS correction generation subsystems is to design and prototype a vehicle positioning system. The purpose is to achieve real-time sub-meter vehicle positioning near CICAS-V intersections for CICAS-V equipped vehicles at relatively low cost while using commercial off-the-shelf hardware.

The prototype design is dependent on the availability of RSE at CICAS-V signalized intersections that have a local GPS base station receiver. This receiver is configured to compute correction factors for the GPS Satellite signals that are needed to make the position result from estimation algorithms match the base station's known (surveyed) fixed location.

This locality of scope contrasts with other popular correction techniques, such as the Wide Area Augmentation System (WAAS) in the U.S, which has ground reference stations spaced approximately 500 miles apart, and, therefore, computes corrections on a regional basis. The field test results conducted to date at real intersections indicate significantly higher real-time vehicle positioning accuracy when compared to the position accuracies obtained through WAAS and Differential Global Positioning System (DGPS) corrections based vehicle positioning systems. For example, at the CICAS-V traffic intersection located in Farmington Hills, Michigan, absolute real-time vehicle positioning errors on the order of less than 0.5m are consistently achieved using the CICAS-V test vehicles.

Figure 5 shows the local DGPS correction generation and broadcast subsystem installed at a traffic point of interest, such as a controlled intersection. The GPS receiver is configured in base-station mode where it computes corrections to GPS satellite signals for other moving (vehicle-mounted) GPS receivers in its vicinity. The correction information is encoded in Radio Technical Commission for Maritime Services (RTCM)-standardized format, such as the RTCM Recommended Standards for Differential GNSS (Global Navigation Satellite Systems) service as defined by the Special Committee (SC) 104 on Differential Global Navigation Satellite Systems (DGNSS). For brevity, the corrections data message format is referred to as either RTCMv3.0 or RTCMv2.3, depending on which SC-104 release of the "Recommended Standards for Differential GNSS" is used. The RTCMv3.0 message format used in the CICAS-V system design consists of single frequency (L1) GPS information.

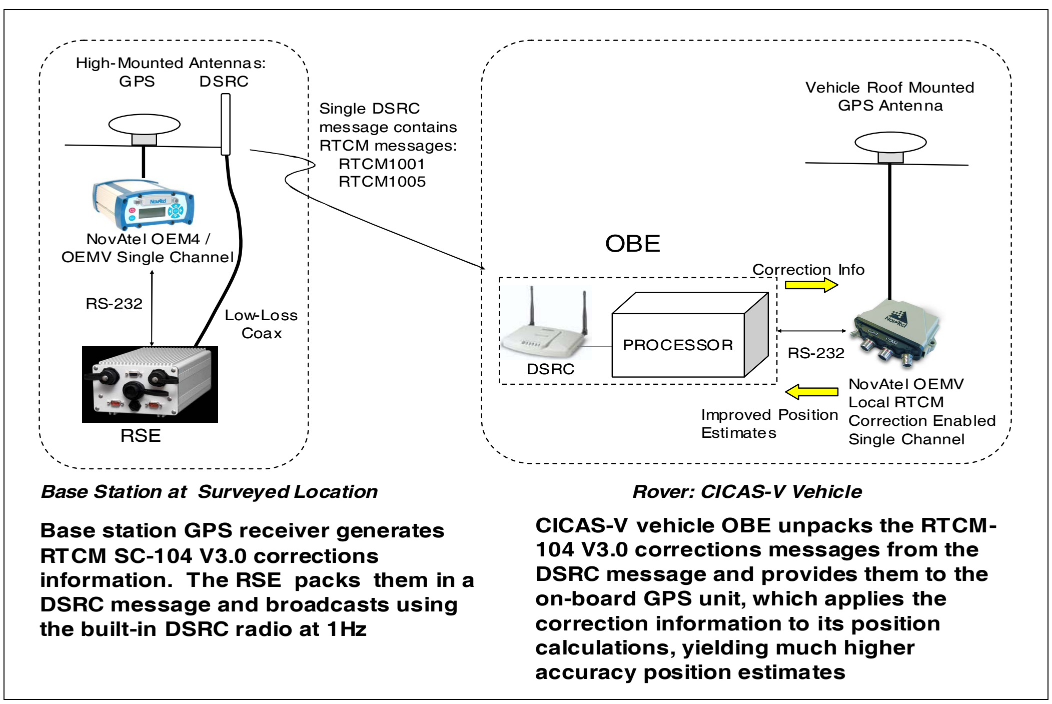

Figure 5: Aerial positioning correction equipment

The RTCM 1001 corrections provide per-satellite GPS pseudo-ranges and carrier phase measurements so the on-board (moving) GPS receiver can compute its position estimate with much higher accuracy and reliability. The RTCM 1001 form [4] of L1-only correction information provides a good accuracy improvement with rather modest communications requirements and impact on GPS receiver workload. For example, only 101 bytes are required per RTCM 1001 binary message that includes range corrections for 12 satellites, and is often smaller according to the number of visible GPS satellites in the current constellation. The amount of correction data that has to be broadcasted in the DSRC link is dependent on the RTCM version used and on the number of visible satellites.

For example, the RTCM v2.3 format requires about 4800 bits per second (bps) to broadcast dual-frequency code and carrier-phase observations or observation corrections of 12 satellites. Similar information content can be transmitted using 1800 bps in the newer RTCM v3.0 format (i.e., for 12 visible satellites, v2.3 requires 372 bytes to transmit data, whereas RTCM v3.0 requires only 8+7.25*12 bytes).

RTCM v3.0 is primarily designed to support Real-Time Kinematic (RTK) operations that normally require broadcasting relatively large amounts of information, and generally implies highly sophisticated forms of correction analysis and error removal. However, the L1-only subset of the RTCM v3.0 format can provide good performance improvements for modest system resource requirements, and works well even with moderately-priced receivers. A minimum of two RTCM SC 104 standard messages are required from the RSE to support local differential L1 solution correction for onboard GPS receivers.

Each RTCM 1001 Message contains the satellite observations (in particular the single frequency [L1-only] GPS pseudo-range and carrier phase measurements) as derived by the base station GPS receiver by comparing the position estimate determined from current satellite pseudo-range observations with the surveyed fixed location of the base station antenna. The base station "works backwards" to compute corrections to the satellite pseudo-ranges that would yield a much more accurate position estimate. Other roving GPS receivers in the surrounding area will generally face the same set of inaccuracies in the GPS satellite pseudo-range observations, so when they apply these pseudo-range correction factors to their own observations, they too will be able to significantly reduce the errors and obtain a more accurate position estimate.

MESSAGE FRAMEWORK

The cooperative nature of the system requires the definition of the messages that are being sent from the intersection to the vehicle. The project defined the following messages as necessary for the system to function:

- Wave Service Announcement (WSA)
- Signal Phase and Timing (SPaT)
- GID Message (GID)
- GPS Correction Message

There are two messages that are to some degree optional but that were implemented. These are:

- Area GID (AGID)
- Traffic Signal Violation Warning Given (TSVWG)

It should be noted that the TSVWG message is the only vehicle-to-infrastructure message.

In order to provide a common framework for all the messages, the project created the Transportation Object Message (TOM) that is based on XML but streamlines the message for byte efficiency. Here only an overview over the basic concept will be provided.

XML is a meta-language ideally suited to dynamic data markup, which quickly became very popular in the software engineering community. XML descended from SGML and is a very expressive, flexible and powerful meta-language. The main disadvantage for XML is the low byte-efficiency, which makes it less indicated for RF transmissions.

TOM was designed after the work conducted in the W3C XML Binary Characterizations Working Group. It was created to be similar to XML but highly streamlined for byte efficiency so it could support transmitting complex application data over DSRC. While XML is well suited for describing data of arbitrary complexity, TOM has similar capability but is limited by the maximum size of an object.

A TOM frame begins each message with a Message Header and ends it with a Message Footer. The framework provides message differentiation and a basic measure of integrity. There may only be one frame per message. Ideally, that frame never exceeds 1,024 bytes to fit into a WSM packet, assuming 200-400 bytes for the security overhead and WSM frame overhead. Everything between header and footer is considered message content, expressed as a set of object tags.

The TOM framework allows all the messages that are received to be treated in the same way in their decoding, which creates efficiency in application development and improves code robustness. Also, it allows for consistent authoring of content across all the different messages. In order to develop the various messages, a TOM compiler was developed that allows the authoring of the message in XML and then converts it into a TOM message.

DSRC BROADCASTS

All the messages are sent as WSM packets according to the IEEE 1609.3 proposed standard [5, 6]. The DSRC spectrum at 5.9 GHz is partitioned into seven channels where the Control Channel (CCH) is currently envisioned as the channel where the safety-relevant messages for Infrastructure-to-Vehicle (I2V) and Vehicle-to-Vehicle (V2V) communications are broadcasted.

To optimize channel utilization, it was decided to broadcast SPaT messages on the control channel (#178) and the GID and GPS correction (GPSC) messages on one of the service channels (all other channels except #172). The control channel is used to broadcast WSA messages. These messages contain information about the intersection the vehicle currently approaches (Intersection ID), the GID version number, and the service channel used for broadcasting. The vehicle OBE can switch its DSRC radio to this service channel to receive the full GID for the intersection as well as GPSC corrections. If the vehicle determines that it has the GID already stored, it will discard the newly received GID but still receive the GPSC messages.

DRIVER-VEHICLE INTERFACE (DVI)

The warning is conveyed to the driver via the DVI. It was not a goal for the project to specify a standard DVI as it is expected that each OEM will develop proprietary solutions in the future. The DVI developed for the project included a visual icon, a speech-based warning and a brake pulse. The tests conducted within the project found this combination to be highly effective. The CICAS-V DVI is presented in more detail in [7].

SYSTEM ARCHITECTURE

The overall system architecture is shown in **Figure 6**.

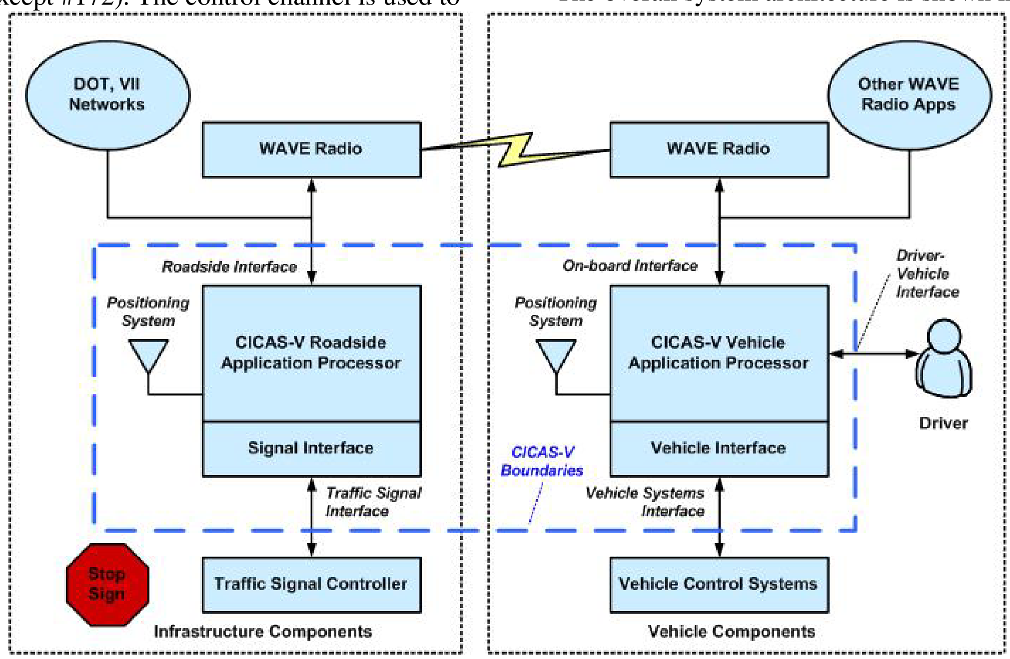

Figure 6: CICAS-V system with interfaces

As it can be seen in Figure 6, the vehicle and the infrastructure systems are very similar. In the following, the system architecture for the vehicle system will be described in greater detail.

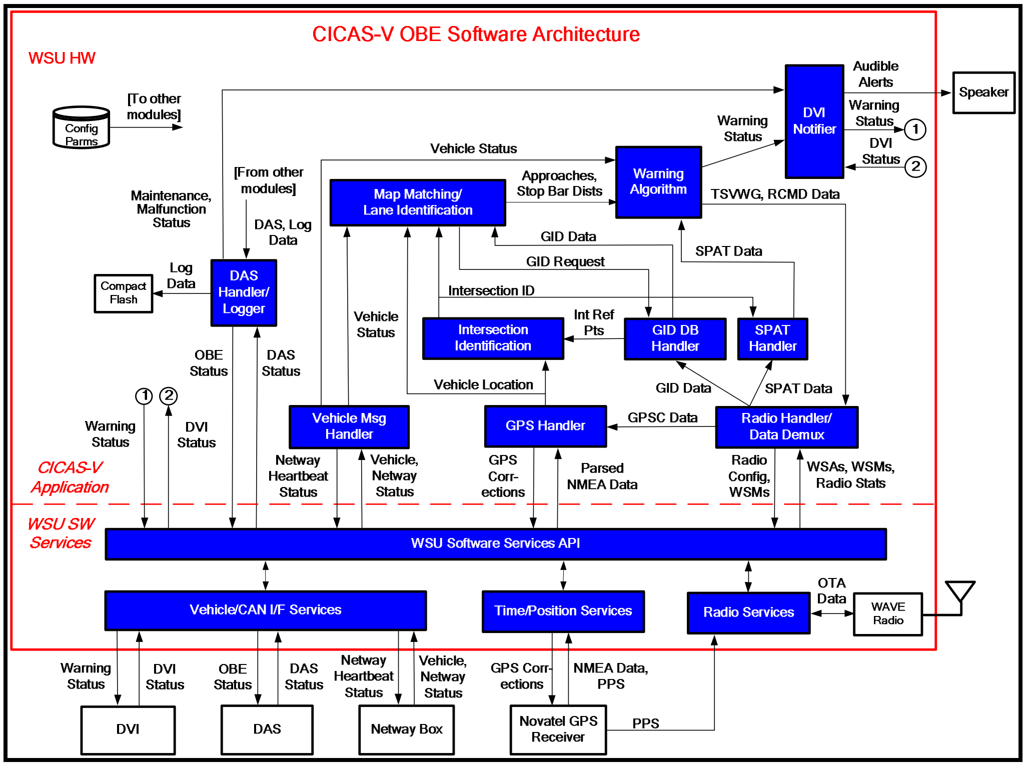

Figure 7: CICAS-V system architecture for the OBE

The software was implemented on a Linux embedded platform, the Wireless Safety Unit (WSU) by DENSO.

The software modules were divided into WSU Software Services that handled the interfaces the DSRC radio, the GPS unit and Vehicle Components, and the CICAS-V application modules.

The CICAS-V Application modules were grouped and divided into two categories:

- Interface/Message Handling Modules – Interface to external devices and/or perform message handling and parsing functions
- Violation Detection Modules – Process the latest vehicle, GPS, GID and SPaT data to determine whether an intersection violation is likely to occur

The modules assigned to each sub-category are listed in **Error! Reference source not found.** below.

Table 1: CICAS-V OBE Application Module Summary

Module	Description
Interface/Message Handling Modules	
Vehicle Message Handler	Interfaced to the Netway device (through the WSU Vehicle/CAN Interface Services) to receive generic CAN messages with vehicle status Transmitted and received heartbeat status information with the Netway
Radio Handler/Data Demux	Interfaced to the WAVE Radio (through the WSU Radio Services) Configured the radio, and polled the radio driver for statistics Transmitted and received WAVE Short Messages (WSMs) Processed received WAVE Service Advertisement (WSA) indications
GPS Handler	Interfaced to the Novatel OEMV GPS receiver (through the WSU Time/Position Services) Output GPS correction (GPSC) data Input GPS time and position data

Module	Description
GID Database Handler	Maintained the GID database Upon receipt of GID data, added a record to the database, or updated an existing record if the data was of a different version Deleted expired GID records Performed WAVE Basic Service Set (WBSS) selection if the GID or GPSC data was being broadcast on the Service Channel
SPaT Handler	Received and parsed the SPaT data Converted the data to a format usable by other modules
DAS Handler/Logger	Interfaced to the Data Acquisition System (DAS) (through the WSU Vehicle/CAN Interface Services) Output OBE status and input DAS status Performed hardware/software watchdog processing and determined whether a maintenance or malfunction condition exists It should be noted that the DAS Handler/Logger supports an independent system just for the collection of data to evaluate the prototype.
Violation Detection Modules	
Intersection Identification	Identified the intersection the vehicle was approaching based on the vehicle location and direction and the GID intersection reference points
Map Matching/Lane Identification	Calculated the most likely lane(s) and approach(es) of the vehicle, and the distance to the stop bar(s) based on the vehicle location and GID data
Warning Algorithm	Determined if an intersection violation was likely to occur Generated Traffic Signal Violation Warning Given (TSVWG) and Remote Command (RCMD) messages to be transmitted to the RSE
DVI Notifier	Interfaced to the Driver Vehicle Interface (DVI) (through the WSU Vehicle/CAN Interface Services) Controlled the DVI icon and flexible warning outputs Transmitted and received heartbeat status information with the visual DVI device Generated audible DVI alerts

SYSTEM INSTALLATION

The components of the intersection installation of the CICAS-V are shown in **Figure 8** and **Figure 9**. **Figure 8** shows the installation of the RSE, the GPS and a Data Acquisition System (DAS) in the intersection controller cabinet at an intersection in Blacksburg, Virginia. **Figure 9** shows the antenna installation (DSRC and GPS) at an intersection in Michigan.

Figure 8: CICAS-V cabinet with GPS, RSE, and Data Acquisition System (DAS)

Figure 9: CICAS-V antenna installation

Due to different intersection configurations, geometries and installation guidelines the installations in Blacksburg, Virginia, Oakland County, Michigan and Atherton, California differed from each other, even though the same components were used. **Figure 10** shows the installation in one of the OEM vehicles.

Figure 10: CICAS-V Vehicle Installation

Figure 10 shows the OBE (DENSO WSU), the Vehicle Interface (Netway) the GPS Receiver (Novatel OEMV) and a DAS (Virginia Tech Transportation Institue). The DAS recorded all the messages from the vehicle bus, the messages that were received from the intersections, the output of the computations from the OBE and the camera images (Forward, Driver Face, Interior of Vehicle, Rearward).

OBJECTIVE TESTING

Since the planned outcome of this project was a prototype ready for a large-scale Field-Operational Test (FOT), the system had to pass objective test procedures. Together with the USDOT a set of procedures was defined and then the system was tested using the procedures on a closed test track with an intersection (the Virginia Tech Smart Road). The test procedures are shown in Table 2.

The tests are divided into types:

- Warning Tests where the system has to give a warning
- Nuisance Tests, where the system must not give a warning
- Engineering tests where the system limits are tested

The tests covered the typical situations that would be encountered by a CICAS-V equipped vehicle approaching a CICAS-V equipped signalized or stop -sign controlled intersection. They were written such that any supplier of a CICAS-V can use them to test whether the system fulfills the performance specifications.

For a warning test to pass, the system had to alert the driver within a distance of (200 ms * vehicle speed) of the correct warning distance as defined in the warning algorithm and all the warning modalities had to come on within 200 ms of each other. The actual value that was achieved was below 100 ms. Each of the tests had criteria associated with it that determined that the test was valid, e.g., the variability of the speed had to be smaller than 2.5 mph around the nominal test speed. Each test had to have at least eight valid runs. The Various Speed Approaches tests for signalized and stop controlled intersections consisted of approaches at three speeds: 25, 35 and 55 mph, each of which needed eight valid runs.

Table 2: CICAS Test Scenarios Overview

Name	Purpose	Kind
Signalized Various Speed Approaches Test	Test whether warning distance is as specified for signalized intersections and given vehicle speed	Objective Requirement Warning

Edge of Approach Testing for Warning	Test whether expected warning is given when vehicle is driven on edge of lane	Objective Requirement Warning
Edge of Approach Testing for Nuisance Warning	Test whether nuisance warnings are avoided when vehicle is driven on edge of lane	Objective Requirement Nuisance
Late Lane Shift Test – Warning	Test whether expected warning is given when shifting from green lane into red lane after red lane's warning distance passed	Objective Requirement Warning
Late Lane Shift Test – Nuisance Warning	Test whether nuisance warning is avoided when shifting from red lane into green lane before red lane's warning distance passed	Objective Requirement Nuisance
Multiple Intersections within 300m Radius: Warning Case	Test whether warning appropriate warning is given for approaching intersection in presence of multiple nearby intersections	Objective Requirement Warning
Multiple Intersections within 300m Radius: No Warning Case	Test whether warning is avoided when approaching intersection in presence of multiple nearby intersections	Objective Requirement Warning
Dynamic Signal Change to Yellow, Too Late to Warn	Test whether warning is avoided on signal change from green to yellow when red arrives after the stop bar	Objective Requirement Nuisance
Dynamic Signal to Red, In Time for Warning	Test whether expected warning is given on signal change from green to yellow when red occurs before vehicle passes stop bar.	Objective Requirement Warning
Dynamic Signal to Green, No Warning Case	Test whether warning is avoided when signal change from red to green before the warning distance	Objective Requirement Nuisance
Stop Sign Various Approach Speeds Test	Test whether warning distance is as specified for stop sign intersections and given vehicle speed	Objective Requirement Warning
SPaT Reflection and Reception	Tests the system performance / system limits when line of sight between intersection and vehicle is obscured by another vehicle	Engineering Test

Table 3: Results of objective testing

Test Name	Speed	Comment	Tests Conducted	Tests Successful	Success Rate	Pass / Fail
Signalized Various Speed Approaches Test	25		8	8	100%	Pass
	35		8	8	100%	Pass
	55		8	7	88%	Pass
Edge of Approach Testing for Warning	35	Right Side	8	8	100	Pass
Edge of Approach Testing for Nuisance Warning	35	Left Side	8	8	100%	Pass
Late Lane Shift Test	35	Right to Left w/Warning	8	8	100%	Pass
	35	Left to Right w/o Warning	8	8	100%	Pass
SPaT Reflection and Reception	35		8	8	100%	Pass

Multiple Intersections within 300m Radius: Warning Case	35		8	8	100%	Pass
Multiple Intersections within 300m Radius: No Warning Case	35		8	8	100%	Pass
Dynamic Signal Change to Yellow, Too Late to Warn	35		8	8	100%	Pass
Dynamic Signal to Red, In Time for Warning	35		8	8	100 %	Pass
Dynamic Signal to Green, No Warning Case	35		8	8	100%	Pass
Stop Sign Various Approach Speeds Test	25		8	8	100%	Pass
	35		8	8	100%	Pass
	55		8	8	100%	Pass
Overall						Pass

As can be seen in Table 3, the system passed all the objective tests with almost 100% of the runs passing. The only failed run happened at one intersection approach where the brake pulse failed to trigger, even though the other warning modalities warned the driver at the correct distance. The SPaT reflection and reception test did not have pass/fail criteria attached to it since it tested the system outside the performance specifications. In this test, the CICAS-V equipped vehicle followed a tractor-trailer within a distance of 4.5 m to see whether enough packages from the intersection could be received to enable the vehicle to issue a correct warning. In all the test runs the warning was issued such that the vehicle was able to come to a stop before entering the intersection crash box but in several instances the warning came more than 200 ms late. The complete description of the objective test procedures can be found in [8], the complete analysis of the objective testing can be found in [9].

DISCUSSION

The development work in the CICAS-V project resulted in a CICAS-V that was deployed in intersections in three states in the United States with different traffic signal controllers and intersection configurations. The installations varied in difficulty due to the location of the traffic signal controller cabinet relative to the antenna placements, the space available in the cabinets, and other local factors. In all cases, the intersection installation was stable and without maintenance is still working in the Michigan intersections, even after a severe winter. The intersection installation could be accomplished with a reasonable amount of effort even for complex intersection installations. The development and test of the intersection GIDs showed that the necessary maps with successive could be developed. The positioning correction methodology used proved that the required accuracy for lane level positioning is achievable and that the overall system is feasible and can be installed at intersections. A final deployment analysis would need a full FOT.

The vehicle part of the CICAS-V was improved in successive releases of the software and extensive system tests were performed to verify all functions and aspects of the system. The software release that was used for the pilot FOT [10] was improved in several subsequent releases using the results from the tests with naïve drivers. The final release of the project was used for the objective tests. The system performed well during the objective tests and was judged to be ready for a large-scale FOT. The passed tests included both Warning Tests where the correct warning had to be given and Nuisance Tests, where an incorrect warning had to be avoided.

The overall performance of the system showed that it is ready for a large scale Field Operational Test. Plans and experimental protocols have been developed as part of the project and can be used to conduct the test [11].

CONCLUSION

The CICAS-V project developed a cooperative intersection collision avoidance system that warns drivers of an impending violation of a traffic control device. The system was installed in several vehicles and intersections in California, Michigan and Virginia. To support the system, message sets, a digital map format for intersection maps, and a map matching and positioning system for accurate positioning in the vehicle were developed. For the evaluation of the system readiness for an FOT with naïve drivers, objective test procedures were developed and the system was tested using those procedures. The CICAS-V passed all the objective tests. The system was also tested with naïve drivers in a pilot FOT and was found to be ready for an FOT. This constitutes the first test of a CICAS-V in a real-world environment and the results show that such a system can function well and can be tested in a large-scale field test with naïve drivers.

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PREDICTION OF PRE-IMPACT OCCUPANT KINEMATIC BEHAVIOR BASED ON THE MUSCLE ACTIVITY DURING FRONTAL COLLISION

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ABSTRACT

The objective of this study is to predict the behaviors of the human body in pre-crash conditions based on the experiment with active human models. In order to simulate the actual pre-crash condition of a car that occurs when the drivers brakes or pre-crash safety system activates in an emergency situation, low speed front impact tests on human volunteers were conducted using a sled-mounted rigid seat, on which each subject sat, sliding backwards on the rails. It was observed that when the subject's muscles were initially relaxed, muscle responses started activation at around 100ms after the onset of acceleration and reached its maximum value at around 200ms. During this time period, most of the individual body region acceleration responses and restraint system reaction forces also peaked. Furthermore, the head-neck-torso kinematics was strongly influenced by the muscle activity. This experiment indicates that muscles can react quickly enough to control the driver's behavior significantly during the low-speed impact, relating to the driver's posture just before the collision. Thus, the active human model with the Hill-type multi-bar muscle was employed to estimate the possible driving posture in an emergency. From the result of this experiment, pre- and post- crash occupant behavior was predicted. For a more detailed understating, a parametric study was conducted that distinguishes the factors presented in real accident cases.

INTRODUCTION

In the discussion of automobile crash safety, it is usual that occupant safety is discussed with a 50% adult male (AM50) or Anthropomorphic Test Dummy (ATD) in a normal sitting posture. However, the posture of the driver's seat occupant varies due to age, gender and physiques. Moreover, further posture changes will occur just before the collision due to occupant evasive maneuvers; thus, it is difficult to keep a normal position just before the collision. **Figure 1** shows the accident type and evasive maneuvers obtained from the Institute for Traffic Research and Data Analysis (ITARDA) in Japan (1993-2004)[1]. This data source consists of 860 of front impact collision (CDC:11F-1F) cases. The accident analysis show that around 50% of the drivers made evasive maneuvers in each accident type; namely, most drivers made evasive maneuvers just before the collision. In addition, driver injury incidence rates of chest with evasive maneuver are relatively larger than those with non-evasive maneuver when compared in each delta-V [2]. Therefore, evasive maneuvers include additional factors such as posture changes and body movement, which must be taken into consideration in discussing the accident analysis results. However, these differences in the driving posture and behavior of the occupant before such collisions is unreadable information from the accident data; thus, it is difficult to quantify the differences in injury mechanisms only from the accident data.

Armstrong et al.[3] examined the bracing effect in their review of prior works on muscle effects. They employed volunteers and demonstrated the strong influence of leg bracing against the toe board. It was found that 55% of the subject's kinematic energy absorption was attributed to the restraint by legs. Cross et al.[4] studied how passengers "brace" and react during pre-impact vehicle maneuvers. This information is related to the real world occupant photographic studies (Bingley et al.[5]). Parkin et al.

[6] studied the effects of driving posture and passenger individuality. It was concluded that the configuration of initial posture, i.e., how people sit in cars, showed marked differences between male and female. According to these previous studies, the causation between these differences and the injuries seen in the accident data has not been clearly explained. Nor has the relationship between evasive maneuver and the amount of posture change or muscle response been quantified yet.

The authors have studied the posture changes caused by pre-braking by means of volunteer tests. The previous study in this series [7][8] was conducted. In this study, the posture of the driver at the moment of pre-braking just before the impact was examined in two different muscle conditions. In one condition, muscle is fully relaxed, and in the other muscle is fully tensed. At the same time, the basic data of posture changes and muscle activation were also measured by using a 3D motion capturing system, and muscle activation electromyography, respectively. Based on the results of this experimental study, the prediction of the driver's posture and posture maintenance mechanisms were investigated. Moreover, this experimental study was applied to the injury prediction approach by using a computer human model to verify the influence of human body posture changes on the occupant injuries in a traffic accident. This in turn leads to further improvement of the effectiveness of occupant crash protection measures such as smart restrain system or adaptive restrain system in the accident. The aim of the current study is to build an injury prediction approach to verify the influence of human body posture changes on the occupant injuries in a traffic accident.

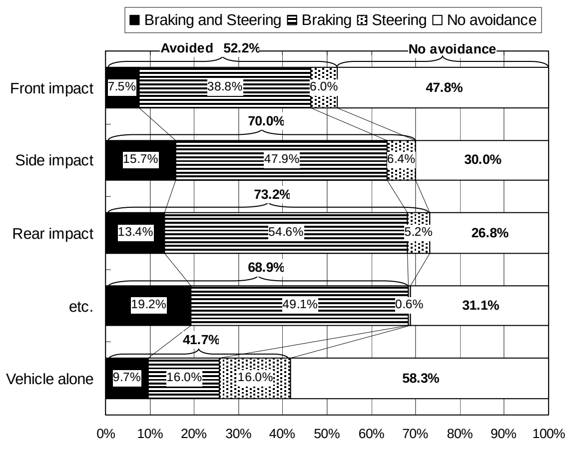

Figure 1. Accident type and evasive maneuver

VOLUNTEER EXPERIMENT

Volunteers and informed consent

Five 22 to 26 year-old male volunteers in good health participated in the series of experiments. The average and standard deviation of the 5 volunteer's anthropometric data is shown in **Table 1**. The protocol of the experiments was reviewed and approved by the Tsukuba University Ethics Committee, and all the volunteers submitted their informed consent in a document complied with the Helsinki Declaration.

Table 1.
Volunteer data

	Age (year)	Height (cm)	Weight (kg)	BMI (kg/m^2)	Sitting height (cm)
Mean	24.1	168.9	61.8	21.5	87.4
±SD	1.5	7.8	11.1	2.6	4.1

Sled apparatus for simulation of low-level impact

Figure 2 illustrates the initial view of the front-impact simulation sled system (hereafter referred to as "Mini Sled"). The front pre-impact sled was designed based on the actual car pre-impact condition in order to simulate the deceleration experienced when the driver brakes or pre-crash safety barking system activates in an emergency situation. The sled is equipped with rigid seat made of steel (hereafter referred to as "R-seat"). Low-level frontal pre-impact was applied to the volunteer by accelerating the sled. The R-seat made of steel was mounted on the sled. In this experiment, a foot plate and a removable steering is equipped on the sled and the reaction forces coming from the plate and wheel were measured by load cells.

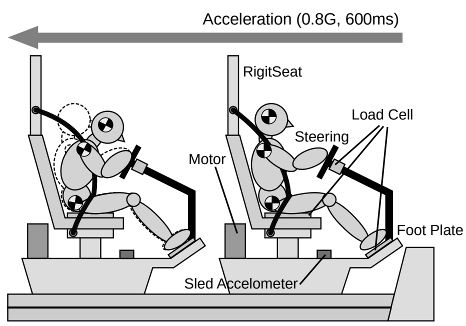

Figure 2. Outlook of the front-impact simulation sled system

Motion analysis and definition of joints and segment region of the full body

The physical motion of the human body and head-neck-torso kinematics at low-level impact accelerations were measured by means of the three-dimensional motion capturing system[9]. The features of this capturing system are that the position of each marker is automatically extracted from a video image caught with several cameras, and the skeleton image which builds up with these markers is translated into three-dimensional coordinates. In the experiment, eight sets of cameras were employed and the landmarks were attached to the defined body locations. The arrangement in this experiment

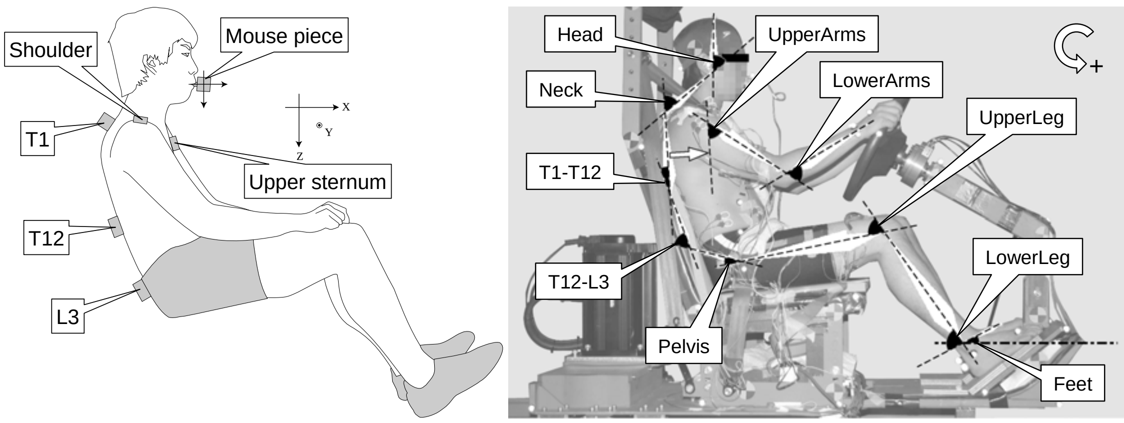

Figure 3. Lateral view of the head/neck/torso/pelvis with mounted accelerometer and definition of the segment and rotational angle between each segment

included landmarks attached to the head (Parietal, Auditory Meatus), shoulder (Acromion), chest (Sternum), back (T1, T11), lumbar (L3), arm (Elbow), hand (Wrist, Back), and leg (Knee). These markers were used as the reference points in order to determine of the head, neck, torso, abdomen, hip and lower extremity locations. From this motion data, a skeleton image is generated based on segments determined by body surface landmarks. **Figure 3** shows the definition of each segment of the head, neck, torso, abdomen, thigh, and the lower legs. With these motion segments, the rotational angle at the joint was recorded, and the differences between subsequent rotational angles were calculated. In order to represent the hip motion separately, a virtual marker was created based on the skin surface marker. To be more precise, the upper torso was separated into five segments (Head, Neck, Chest, Abdomen, Pelvis), and the joint angle at each connection point (Head, Neck, T1-T12, T12-L3, Pelvis, Upper Leg, Lower Leg, Upper Arms, Lower Arms) was calculated with the motion capturing software.

Acceleration measurement

In order to monitor the motion of the volunteer at the time of impulse, accelerometers were placed both on the body surface and the sled. Since the head motion was three-dimensional, tri-axial accelerometers and a tri-axial angular velocity meter were attached to the mouth via the mouthpiece, the first thoracic vertebra (T1), the twelve thoracic vertebra (T12) and the lumber vertebra (L3). The fixtures shown in **Figure 3** were fabricated for the installation of accelerometers on the body of each subject. The acceleration of the shoulder and chest were measured by the tri-accelerometer attached to the surface of the acromion and the front chest around the sternum region with a surgical tape, over which double-coated tape was adhered.

Electoromyography

Muscle activity was measured by means of surface electromyogram, the timing of which was synchronized with the three-dimensional movement data. EMG electrodes were attached to the skin over the major muscles of the subject. **Table 2** indicates the locations of the surface electrodes, and "M." stands for muscle. The measured muscle activation during the impact was analyzed by systematic processing, and the average rectified value (ARV)[7] was obtained. Each muscle response was normalized by its own maximum muscle activation value (ARV) in the tensed case.

Table 2.
Location of the muscle

Neck	M. Sternocleidomastoideus M. Paravertebralis
Torso	M. Latissimus Dorsi M. Erector Spinae
Abdomen	M. Rectus Abdominis M. Obliquus Externus Abdominis
Lower Extremity	M. Biceps Femoris M.Rectus femoris M. Gastrocnemius
Upper Extremity	M. Biceps Brachii M. Triceps Brachii M. Deltoideus

Experimental conditions

Five healthy males were selected as test subjects. In order to examine the effect of muscle activity on the physical motion in the pre-crash situation, the experiments were conducted in two conditions: a relaxed state, in which the volunteers were subjected to the impact in the state of relaxed muscles, and a tensed state, in which volunteers intentionally tensed their muscles. Test subjects were instructed so that they could assume each of these muscle configurations. During the test, the muscle activation was monitored to determine to what extent the subjects were relaxed or tensed. In the relaxed case, the subjects were required to be fully relaxed until the body motion was naturally stopped. For the safety of the subjects, a seatbelt was used to immobilize the waist of each subject. On the other hand, in the muscle-tensed cases, the subjects were instructed to tense their all muscles intentionally. In this case, a steering was installed to reconstruct the pre-crash condition in which the driver tenses their muscle to hold the steering wheel for bracing. The 3-point seatbelt was also attached to the shoulder to prevent the contact between the upper torso and the steering. The seatbelt was adjusted to the length of the abdominal and chest regions; thus, these belts were not pre-tensioned at the initial stage. For the purpose of comparison, the subjects were solicited to try to maintain their initial posture by tensing their muscles. Applying the acceleration to the sled while the subjects were assuming the same initial posture, the differences due to muscle activation could be clearly seen in the motion of their upper torso.

EXPERIMENTAL RESULTS

Subject's motion, acceleration response and EMG

In order to investigate the effect of the muscle condition, a series of experiments were conducted on the five volunteers in each case as shown in **Table 3**. The impact phenomenon seen in the typical frontal collision case can be described by the motions observed by three-dimensional movement analysis system, the acceleration at each region of the subject, and the electromyographic response. A subject's motion, acceleration response, and EMG are divided into four phases.

Table 3.
Test Matrix

5 adults

Impact acceleration	Direction	Muscle condition	Boundary condition
0.8G	Front	Tensed	Shoulder belt Lap belt Steering
		Relaxed	Lap belt

In this section, the results of the experiments conducted with an impact acceleration of 8.0 m/s^2 using a rigid seat are described. The following results were summarized according to the two different muscle conditions of pre-crash acceleration as time sequential changes. Further explanation of pre-crash conditioning in the two different muscle conditions are described in **Figure 4-7**. **Figure 4** and **Figure 5** show the sequential images of a subject's motion taken both by the high-speed camera and by the 3D motion capturing system. In addition, subject's motion, response to the acceleration and EMG are divided into four phases as illustrated in **Figure 7**. This figure shows the time histories of resultant acceleration and angular velocity of the head, T1, T12, and L3. In addition to the acceleration, the time histories of reaction forces with the belt, footplate, and steering wheel are shown. Moreover, the time histories of EMG response of each muscle of the subject are indicated. Finally, the time of acceleration onset is set at zero (0ms) in the time history diagram.

Motion observed by sequential picture images and 3D movement analysis system (Forward motion kinematic) - Because of the inertial force generated by the acceleration of the sled, the subject's upper torso started to move forward, while the head was moving backward relative to the first thoracic spine (T1) in the relaxed case. As a result of this phenomenon, the neck that links the head and torso started to extend. Moreover, T10 and T1 showed a ramp-up motion. With the subject's the body trunk restrained to the seat by a lap belt, the arched rotation of the upper torso started at around 200 ms. Simultaneously, the neck also started to rotate (flexion). Compare with the muscle-relaxed case, the upper torso motion is constrained by the muscle activation in the muscle-tensed case. With the subject's body trunk restrained to the seat with the reaction force from the steering wheel through the arm, the forward motion of the upper torso started to fold back at around 200 ms.

Acceleration at each region of the subject and loads - The constant acceleration of 8.0(m/s^2) was applied to the sled, and this acceleration appeared with the acceleration of L3 close to the sled in initial stage. Then, the lumber acceleration was transferred to the head of T12 and T1 one by one. The magnitude of L3 and T12 acceleration indicated the maximum value at around 150 ms, and the head and T1 acceleration gradually increased due to the forward motion of the upper body. According to the angular velocities of the L3, T12, T1, and Head, each portion started to rotate at around 100ms. Then, the L3, T12 angular velocity was getting decreased, and the magnitude of T1 and head C.G. angular velocity reached the maximum value at around 300ms. Compared to the muscle-relaxed case, the upper torso motion is constrained by the muscle activation in the muscle-tensed case. Therefore, the maximum value of acceleration, angular velocity, and the seatbelt force decreased. The maximum value of T1 and head were indicated at around 200ms. In addition, the flexional angular velocity of the head and neck reached maximum at around 150 ms, when the head-neck deformation started to fold back. The magnitude of this acceleration decreased due to the activation of the muscles after 200 ms. On the other hand, L3 angular velocity converged to zero, and the magnitude of T1 and head angular velocity reached a positive value (Extension). The angular velocity indicates a miner oscillation mode because the shoulder-belt and lap-belt started to react with the forward motion of the torso. The magnitude of foot plate and steering load indicated the maximum value at around 200 ms, and these reaction forces are strongly correlated to the muscle activation at lower extremity and upper extremity. The reaction force of footplate and steering is converged to 100 N by discharging the lower and upper extremity muscle, when the subject found an appropriate balance between the muscle activation and the inertia effect (**Figure 5**). Therefore, the acceleration and angular velocity converged to zero.

Electromyographic response- Because of the muscle-relaxed condition, the upper torso started to move forward, and the major muscle activation was not detected except M. Erector Spinae, M. Biceps Femoris, and M. Gastrocnemius. In relation to the neck link motions, discharge of M. paravertebralis slightly activated at around 100 ms. Moreover, the position of the body trunk moved forward, and M. Biceps Femoris and M. Gastrocnemius normalized ARV value are rapidly increased at around 150ms. Then, the muscular discharge of the neck, torso, and leg disappeared.

In the muscle-tensed case, the body trunk was restrained to the seat due to the muscle activation. Therefore, the acceleration started to decrease and the angular velocity of each body region converged to zero. The muscle activation is discharged continuously, and the posture is maintained by the resistance force from the footplate and the steering wheel. Regarding the muscle response, most of the muscles are discharged before the impact (0ms) except M. sternocleidomastoideus and M. paravertebralis .

Differences in HEAD, NECK, and TORSO Motions related to the muscle responses and restrain effect

It has been detected that the pre-impact tension of muscle affects the physical motion at low-level impact, and this muscle effect is mostly related to the rotational angle of head, neck, and torso. Therefore, the rotational motion of the upper torso was analyzed based on the trajectory of each landmark measured by the 3D motion capturing system. **Figure 8** shows the average values of the maximum flexional and extensional angles at the joint. The average value was calculated from the data of the five male volunteers. For the purpose of comparison, the tensed and relaxed muscle cases are shown in these figures. As for the rotational angle of each joint, the primary value was set as zero (0). The plus (+) direction indicates extension, while the minus (-) direction

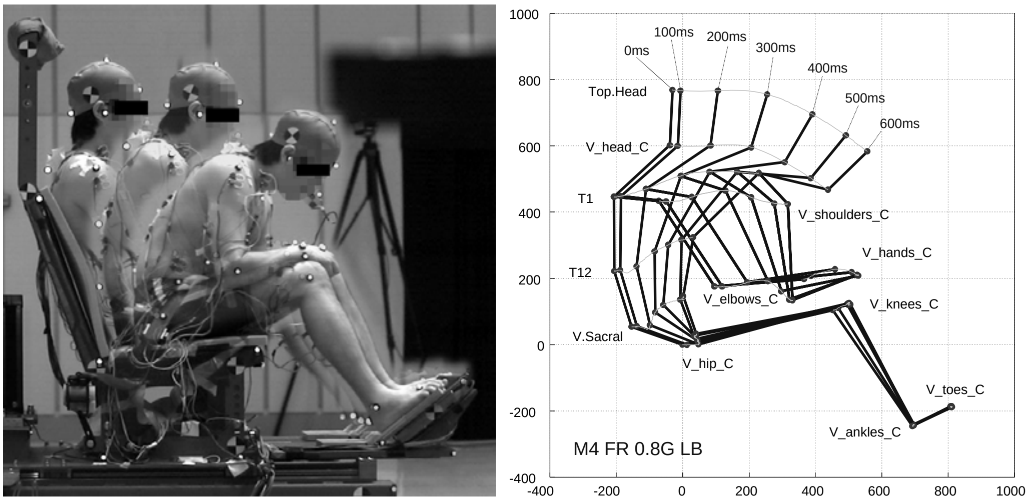

Figure 4. Physical motions from the 3D motion capturing system (Male, 0.8G: Relaxed)

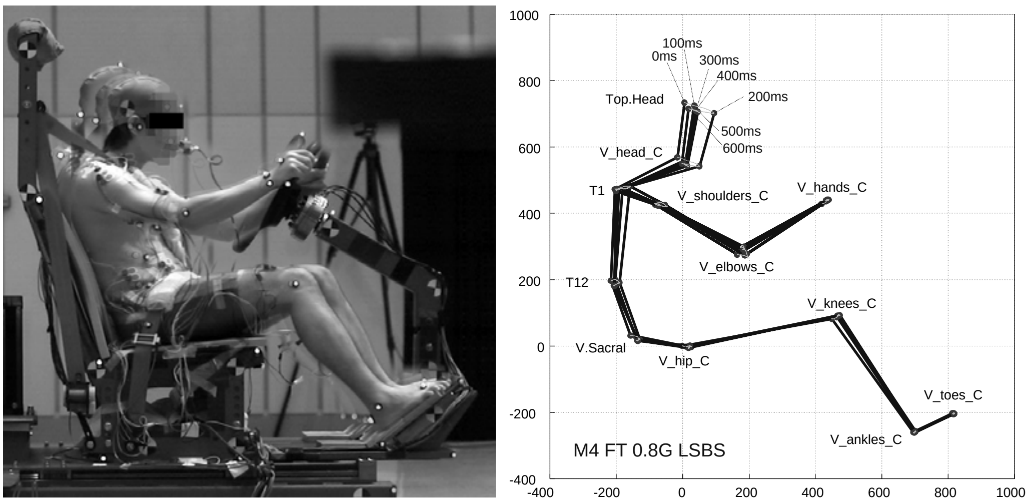

Figure 5. Physical motions from the 3D motion capturing system (Male, 0.8G: Tensed)

indicates flexion. Because of the muscle activities, the major angle difference between the lower leg and the feet could not be identified in the experiment. In the muscle- relaxed case, the flexional motion of the pelvis (Pelvis) is dominated in the body trunk. The extensional motion of the head (Head) and lower extremity (Upper Leg) were identified in the muscle-relaxed condition.

On the other hand, in the case of tensed condition, the major flexional motion was detected in the neck (Neck), thorax (T1-T12), and upper extremity (Upper Arms) area. The head (Head), pelvis (Pelvis), lower extremity (Upper Leg) and upper extremity (Lower Arms) showed extensional motion.

Muscle activities during pre-braking

According to the kinematic and muscle activity in the experimental results in **Figure 4-7**, the subject's upper torso and head-neck motion is constrained by the muscle activation. In addition, the torso motion is restrained by the resistance force from the upper extremity which is connected to the steering wheel. As a result of this phenomenon, upper torso motion was strongly affected by the muscle and the boundary condition in the pre-crash situation. **Figure 9** indicates the average value of the integrated normalized ARV to define the each muscle activation during the impact. This value is calculated from the integration of average time history of normalized ARV value with five volunteers in both relaxed and tensed case. The interval of integration is between 0ms to 600ms when the sled is moving in the constant acceleration. In the muscle-tensed case, most of the muscles become larger than the relaxed case except M. Rectus Femoris and M. Biceps Femorise. Particularly, M. Sternocleidmastoideus (Neck), M. Rectus Abdominis (Abdomen), M. Gastrocnemius (Lower Extremity) and Upper Extremity have a significant difference in the amount of integrated normalized ARV between muscle-relaxed case and tensed case.

The result of the integrated value indicates the muscle condition working against the forward motion during the impact. These muscle activities were strongly related to the motion of the upper torso. The limitation of the posture-control with muscle activation was identified based on the activation level.

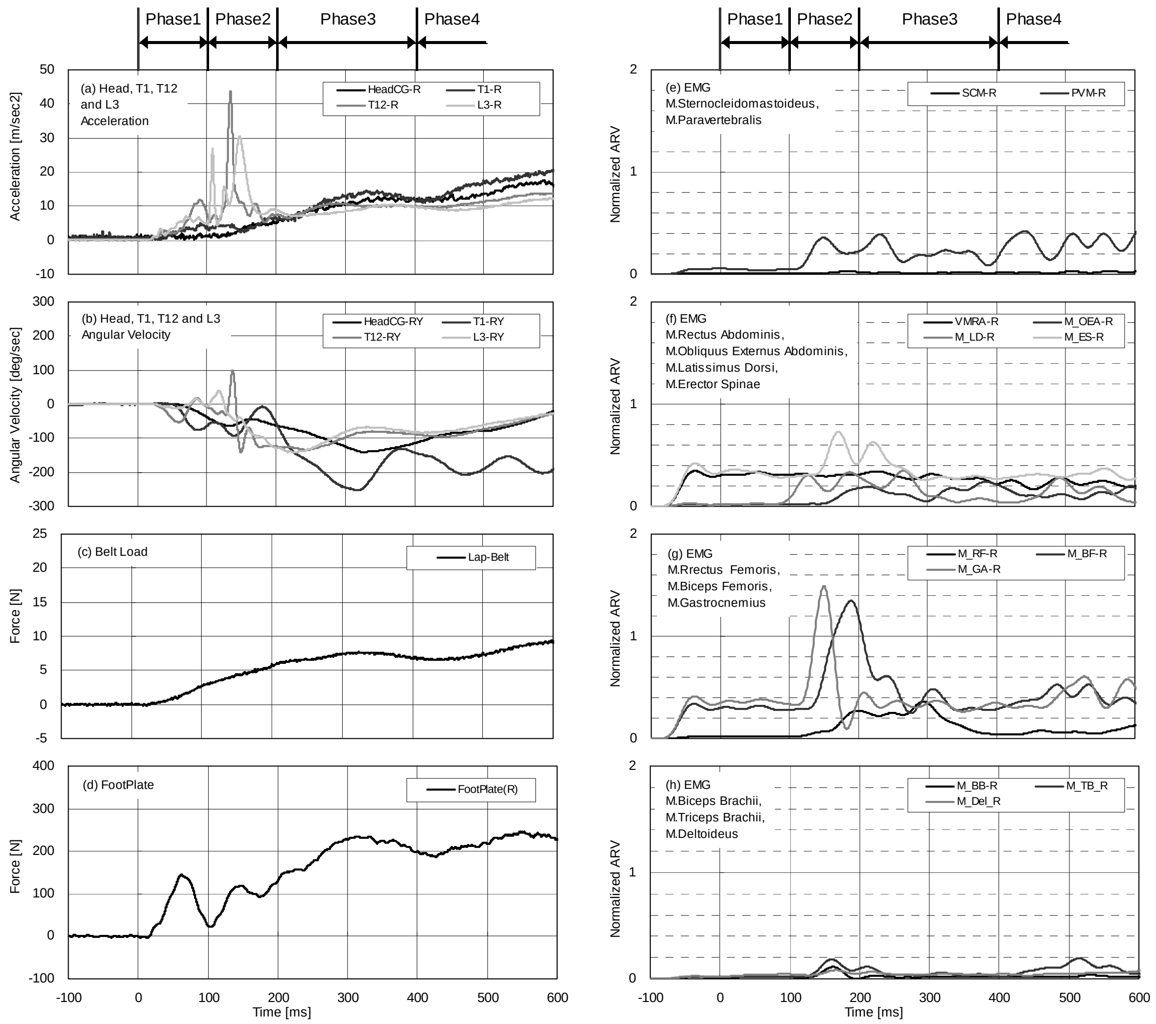

Figure 6. Time histories of resultant acceleration, angular velocity, restraints load and EMG (Male, 0.8G: Relaxed)

These muscle activations should be taken into account in predicting this pre-crash phenomenon with the computer model.

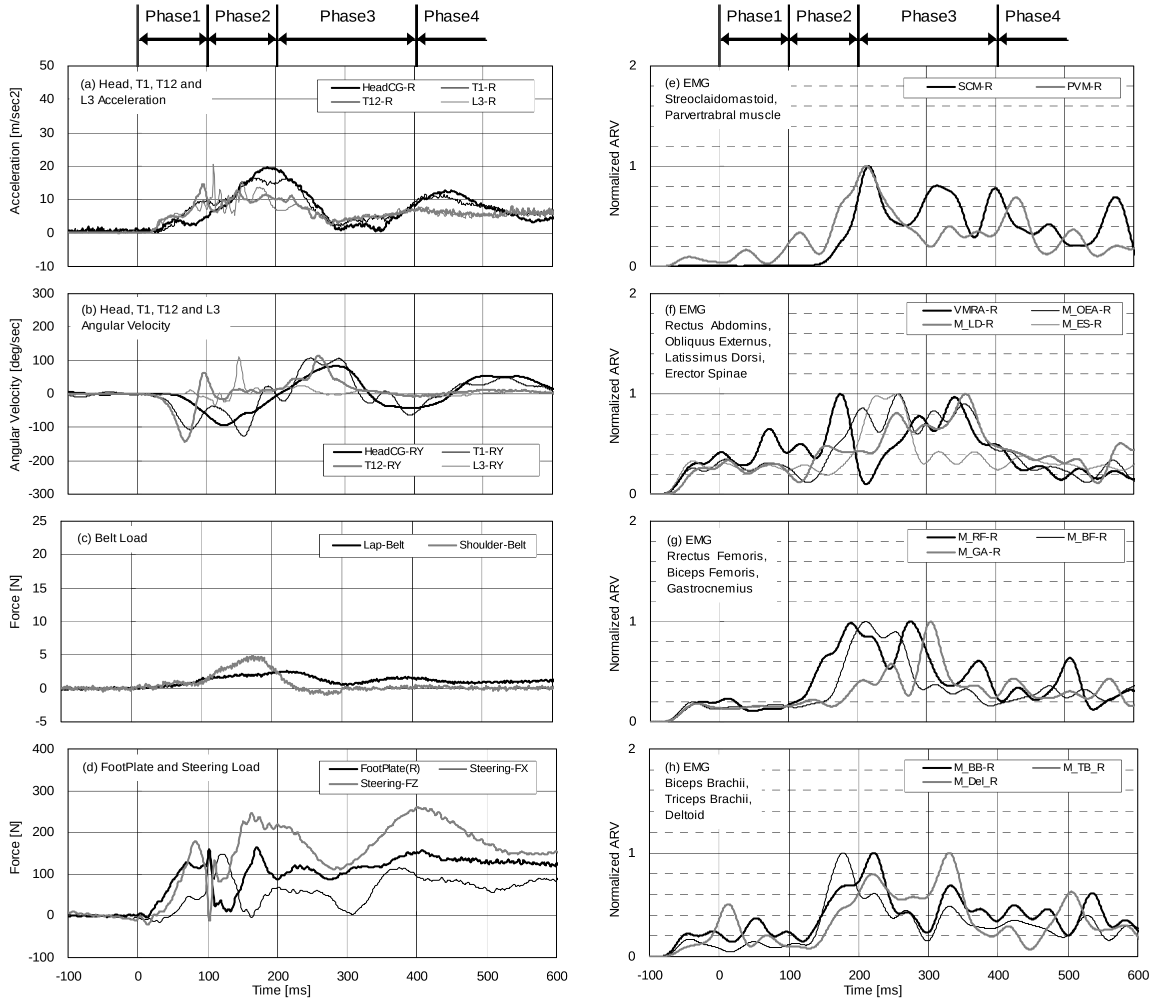

Figure 7. Time histories of resultant acceleration, angular velocity, restraints load and EMG (Male, 0.8G: Tensed)

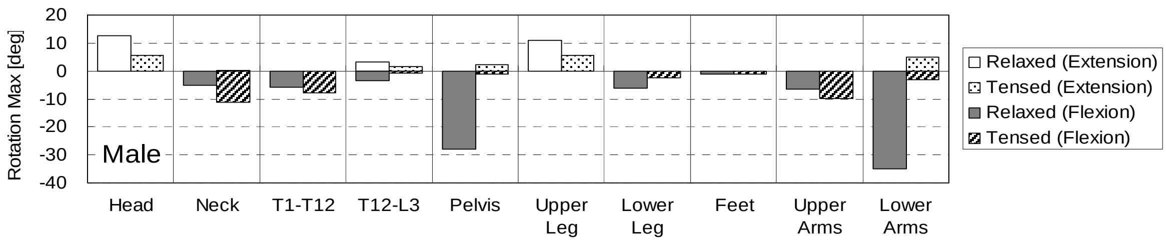

Figure 8. Maximum flexion and extension angle of each joint

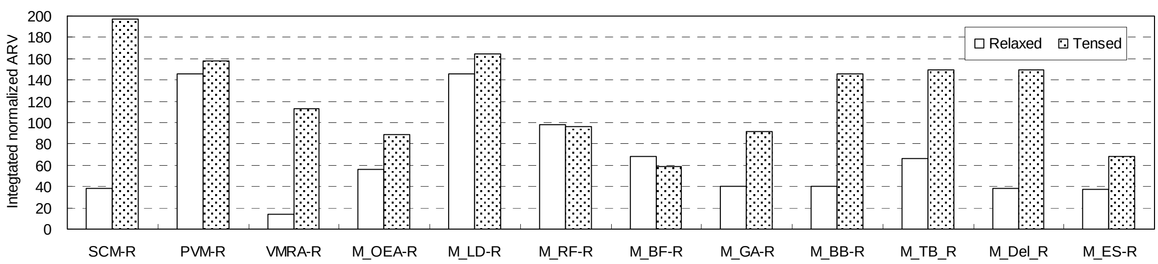

Figure 9. Activation of the muscles during the impact

NUMERICAL STUDY

Prediction of impact posture changes due to pre-crash condition

Active human model –It can be said that the experimental result indicate that the physical motion of the human body under pre-crash condition can be predicted. Therefore, the effect of the posture change caused by pre-crash condition was estimated by using MADYMO TM [10] with a multi-body adult male as the occupant model (**Figure 10**). This computer model is based on a rigid body model that incorporates muscle effect by using the hill-type muscle model. The muscle repose measured from the acceleration experiments was directly applied to the major muscles in order to simulate this acceleration's effect on the human body. To populate the design space of occupant anthropometric properties, the scaled rigid body model is developed by using GEBOD [10] which is constructed by the human anthropometric data. To examine the reliability of the MADYMO occupant model, the current human model was validated against the results of the experiments [11]. The validation was done against the impact tests at 8.0 m/s^2 in muscle relaxed and tensed cases which are described in the previous section, and it included the kinematics of the head-neck complex and whole body motion. Therefore, the validation of the modeling of these impacts was done only in terms of the posture change during the low-speed impact.

Baseline model -The baseline model used in this study was a multi-body representation of the driver's side interior compartment of a mid-size sedan car. The vehicle interior consists of the standard three-point belt system, a steering wheel, a knee bolster, and a footplate (**Figure 10**). The mechanical property of each component is validated with the experimental study. In this study, the accident scenario was reconstructed to evaluate the effect of posture change in the pre-crash condition. Therefore, the pre-crash phase which was defined in the volunteer test (constant deceleration 8.0 m/s^2: Duration: 0-600ms) is considered just before the collision and the deceleration pulse taken from the barrier test with mid-size sedan car (delta-V of 50 km/h) is applied to the model.

Sensitivity analysis

Design parameter and injury criteria -Three design parameters are mainly related to posture change in the pre-crash condition. In the previous study on the volunteer test [7], the small female subject showed the different trajectory from the male. Therefore, the anthropometric size should be one of the parameter in sensitivity analysis. Bose et al. [12] proposed the several kinds of initial posture based on the computer model, and it showed large difference in the injury outcome from the computer simulation. For this reason, the muscle response, anthropometric size, and initial posture that are considered as deign parameters in this simulation, and this study calculate the contribution of each parameter to the injury outcome. The head injury criterion (hereafter referred to as HIC_{36}) and chest acceleration for 3ms (hereafter referred to as C_{3ms}) were employed for the evaluation of injury. The variation of each of the design parameters is listed in **Table 4**. The combination of the muscle response, anthropometric size, and initial posture are carried out, and the total number of simulations is eighteen cases. The variation of each parameter is described as follow. The muscle response is defined as two condition from the experimental result (Tense and relax). The anthropometric size is based on the Japanese anthropometric male database and defined as three types (AM05, AM50, AM95). The initial posture is referenced to the literature [5][6][11] and three kinds of posture is defined (STD: Standard, UPR: upper body upright, FOW: upper body forward to steering column) .

Sensitivity Evaluation

The sensitivity information of each parameter is calculated by the analysis respect to the HIC_{36} and C_{3ms}. **Figure 11** shows the effects on individual injury values by changes of design parameters from the HIC_{36} and C_{3ms}. The HIC_{36} is sensitive both to the anthropometric size and to the muscle response. **Figure 12** indicates the eighteen cases of HIC_{36} respect to the anthropometric size (AM05, AM50, and AM95) in muscle relaxed and tensed case. In this figure, HIC value is normalized by the output value from the standard condition (Muscle Tense, AM50, STD). Compared with the muscle-tensed case, the variation of HIC_{36} is larger than that in the muscle-relaxed case. The reason for this difference is that the pre-crash phase defined in this simulation causes not only a posture change but also a change in body velocity due to inertial forces. Therefore, the contact speed between the head and the steering wheel changes in the muscle-relaxed case. On the other hand, the C_{3ms} is very sensitive to the initial posture. **Figure 13** indicates the eighteen cases of C_{3ms} respect to the initial posture (STD: Standard, UPR: upper body upright, FOW: upper body foward to steering column) in muscle relaxed and tensed case. The value of C_{3ms} is also normalized by the output value from the standard condition (Muscle Tense, AM50, STD). Compared with the muscle tensed case, large variation C_{3ms} can be detected in the muscle relaxed case. This phenomenon is also related to the pre-crash phase defined in this simulation, and the difference of initial posture affects the relative chest velocity to the steering. Therefore, the 3ms criterion value of the chest deceleration variation is increases. From this calculation, the effect of pre-crash phase is predicted by using the computer human model. For a more detailed understating of the mechanisms, further study will be needed to distinguish the parameters that are present in real accident cases.

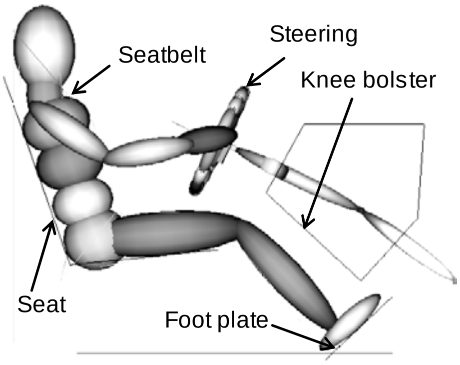

Figure 10. Computer human model with the driver's side interior compartment of mid-size car

Table 4.
Variation of design parameter

	Muscle response	Anthropometric size	Initial posture
18 case	Relaxed	AM05	STD
		AM50	UPR
	Tensed	AM95	FOW

DISCUSSION

Mechanisms of posture changes during pre-crash condition

The estimation from the results of measurement system indicates a significant correlation between the discharge of muscle force and the kinematic of each body part. For example, the head-neck-torso acceleration (HeadCG, T1, T12, and L3) increases, but decreases when the volunteer intentionally tensed their muscle. The muscle-tensed effect is clearly detected in the magnitude of acceleration and angular velocity compared to the muscle-relaxed condition. This is not only due to the back and abdominal muscles, but also due to the upper and lower extremity muscles discharged from the impact (0 ms). In other words, the upper torso was subjected to posture-control provided by these pre-tensed muscle condition in which activation level is around 20-40 % of maximum muscle. Following the timing of the muscle activation with upper and lower extremity, the steering wheel and the footplate show the reaction force continuously. Thus, the subject found the appropriate balance to control the upper body motion by using the reaction force from the steering and the footplate.
In the relaxed case, the subjects were required to be fully relaxed until the body motion was naturally stopped. However, a natural muscle 'stretch receptor' activated and this muscle activation temporarily seen in the back and lower extremity to control excessive motion. This protective mechanism works more effectively when the steering is installed in the system.

Effect of muscular Tension

In this study, a steering was installed to constrain the hip and chest in order to simulate real pre-crash conditions. It was identified that the pre-acceleration tension of muscles exerted influence on the physical motions compared to the relaxed case; however, this effect greatly reduced from that detected in the cases of relaxed cases. In comparing rotational angles between tensed and relaxed cases per body region from pelvis to head, ante-extensional motion due to muscle tension was detected at the neck region (Head: **Figure 8**). In this region, the posture-control effect of the rotational angle due to muscle tension was around 60%. On the other hand, the hip region (Pelvis: **Figure 9**) shows slight flexional rotational motion in tensed cases. In the relaxed cases, the hip region showed the largest flexional motion. Consequently, it was detected that the rotational angle of hip region was strongly affected by the upper torso motion restrained by the steering in the front impact case. Therefore, the boundary condition effect is important in discussing the stability of the posture under low speed acceleration.

Prediction of the effect of posture change for the injury

From the result of sensitivity analysis of the muscle response, anthropometric size and initial posture were selected as design variable. Injury values such as HIC_{36} and C_{3ms} were sensitive to the anthropometric size and initial posture respectively. However, these results strongly affected by the muscle condition and the different tendency are shown in **Figure 12** and **Figure 13**. As for the head injury criteria, the HIC_{36} value increases when the anthropometric size gets larger in the muscle-tensed case, and this is because of the inertia effect caused by the occupant's mass. On the other hands, the relaxed effect is clearly detected in the muscle relaxed case. For example, when the initial posture is set as FOW (upper body forward to steering column), HIC_{36} value decreased even though the occupants mass increased. This is because of the distance between the head and the steering wheel. In the pre-crash phase, the occupant upper torso inclines to the steering, and the head is almost attaching to the steering wheel when the crash deceleration is applied. Therefore, the contact speed when the occupant hits their head to the steering is almost close to zero.

As for the 3ms criterion value of the chest deceleration (C_{3ms}) value tends to increases when the initial posture (STD: Standard, UPR: upper body upright, FOW: upper body forward to steering column) is close to the steering in the muscle-tensed case and this is because of the contact between the chest and the steering wheel during the impact. In the muscle-relaxed case, because of the difference of the initial posture, the relative speed between the chest and the wheel is changed during the impact. This speed depends on the balance between the belt force and the inertia force generated by occupant's mass. The sensitivity analysis provides a guideline about the effects on injury levels by changing the design parameters. This is the preliminary study of the effect of posture change with active human model. For more detail analysis, several parameter studies are needed to understand the mechanisms of posture change during the impact.

Limitation of this study and suggestion for further research

The number of the subjects in this study was limited. Therefore, the data were insufficient to discuss the difference between tensed and relaxed muscle condition. In addition, modeling of occupant motions of the body is necessary to solve the muscle cooperation problem and the solution of this problem is to activate the muscle model. For reliable qualitative validation of the model, it is necessary to analyze the relationship between the kinematic and muscle activation in detail in order to obtain the information of muscle effect. This could be done in a co-operation between the tests and simulations.

CONCLUSION

The result of this study concludes that the effects of muscular tension on each body motions have been clarified, and the physical motion of the driver side occupant is predicted in the pre-crash condition. Furthermore, it has been identified based on acceleration, EMG electrodes and the reaction forces that differences in muscle activity govern the motion of the body in each phase. Finally, it has been found that the muscles that most highly activated when the occupant made a pre-braking action were the neck and abdominal muscles. These parameters are important factors in discussing the subject's motion with the restraints system just before the collision. In addition, the steering also supports the driving posture and stabilizes the pelvis motion. The present human body model adequately represents the general kinematics of the physical motion detected in

Figure 11. Effect of design parameter changes on injury value

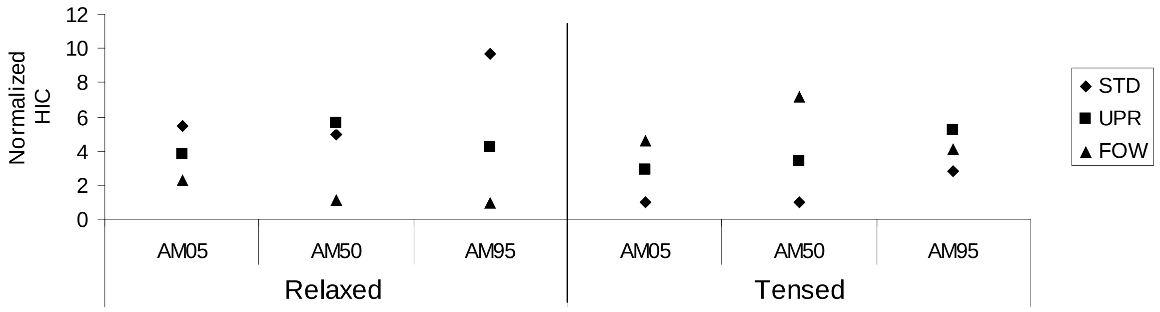

Figure 12. Distribution of normalized HIC_{36} respect to the anthropometric size

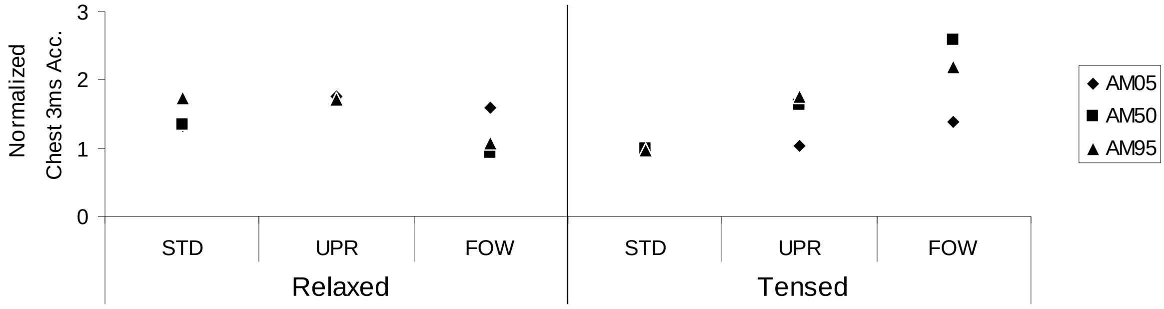

Figure 13. Distribution of normalized C_{3ms} respect to the initial posture

pre-impact braking conditions. This, in turn, indicates that the EMG data of major muscles significantly influences the physical motion, because these input variables are directly taken from the volunteer tests. This model is currently in the improvement phase, and its practical application and injury level prediction will be completed by using a finite element model in the next stage.

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THE EFFECTS OF AUTOMATIC EMERGENCY BRAKING ON FATAL AND SERIOUS INJURIES

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ABSTRACT

The introduction of automatic emergency braking changes the distribution of impact severity thus the resulting injury risk. In the calculation of the possible safety impact, risk functions must be used. These functions can be derived in different ways. In this paper, matched pair techniques have been used to study if the power models developed by Nilsson can be used.

By applying the risk functions on theoretical changes of impact speed as a result of pre impact braking, the possible effectiveness on fatal and serious injuries can be estimated. It was found, that such braking can offer major benefits. A reduction of speed before impact with 10 % can reduce fatal injuries in car crashes with approximately 30 %.

INTRODUCTION

It is well known that speed and change of velocity in crashes are highly related to risk of injury and the severity of injuries (Elvik et al 2004). While the risk of being involved in a crash is only marginally increased for increased speed, injuries and especially serious to fatal injuries are dramatically related to even small changes in travel speed or change of velocity in a crash.

The relation between speed and injury has been demonstrated empirically, theoretically as well as mechanically and on all levels such as at the macro level, in individual crashes as well as on the micro level for biological tissue (Elvik et al 2004). While this is nothing new or controversial, there are still doubts about how risk functions at micro and macro level should be developed and understood. While it is clear, that changes in average travel speed have a major impact on especially serious and fatal injuries, it is also clear, that it is not travel speed in itself that is injurious but rather rapid energy transients in crashes. It can even be questioned if the change of velocity is the best predictor for the risk of injury when in fact mean and peak acceleration is more relevant, although change of velocity and acceleration are of the correlated but not necessarily causally related (Kullgren 1998).

In the traffic safety literature and in practice, the power models are used to describe the relationship between travel speed on a macro level and risk of injury. The power model was firstly applied by Nilsson (2004) in the early 1970s and has since then been validated and evaluated several times. The function, or rather functions, has been revised several times, but in essence the proposed functions have been close to each other.

In the biomechanical and injury epidemiological literature, the relationship between impact severity, i e change of velocity, and injury has been described as dose response functions with increasing slope (Evans 1986). Both power as well as other continuously increasing functions has been applied to injury data (Krafft 2000a and b). There are many examples for both car occupants as well as pedestrians and also in different crash configurations and trajectories (Elvik et al 2004).

Crash protection for cars has been increased radically over the past 10 years or so, and to such extent that it can be not only demonstrated in simulated impact tests, but also in epidemiological studies (Lie and Tingvall 2002). It has also been demonstrated many times that the mass relation between cars in two car crashes is correlated to injury risk and severity (Krafft 2000a and b). In both examples, speed and change of velocity are critical factors. While in the former example, the consequence of improved safety is that the car can be crashed at a higher speed with the same injury outcome, or rather that for a given speed or speed distribution, the risk of injury and the severity of injury has been reduced. This factor can possibly

be measured in speed capability i e that the improvement can be expressed in terms of speed.
In the latter case, it is obvious that the change of velocity can vary greatly with mass relations in two car crashes and that this is important for injury outcome. In both cases, though, it has been observed, that fatal and serious injuries are more affected by speed and change of velocity, than minor injuries (Nilsson 2004, Elvik et al 2004). This is much in line of the implication of the power model for the overall relationship between travel speed and injury risk.

While the link between travel speed and impact speed is not fully understood, it seems logical that there is some kind of relationship, and therefore it is of interest to study if the power model for travel speed could be used also for car safety and the relation between impact speed and injury outcome.

More recently, cars have been developed and introduced with autonomous automatic emergency braking. Such systems can react to a car in the same direction, to fixed objects and to pedestrians, but are also likely to be expanded to oncoming vehicles and even vehicles in oblique direction. In some situations crashes can be avoided, in other situations crashes can be less severe, mitigated, by braking before impact. Some systems can use almost full braking power, and brake almost 2 seconds before impact. In doing so, speed before impact can be reduced by maybe up to 35 km/h or even more in some situations. This is a substantial change of impact severity.

In order to calculate the potential effects of automatic emergency braking, it is essential to use a solid link between velocity and injury.

The aim of the present study was to;

- With empirical data evaluate if variations in change of velocity in a crash and the resulting outcome can be described by the power model.
- Estimate the importance of automatic emergency braking

THE POWER MODEL

In simple terms the power model is a concept containing a set of power functions for crashes, minor injuries, serious injuries and fatal injuries. The functions are describing relative changes and can normally not give a direct link to absolute travel speed or absolute change of velocity in a crash. Below are the functions as presented by Nilsson (2004).
Number of fatal crashes:
$Y_1 = (V_1/V_0)^4 * Y_0$

Number of fatalities:
$Z_1 = (V_1/V_0)^4 * Y_0 + (V_1/V_0)^8 * (Z_0 - Y_0)$

Number of serious crashes:
$Y_1 = (V_1/V_0)^3 * Y_0$

Number of serious injured:
$Z_1 = (V_1/V_0)^3 * Y_0 + (V_1/V_0)^6 * (Z_0 - Y_0)$

Number of slight crashes:
$Y_1 = (V_1/V_0)^2 * Y_0$

Number of slightly injured:
$Z_1 = (V_1/V_0)^2 * Y_0 + (V_1/V_0)^4 * (Z_0 - Y_0)$

The following estimates based on a meta analysis, were proposed by Elvik et al (2004), to be used. They were validated against minor to moderate changes in travel speed. The differences between crash outcome and outcome for an individual should be noted. In the present study, the result of the meta analysis has been used.

Crash or injury severity	Exponent	Interval
Fatalities	4.5	4.1-4.9
Seriously injured	3.0	2.2-3.6
Slightly injured	1.5	1.0-2.0
All injuries	2.7	0.9-4.5
Fatal crashes	3.6	2.4-4.8
Serious injury crashes	2.4	1.1-3.7
Slight injury crashes	1.2	0.1-2.3
All injury crashes	2.0	1.3-2.7
Property damage only crashes	1.0	0.2-1.8

One major issue in using the power models for either crashes or their outcome, or using it for crash outcome given that a crash has occurred would be that the power for a fatality, serious injury or minor injury would be reduced by 1. That would mean that for fatalities the power is 3.5, for serious injuries 2 and for minor injuries 0.5. This is well in line with that the probability of a crash only is just linear. It is however important to keep this property of the power models in mind when studying either travel speed and outcome or crash protection given that a crash occurs. It would also be important to keep this in mind when looking at different technologies and the distinction of for example emergency braking where the full power levels would be used, or improved occupant protection through improved restraints or structure where the reduction of power would be applied. In table 1, the impact of changes in speed on injuries of varying severity can be seen. An increase of 10% on speed can be seen to increase minor injuries with 15%, serious with 33% and fatal injuries with 53%. The differences in the impact of speed change become even larger with larger increase or decrease of speed.

Table 1.
The influence of changing speed on the increase or decrease of the relative number of minor, serious and fatal injuries with power 1.5, 3.0 and 4.5

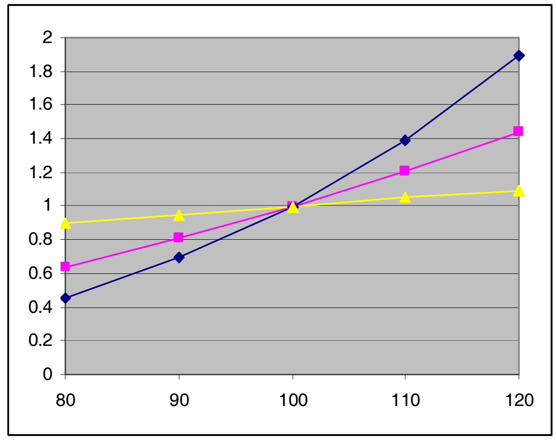
Speed, index	Minor injuries	Serious injuries	Fatal injuries
80	0,72	0,51	0,37
90	0,85	0,73	0,62
100	1	1	1
110	1,15	1,33	1,53
120	1,31	1,73	2,27

In table 2, the lower power levels have been applied, as in the case where only the outcome given a crash is considered. It can be seen that especially for minor injuries, the impact of speed becomes limited while for fatal injuries, the impact is still substantial. The figures can also be seen in figure 1.

Table 2.
The influence of changing speed on the increase or decrease of the relative number of minor, serious and fatal injuries with power 0.5, 2.0 and 3.5

Speed, index	Minor injuries	Serious injuries	Fatal injuries
80	0,89	0,64	0,46
90	0,95	0,81	0,69
100	1	1	1
110	1,05	1,21	1,40
120	1,09	1,44	1,89

Figure 1.
Risk functions for minor, serious and fatal injuries with power 0.5, 2.0 and 3.5 relative to speed index



Risk calculations in the present study were based on matched pair technique. The validation of the power model was in most cases based on the relation between fatal, serious and minor injury. In the first analysis of the relative importance of improved crash protection of newer cars, the relative risk was calculated in two car crashes where the case car population was matched with the average crash population.

In the second analysis, the opposite cars were varied with mass, so that the relative importance of increased and decreased change of velocity could be calculated. This is done under the assumption that relative impact velocity is the same across all masses within the mass range 900 to 1500 kg.

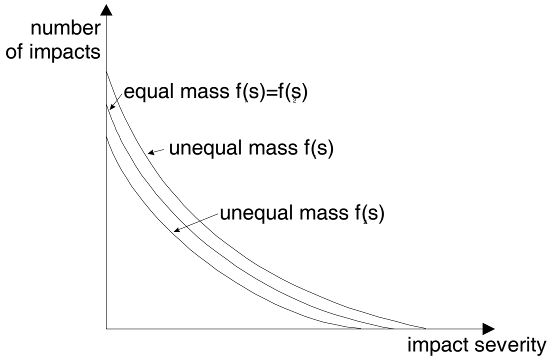
METHOD

Basically, the change of velocity can be calculated from the law of the conservation of momentum;
Delta v = $V_{rel} (M_2 / M_1 + M_2)$,

V_{rel} is the relative velocity and M_1 and M_2 the masses of the two vehicles colliding.
This relation is true even if the two vehicles involved do not have a common velocity after the impact. If the masses are equal, both vehicles will undergo the same change of velocity. This method uses this fact, and that any deviation in mass can be transferred to differences in change of velocity, as long as the individual masses are known (Figure 2). The method cannot generate absolute figures, only risks relative to each other.

Instead of generating new risk functions, the method uses the change on the exposure distributions and the resulting change in risk.

Figure 2.
Impact severity (delta-V) for cars in matching crashes for equal mass:
$f_1(s) = f_2(s)$ and unequal mass: $f_1(s) \neq f_2(s)$ where car 1 is of less mass than car 2



The basis for the statistical method is the paired comparison technique, where two car accidents are used to create relative risks. The method was initially developed by Evans (1986), but has been developed further for car to car collisions by Hägg et. al. (1992). The assumption for the method is that the risk of injury is a continuous function of change of velocity. This assumption might conflict with safety features such as airbags that might generate a step-function. This would have to be further investigated. Another assumption is that injuries in one car are independent from the injuries in the other car, given a certain accident severity.
For a given change of velocity the risk of an injury is p_1 and p_2 in the two cars, respectively. For that change of velocity, the outcome of the accident is described in table 3. The outcome of summing over all change of velocities is described in table 4.

Table 3.

Probabilities of injury to driver in car 1 and 2 in a segment of impact severity

		Driver of Car 2		
		driver injured	driver not injured	Total
Driver of Car 1	driver injured	$n_i P_{1i} P_{2i}$	$n_i P_{1i} (1-P_{2i})$	$n_i P_{1i} P_{2i} + n_i P_{1i} (1-P_{2i}) = n_i P_{1i}$
	driver not injured	$n_i (1-P_{1i}) P_{2i}$	$n_i (1-P_{1i}) (1-P_{2i})$	
	Total	$n_i P_{1i} P_{2i} + n_i (1-P_{1i}) P_{2i} = n_i P_{2i}$		

Table 4.

Sums of probabilities of injury to driver in car 1 and 2 in a segment of impact severity

		Driver of Car 2		Total
		driver injured	driver not injured	
Driver of Car 1	driver injured	$\sum_{i=1}^{m} n_i P_{1i} P_{2i} = x_1$	$\sum_{i=1}^{m} n_i P_{1i} (1-P_{2i}) = x_2$	$\sum_{i=1}^{m} n_i P_{1i} P_{2i} + n_i P_{1i} (1-P_{2i}) = n P_1$
	driver not injured	$\sum_{i=1}^{m} n_i (1-P_{1i}) P_{2i} = x_3$	$\sum_{i=1}^{m} n_i (1-P_{1i}) (1-P_{2i}) = x_4$	
	Total	$\sum_{i=1}^{m} n_i P_{1i} P_{2i} + n_i (1-P_{1i}) P_{2i} = n P_2$		

The relative risk of an injury, for vehicle 1 to 2, given a certain change of velocity distribution is therefore:

$$R = (x_1 + x_2) / (x_1 + x_3) = \frac{\sum n_i P_{1i}}{\sum n_i P_{2i}} = \frac{\sum n_i P_{1i} P_{2i} + \sum n_i P_{1i} (1 - P_{2i})}{\sum n_i P_{1i} P_{2i} + \sum n_i (1 - P_{1i}) P_{2i}}$$

The method is unbiased for any combination where the vehicles are of the same weight; i.e. the mass ratio is 1. If the vehicles are of different weights, the two vehicles will undergo different changes of velocity, which will have to be compensated for. Generally, we can introduce any component, K that will affect the risk of injury in either, or both of the vehicles. If we let K_1 denote this factor in vehicle 1, and K_2 in vehicle 2, this will lead to:

(1) $n_i P_{1i} P_{2i} K_1 K_2 / n_i P_{2i} K_2 + \ldots + n_i P_{1i} P_{2i} K_1 K_2 / n_i P_{2i} K_2 = \sum_{i=1}^{m} n_i P_{1i} P_{2i} K_1 / \sum_{i=1}^{m} n_i P_{2i}$

$$= K_1 \sum_{i=1}^{m} n_i P_{1i} P_{2i} / \sum_{i=1}^{m} n_i P_{2i}$$

To solve the equation, cars of different weights will be used, where the weights are known. K will therefore denote the role of change of velocity, and could be a constant, or a function of, say, change of velocity.

(1) is estimated by $K_1 (X_1 / (X_1 + X_3))$ (2) and, $K_1 = \dfrac{\left(X_1/(X_1+X_3)\right)_{m_b}}{\left(X_1/(X_1+X_3)\right)_{m_a}}$ (3) where,

m_a and m_b are mass relations in the matched pairs. These mass relations are transformed to relative change of velocity by

$$\frac{m_b}{m_a} = \left({m_2}/{(m_1+m_2)} \right)_b / \left({m_2}/{(m_1+m_2)} \right)_a$$

The analytical functions chosen to describe the risk functions have been applied simply using either a linear function or a power function. This issue would have to be further investigated using more advanced material.

It is obvious, that while the importance of a marginal change of velocity will be calculated, as well as parts of the risk function, absolute values cannot be given. If this is to be done, a key value must be brought into the equation.

MATERIAL

Police reported data containing at least one injured person on two car crashes in Sweden year 1996-2006 was used for the analysis. While police reported crash data is known to suffer from a number of quality problems, none of them is likely to influence the findings of this study to any large degree.

RESULTS

Two analyses were conducted. In the first, cars of different year models were compared, one set of vehicles from year model 1988 to 1990 and one set from year model 1998 to 2000, in order to study if both older and newer car crash protection could be described by the power model. In table 3, the risk ratios with matched pairs could be seen. While the result cannot be fully explained by improved safety but also increase in weight, it is obvious that the risks have decreased dramatically for fatalities and much for serious injuries while minor injuries have only been affected slightly.

Table 5.
Relative risk of minor, serious and fatal injury for cars of different year models and equivalent speed reduction

	1988-1990 Relative risk	1998-2000 Relative risk	Injury reduction %	Speed equivalent %
Minor injuries	1.02	0.99	- 3	- 6
Serious injuries	1.18	0.86	- 27	- 14
Fatal injuries	1.35	0.81	- 40	- 14

It can be seen in table 5, that the resulting speed reduction is similar for the three injury severity levels. The equivalent speed reduction for minor injuries is slightly lower, but if a 14% speed reduction would be applied, the reduction in injury risk would have to be 7% instead of 3%, which is a small difference.

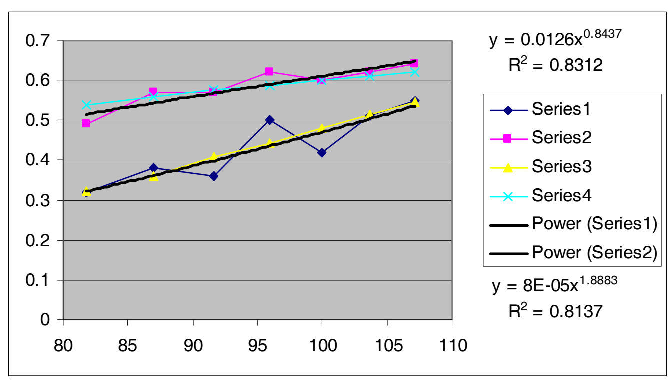
In the second analysis, the importance of change of velocity is demonstrated. By varying the weight of the opponent vehicle, the change of velocity component could be studied in isolation. This can be seen for minor and serious injuries.

Table 6.
Expected and real outcome

Weight kg	Rel Delta V	Expec. SI	Expec. MI	Outcome SI	Outcome MI
900	81.8	0.32	0.54	0.32	0.49
1000	87.0	0.36	0.56	0.38	0.57
1100	91.7	0.41	0.58	0.36	0.57
1200	96.0	0.44	0.59	0.50	0.62
1300	100	0.48	0.60	0.42	0.60
1400	103.7	0.52	0.61	0.51	0.62
1500	107.1	0.55	0.62	0.55	0.64

In figure 3, the data from table 6 has been used to generate regression functions for the real life outcome of relative risks for increasing weight of the opposite car, i e higher change of velocity. The function reinforce that the best representation of a power function of more or less the same order as predicted by the power model. For minor injuries, the power is 0.84 instead of 0.5, and for serious injuries 1.89 instead of 2. Fatal injuries could not be calculated because of small numbers.

Figure 3.
The relation between relative change of velocity (x-axis), real outcome of serious and minor injuries (series 1 and 2), predicted outcome for serious and minor injury (series 3 and 4) and regression lines and functions



In order to control for all severity types, including fatalities, a double pair match with the relative risks between two vehicles was conducted. It was estimated through the power functions that the relative risk would vary with the weight for both vehicles, so that for serious injuries, the risk for increasing weight would be doubled, and contrary for the opposing vehicle. The opposite vehicle would always be the average car with an average weight of 1300 kg.

Figure 4.
Calculated (series 1) and actual (series 2) matched pair risks for cars of different weights, minor injuries. Relative speed refers to case car

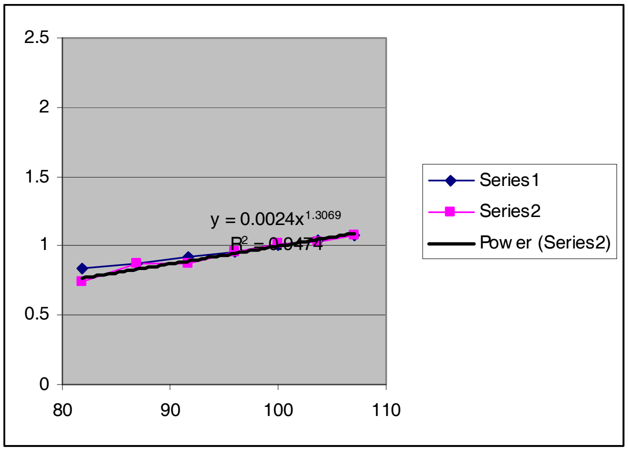


Figure 5.
Calculated (series 1) and actual (series 2) matched pair risks for cars of different weights, serious injuries. Relative speed refers to case car

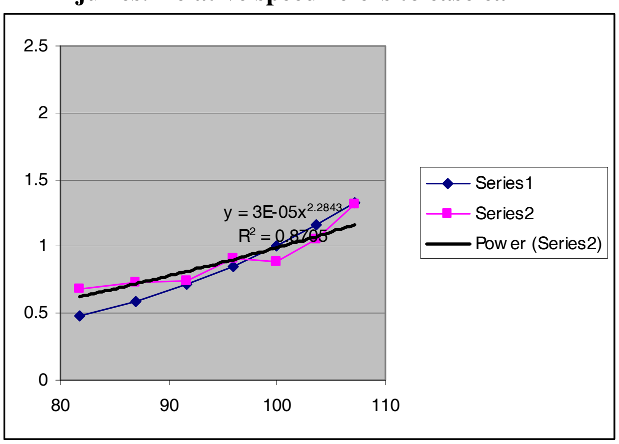
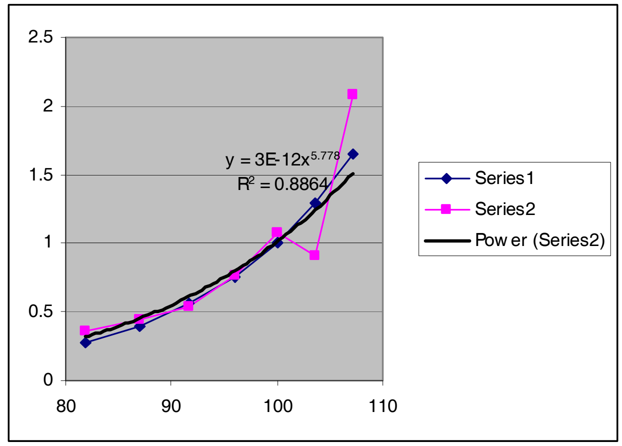


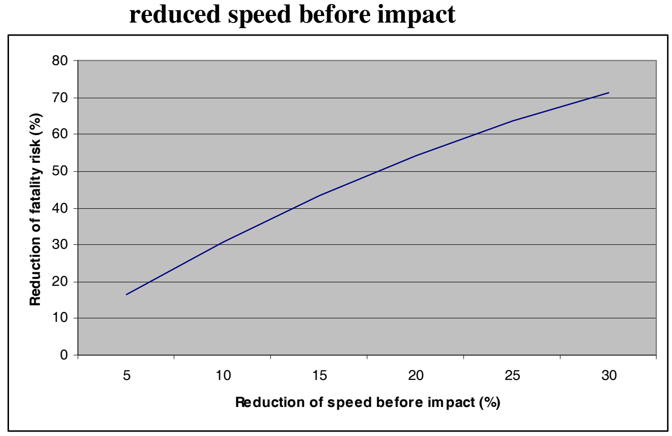
Figure 6.
Calculated (series 1) and actual (series 2) matched pair risks for cars of different weights, fatal injuries. Relative speed refers to case car



Figures 4 to 6 shows that the relationship between speed via relative change of velocity is almost totally in line from what could be expected from the power models. Even for fatalities, with the extreme power of changing speed, expected and real life outcome are very close. In that sense, there is not much to be explained by any added risk reduction from improves safety from more heavy cars, most of the variation could be explained simply by varying change of velocity.

The potential effects of automatic emergency braking can be calculated using the power model. While in case of braking before impact, both the energy level as well as change of velocity will be altered. Using the power model for the calculation of the effects can only pick up the change of velocity. Simply used, a reduction of speed before impact by, say, 10 %, gives a reduction of fatality risk by 31 % and the risk of a serious injury by 19 %.

Figure 7.
The reduction of fatality risk (%) in relation to reduced speed before impact



DISCUSSION

The relation between speed, speed reduction and the risk of injury of different severities is well known and generally established (Elvik et al 2004). The underlying theory is less well known and explained, but the fact that the more serious injury, the more sensitive to change of velocity seems to be found in many different kinds of studies (Kullgren 2008)

The idea that car safety can be described, at macro level, in speed and speed reduction seems natural but has only been used in looking at change of velocity studies. In this study, it is demonstrated that speed and change of velocity play a major role in explaining variations on safety. Furthermore, is has been demonstrated that the power model, implying that the impact of speed would vary with injury severity, is valid. The finding, that the power models are valid, is not in itself surprising, but has a number of implications, where one is demonstrated in this study.

The results can be used to demonstrate the impact of active or integrated safety systems like brake assist (EBA) or autonomous emergency braking and for validation of the safety impact of such systems. It can be expected that emergency braking, if reducing the speed before an impact with, say 10 %, can reduce the risk of a fatal injury with approximately 30%. This would be expected in crashes into fixed objects, while the reduction would be different in a car to car frontal collision where occupants in both vehicles would benefit. The total effect in a frontal impact would though not be lower, in fact the likely outcome is an even greater effect. Based on analysis of data from crash recorders Kullgren (2008) estimated a reduction of AIS2+ injuries in frontal crashes of more than 40% if the impact speed could be reduced with 20 km/h in all cashes. The studies show a major if not dramatic consequence of new technology and probably more than what is expected intuitively.

The method used could only pick up the consequences of reducing speed before impact on the change of velocity. The crash energy would also be reduced thus limiting the risk of intrusion, which also influence injury risk. The expected benefits of braking are therefore likely to be larger than presented here.

There are other methods to generate risk functions, such as crash recorders (Kullgren 1998, Kullgren 2008). Such methods have the potential to also increase the knowledge about distributions of absolute impact velocities or at least distribution of change of velocity. In doing so, the effects of braking could be further estimated.

Braking before impact could also avoid crashes, which would imply that the power should be raised by one unit, leaving us with even higher effects. This could be the case for pedestrian impacts. If the power 4.5 would be used, a 10 % reduction of speed before impact would lead to a 40 % reduction of fatalities. The data in this study can though not be used to validate the risk functions for pedestrian impacts, and whether the power model is applicable for pedestrians.

Finally, the study once more demonstrate the general impact of speed, and that speed is more related to the outcome of a crash rather than the incidence of a crash. While this might not be how citizens perceive the role of speed, the introduction of automatic emergency braking implies that such knowledge should be brought to the general public to increase the demand for automatic braking systems.

CONCLUSIONS

- By using empirical data, it seems that the power models are applicable to estimate the role of change of velocity on fatal and serious injury
- By using the power models, it can be estimated that automatic emergency braking can have a major effect on fatal and serious injury. A 10 % reduction of speed before impact can lead to 30 % reduction of fatality risk and 19 % on the risk of a serious injury

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USAGE OF SURROUND SENSOR INFORMATION FOR PASSIVE SAFETY – CHALLENGES AND CHANCES

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ABSTRACT

In this paper an approach of using surround sensor information for passive safety is being proposed. The combination of active and passive safety is necessary to reach the high aims to reduce the fatalities in road traffic up to 50% since 2000. Especially the surround sensor, like the video sensor, offers lots of information that can beneficially be used for advancing the current passive safety systems and design new functions that are not possible with current state of the art passive safety sensors.
An overview about such possible passive safety functions is given with subject to the necessary sensor requirements. These requirements are derived among others from accident statistics and the required restraint system which should be activated. A major outcome of this evaluation, the different sensor requirements for comfort and safety functions, is presented.
As an example for such kind of passive safety functions, the Video-supported pedestrian protection is presented with focus on reducing the crash severity by activation of a brake system and by supporting the current pedestrian protection system to pop up the hood by recognizing the pedestrians.
As another example, Video-based PreSet and Video-based PreFire are presented with focus on protecting the occupant in the best way possible by an optimal choreography of the reversible and irreversible restraint systems. Therefore, the sensor characteristic must be slightly different and well designed to the special functional variant.
In the end a first indication about the potential of such systems and a forecast of future systems is given.

INTRODUCTION

In the European Union still almost 40.000 people die in traffic annually. The aim is, to halve the fatalities from the year 2000 to the year 2010 of the road fatalities (see fig. 1). Current active and passive safety systems have done the first step in this direction. But the current status illustrates, that the set target will probably not be reached in 2010.

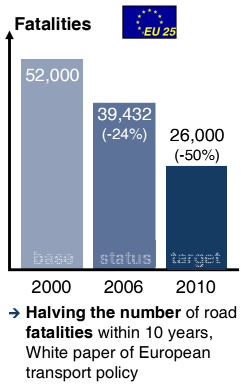

Figure 1. Overview of aim to reduce the fatalities in EU and the current state (see [1])

Nevertheless a positive trend can be seen. Currently the equipment with active and passive safety systems will be supported by legislation and consumer tests (e.g. EuroNCAP).
In the market two movements are perceived for the combination of active and passive safety. On the one hand the functional enhancement of existing hardware, like the use of radar-sensor information for passive safety functions or the use of night vision information for pedestrian recognition is known. The target here is, to use synergies of the systems without influencing the requirements of the specific components. On the other hand the specialization of the surround sensors for optimal use for passive safety is another trend. The chance here is to address new functions which are necessary to handle megatrends like CO_2 reduction for example.

Motivation Of Using Surround Sensor Information For Passive Safety

The expectations in surround sensors are legitimate. With the help of the surround sensors many important information can be produced prematurely. This will be clear as follows.

Physical Motivation – To determine the crash severity the following parameters are relevant:

- Impact velocity
- Crash type (e.g. full frontal crash, offset crash, …)
- Mass / stiffness of crash participant.

Traditionally the typical crash sensors, like acceleration sensors, allow gaining information about

- Mass / stiffness of crash participants
- Crash type (e.g. by using y-part of crash signal).

Basically, the acceleration sensors can provide this information, but typically not within the required time.

The Surround sensors allow getting additional information about

- Impact velocity
- Crash type
- Object type

The advantage compared to the typical crash sensors is that this information is available before the crash. So the information could be used already at the beginning of the crash.

Basically, a lot of surround sensors can deliver one or more of the above mentioned information. But they often differ in the quality of the information. Radar sensors for example deliver a high precision of the closing velocity or distance (see [2], [3]). A mono video-sensor for example offers the potential to deliver a first indication of the crash type (e.g. offset-crash) and the object type.

Many mono video based systems are already in the market. They are used for a wide set of different functions like Night View, Road Sign Recognition and Lane Departure Warning. Additionally the detection of traffic scenario relevant objects is possible. When looking at these functions, there is a trend in delivering the mentioned functions all from the same camera.

It is obvious that the market penetration and the increasing number of such systems give the opportunity to use this information also for passive safety functions, especially the object information without modification of the requirements.

Overview Of Possible Passive Safety Functions

The passive safety covers two topics in general, the pedestrian protection and the occupant safety.

The scope of pedestrian protection is to protect the pedestrian in case of an unavoidable accident. In 2005 for example 18% of all fatalities in European road traffic are pedestrians (see fig. 2). Currently the protection is reached by structural measures (passive solution) and by activation of a pop up hood (active solution). In case of using acceleration sensors in the bumper that detect the collision with a pedestrian and the system activates the pop up hood by a pyrotechnical activation for example. The function Video-supported Pedestrian Protection could be helpful here to classify the collision objects in an alternative way or to reduce the degree of freedom of acceleration-sensor-based classification.

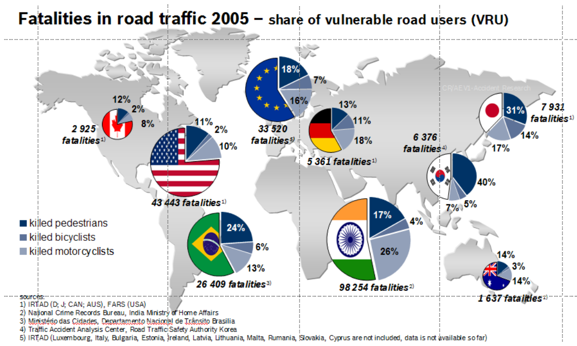

Figure 2. Fatalities in Road Traffic 2005 – Share of VRUs (see. [4])

The scope of occupant safety is to protect the occupant by activation of available restraint systems to reduce the injury risk. Video-based PreSet and Video-based PreFire are two possible functions, who assist to generate an optimized firing choreography and to couple the occupant early on the deceleration of the vehicle. These functions address up to 40% of all accidents (30% of all collisions, see fig. 3). The PreSet functionality is already represented in the market based on radar or lidar information.

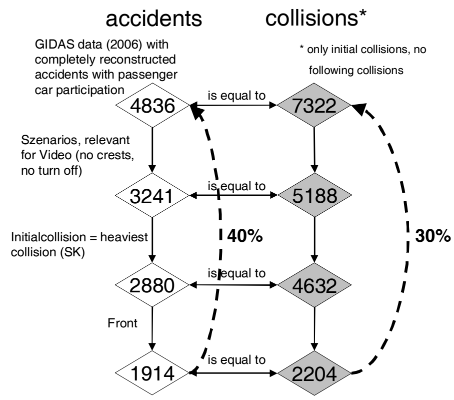

Figure 3. Accident data base analysis of Potential for PreCrash functions

Video-supported Pedestrian Protection

The function Video-supported Pedestrian Protection (VPP) supports the conventional pedestrian protection, which is already in the market.

This support can basically be given in two ways:

- Direct classification, which means that the video sensor information is used to recognize a collision object as a pedestrian
- Indirect classification, which means that video information is used to support the acceleration sensors of state of the art pedestrian protection systems.

The direct classification can be done using strong or weak classification approaches.

By saying strong classification approach, pattern matching and the use of trained classifiers with the focus on shape and appearance are meant. Strong classification of pedestrians for pedestrian protection, which has to work milliseconds before crash is a very challenging task. In this phase before the crash happens, a pedestrian is partly occluded and can be in a variety of different poses and orientations in front of the vehicle. That is why a weak classification offers more robust support to a pedestrian protection function.

By weak classification, methods using more general features like size and aspect ratio combined with generic features like motion are meant. Especially motion patterns are very powerful for classification, because over 90% of the hit pedestrians are moving before the collision happens (see fig. 4) and 75% cross from left or right (see fig. 5). Measuring motion by using optical flow gives strong support to detect and classify pedestrians. Due to the fact that VPP only needs information at the time of impact, even not moving pedestrians can be detected shortly before collision by the parallax caused through the elevation of the pedestrian.

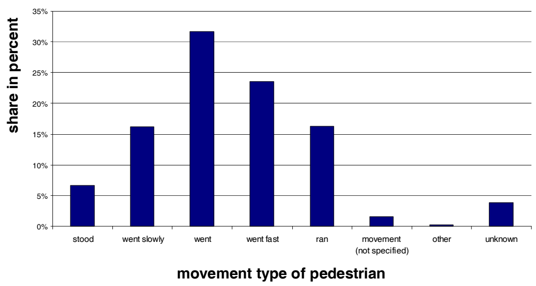

Figure 4. Distribution of the movement types of pedestrians before crash

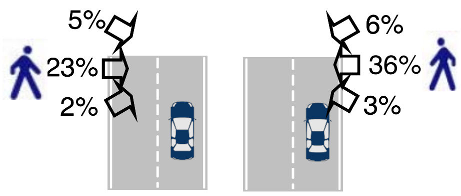

Figure 5. Moving directions of pedestrians before crash

Both methods of classification can be realized with current cameras in principle. But they suffer from limited resources and detection capabilities as well as classification performance.

Indirect classification supports the classification given by the state of the art pedestrian protection systems. The benefit given by video sensors can be found in the better adjustment of fire thresholds according to the information given by the video sensor (e.g. impact position). This can be also fulfilled by using weak classification method as described above.

The aim of both classification methods (directly / indirectly) is to enhance the fire decision characteristics, for example by better separation of the mayfire object from the mustfire objects.

Regarding the necessary field of view, an opening angle of 40° is a possible choice. 100% of the fatal accidents can be addressed by selecting this opening angle and nearly 86% of all badly injured people (see Table 1). By the way, the opening angle of many state of the art video based driver assistance systems is 40°.

Table 1.
Cases of Pedestrian accidents covered according to field of view

	Cases in the range of the field of view		
	slightly injured	badly injured	fatal
± 10°	49,2%	58,7%	84,9%
± 20°	80,0%	85,9%	100,0%
± 30°	90,4%	95,1%	100,0%
± 40°	93,9%	95,8%	100,0%
± 50°	96,4%	97,6%	100,0%
± 60°	97,3%	97,6%	100,0%

A second effort is to support the pedestrian protection in reducing the impact velocity by preparation or activation of the brake system. For this function it is necessary to use a surround sensor who delivers the closing velocity and the time to impact. Mono video is not able to deliver metric information like distance or velocity directly from the sensor. Furthermore pedestrians are strongly varying objects which are very hard to be modeled. Due to these facts the use of a stereo video system is strongly recommended.

Test scenarios, based on GIDAS data base information [5], show that for pedestrian protection the closing velocity will be reduced by around 15%. The underlying assumption is that the system is able to build up the brake pressure to reach a deceleration of 4 m/s² in 400 ms and continues the braking for another 400 ms. To activate the brake system the requirements for the necessary attributes, like closing velocity or time to impact, are higher than for support of classification, because of the avoidance of an inadvertent activation.

The third manner is to warn the driver or the pedestrian in a critical situation that could result in a collision.

The last two points are mostly covered by the BMBF project AKTIV with extensive studies.

Video-based PreSet

The name PreSet stands for **Pre**Crash **Set**ting of algorithmic parameters. The main functionality is to reduce the severity of injury in the case of a crash by optimized deployment of restraint systems. Therefore a high accuracy of the information about

the relevant parameters which define the crash severity is needed.
If Video-based PreSet is realized with a mono video system it is only possible to get information, like offset/overlap and object type of a high quality. According to the accuracy of the desired information there are two ways of data acquisition: One is to get the exact offset and overlap information at the time of impact. Then the distance is known and the relevant data can be calculated from the image dimensions and positions. The second one is to get information before the impact, a model of the collision object has to be assumed. Assuming the collision object is a passenger car, then the width is known and the relevant data can be derived.
Also knowing the type of the collision object by classification helps to prepare the restraint systems accordingly.
Regarding the necessary field of view for PreSet, an opening angle of 40° is also a good choice. Once again, 100% of the fatal accidents can be addressed by selecting this opening angle, and almost 95% of the badly injured people (see Table 2).

Table 2.
Relevant cases of crashes covered according to field of view

Cases in the range of the field of view

	unviolated	slightly injured	badly injured	fatal
± 10°	73,3%	75,0%	86,3%	94,1%
± 20°	81,9%	88,0%	94,8%	100,0%
± 30°	88,4%	92,3%	97,2%	100,0%
± 40°	92,6%	96,3%	98,2%	100,0%
± 50°	95,1%	98,1%	99,1%	100,0%
± 60°	96,3%	98,7%	99,6%	100,0%

If the mono video deliver offset/overlap information in the required quality the algorithmic thresholds can be modified to recognize an offset-crash earlier (see fig. 6).

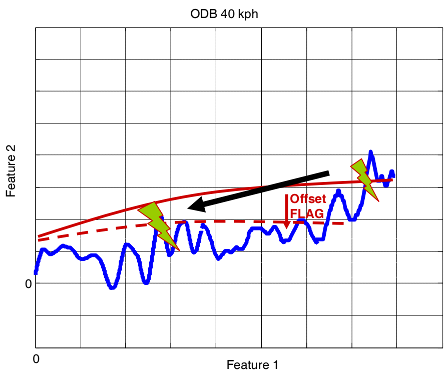

Figure 6. Active principle of a threshold modification in case of offset-information

If the mono video deliver a reliable classification of the object it is possible to make a first estimation of the mass and stiffness of the collision object. With this information it is possible to modify the algorithmic thresholds in the same manner as shown above. In this case the modification is done for all crash types.
If the surround sensor allows getting additionally closing velocity and time to impact in the required quality, then it is possible to prosecute a complete approach in dependency of the expected crash severity.

Video-based PreFire

The name PreFire stands for **Pre**Crash **Fi**ring of **re**versible restraints. The main functionality is preconditioning of the occupant before the crash happens. Because under real driving conditions, the occupants of a vehicle are in many cases not in the optimal position for the best protection offered by today's restraint systems.
For this function it is necessary to get high quality information about the distance and the closing velocity of the objects, preferential to reduce possible faulty activations. If the sensor delivers additional offset and overlap information about the objects the number of inadvertent activations could be reduced significantly.

Challenges And Chances Of Future Systems

On the bases of the already mentioned functions it appears that these functions have different requirements for using surround sensor information. All in all the passive safety systems will adjust their functions on the following information:

- Closing velocity
- Time to impact
- Offset, overlap
- Impact angle
- Contour (point of impact)
- Mass / stiffness of participant

With these attributes on the interface the passive safety is well prepared for the future to enhance the protection of the system. It is evident that the surround sensors could not deliver all information in the best quality. For example, currently there is no existing surround sensor who delivers exact data about the mass and stiffness of an object, but in future C2X-information can complete this. The challenge here is to use the transmitted information in the best possible way.
In the future two trends can be seen in the market: On the one hand, the trend for further networking with existing surround sensors (see also [6], [7]) and on the other hand, developing specialized surround sensors for passive safety. These specialized sensors have to fulfill the high requirements of passive safety more exactly for

further improvement of the passenger protection. Such sensors then allow the use of information for example for new functions like PreAct or PreTrigger. The function PreAct – **Pre**Crash **Act**ivation of structure elements – will modify the stiffness of structure elements of the vehicle before the crash happens. The advantage here is to use an additional control element for further optimizations of the crash choreography or further pedestrian protection. The modification of the front structure provides potential for weight reduction with equal safety for the occupant. This will have positive effects on CO_2 reduction. The function PreTrigger – **Pre**Crash **Trigger**ing of irreversible restraints – will activate new irreversible restraints (e.g. smart airbags [8]) even before the crash contact. This new functions will require high quality of the information from the surround sensors or C2X communication in a high data rate.

CONCLUSIONS

New functions for driver assistance like Adaptive Cruise Control, Lane Departure Warning, Road Sign Recognition etc. use many different surround sensors to process the information about the vehicle's environment. This information can be used to enhance the classical passive safety functions. When looking at the requirements of such functions, it shows up that the sensor field of view is suitable for a wide range of addressable accidents. Considering the required latency times, update rates and accuracy, it comes out that these numbers are often not met by current surround sensors for driver assistance functions.
To reach all theses requirements for passive safety functions, the sensor performance still needs to be improved. This will be a chance to enhance the protection of passengers and pedestrians.

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PRE-CRASH PHASE ANALYSIS USING A DRIVING SIMULATOR. INFLUENCE OF ATYPICAL POSITION ON INJURIES AND AIRBAG ADAPTATION.

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ABSTRACT

This paper deals with an approach to analyze driver behavior during critical events using a driving simulator. A scenario of an unavoidable crash is simulated. Eighty subjects have participated to this experiment. Drivers' behavior is video recorded, as well as many mechanical and physiological measurements. Most of drivers are observed to swerve away to avoid the collision. This leads many of them to have one arm in front of the steering wheel at time of crash. The drivers' trunk and arm positions during the collision, observed on the simulator, are analyzed with numerical simulations of a 56 km/h frontal collision. The results of the computational runs put forward injurious situations, especially when the driver's arm is behind the steering wheel and hits the head under airbag deployment. Then, an experimental campaign of airbag deployment with a hybrid III 50th percentile dummy is carried out to correlate numerical simulations. Finally, new airbag generations, allowing slower deployment, are tested. They induce a reduction of injury severity in the case of Out of Position (OOP).

INTRODUCTION

Vehicle safety is the major issue when designing a car. Many studies deal with the communication between drivers and driver support systems, with aim to assist driver from normal driving situation to critical one. Large improvement in active and passive safety technologies in vehicle has helped to reduce the number of accidents significantly. Active security operates before an incident and includes prevention (Anti-lock Brake Systems, Electronic Stability Program, etc) to avoid a crash. Passive safety concerns the period after the crash, it tries to protect occupants and pedestrians to minimize car occupant injuries. Main examples of passive security systems are airbags and seat-belts. These restraint systems are designed to minimize injuries during an impact by smoothly absorbing the kinetic energy of the occupant during a crash event [7].

In order to quantify the efficiency of the passive security systems on injury severity, normalized crash tests are performed with crash test dummies. The injury level is approximated using specific criteria related to critical body segments such as the Head Injury Criteria (HIC) and the Thoracic Trauma Index (TTI). Precise rules are imposed by the norm to position the dummy, whose posture must represent a seated and restrained driver. Particularly, the hands are on the steering wheel and the superior part of the torso leans against the backseat. Thus, passive systems efficiency does not take into account the driver anthropometry, real comfort driving position and reflex reactions facing an incident. The non normalized postures are called 'out-of-position' (OOP) postures. Some OOP postures, defined to be the most prejudicial for car occupants, have been tested by the NHTSA. For example, crash tests are performed with a dummy positioned with the torso as close as possible to the steering wheel, or, with the dummy face (nose) touching the top of the steering wheel [11]. In these tests, the dummies are not restrained by the seat-belt. Nevertheless, the standardized and these OOP crash tests do not take into account real postures that a driver or a passenger adopts at the time of crash.
This study is designed to investigate how a car driver modifies his posture just before a frontal crash and then to quantify the influence of these observed pre-crash postures on injury mechanisms by computer simulation. Experiments are performed by using car driving simulators, in which an unavoidable frontal accident is carefully designed. Risk pre-crash positions are observed and are modeled using a digital human model. Static airbag deployment test are performed to validate simulations with a hybrid III 50th percentile dummy. Finally, new generation of airbags is tested, using bonded bags. This allows a slower deployment, in order to reduce injuries.

METHODS

The LAMIH driving simulator, SHERPA

Two experimental campaigns are carried out with the static and the dynamic LAMIH car driving simulator, SHERPA (French acronym for 'Simulateur Hybride d'Etude et de Recherche de PSA Peugeot Citroen pour l'Automobile'). A description of the static car driving simulator can be found in [8]. The dynamic driving simulator is derived from a Peugeot 206 mounted on a hexapod composed by six electric jacks (Figure 1a). The front and rear scenes are projected by LCD screens. For both campaigns, the same crash scenario is reproduced.

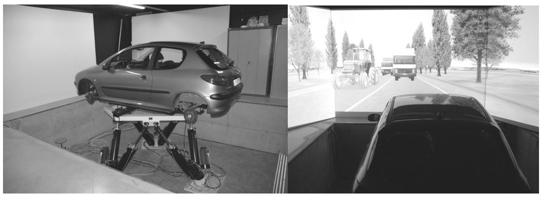


Figure 1. a) Dynamic driving simulator. b) 180° front visual field before a crash.

Experimental design

The experiment is designed to investigate the influence of driving responses on crash occurrence. Each subject encounters an emergency traffic event during the experimental drive. The subjects believed they were participating to an ergonomic study so they could not predict the existence and the location of the collision. The scenario is as follows.
The collision occurs on a main road segment. The driving environment is composed of a road with two lanes, separated by a white line. This road is bordered with trees. A truck suddenly appears into the lane used by the host vehicle (i.e. driving simulator) such that the scenario could not be expected by the subject. This vehicle overtakes a tractor on his way. The presence of trees along the side of the road and the trucks make the crash unavoidable (Figure 1b). To increase the level of reality, a real physical impact is added. At the moment of the virtual crash, a substantial foam rubber block impacts the windscreen of the car, and the sound of a truck horn is emitted.
Eighty randomly-selected subjects have been recruited to participate to this driving experiment. Most of subjects are aged between 22 and 30 years old, with more men than women. The mean weight and height of the subject is 78 kg and 1.77 m respectively. All participants have a valid driving license. Half of them have driving experience of 8-27 years. The other half of the subjects has their driving license for less than 7 years.

Experimental procedure

Subjects first provide their personal information—sex, age, and driving experience. Anthropometric data are measured in a calibrated space to allow a postural reconstruction method [5,6].
Experimental instructions are given for the driving task and subjects are instructed by assistants in how to operate the simulator.
After a short training session designed to familiarize the subjects with the simulator, each subject is asked to drive a 50-kilometer dual carriageway (35 to 40 minutes). The run is mainly composed of main roads, with a small section of motorway. Throughout the trip, regular traffic is reproduced so that subjects respect the Highway Code and adapt their driving to the presence of other cars. Five minutes before the end of the experiment, a stress situation occurs to make the driver attentive: a car, approaching a crossroad from the right, runs the stop sign, which may lead to an accident with the subject vehicle. This situation is designed to remind subjects that unpredictable events may happen at any time. After a few minutes, the unavoidable crash situation is introduced. At the end of the run, drivers are asked to fill out questionnaires evaluating their driving characteristics (behavior patterns), their reactions to each separate situation and the realism of the experiment.

Measurements

For both campaigns, the videos of front and back screen, as well as driver views are recorded during the experiments (Figure 2).

Figure 2. Interiors views of video recording during the crash.

The driver-vehicle-environment interaction parameters are measured, such as impact velocity, time of crash, steering wheel position, state of the pedals, gear lever position and the arrangement of the vehicles on the road. Furthermore, mechanical and physiological measurements are added for the second campaign with the dynamical driving simulator. Mechanical data include the forces and torques transmitted by the driver to the steering wheel, the seat and the brake pedal. Physiological data include heart rate, respiratory and electrodermal activities, skin temperature and electromyography data of few muscles of the upper and lower limbs (triceps brachii, biceps brachii, trapezius, wrist extensor, quadriceps, soleus muscle, tibialis anterior, ischio). All these signals are triggered with videos and simulators events. These physiological measurements can be used to investigate human incident detection. The mechanical measurements serve to improve computational simulations.

Results

Simulation realism

Subjective and objective data are collected to evaluate the realism of the experiment [8]. Subjective data include both the driver's verbalizations and their answers to questions evaluating their driving behavior and their reactions. Objective data include the time needed to release the accelerator, to brake, to engage the clutch, to change gears, as well as, the amplitude of the braking and swerving maneuverings provoked by the truck passing. It can be concluded that most of the subjects have reacted as they would have done in real situation.

General driving characteristics

All subjects react to the traffic accident by actions on pedals and/or steering wheel. General driving performances are presented in Table 1. The average speed in town is calculated from the host vehicle speed at 50 m after the enter town panel and its speed at 50 m before the exit town panel. The collision occurs on a main road segment. The average driving speed of the host vehicle is 76.3 km/h. This speed is quite steady until the truck appears on the lane (the truck is visible at 150 m). Then, most of subjects brake. The average deceleration rate is 1.6 m/s². The overlap of the vehicles during the impact is 61.8% and the angle between the truck and the host vehicle vary from -18.8° à 5.1°. Most of subjects try to avoid the truck on the left. Six percent of drivers avoid the collision.

Table 1.
General driving performances

	Mean	Min	Max	SD
Motorway speed (km/h)	122.6	97.8	135.7	8.6
Highway speed (km/h)	65.3	59.4	71.0	3.0
City speed (km/h)	48.9	32.9	60.0	5.9
Speed at 150m before crash (km/h)	76.3	50.7	96.1	10.3
Speed when truck passes (km/h)	78.5	58.4	94.5	8.6
Speed at crash time(km/h)	70.6	45.7	90.8	10.1
Collision overlap (%)	62.4	4.4	99.3	27.0
Collision angle (°)	-2.0	-18.8	5.1	5.1
Distance when truck passes (m)	29.6	18.3	39.0	4.7
Deceleration from truck passing to crash (m/s²)	1.6	3.8	-0.4 (Acc.)	1.0

Effort analysis

The Figure 3 indicates the position and the positive direction of force sensors. A pressure map is added to locate efforts on the seat.

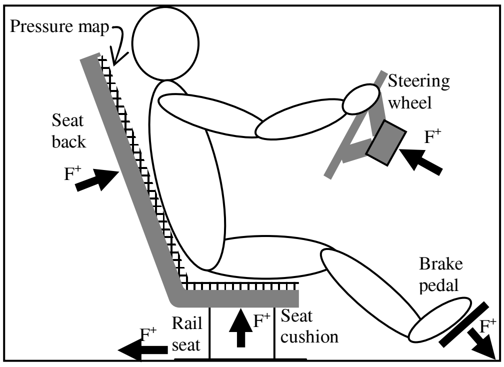


Figure 3. Sensor positions.

At the end of the experiment, subjects are asked to push the steering wheel and the pedals with maximal voluntary efforts, with hands placed in a 10 and 2 o' clock position. The efforts measured in the seat, the steering wheel and the pedals are denoted F_{full}. The same experiment is reproduced but with pulling on the steering wheel. The values of F_{full} are used to normalize efforts measured during experiment. If the driver pushes the steering wheel during impact, the F_{full} efforts measured during pushing out are used to normalize the values. If the driver pulls on the steering wheel during the crash, the F_{full} efforts measured during the pulling on are used to normalize the values. This normalization allows to compare driver efforts independently of their morphological variability.
Four situations are analyzed:
1) Quiet situation: time interval from -50s to -5s before the truck appearance time in the frontal view.
2) 150 m before crash: time interval from -0.5s to 0.5s of the truck appearance time.

3) Truck passing: time interval from -0.5 s to 0.5s of the white line crossing time.
4) Crash: time of the collision (the vehicle hits the truck).
For each driver, the efforts exerted on the seat (cushion and back), the steering wheel, the adjustment rail of the seat and the pedals are computed for each situation. Except for the crash time, these forces correspond to mean values computed on the corresponding time interval.
For each situation, inter-individual statistics are presented (Table 2.):
-Min F: minimum effort among all drivers
-Min F/ F_{full}: minimum ratio among all drivers
-Max F: maximum effort among all drivers
-Max F/ F_{full}: maximum ratio among all drivers
-Mean: mean of all drivers efforts and ratio
-Std dev.: standard deviation

Table 2.
External forces during track

Seat back	Min (F)	Min (F/F_{full})	Max (F)	Max (F/F_{full})	Mean value	Std dev.
Quiet situation						
F (N)	**-220.7**	-70.9	**-42.9**	-220.7	-131.2	47.1
F/F_{full} (%)	38.6	**5.8**	6.9	**38.6**	17.1	7
F_{full} (N)	-571.8	-1231.1	-622.3	-571.8	-811.9	259.1
150 m before crash						
F (N)	**-199.4**	-76.2	**-41.7**	-198.1	-127.7	46.2
F/F_{full} (%)	24	**6.2**	6.7	**34.6**	16.6	6.5
Fsat(N)	-831.3	-1231.1	-622.3	-571.8	-811.9	259.1
Truck pass						
F (N)	**-233.8**	-32	**-32**	-233.8	-132.3	50.3
F/F_{full} (%)	40.9	**5.1**	5.1	**40.9**	17.1	7.2
F_{full} (N)	-571.8	-622.3	-622.3	-571.8	-811.9	259.1
Crash						
F (N)	**-1078.3**	-225.2	**-225.2**	-1078.3	-503.3	194.5
F/F_{full} (%)	188.6	**19.1**	19.1	**188.6**	66.6	32.9
F_{full} (N)	-571.8	-1176.8	-1177	-571.8	-811.9	259.1

Cushion seat	Min (F)	Min (F/F_{full})	Max (F)	Max (F/F_{full})	Mean value	Std dev.
Quiet situation						
F (N)	**-687.9**	-351.9	**-300.0**	-527.3	-401.7	90.8
F/F_{full} (%)	82.4	**64.1**	89.8	**92.0**	78.9	7.6
F_{full} (N)	-834.4	-548.9	-334.2	-573.0	-509.9	104.5
150 m before crash						
F (N)	**-687.6**	-348.6	**-300.2**	-530.9	-408.1	88.7
F/F_{full} (%)	82.4	**63.5**	89.8	**92.6**	80.2	6.9
F_{full} (N)	-834.4	-548.9	-334.2	-573.0	-509.9	104.5
Truck pass						
F (N)	**-708.5**	-366.7	**-300.8**	-533.5	-408.3	89.7
F/F_{full} (%)	84.9	**66.8**	90.0	**93.1**	80.3	6.9
F_{full} (N)	-834.4	-548.9	-334.2	-573.0	-509.9	104.5
Crash						
F (N)	**-522.5**	-114.1	**-114.1**	-516.1	-259.5	102.5
F/F_{full} (%)	62.6	**24.0**	24.0	**110.2**	51.1	18.0
F_{full} (N)	-834.4	-475.7	-475.7	-468.2	-509.9	104.5

Seat rail	Min (F)	Min (F/F_{full})	Max (F)	Max (F/F_{full})	Mean value	Std dev.
Quiet situation						
F (N)	**79.4**	82.5	**199.1**	133.3	125.9	33.2
F/F_{full} (%)	19.9	**15.3**	32.6	**42.1**	25.2	7.4
F_{full} (N)	399.8	538.4	611.4	316.5	520.4	122.0
150 m before crash						
F (N)	**79.2**	81.8	**198.9**	134.8	125.5	33.4
F/F_{full} (%)	19.8	**15.2**	32.5	**42.6**	25.1	7.5
F_{full} (N)	399.8	538.4	611.4	316.5	520.4	122.0
Truck pass						
F (N)	**80.1**	87.9	**205.5**	137.4	129.0	34.5
F/F_{full} (%)	20.0	**16.3**	40.8	**43.4**	25.8	7.6
F_{full} (N)	399.8	538.4	503.9	316.5	520.4	122.0
Crash						
F (N)	**216.5**	216.5	**821.0**	760.1	537.2	151.6
F/F_{full} (%)	28.8	**28.8**	134.3	**240.2**	111.5	48.1
F_{full} (N)	752.5	752.5	611.4	316.5	520.4	122.0

Steering wheel	Min (F)	Min (F/F_{full})	Max (F)	Max (F/F_{full})	Mean value	Std dev.
Quiet situation						
F (N)	**-34.4**	16.4	**16.4**	-34.4	-6.8	13.0
F/F_{full} (%)	8.3	**-5.8**	-5.8	**8.3**	0.6	3.6
F_{full} (N)	-414.6	-284.1	-284.1	-414.6	-124.1	461.4
150 m before crash						
F (N)	**-29.8**	20.2	**20.2**	-28.7	-7.1	13.5
F/F_{full} (%)	-3.9	**-7.1**	-7.1	**7.3**	0.8	3.6
F_{full} (N)	769.8	-284.1	-284.1	-394.6	-124.1	461.4
Truck pass						
F (N)	**-60.7**	-14.0	**22.8**	22.8	-14.9	20.6
F/F_{full} (%)	8.4	**-4.5**	14.7	**14.7**	3.8	5.2
F_{full} (N)	-724.4	313.4	155.1	155.1	-124.1	461.4
Crash						
F (N)	**-561.1**	29.3	**210.2**	210.2	-92.7	167.2
F/F_{full} (%)	135.3	**4.7**	135.6	**135.6**	38.0	40.6
F_{full} (N)	-414.6	629.3	155.1	155.1	-124.1	461.4

Brake pedal	Min (F)	Min (F/F_{full})	Max (F)	Max (F/F_{full})	Mean value	Std dev.
Quiet situation						
F (N)	**-0.1**	-0.1	**1.8**	1.4	0.5	0.5
F/F_{full} (%)	0.0	**0.0**	0.2	**0.7**	0.1	0.2
F_{full} (N)	571.0	571.0	817.3	207.5	529.0	241.6
150 m before crash						
F (N)	**-0.4**	-0.4	**2.1**	1.3	0.5	0.6
F/F_{full} (%)	-0.1	**-0.1**	0.3	**0.6**	0.1	0.2
F_{full} (N)	416.6	416.6	817.3	207.5	529.0	241.6
Truck pass						
F (N)	**0.4**	0.4	**87.1**	30.0	26.6	21.5
F/F_{full} (%)	0.1	**0.1**	14.0	**14.5**	5.8	4.2
F_{full} (N)	722.0	722.0	621.8	207.5	529.0	241.6
Crash						
F (N)	**78.4**	96.1	**502.9**	291.1	245.0	122.7
F/F_{full} (%)	29.6	**11.8**	80.9	**85.9**	51.1	21.1
F_{full} (N)	265.4	812.8	621.8	339.0	529.0	241.6

Each table corresponds to a measurement channel (cushion seat, back seat, longitudinal adjustment rail of the seat, steering wheel, brake pedal).

Figure 4, Figure 5, Figure 6, Figure 7 and Figure 8 present the evolution of the ratio F/F_{full} for all measurement channels and for all drivers.

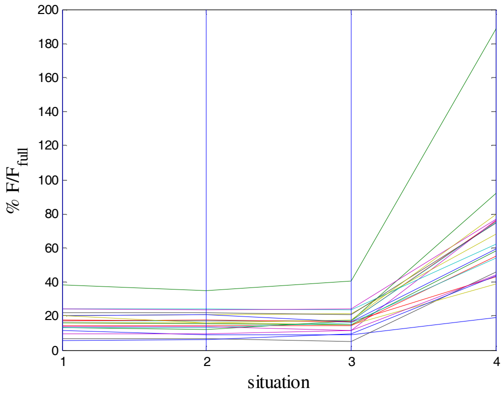


Figure 4. Evolution of seat back ratio for subjects until crash.

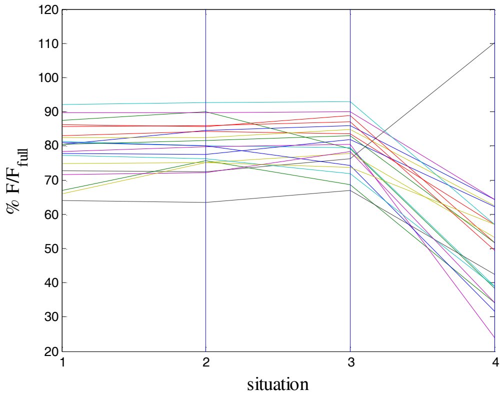


Figure 5. Evolution of cushion seat ratio for subjects until crash.

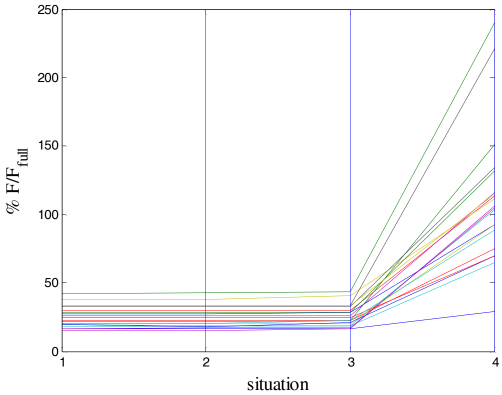


Figure 6. Evolution of seat rail ratio for subjects until crash.

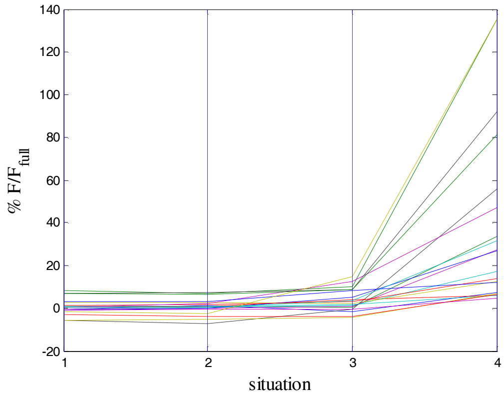


Figure 7. Evolution of steering wheel ratio (compression) for subjects until crash.

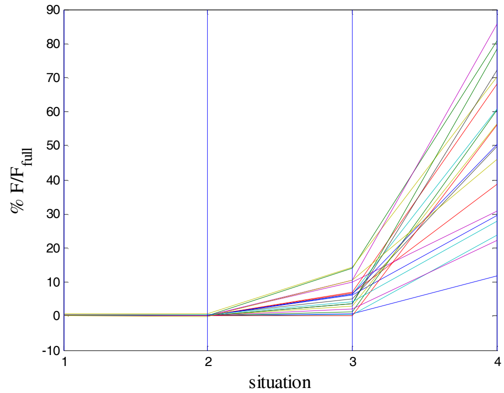


Figure 8. Evolution of brake pedal ratio for subjects until crash.

Global positions of the drivers remain unchanged until the truck crosses the white line. During the quiet situation, no force is exerted on the braking pedal. Then, drivers brake suddenly. The mean effort exerted on the pedal when the truck passes the tractor is 27N. It increases to 245N at the moment of the collision. The maximal effort value recorded at this moment is 503N (81% of F_{full} pedal). This induces an increase of seat back and rail efforts and a decrease of seat cushion efforts. The mean value of seat back and rail efforts are steady until the time of crash (130N) then grow to around 500N. The seat cushion effort reduces from 400N to 260N. Only one person embeds in the seat cushion (increase of cushion seat force). The mean efforts exerted on the steering wheel passes from -10N to -93N (pushing out) at the moment of the impact. At this time, the maximum value is 561N and corresponds to 135% of F_{full} steering wheel. This can be explained by the fact that F_{full} efforts are sustained efforts while driving efforts are instantaneous efforts.

Hands and Chest positions

Injury to the upper body is the main risk in a frontal crash. The positions of chest and hands are analyzed from the recorded videos at the moment of impact.

Hand positions

At the beginning of the experiment, subjects adopt a 10 and 2 o'clock position or 9 and 3 o'clock position. Comfort position is observed only after twenty minutes. For the left arm, subjects often rest their arm by putting their elbow on the window sill or the forearm on their thigh. For the right arm, drivers often rest their arm by laying their right hand on the gear lever or the forearm on their thigh. Subjects regularly come through one comfort position to another one.
Then, during the crash event, most of drivers try to control the situation by swerving, to avoid the truck in front of them. Table 2 and Table 3 describe upper limb positions when the truck overtakes the tractor and at the moment of impact, respectively.

Table 2.
Hand positions at truck pulling out time

Positions	Left hand	Right hand	%
1	On the steering wheel	On the steering wheel*	65.74
2	On the steering wheel	On the gear lever	18.57
3	On the steering wheel	On the right thigh	7.14
4	On the left thigh	On the steering wheel	2.86
5	On the air	On the steering wheel	2.86
6	On the hub	On the steering wheel	1.43
7	On the steering wheel	On the handbrake	1.43

* whose 2,86 % have their left elbow on the window sill
* whose 5,72% have their right forearm laid on their right thigh

Hand position analyses, at the moment of truck pulling out (Table 2.), show that more than 90% of the subjects have their left hand on the steering wheel and their right hand either on the steering wheel (66%), the gear lever (19%) or the right thigh (7%). These positions correspond to an evolution position instead of a comfort position, since these positions are observed when subjects see the truck at the horizon. Indeed, subjects generally replace their hands on the steering wheel when a disturbing event appears in their vision field (for example, when the subject is overtaken, when a truck is approaching or when a vehicle is braking).
At the moment of impact, more than 90% of the subjects have their left hand on the steering wheel and their right hand on the steering wheel (54 %) or on the gear lever (37 %) (Table 3). The remaining 9% of the subjects have their left hand on the steering wheel and their right hand on the handbrake, their thigh or intermediate position (for example between the steering wheel and the gearshift).

Table 3.
Hand positions at the time of impact

Positions	Left hand	Right hand	%
1	On the steering wheel	On the steering wheel	52,86
2	On the steering wheel	On the gear lever	35,71
3	On the steering wheel	On the air*	7,14
4	On the steering wheel	On the handbrake	1,43
5	On the steering wheel	On the thigh	1,43
6	On the air	On the steering wheel	1,43

* for example when the subject tries to take the gearshift.

The distribution of the hand positions in the environment is presented in Figure 9.

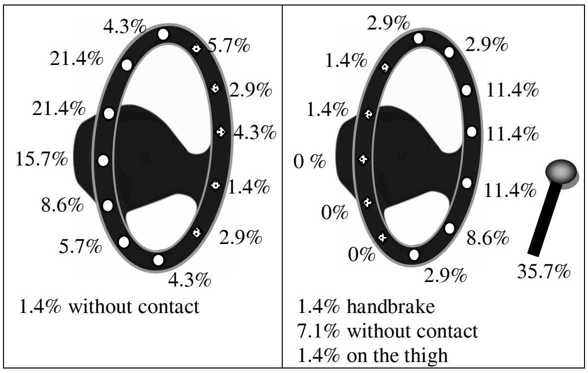


Figure 9. Percentage of subjects' left and right hand positions on steering wheel.

In 17% of cases, the left hand is in a 1 to 5 o'clock position. For 2.8% of cases, the right hand is in a 10 or 11 o'clock position. All these positions, which represent a total of 19.8 % of cases, are potential risk positions. Indeed, in these cases, the forearm is placed in front of the hub and is likely to be projected against driver face under airbag deployment. Prior to impact, 100% of the subjects have braked and 54.26% have declutched. This can explain that 35.7% of the subjects have their right hand on the gear lever. Indeed, a strong braking is often associated with declutching. Concerning the normative position in a frontal impact, 21.4% of subjects have their left hand in a 10 o'clock position, 11.4% have their right hand at 2 o'clock, but only 7.14% of subjects are in a 10 and 2 o'clock position.

Upper body positions

The positions of the upper body are observed when the truck is approaching the driver's car. Five classes of behaviours are defined (Figure 10):
(i) Posture 1 - 22 % have no postural change,
(ii) Posture 2 - more than 67 % move backward to anticipate the crash,
(iii)Posture 3 - at the same time, 57 % of those who move back make a rotation of their chest,

(iv)Posture 4 - less than 3 % make a trunk rotation without moving backward,
(v) Posture 5 - 8 % move head towards the steering wheel.

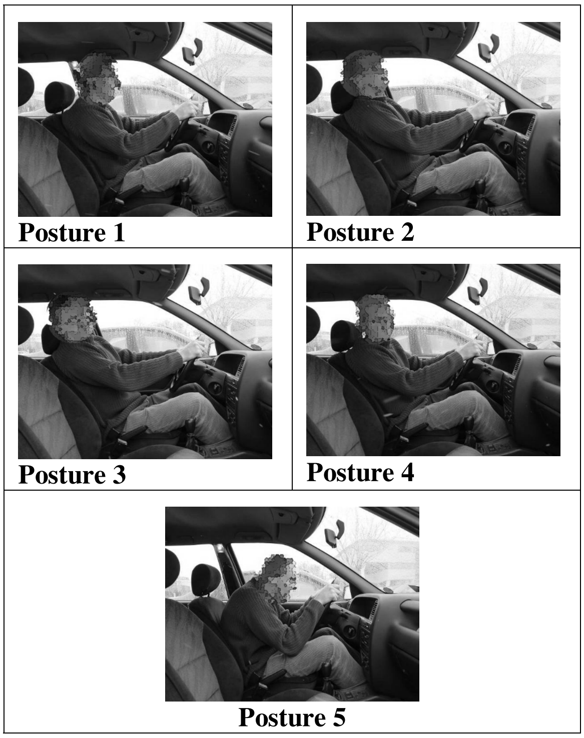


Figure 10. Upper body positions.

These results clearly show that very few subjects adopt a standardized chest driving position during the collision. The influence of these driver positions (hand positions and upper limb movements) on injuries are investigated numerically with the software Madymo®. Upper limb injury criteria are compared between a standard 10 and 2 o'clock position and OOP observed on the driving simulator.

BIOMECHANICAL ANALYSIS

The biomechanical analysis is made with a numerical model of the crash dummy Hybrid III 50th percentile male available in Madymo® database. The position of the dummy is determined from real driver pre crash posture by a postural reconstruction method.

Pre-crash posture measuring

A postural reconstruction method like in [5,6] can be used to approximate joint angles of driver upper limbs at time of crash. From at least two photos of different views taken in a calibrated space, the software MAN3D developed by the INRETS [12] allows to adjust the anthropometric dimensions and joint angles of a virtual dummy on an experimental subject. These data can be transferred to Madymo to position the numerical dummy model as in real conditions.

Madymo® simulation

For this study, the existing model for frontal crash available from Madymo® is used. Load applied to the virtual dummy (Hybrid III 50th percentile male dummy) corresponds to the deceleration undergone by a car during a head-on collision at 56 km/h. Non finite element seat-belt is used to secure the dummy. Simulations are performed for five different chest postures and two various hand positions (Figure 11 and Figure 12). Contacts between arm and head, and, between arm and airbag, are added. Their definitions are based on existing contacts between other limbs and airbag (thorax/airbag).
The peak linear acceleration, the HIC15 and the 3-MS injury criteria are calculated for the head. Injuries to the neck are predicted by the neck injury predictor Nij. The Nij is the collective name of four injury predictors corresponding to different combinations of axial force and bending moments: NTE tension-extension, NTF tension-flexion, NCE compression-extension, NCF compression-flexion. For frontal collision, the neck injury predictor of NTF (tension and flexion moment) is usually higher than the other neck injury predictor. The neck injury predictor can be evaluated in two different manners. According to the Madymo, none of predictor may exceed a value of one. Nevertheless, the FMVSS No.208 specification [3,10] requires that none of the four Nij values exceed 1.4 at any time during the event. In this study, the Nij is evaluated according to Madymo assessment. All these values are reported in Figure 11 and Figure 12.
Posture 1-1 represents the normalised driving posture. The peak linear head acceleration reaches 62.7 g. The head injury criteria values, HIC15 are estimated at 342.
All head injury criteria values, for the other four chest postures with hands at 10 and 2 o'clock, increase as compared to the model at normalised posture (Figure 11). Nevertheless, lower head injury criteria values are recorded for the posture 4-1 according to posture 2-1 and posture 3-1. This can be explained by the distance between the torso and the steering wheel. Indeed, for these latter postures, the dummy has the upper body leaned against the seatback. So, a greater distance exists between the dummy torso and the steering wheel than for posture 4-1. This allows the dummy to take speed during impact. Thus, the dummy hits the airbag with a higher speed and a greater impact force. The slight head rotation in posture 3-1 increases the maximum head acceleration and injury criteria compared to posture 2-1 without head rotation.

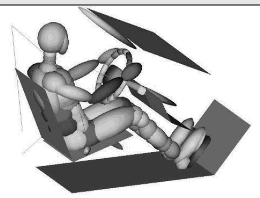
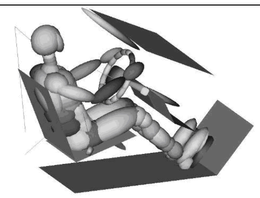
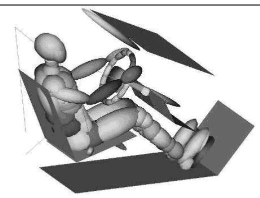
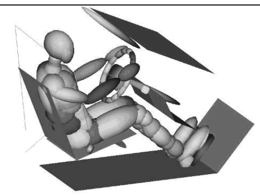
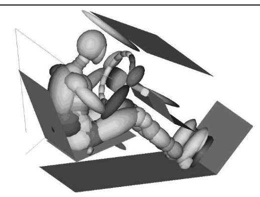
Chest \ Hands	Standard position
Standard position **posture 1-1** **Max.lin.acc (g)** **HIC15 (<700)** **3MS (g) (<80)** **Max Nij (<1)**	 **62.7** **$342.0_{15.0ms}$** **56.4** **0.4**
Backward movement **No chest rotation** **posture 2-1** **Max.lin.acc (g)** **HIC15 (<700)** **3MS (g) (<80)** **Max Nij (<1)**	 **78.2** **579.415.0ms** **71.6** **0.46**
Backward movement **Chest rotation** **posture 3-1** **Max.lin.acc (g)** **HIC15 (<700)** **3MS (g) (<80)** **Max Nij (<1)**	 **78.4** **$610.0_{15.0ms}$** **72.8** **0.46**
No backward movement **Chest rotation** **posture 4-1** **Max.lin.acc (g)** **HIC15 (<700)** **3MS (g) (<80)** **Max Nij (<1)**	 **66.9** **$412.3_{15.0ms}$** **61.5** **0.38**
Forward movement **No chest rotation** **posture 5-1** **Max.lin.acc (g)** **HIC15 (<700)** **3MS (g) (<80)** **Max Nij (<1)**	 **91.3** **809.415.0ms** **84.2** **0.74**

Figure 11 - Postures and injury criteria for a standard hand position.

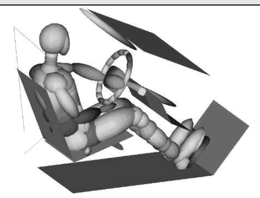
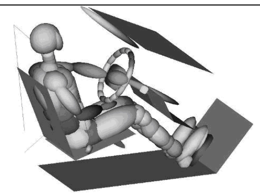
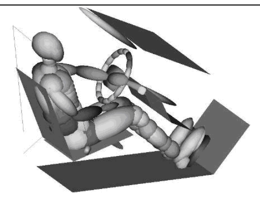
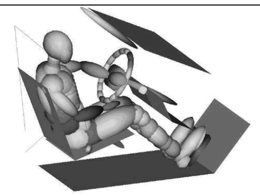
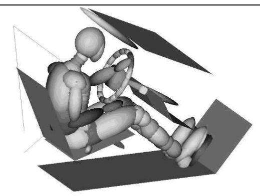
Chest \ Hands	Atypical position
Standard position **posture 1-2** **Max.lin.acc (g)** **HIC15 (<700)** **3MS (g) (<80)** **Max Nij (<1)**	 **730.0** **$14761_{2.2ms}$** **80.3** **4.15**
Backward movement **No chest rotation** **posture 2-2** **Max.lin.acc (g)** **HIC15 (<700)** **3MS (g) (<80)** **Max Nij (<1)**	 **761.4** **$19814_{2.2ms}$** **96.9** **4.27**
Backward movement **Chest rotation** **posture 3-2** **Max.lin.acc (g)** **HIC15 (<700)** **3MS (g) (<80)** **Max Nij (<1)**	 **615.5** **$12160_{2.3ms}$** **172.7** **4.19**
No backward movement **Chest rotation** **posture 4-2** **Max.lin.acc (g)** **HIC15 (<700)** **3MS (g) (<80)** **Max Nij (<1)**	 **980.6** **$26977_{2.0ms}$** **83.1** **2.97**
Forward movement **No chest rotation** **posture 5-2** **Max.lin.acc (g)** **HIC15 (<700)** **3MS (g) (<80)** **Max Nij (<1)**	 **463.1** **$5237.2_{1.9ms}$** **46.7** **2.97**

Figure 12 - Postures and injury criteria for a non standard hand position.

However, posture 5-1 is the most injurious position (the HIC15 is over the Injury Assessment Reference Values (IARV) (<700)). In this case, the dummy head is very close to the steering wheel. During impact, the airbag deploys at very high speed and directly pushes the face of the dummy. As a consequence, the neck bends rearward and the head is launched backward.
A significant increase in the maximum linear head acceleration is observed for the five chest postures with the left hand at the right side of the steering wheel (posture 1-2 to posture 5-2) (Figure 12). The HIC15 for all these models are well over the existing tolerance limit for the frontal impacts. For the five chest postures, the airbag projects the arm against the head. This phenomenon corresponds to a critical situation which can lead to a mortal traumatism. The 3-MS injury criterion, calculated for the head, depends on how the arm hits the dummy head. For the posture 3-2, the left arm hits the right lower chin. As a consequence, the head is turned violently to the left. For posture 2-2 and posture 4-2, the arm hits the dummy at the lower chin. So, the neck is tilt backward. As neck model stiffness is larger in forward/rearward bending than in lateral bending, the 3MS-injury criterion is higher for posture 3-2 with a value of 172.7 g.
The maximum linear head acceleration and the 3MS injury criterion calculated for posture 5-2 have slightly lower values compared to the four other postures. In this case, the arm is very close to the head. So, the coupling between the arm and the head occurs earlier. Hence, the relative velocity is lower. The IARV for the head 3MS-injury criterion is 80 g. Except for posture 5-2, values obtained exceeds this limit.
The Nij values, for posture 5-1 and postures with the left hand on the right side of the steering wheel, exceed the acceptable limits. This indicates that the impact causes lasting neck impairment. Moreover, neck injuries are more likely to occur in the driving posture with one hand placed just in front of the airbag than in other postures.

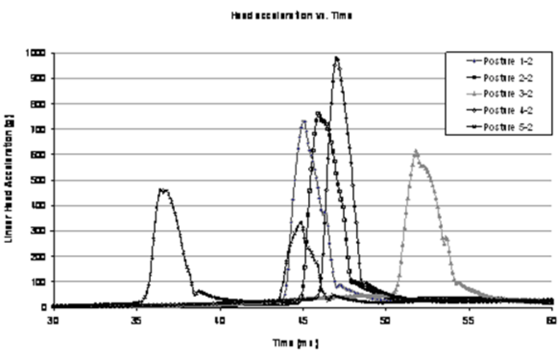


Figure 13. Linear head acceleration versus time plot for models with the left hand at the right side of the steering wheel.

For the atypical postures, extremely high values of linear head acceleration are observed (Figure 13). Using HIC values as injury criteria estimation would not be realistic in this case. Indeed, HIC is a function of the area under graph linear head acceleration over the time interval when a peak is observed. The phenomenon of extremely high HIC scores results from the sharper acceleration spike and substantially shorter HIC time interval (indexed values in Figure 11 and Figure 12) for the models with the left hand positioned on the right side of the steering wheel. The 3MS injury criterion is preferred, here, for the head since the value of maximum linear head acceleration is always being estimated for a time window with a width of 3 ms.

Numerical simulations, realized with Madymo®, show the importance of driver positions at the moment of impact in the assessment of neck and head injuries. However, this first approach shows some limitations. Contact definitions and arm kinematics have to be validated. So, airbag deployment tests are performed with a hybrid III 50th percentile dummy.

AIRBAG TESTS AND NUMERICAL VALIDATION

Tests are performed in collaboration with Zodiac Automotive.
The vehicle environment is reconstructed. The dummy Hybrid III 50th percentile Male is positioned according to car driving simulator experiment observations with its left arm behind the steering wheel (Figure 14). Tests are performed with a conventional airbag (sewn cushion, open event, pyrotechnical technology). Tests are performed in static.

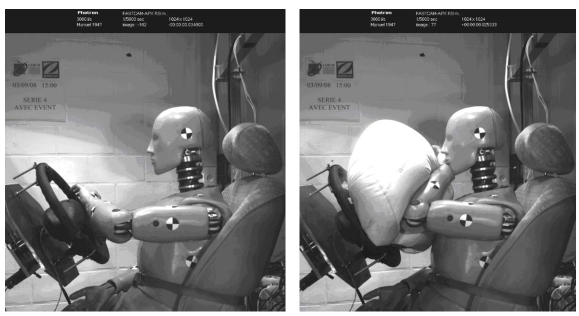


Figure 14. Crash test dummy.

Then, the static test with the conventional airbag cushion is reproduced on Madymo® (Figure 15). The inflator mass flow rate and blowhole characteristics of the numerical airbag model are adapted to reproduce the deployment of the real airbag cushion. The characteristics of the contacts head/arm and arm/airbag are tuned in order to reproduce the experimental linear head acceleration (Figure 15).

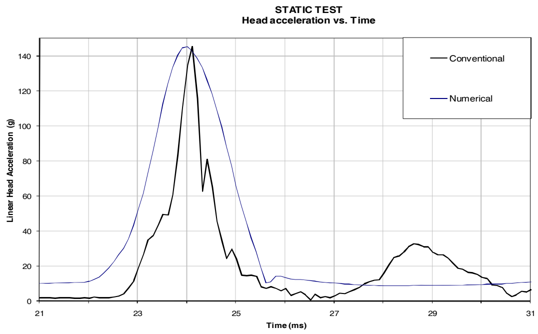


Figure 15. Linear head acceleration for the experimental and the numerical models.

Predicted head linear acceleration is correlated reasonably well with test data as shown by the experimental and numerical curves. The timing and value of the peak acceleration is well estimated. The width of the peak is larger for numerical head acceleration. This may be due to damping coefficients for contacts head/arm and arm/airbag.

This validated model is used to reproduce dynamical tests (a 56 km/h frontal collision) (Figure 16). Simulations are performed for the two various hand positions (standard posture with hands at 10 and 2 o'clock and atypical posture with left hand on the right side of the steering wheel) and the dummy back leaned against the seatback (posture 1-1 and posture 1-2). The injury criteria values are presented in Figure 16.

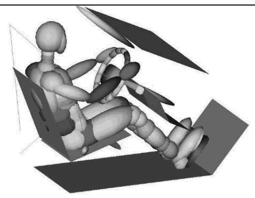
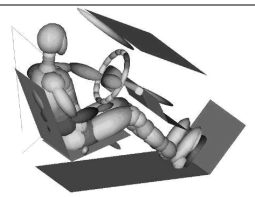
posture 1-1	
Max.lin.acc (g)	**50**
HIC15 (<700)	$\mathbf{200.0_{15.0ms}}$
3MS (g) (<80)	**44**
Max Nij (<1)	**0.3**
posture 1-2	
Max.lin.acc (g)	**145.0**
HIC15 (<700)	$\mathbf{2730_{1.2ms}}$
3MS (g) (<80)	**36**
Max Nij (<1)	**1.1**

Figure 16. Injury Criteria obtained for the validated model (conventional airbag).

The linear head acceleration obtained with the validated model for standard and atypical postures are illustrated in Figure 17.

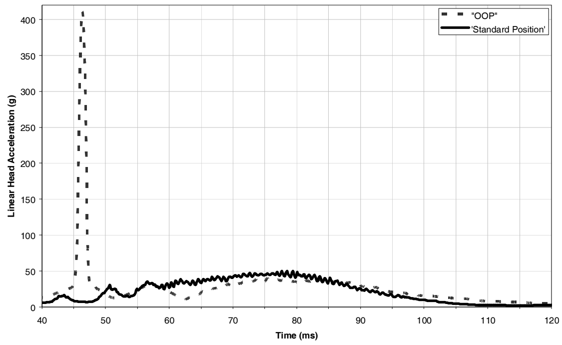


Figure 17. Linear head acceleration obtained with the numerical validated model for a standard and atypical position (conventional airbag).

It can be concluded that contact characteristics strongly influence the results. Values obtained for the normalized position (posture 1-1) are quite similar for the two models. Values obtained with the validated model for the atypical position (posture 1-2) are lower than those obtained with the standard Madymo model. Nevertheless, the atypical position, with the arm behind the airbag, is still injurious for the head and the neck.
The other chest postures need to be modeled with the validated model.

NEW AIRBAGS GENERATION

Nowadays, airbag cushion benefits are clearly demonstrated by statistic when the number of crash is not decreasing. All major OEM are now working on the crash avoidance refer to the last FISITA 2008 conference about car safety. Airbag cushion can use the latest technology to avoid occupant injuries and improve protection of occupants in case of crash.The latest developments in automotive safety technology will permit an early detection of potential crash situations. Recent publications [2] mentioned the possibility to trigger Airbag units about 100 ms before the crash really occurs. Pre-crash detection will permit a slower inflation of the cushion thus preventing the risk of severe damage in case of OOP situation. But it will be impossible to synchronize the triggering of the Airbag unit with the impact of the occupant in the cushion, that the reason why we would need a tight bonded airbag, able to sustain the pressure for a longer time than traditional sewn bag.
The delay between pre-crash triggering and occupant impact will depend on the intelligence of the system. But we can imagine that to be functional under most crash cases, the cushion will have to be available during at least 500 ms.
Some requirements for the Airbag unit can be drawn from this short description: the cushion has to be tight to maintain the pressure during the

requested time; The inflator must be from cold gas technology to prevent the pressure drop due to a quick gas temperature decrease; The cushion has to be fitted with a device that detects occupant impact: the cushion remains tight before impact and has a controlled restraint after impact thanks to the opening of a vent hole.
Following is the description of 2 tests that demonstrates that Airbag units suitable for pre-crash systems are possible using technologies already available on the market:

• airtight bonded cushion using Peribond technology from Zodiac Automotive,
• pure helium cold gas generators form ISI-Automotive,
• patented silicone membrane from Zodiac Automotive.

The first test is to show the difficulty to ensure the specific requirements of a pre-crash Airbag unit with a sewn cushion. A comparison of the pressure drop for a sewn and a bonded cushion is presented on Figure 18. Both cushions are built to have the best performance in terms of leakage:

• low permeability of the coated fabric,
• high construction to have low combing,
• no vents to simulate a system having an intelligent opening at occupant impact,
• pure helium cold gas inflators from ISI Automotive.Prototype

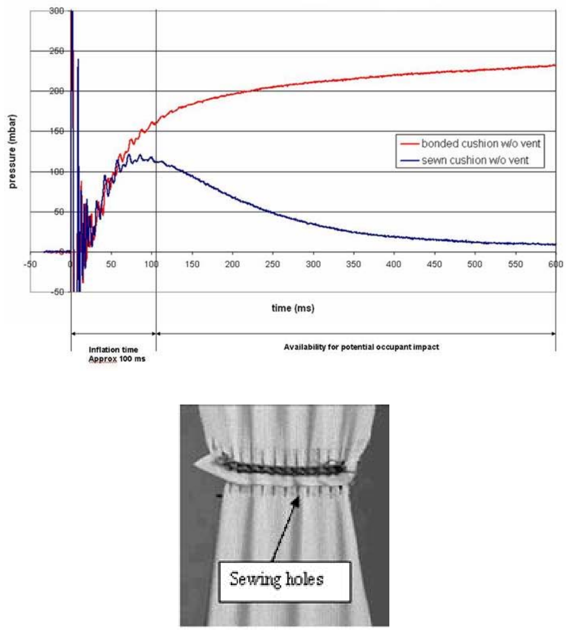


Figure 18. Pressure drop comparison between a sewn and a bonded cushion (left). Sewn cushion (right)

It can be concluded that the bonded cushion is available for occupant impact during more than 500 ms and the pressure level is maintained within 75 mbar, whereas the level of pressure of the sewn cushion is uncertain and is too low at the time of occupant impact. Pressure drop on sewn cushion is due to stitch holes on the fabric and gaps between the 2 fabric panels (Figure 18).
In the second test, a tight peribond bag is impacted after 150 ms. Figure 19 is showing the performance results of both tight peribond assembly and silicone membrane. Airbag pressure is ready for occupant protection during more than 200 ms. The silicone membrane remains closed until the impact, then open to ensure the restrain performance of the impactor.

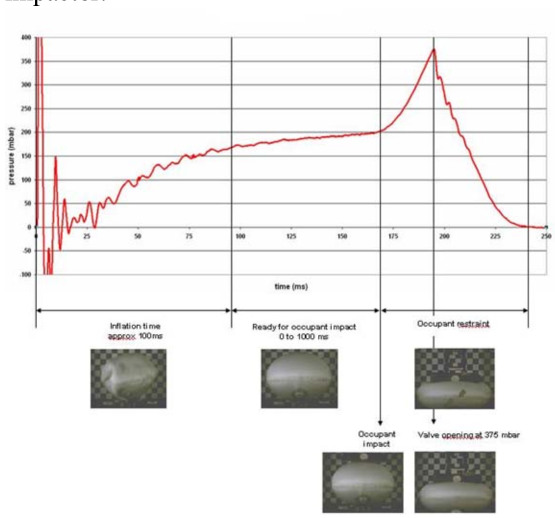


Figure 19. Dynamic test – pre crash simulation.

Then, tests are carried out with the crash dummy positioned with its left arm behind the steering wheel (Figure 14). Tests are performed with a conventional airbag (sewn cushion, open event, pyrotechnical technology) and with two airbag prototypes (bonded cushion, two pure helium cold gas generators (0.095 L – 620 bars) (0.047L – 620 bars), patented silicone membrane). In one case, the two helium generators are released at the same time. In the other case, the small generator is activated first, then the second is released after 10 ms. These cases will be referred afterwards as ‘proto_0 ms’ and ‘proto_10 ms’ airbag respectively. Figure 20 presents the linear head acceleration of the dummy versus time for the three airbag tested.

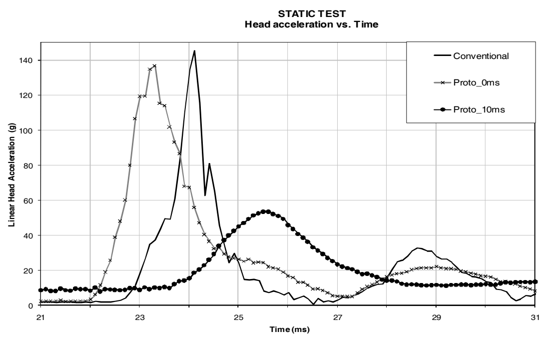


Figure 20. Linear head acceleration obtained for static tests with a sewn cushion (conventional) and bonded cushions (proto_0ms and proto_10ms).

From experimental tests, it can be concluded that the peak linear head acceleration is significantly reduced for the ‘proto_10ms’ airbag compared to the conventional and the ‘proto_0ms’ airbags. Indeed, with the ‘proto_10ms’, the airbag is multi stage inflated. So, the arm is projected less rapidly against the head. This explains the head acceleration decrease.

Prototype Airbags still have to be simulated, that requires characterization of the mass flow of helium generators.

CONCLUSION AND PERSPECTIVES

This paper focuses on frontal pre-crash driving postures. An unavoidable crash is reproduced on a car driving simulator and driver reactions are investigated. The main result is that none of the subjects adopts the standard driving position used in crash experimentations. Indeed, most of subjects swerve away to avoid the collision. This induces forward or backward movements and/or rotation of the chest. Only few person stays in a 10 and 2 o'clock position. Furthermore, a third of the subjects have their left hand placed in front of the steering wheel. Since airbags are usually mounted in the hub, this may represent a rather risky position.

These ‘OOP’ postures are reproduced with Madymo®. The driver is simulated with the Hybrid III 50th percentile dummy model. Postures observed on the car driving simulator, at the moment of impact, are estimated. A 56 km/h frontal collision is imposed. Head and neck injuries sustained by the driver are assessed. By comparing the numerical response for the models in an ‘OOP’ posture and in a normalized posture, it is found that head (3-MS and HIC) and neck (Nij) injury criteria are severely increased when the arm is placed in front of the steering wheel. Indeed, in this case, the arm is projected against the head under airbag deployment. Furthermore, the non-normalized chest posture influence too injury criteria. Having the chest and the head too close to the steering wheel induces serious neck and head injuries. In this case, the airbag, deploying at a very high speed, directly pull the dummy face inducing serious neck bending and violent head launching. This is also the case for small size people who usually sit near the steering wheel.

The very high value of HIC and 3MS head injury criteria and the high linear head acceleration peak can be due to the definition of the contact between the arm and the head. So, these numerical results have to be validated. An experimental campaign of static airbag deployment has been done with a hybrid III 50th percentile dummy. Tests are performed with a conventional airbag (sewn cushion, open event, pyrotechnical technology) and with two airbag prototypes (bonded cushion, two pure helium cold gas generators allowing mono or multi stage inflating, patented silicone membrane). The dummy is seated with the left arm in front of the hub. From these experiments, it is observed that bonded cushion is better suitable to maintain pressure until occupant impact and that linear head acceleration of the dummy is significantly reduced with multi stage inflated bonded cushion. Thus, slower airbag deployment could reduce airbag violence.

Currently, the configuration of passive restraint systems is almost universal (driver cushion inside the steering wheel, passenger airbag in the dashboard, side airbags in the seats, curtains in the roof). This configuration is driven by the architecture of the cars but also from specific requirements in terms of time to position (TTP); very quick time for position side airbags due to late detection of side impact and proximity of the door; higher time for frontal airbags due to earlier detection of frontal impact, higher volume to inflate and risks of OOP. Having detected the crash and triggered the Airbags earlier, TTP is no longer a determinant requirement for the conception of protection systems. The way to protect the occupants could be imagined completely differently. For instance, mixing the protection of a curtain and front and rear side airbags in a single airbag unit could lead to great savings in terms of number of generators, wiring, electronic equipments and consequently savings in price and weight. New protective features could also be added to current cushions. For instance, an extension of a driver airbag to protect from the A-pillar on partial side crashes.

It is believed that physiological data obtained from the experimental study on the dynamic simulator can help to find ‘human sensor’ to detect dangerous situations, as potential collisions between the host vehicle and other road users or obstacles, before the impact occurs (acceleration of heart rate, sudden braking …).

Furthermore, the numerical simulation, realized with Madymo®, shows the importance of driver positioning at the moment of impact in the assessment of neck and head injuries, and the influence of contact definitions on dummy responses. However, this first approach shows some limitations. First, it only represents the global behavior of the subject. Indeed, as the dummy head and arm are rigid, all the kinematical energy of the arm is transmitted to the head. This induces unrealistic high head acceleration and very high HIC value. So, a human model, with a deformable arm, should be used for a better prediction of head and arm injuries. Second, this approach doesn’t take into account the driver muscular clenching during crash event. So, active muscles should be included in the model to take into account reflex reactions facing an incident.

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THE EFFECT OF PRE-PRETENSIONING IN MULTIPLE IMPACT CRASHES

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ABSTRACT

German In-Depth Accident Study (GIDAS) data from 1999 to 2007 was compared to Hanover Medical School (MHH) data from 1973 to 1987 and it was found that the relative percentage of passenger cars sustaining more than one impact in a crash, so called multiple impact crashes, has increased by about one third within the last two decades. An analysis of 9316 GIDAS accidents from 1999 to 2007 showed a three-fold greater risk of severe injury and a four-fold greater risk of fatal injury for a multiple as opposed to a single impact crash.
This study analyses multiple impact crashes in general and in particular occupant protection by out-of-position mitigation between impacts.

It was found that in two thirds of all multiple impacts with severe injury outcome, the irreversible restraint systems, front airbags and pretensioners, were not activated in an initial front impact. The corresponding proportion for non-activation of side and curtain airbags in initial side impacts was approximately fifty percent.
To evaluate the risk of occupant out-of-position and the effect of one type of reversible system, a retractor pre-pretensioner, a finite element sled model including the human body model THUMS, was used.
In the simulation of initial front impacts with different changes of velocity, followed by a braking sequence, the pre-pretensioner leads to an obvious reduction in the forward chest displacement of the human model. Furthermore, depending on the pre-pretensioner force, the human model may be pulled back into its initial seating position.
The calculated time distribution between initial and subsequent impacts with a median of 0.6 to 0.8 seconds, was used for the evaluation of "pre-crash" measures.
The effectiveness of pre-pretensioning to position the occupant between impacts, ranges from 24% with 200N, to 93% with 400N pre-pretensioning force.

INTRODUCTION

Consumer rating crash test results, which usually have higher requirements than legal crash tests, have become a leading argument for the sales success of a vehicle model and therefore are an important orientation for vehicle manufacturers (OEMs) in the development and integration of safety innovations. However, there is a foreseen risk that the safety development might be more oriented toward rating tests rather than on the potential benefit for real traffic accidents [1].

Both crash tests required by legislation and consumer tests reproduce single impact crashes either in vehicle-to-vehicle or in vehicle-to-object constellations. Multiple impact scenarios have not yet been considered in these test modes. As a consequence, passive safety measures, especially irreversible systems, are generally optimised for occupant protection in only one impact.

The results from a MHH study [2] on multiple impact crashes, conducted in 1987 for the German Federal Highway Research Institute (BASt), showed that about 18% of the passenger cars were involved in multiple impact crashes. Studies based on the US National Automotive Sampling System / Crashworthiness Data System (NASS/CDS), the UK Co-operative Crash Injury Study (CCIS) and GIDAS data stated that the percentage of occupants involved in a multiple impact crash is around one quarter, whereas the percentage of severe (AIS3+) injuries in multiple impact crashes accounts for 30% to 42% [3], [4]. US data publishes that the risk of severe injury is more than two times higher in a multiple impact crash than in single impact crashes. Head and trunk were the body regions that showed a significantly higher risk of severe injury [4], [5]. UK and German accident data confirmed that head and thorax are the most often MAIS3+ injured body regions in multiple impact crashes [3].

In two multiple impact studies, the benefit of independent deployment of front and side airbags and the benefit assumed for maintaining airbag inflation for a longer time period [3], [6] was discussed. Furthermore, an enlarged protection range of restraint components was proposed for out-of-position occupants after an initial impact [3].

The initial stage of this study provides statistics for multiple impact scenarios and injury outcomes for involved occupants. The activation probability of irreversible occupant restraint systems was used to determine the potential benefit of reversible restraint systems such as seat belt pre-pretensioners (pre-impact, seat belt, tensioner). Furthermore, the time distributions between impacts have been calculated to gain information about the time span for pre-crash measures before a subsequent impact.

Using the human body model, THUMS, the time to pull an occupant back in position after an initial front impact by pre-pretensioning, was derived. The effectiveness of pre-pretensioning at different force levels is shown for various first impact severities, by comparison of the time required to pull an occupant back to normal position and the time available between subsequent impacts.

METHODOLOGY

Definitions

Defining certain terms was necessary for the correct interpretation of results. Although the expression “crash” in “single impact crash” or “multiple impact crash” may seem to be on an accident level, a vehicle level has been expressed.
The term “impact” means that a vehicle sustains a change of velocity in a very short time interval while position remains practically unchanged. All coded impacts, independent on delta V, are considered in this study.

In a single impact crash, a vehicle sustains only one collision with a vehicle, an object, a person or an animal. A multiple impact crash is present if one vehicle sustains two or more collisions. It does not mean that two or more vehicles are involved in an accident.
The term “rollover crash” or “rollover” relates to vehicles that sustain a non-planar motion and reach a position at least 90º rotated over the longitudinal or lateral vehicle axis.
The expression “severe injury” is used for occupants with MAIS3+ injury outcome. This also includes fatalities. Nevertheless, fatalities will be presented separately.

The GIDAS Project

The GIDAS project is a joint venture of the FAT (German Automotive Research Organization) and the BASt (German Federal Highway Research Institute). The project was started July 1st, 1999 and is still running. Data from approximately 2000 accidents yearly was recorded at two sites; Hanover, Dresden and surroundings [7].
A statistically developed sampling plan defines the work shifts for the teams, which covers 12 hours per day. If an accident occurs with at least one injured person suspected, the GIDAS team is notified directly by the local police or rescue service via radio communication. GIDAS’s investigation teams approach the crash scene with blue-lights [8]. This near immediate, on-the-scene investigation allows data collection of marks and traces available only for a short period of time after the accident. Sample criteria for the GIDAS database are that at least one accident participant has been injured and the accident occurs within the shifts and the specified regions.

Data Aggregation and Weighting

For specific research questions, filter criteria need to be applied to real world accident data. For this study, the GIDAS data from July 1999 to July 2007 was used with two general filters applied:

- Only cases with completed reconstruction
- Only passenger cars

After application of these filters the data set consisted of 9316 accidents, involving 13392 passenger cars with 15639 occupants, sustaining 18169 impacts. The data aggregation and statistical analysis were conducted with the software SPSS version 15. Furthermore, the software SAS 9.1 and the Enterprise Guide 4.1 were used for specific analyses.

The sampling plan for GIDAS was developed and stepwise improved to be representative of German national statistics. Nevertheless, studies have considered the application of weighting factors for specific research questions [9], [10]. Relative weighting factors were calculated to evaluate the generalisability of the analysed data.

Rollovers

The treatment of rollovers in previous multiple impact studies has been different. They were either included without separate examination [6], included with association of roof impact as rollover [4], or they were excluded from the data sets [5], [11]. One study presents more detailed rollover figures [3]. From both CCIS and GIDAS data, it was reported that rollovers mainly occur in multiple impact crashes [12]. This study considers rollovers in the statistical analysis. For the effectiveness assessment of pre-pretensioners, rollover crashes have not been considered, as the coded GIDAS variables up until 2007 do not enable the calculation of time between impacts for these scenarios.

Delta V Groups

The change of velocity (delta V) is grouped in five ranges for the analysis. Besides an impact severity evaluation the ranges also consider an appropriate impact frequency distribution for further analysis.

The following delta V ranges have been defined:

- minor delta V (0 – 5 km/h)
- low delta V (6 – 15 km/h)
- moderate delta V (16 – 25 km/h)
- medium delta V (26 – 50 km/h)
- high delta V (>50 km/h)

Occupant Injury Outcome

The occupant injury analysis was conducted for belted occupants only. The exclusion of vehicles with only unbelted and "belt status unknown" occupant(s), resulted in a 19.6% reduction of single impact crashes and a 19.8% reduction of multiple impact crashes. Therefore this data-filtering step did not influence the relative proportion of single to multiple impact crashes.

Triggering of Irreversible Restraint Systems

It is not always obvious in a multiple impact crash which impact leads to the deployment of the irreversible restraint device.
To analyse the deployment threshold in a simplified system model, univariate logistic regression was applied to determine the probability of irreversible restraint activation depending on delta V. All single impact passenger cars equipped with the corresponding irreversible restraint system are classified by a status variable (0 = not activated) and (1 = activated). Pretensioner activation was coded accordingly to the airbag deployment status, because the airbag activation was easier to identify and therefore a more reliable variable. Deployment threshold differences between pretensioners and airbags are, therefore, not considered.
As the delta V is a vector and has both magnitude and direction, it is transformed into a longitudinal and lateral scalar component by usage of the change of momentum angle.

The probability of deployment is calculated with use of the logit $(\beta_0 + \beta_1 x)$ including two regression coefficients $\beta_{0,}\beta_1$ (Equation 1).

$$p(x) = \left(\frac{e^{(\beta_0 + \beta_1 x)}}{1 + e^{(\beta_0 + \beta_1 x)}} \right) \qquad (1).$$

The application of a multivariate regression with predictors other than delta V may provide a more accurate estimate of the deployment threshold. However, the number of vehicles with activated restraint devices involved in multiple impact crashes is too small for the application of multivariate regression.

Reversible versus Irreversible Restraint System

Reversible restraint systems can operate far below the threshold of irreversible restraint systems. In general, the trigger level is more dependant on comfort than safety criteria.
To estimate the benefit of reversible restraint systems, like pre-pretensioners, multiple impact crashes were compared by triggering versus non-triggering of irreversible restraint systems at first impact.

The analysed crash scenarios were:

- Front - Front
- Front - Side
- Front - Multiple
- Side - Front
- Side - Side
- Side - Multiple

The term "Multiple" in the above scenarios expresses a combination of subsequent impacts in three or more impact crashes.
To consider the importance of the injury outcome, only MAIS2+ and MAIS3+ crashes respectively, were selected.

Time between Impacts

The time between impacts was not a variable in the GIDAS database status July 2007. Therefore these times had to be computed from existing variables.
For vehicles with constant velocity between impacts, the time was calculated by the distance between impacts and the vehicle velocity. Where the vehicle was braked, skidded or accelerated between two consecutive impacts, a mean acceleration was also considered.
For 2076 passenger cars that sustained a multiple impact crash, the times between the impacts and the overall scenario time were calculated.

As the span of time between impacts can have only positive values and there was a higher frequency of shorter time spans but only a few very long time spans, a gamma distribution was applied to describe the calculated time distributions.

The gamma distribution function is valid for $t > \theta$, where θ is the threshold parameter, σ is the scale parameter ($\sigma > 0$) and α is the shape parameter ($\alpha > 0$) (Equation 2).

$$p(t) = \frac{1}{\Gamma(\alpha)\sigma}\left(\frac{t-\theta}{\sigma}\right)^{\alpha-1} \exp\left(-\left(\frac{t-\theta}{\sigma}\right)\right) \quad (2).$$

The displayed cumulative percentage curves for the scenario time and the times between impacts are generated by the estimated quantiles of the gamma distribution.

The scenario time is defined as the time span from the first to the last impact and summarizes the time between impacts. The impacts themselves were not considered having temporal length. It is to be noted that rollovers were not considered in the scenario time calculation.

THUMS Simulation Model

The human body model THUMS (Total Human Model for Safety, adult male 50%ile version 2.21-040407) was used in a generic sled model to simulate the forward displacement of the occupant due to an initial frontal impact and to estimate the time to pull the occupant back to a normal seating position by a pre-pretensioner.
Different frontal impact levels were defined to represent previously defined delta V ranges where the mean delta V was below the 50% deployment probability of irreversible front restraint devices. This implies that both pretensioner and frontal airbags were not activated in the simulation model. The initial impact time was considered with a temporal length of 150 milliseconds. After the initial impact, a constant negative acceleration according to the distribution of the coded deceleration between subsequent impacts in GIDAS, was applied to the sled model with the aim of reflecting braking and skidding of the vehicle, respectively.
The pre-pretensioner was activated at the beginning of the initial front impact. Simulations without pre-pretensioner activation were used as references. The pre-pretensioner force was measured from the shoulder to the b-pillar loop. Forward displacement of the chest is measured at the 8th thoracic vertebra in a purely horizontal longitudinal direction. The measurement position corresponds to a HIII 50%ile, chest x-accelerometer position. The pull back time defines the time from end of the first impact (150ms) until the occupant's chest has reached the original position in the longitudinal x-direction. The initial occupant seating position corresponds to ECE-R94 (EU 96/79) [13] for a 50%ile occupant size. The second impact was not simulated. Muscle activation was not utilized for the THUMS model.

Effectiveness of Pre-Pretensioning

Passenger cars sustaining an initial front impact below the 50% probability of irreversible front restraint activation (N) can be split in two groups by comparison of the time between impacts (t_{BI}) and the time to pull the occupant to the normal seat position (t_{IP}) (Equation 3).

$$N = N_{t_{BI} \geq t_{IP}} + N_{t_{BI} < t_{IP}} \quad (3).$$

The effectiveness (E) of pre-pretensioning was calculated by the proportion of vehicles exposed to an interval between impacts equal to or greater than the time required to pull the occupant back into the normal seating position (Equation 4).

$$E = \frac{N_{t_{BI} \geq t_{IP}}}{N} \quad (4).$$

RESULTS

Data Weighting

When the data set was split into groups by injury outcome according to the police record, the relative weighting factors for the GIDAS data were:

- Slightly injured: 1.10
- Severely injured: 0.85
- Fatally injured: 0.72

A factor equal to 1.00 represents a percentage in GIDAS that corresponds to the national statistics, a factor below one expresses over-representation, and a factor above one expresses under-representation.

As the main analysis results are presented as a relative comparison between single and multiple impacts or focus on MAIS3+ injured persons only, the bias of the dataset towards severe and fatal injuries was assessed to be of lesser importance. Therefore the data set was not weighted in this study, but the given weighting factors could be applied for evaluation beyond this study.

Multiple Impacts Crashes

Twenty-four percent of all passenger cars in the GIDAS data sample sustained a multiple impact crash.
Two-impact crashes accounted for 16%, three-impact crashes for 5% and four-impact crashes for 2% of all passenger cars. Less than 1% of all

passenger cars were exposed to more than four impacts in one crash (Table 1).

Table 1.
Frequency of impacts GIDAS 1999-2007

GIDAS Data (1999 - 2007)	Passenger Cars		
		Percent	
Crash Type	Freq.	All Impacts	Multiple Impacts
Single Impact	10184	76.0%	
Multiple Impacts	3208	24.0%	100.0%
2 Collisions	2151	16.1%	67.1%
3 Collisions	699	5.2%	21.8%
4 Collisions	250	1.9%	7.8%
5+ Collisions	108	0.7%	3.3%
Total	13392	100.0%	

If all vehicles that sustained a rollover were excluded from the sample, the relative percentage of multiple impact crashes was reduced from 24.0% to 20.5% (Figure 1).

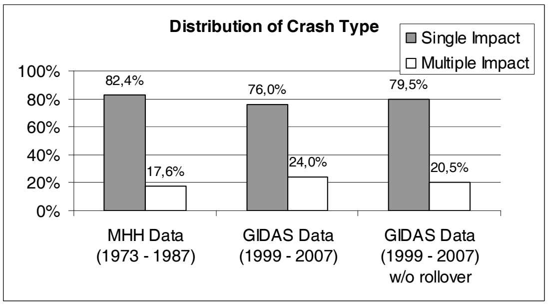

Figure 1. Distribution of crash type.

Rollovers were sustained by 4.4% of all passenger cars, of which 4.0% were involved in a multiple impact crash and 0.4% involved in a single impact crash.

Pre-Crash Velocity

Multiple impact crashes are often associated with high-speed crashes, as it is more likely to sustain a subsequent impact if the kinetic energy is high after the first impact.

The median (50% percentile) pre-crash velocity in two impact crashes was nearly twice as high as the median for single impact crashes.

Approximately 50% of all vehicle crashes with three or more impacts had a pre-crash velocity higher than 100 km/h (Figure 2).

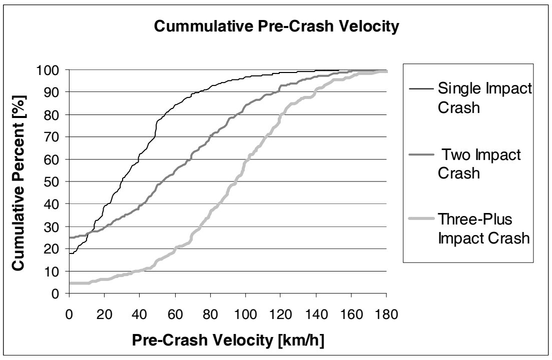

Figure 2. Cumulative pre-crash velocity distribution for single, two, and three-plus-impact crashes.

MAIS3+ and Fatality Risk

In Table 2 single impact crashes are denoted "SIC" and multiple impact crashes "MIC". Injury risk is calculated as the quotient of occupants with MAIS3+ and fatal injury, respectively, and all exposed occupants. The abbreviation "CI [+/-]" shows the confidence interval for the injury risk.

Table 2.
Injury risk in single and multiple impact crashes

all	SIC	CI [+/-]	MIC	CI [+/-]	Ratio
MAIS 3+ Risk	1.5%	0.2%	4.7%	0.7%	3.1
Fatality Risk	0.5%	0.1%	2.2%	0.5%	4.7
Rollover only	SIC	CI [+/-]	MIC	CI [+/-]	Ratio
MAIS 3+ Risk	5.2%		7.6%	2.0%	1.5
Fatality Risk			3.0%	1.3%	
w/o Rollover	SIC	CI [+/-]	MIC	CI [+/-]	Ratio
MAIS 3+ Risk	1.5%	0.2%	4.1%	0.7%	2.8
Fatality Risk	0.5%	0.1%	2.0%	0.5%	4.3

The risk of a serious injury was approximately three times higher in a multiple impact crash compared to a single impact crash. For fatal injury the risk was approximately five times higher.

With the exclusion of rollovers, which occur mainly as multiple impact crashes, the ratios for severe and fatal injury risk between single and multiple impact crashes were slightly lowered.

The significance of the difference in MAIS3+ and fatal injury risks for single and multiple impact crashes without rollover is shown in Figure 3.

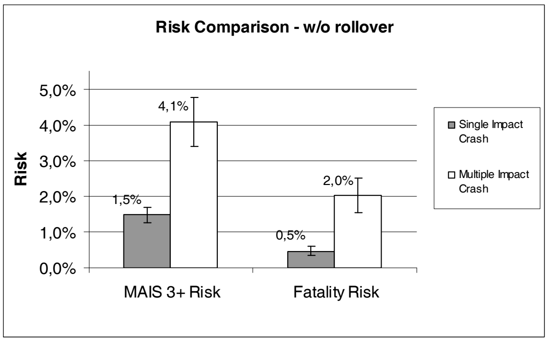

Figure 3. Risk comparisons with confidence intervals for single and multiple impact crashes without rollover.

The MAIS3+ injury risk was calculated for specific two-impact scenarios (Table 3). For three or more impact scenarios the number of MAIS3+ injured occupants per scenario was too small to derive a risk of severe injury with confidence intervals.

The comparison to single impact crashes (Table 4) shows, that the MAIS3+ injury risk in a multiple impact crash is generally higher than in a single impact crash.

Table 3.
MAIS3+ risks in multiple impact crashes

Scenario	MAIS3+ risk	Confidence interval
Front – Front	3.2%	+/- 2.1%
Front – Side	5.5%	+/- 2.5%
Side – Front	4.8%	+/- 2.4%
Side – Side	3.9%	+/- 1.9%

Table 4.
MAIS3+ risk in single impact crashes and rollovers

Scenario	MAIS3+ risk	Confidence interval
Single Front	1.6%	+/- 0.3%
Single Side	1.8%	+/- 0.5%
Single Rear	0.1%	-

The MAIS3+ injury risk in a front-side and side-front collision was about three times higher and for front–front and side–side about two times higher compared to a single front or single side impact. An MAIS3+ injury outcome was rarely found in single rear impacts.

Triggering of Irreversible Restraint Systems

The probability of irreversible front and side restraint systems activation in single impact crashes was derived from the GIDAS data.

The logistic regression for front restraint device deployment probability in a front impact was based on 2089 vehicles equipped with driver airbag, from which 735 were activated.
For side protection systems the deployment probabilities for side airbag only and side airbag plus curtain airbag were determined by logistic regression.
One hundred and seventy vehicles exposed to a side impact were equipped with a side airbag. In 52 vehicles the side airbag was activated. In 8 of 36 vehicles exposed to a side impact, both side and curtain airbag were deployed.

The probability of front airbag deployment depending on the longitudinal delta V during a front impact is shown in Figure 4.

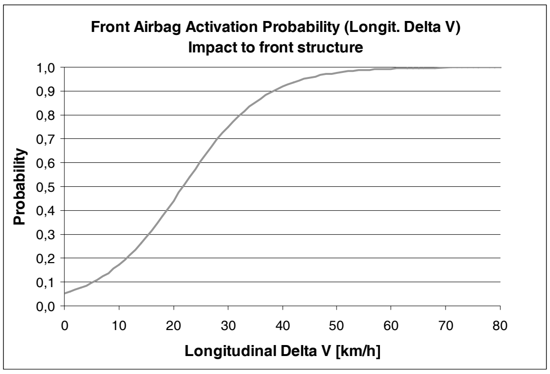

Figure 4. Front airbag deployment probability by longitudinal delta V.

Regression coefficients and percentages were calculated for front airbag, side airbag only and side plus curtain airbag deployment probability (Table 5, 6 and 7).

Table 5.
Front airbag deployment probability

Front Airbag Deployment Probability Regression Coefficients				
β_0			β_1	
-2.897			0.133	
Probability	25%	50%	75%	95%
Long. delta V	13 km/h	22 km/h	30 km/h	44 km/h

Table 6.
Side Airbag only deployment probability

Side airbag only deployment probability Regression coefficients				
β_0			β_1	
-1.640			0.074	
Probability	25%	50%	75%	95%
Lat. delta V	7 km/h	22 km/h	37 km/h	N/A

N/A = Not applicable, no data available

Table 7.
Side plus curtain airbag deployment probability

Side plus curtain airbag deployment probability Regression Coefficients				
β_0		β_1		
-2.481		0.161		
Probability	25%	50%	75%	95%
Lat. delta V	8 km/h	15 km/h	22 km/h	N/A

N/A = Not applicable, no data available

The 50% deployment probability of a front airbag and side airbag only are presented by a longitudinal and lateral delta V of 22 km/h, respectively. For the combination side and curtain airbag the 50% activation probability was present at a lateral delta V of 15 km/h.

Scenarios for Reversible Restraint System Evaluation

In about two thirds of multiple impact crashes with MAIS2+ or MAIS3+ injury outcome the irreversible (front) restraints were not triggered in an initial front impact. If the first impact was a side impact, the proportion of non-activated, irreversible side protection systems corresponds to approximately 50% (Table 8 and 9).

Table 8.
Percentage of "no trigger" for irreversible restraint systems in first impact, MAIS2+

Vehicles with at least one AIS2+ injured occupant			
Initial impact: Front		Initial impact: Side	
Front – Front	64%	Side – Front	39%
Front – Side	65%	Side – Side	59%
Front – Multiple	100%	Side – Multiple	89%
All subsequent impacts			
Front – x	67%	Side – x	50%

Table 9.
Percentage of "no trigger" for irreversible restraint systems in first impact, MAIS3+

Vehicles with at least one AIS3+ injured occupant			
Initial impact: Front		Initial impact: Side	
Front – Front	83%	Side – Front	21%
Front – Side	53%	Side – Side	60%
Front – Multiple	100%	Side – Multiple	86%
All subsequent impacts			
Front – x	71%	Side – x	48%

Evaluation of Vehicle Acceleration before and after Initial Front Impact

To enable the simulation of representative impact scenarios below the threshold of irreversible restraint systems the acceleration situation of vehicles before and after the first impact was investigated.
The results showed that approximately 30% of all vehicles braked or skidded before an initial front impact (neg. Acc.), whereas this proportion increased to over 80% after initial front impact.
Less than 10% of the passenger cars had a constant velocity (no Acc.) between initial front and subsequent impact (Figure 5).

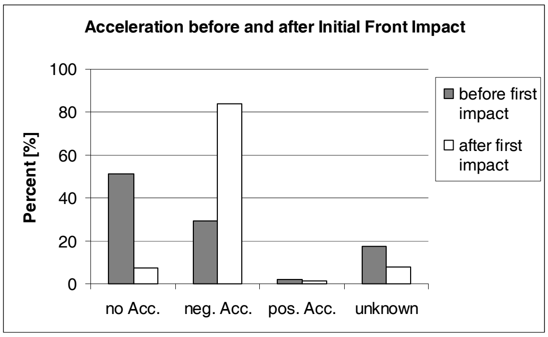

Figure 5. Vehicle acceleration status before and after initial front impact.

The quantile plot shows the cumulative distribution of mean deceleration in [m/s^2] for the vehicles that braked or skidded after the initial front impact (Figure 6)

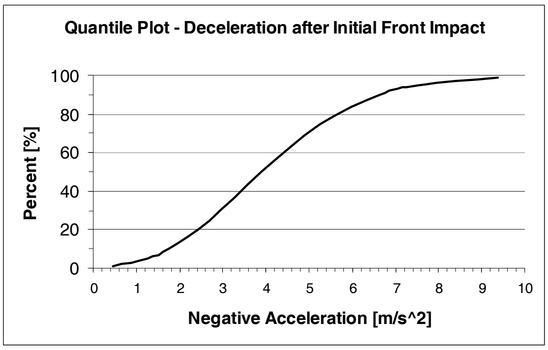

Figure 6. Quantile plot for mean deceleration of vehicles after initial front impact.

Roughly 95% of all passenger cars that sustained an initial front impact had a mean deceleration of less than 7m/s^2.

THUMS Simulation of Occupant Pre-Pretensioning after Initial Front Impact

The simulation scenarios were defined according to the results from real traffic accidents. Only those delta V ranges were considered for which the mean delta V of the category was below the 50%

deployment probability of irreversible restraint systems. All initial front impacts were simulated with duration of 150 milliseconds.
The corresponding (constant) deceleration during the impact was calculated based on the given mean delta V per range and the impact period (Table 10). The minor delta V impact was equivalent to a braking sequence.

Table 10.
Simulation of initial front impact

Delta V range	Mean Acceleration	Mean Delta V
Minor (1-5 km/h)	0.7g / 150ms	~4 km/h
Low (6-15 km/h)	2.0g / 150ms	~10 km/h
Moderate (16-25 km/h)	4.0g / 150ms	~20 km/h

After the first impact, a constant negative acceleration of 0.7g was applied to the sled model according to previous results (Figure 5 and 6).

When no pre-pretensioning was applied, the THUMS simulation results showed a maximum longitudinal chest displacement of 9 cm for the minor delta V impact, 11 cm for the low delta V impact and 15 cm for the moderate delta V impact (Table 11).

For example, with the application of a pre-pretensioning force of 200N (400N), the forward displacement of the chest of the THUMS model was reduced from 9 cm to 3 cm (0 cm) for the minor delta V impact.

The pre-pretensioning force necessary to pull back the occupant to its original position was dependent on the delta V. For low delta V a force of 300 N is required, while a force of 200 N was needed for moderate delta V.

Table 11.
THUMS simulation results for chest displacement (CD) and occupant in position time (IPT)

THUMS Simulation Results						
PPT Force [N]	Minor delta V		Low delta V		Moderate delta V	
	0.7g 150ms		2.0g 150ms		4.0g 150ms	
	CD [cm]	IPT [s]	CD [cm]	IPT [s]	CD [cm]	IPT [s]
w/o	9	N/A	11	N/A	15	N/A
200	3	N/P	9	N/P	14	0.37
300	0	0	8	0.36	13	0.27
400	0	0	7	0.26	12	0.21

N/A = Not applicable
N/P = Chest not fully pulled back by the pre-pretensioning force

Effectiveness of Pre-Pretensioning

For the effectiveness of pre-pretensioning the time elapsed between the impacts in the GIDAS data sample was calculated. The estimated quantiles of a gamma distribution were used to describe the cumulative percentage distribution of the time between the first and second impacts for minor, low and moderate delta V impacts (Figure 7).

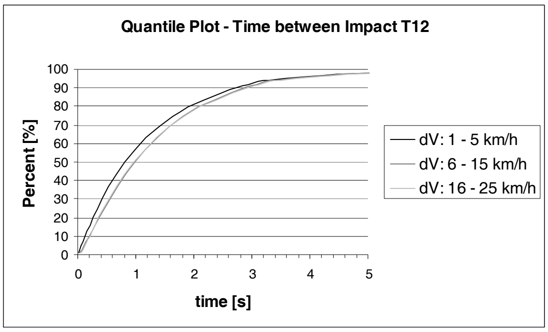

Figure 7. Quantile plot for gamma distribution of time between impacts with minor, low and moderate delta V at the first impact

Additionally, the gamma distribution parameters for the minor, low and moderate delta V first impacts are shown (Table 12).

It is noted that the distribution characteristic for low and moderate delta V were nearly identical and therefore only shown in one table.

Table 12.
Gamma distribution parameters for time between impacts

Time between Impacts Minor delta V		
Parameter	Symbol	Estimate
Threshold	Theta	0.00
Scale	Sigma	1.22
Shape	Alpha	0.96
Time between Impacts Low and Moderate delta V		
Parameter	Symbol	Estimate
Threshold	Theta	0.00
Scale	Sigma	1.07
Shape	Alpha	1.22

The distribution of the delta V ranges below the 50% activation probability of front restraint systems was considered for the calculation of the pre-pretensioner effectiveness (Table 13).

Table 13.
Distribution of delta V ranges below the 50% activation probability of front restraints

Time between Impacts - Gamma Distribution		
Delta V range	Percent	Cum. Percent
Minor (1-5 km/h)	39.5%	39.5%
Low (6-15 km/h)	30.2%	69.7%
Moderate (16-25 km/h)	30.3%	100.0%

The following results for the effectiveness of pre-pretensioning after an initial front impact were derived:

- 200N: 24% effectiveness
- 300N: 90% effectiveness
- 400N: 93% effectiveness.

Thus with, for example, a pre-pretensioner force level of 300N in 90/100 vehicles that sustained an initial frontal impact the occupants were pulled back in position before a subsequent impact.

DISCUSSION

The comparison of the multiple impact crash frequency between this study and the BASt report from 1987 lacks information for the sampling criteria for the BASt report. Nevertheless, it was stated that older MHH data was more biased towards severe and fatal accidents than the current analysed GIDAS data, collected along with the TU Dresden [14]. As the risk of severe or fatal injury is much higher in a multiple than a single impact crash it is obvious, that the older MHH data is more likely to over-represent multiple impact crashes. Therefore it can be stated that the relative percentage of multiple impact crashes has increased by about one third in the last two decades.

The calculations for the deployment probability of irreversible occupant protection systems are based on a univariate regression model depending on delta V alone. This is a gross simplification of complex occupant restraint system algorithms, but considered acceptable for plain statistical usage. One may assume an identical deployment probability for side airbag only and side plus curtain airbag. It can be noted that the vehicles equipped with both side and curtain airbags were generally newer and, moreover, that the number of these vehicles was limited in the sample.

We propose an approach towards a benefit analysis method for pre-pretensioner in multiple impact crashes. The method is based on a system model including the human body model THUMS, where both the vehicle interior and the occupant model have been validated mainly for higher impact velocities than used in this study. Also, muscle activation was not considered in the model, which is seen by the large head displacements in Figure 8. Therefore, the displacement of the chest was used instead of head displacement as a more reliable measurement. In comparison to volunteer experiments, differences might also be expected.

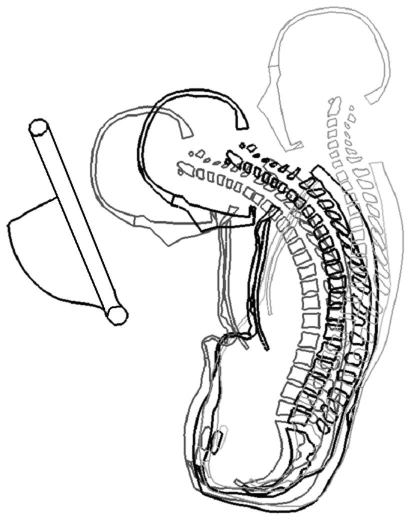

Figure 8. THUMS displacements for initial position (light grey), without pre-pretensioning (grey) and with pre-pretensioning 400N (black).

The pullback force was seen to depend on the delta-V due to the rebound of the occupant upper body and head. A lower force to reposition the occupant was thus required for the moderate delta V case (with large rebound) compared to the low delta V case (with small rebound). Volunteer tests with the moderate delta V level do not seem to be feasible as they are likely to induce harm.

The effectiveness of a pre-pretensioner to pull back the occupant into the normal seating position after an initial side impact has not been discussed. It might be assumed that the possibilities of the pre-pretensioner are smaller due to the reduced lateral restraint function of a seat belt. But this is part of further investigations.
Several reversible occupant restraint solutions have already been presented discussing an enhanced lateral fixation of the occupant, e.g. 3+2-point belt, or active seat side bolsters [15], [16].

The calculation of the overall scenario time can be used for further evaluation of the occupant protection benefit in multiple impact crashes with curtain airbags that have longer stand up capabilities, e.g. when activated in an initial impact.

The quantiles for gamma distribution of the scenario time show that 90% of all multiple impact crashes with a side and curtain airbag deployment in the first impact have an overall scenario time of less than 4 seconds. Ninety five percent of these crashes do not exceed 5 seconds (Figure 9). Multiple impact crashes including rollovers were not considered.

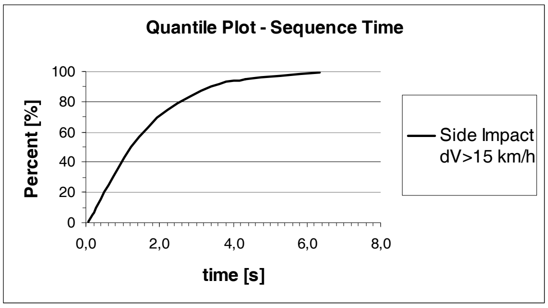

Figure 9. Quantile plot for gamma distribution of overall scenario time after curtain airbag activation.

The gamma distribution parameters which describe the distribution uniquely, are presented in Table 14.

Table 14.
Gamma distribution parameters for overall scenario time after curtain airbag activation

Scenario Time - Gamma Distribution		
Parameter	Symbol	Estimate
Threshold	Theta	0.03
Scale	Sigma	1.19
Shape	Alpha	1.32

The potential protection benefit by a curtain airbag with a stand up time of about five seconds is obvious and it represents available technology, although it has been developed mainly for rollover protection.

In general, the pre-pretensioner shows a very high potential to reduce out-of-position in frontal impacts, especially those with a small delta V, and additionally pull occupants back into previous the seating position. One boundary condition is a smart activation and force level algorithm, ensuring that no additional harm is induced by pre-pretensioning.

CONCLUSIONS

The comparison of MHH data 1973-1987 and GIDAS data 1999-2007 reveals that the relative percentage of passenger cars sustaining a multiple impact crash has increased in the last two decades by about one third.

The risk of sustaining a severe injury is three times higher in a multiple impact crash than in a single impact crash and for fatal injury the risk is four times higher, even if rollover crashes are excluded.

With use of the 50% probability deployment thresholds in about two thirds of all multiple impact vehicles with at least one MAI3+ injured occupant, the front airbag is not activated in the first impact. When the first impact is a side impact, the percentage of non-deployed side and curtain airbag is about 50%. This reveals an obvious potential for a reversible occupant restraint system like a pre-pretensioner to retain or retract the occupant in position.

To assess the occupant forward displacement during an initial frontal impact, a finite element sled model including the human body model THUMS and standard interior safety systems was used. No muscle activation was applied.
The activation of a pre-pretensioner with different force levels demonstrates a major benefit firstly in reducing occupant out-of-position, especially in impacts with a small delta V, and secondly in getting the occupant back into the original seating position.

With a pre-pretensioning force of 200N the occupants in 24% of the vehicles, sustaining a front impact without front airbag activation (50% probability), are in position before a subsequent impact. With a pre-pretensioning force of 300N this percentage is increased to 90%. With 400N pre-pretensioning force, an effectiveness of 93% is achieved.

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The Mercedes-Benz Experimental Safety Vehicle 2009

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ABSTRACT

The way was paved for the first ESV Conference in the early 1970s by the development and discussion of what were called Experimental Safety Vehicles. From the outset, Mercedes-Benz played an active role in this initiative. Up until the mid-1970s, over 20 Mercedes-Benz ESFs (for Experimental Sicherheits Fahrzeug) were built and presented. This short period of time also witnessed the development of basic innovations, some of which represent crucial milestones for vehicle safety:

- Structural safety
- Anti-lock Braking System (ABS)
- Belt pre-tensioner and belt force limiter
- Airbags
- Side impact protection
- Electronic Stability Program (ESP)
- Partner Protection Systems

For the ESV Conference in 2009, Daimler is re-creating this pioneering paradigm shift and developing a new Experimental Safety Vehicle, the ESF 2009. Based on the very latest safety features, such as Advanced Driver Assistance Systems, Adaptive Restraint Systems, and Integrated Safety Systems (PRE-SAFE®) [1], the ESF 2009 will present and demonstrate solutions for the requirements and safety challenges of the future.

This paper presents the safety features that Mercedes-Benz is focusing on to address vehicle and road safety requirements in the future.

In pursuit of our vision of accident-free driving and high-performance occupant safety, the paper looks at the following subjects and solutions, which could provide further sustainable advances in the field of vehicle safety:

- Systems for enhanced perception
- Vehicle communication
- Invisible protection zone
- Driver Assist Systems
- PRE-PULSE and innovative occupant protection systems
- Safety of alternative drive systems

The paper will describe functional models of the different safety features, their potential safety benefits, and feasibility requirements. The main goal of the Mercedes-Benz ESF 2009 is to illustrate mid and long-term safety features and to promote discussion on their relevance for achieving improved traffic safety.

INTRODUCTION AND MOTIVATION

Vehicles from then (Fig. 1) already considered topics relating to both active and passive safety together. This integrated safety approach, based on the technology of the day, offered glimpses of the type of improvements in vehicle safety that were to come. Today, most of the systems that were considered revolutionary at that time can be found in the series production vehicles of virtually every manufacturer. No further experimental safety vehicles have been assembled anywhere in the world, or presented at the ESV conference, since 1974.

In constructing a new experimental safety vehicle (Fig. 2), the intention of Mercedes-Benz is to again promote holistic discussion of the subject of vehicle safety.

Figure 1: ESF 13 from 1972

The hope is to present feasible new solutions based on today's technologies and illustrate the potential they offer. Systems whose production breakpoint is not yet possible from a present-day perspective have been consciously included to elicit discussion of the basic requirements and technological advances that will be required.

Figure 2: The ESF 2009

DESCRIPTION OF THE MAIN TOPICS

The scope of this paper does not permit a comprehensive explanation of the circa 30 topics from six different areas. Selected systems have therefore been presented in more detail as being representative for each of the topic areas. The following areas were included in the ESF 2009, grouped according to the integrated safety approach [2], i.e. ranging from accident prevention and protection for the occupants during an accident to the measures that can be taken after an accident.

Systems for enhanced perception

One area that offers considerable potential for reducing accident statistics is improved perception of the traffic situation by the driver and other road users.

The topic "Adaptive High Beam with Spotlight" offers a solution for extending the visibility of other road users and differentiating between them. The hazard signal used by this technology is provided directly in the traffic situation. The technical solution in the ESF 2009 gives an example of how the inherent visibility of the vehicle can be improved for other road users, particularly from the side. In this case, the inherent visibility was improved using passive reflective measures.

Both topics are described in more detail in the presentation of each later in this paper. The topic of Intelligent Night View for active night vision recognition and for accentuating the visibility of pedestrians and animals is also examined.

Vehicle communication

Vehicle communication systems for accident prevention or rescue will make an important contribution on the way to achieving safer driving. Communication between vehicles offers crucial added value, especially in situations that could be adequately defused with the help of an early warning system, or where a vehicle surrounding sensor system, e.g. in concealed situations, cannot offer any added value. However, at this point, a single-manufacturer solution cannot help us achieve our goal. Instead, what is needed is a successful collaboration between a large number of manufacturers and suppliers with the aim of developing uniform standards and a model for rapid market penetration of the technologies involved. For that reason, this important topic has also been included in the vehicle.

Driver Assistance Systems

Systems to prevent and reduce the severity of accidents represent an important basis for future developments to improve vehicle safety. Building on improved and extended vehicle sensing systems (e.g. radar and stereo cameras), new assistance functions will become possible that will help the driver, e.g. in critical situations at intersections.

The assistance systems in the ESF 2009 address the topics of improving longitudinal and lateral guidance, as well as general perception.

Specifically, these are as follows:

The blind spot assistance system can not only trigger a warning, but also help avoid a potential collision with a vehicle in the blind spot by braking individual wheels.

The extended Lane Assistant also comprises an alarm level, and, if it recognizes the danger of a critical departure from the lane, intervenes by applying independent wheel braking to correct the steering course. At a later stage of development, corrective steering intervention can also occur if collision objects are identified.

Traffic sign assistance system to visualize the currently applicable speed limit.

Virtual crumple zone

Several manufacturers have recently introduced systems to help the driver in situations with a high risk of rear-end collisions. With its introduction of the PRE-SAFE® brake in 2006, and the enhanced version with an emergency braking function in 2009, Mercedes-Benz brought onto the market the final stage of development for the present in a bid to counter the risks posed by escalating parallel traffic. The PRE-SAFE® brake system combines acoustic and visual warnings, adaptive brake assistance, and autonomous partial and emergency braking to offer an all-round package that helps to avoid an accident, or to reduce kinetic energy before a possible collision. Preventive occupant protection functions are also activated. The Brake Bag in the ESF 2009 represents a further development stage. This will be explained in more detail in a later section.

PRE-PULSE and innovative occupant protection systems

To date, the development of occupant protection systems has focused on extending the protective space, and on adaptive restraint systems. Extended fitting of airbags down into the subcompact range, and refinement of the seatbelt with pretensioning and force limiter have greatly reduced the loads to which occupants are subjected in accident situations. Over the last few years, however, we have witnessed an asymptotic trend in the reduction of forces under the specified load conditions. If we consider conventional restraint systems, even experts believe that the possibilities for further development in the future are slim.

Nevertheless, if we consider the pre-accident phase, links can be created between reversible and conventional occupant protection systems that, in combination, open up further possibilities. One example of this is the forward-thrusting PRE-PULSE Side occupant protection system, which will be presented in a later section.

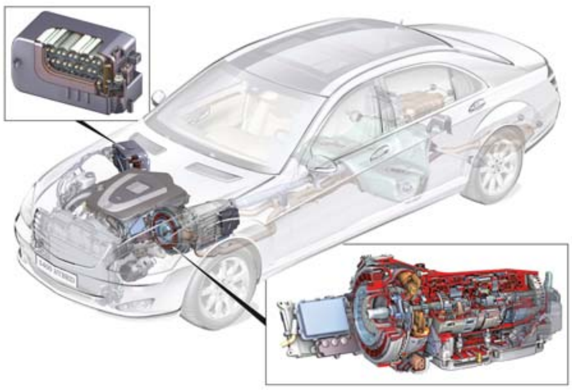
A further area where occupant protection can be improved is in the rear seat row, which has different requirements to the front seat row. On the one hand, children are transported in this area, so that occupant protection systems must meet the requirements for this occupant group. Similarly, the requirements for a chauffeur limousine, as in the present luxury vehicle segment, are quite different as regards occupant protection. The solutions presented for child safety and the belt bag should prove enhancements to the range of protective equipment, and will be described in more detail as part of the vehicle presentation.

On the question of resolving the conflicting objectives of body rigidity and lightweight construction, the topic "inflatable structure" will be addressed and presented separately in a later section.

Safety of alternative drive systems

The ESF 2009 is equipped with a modern hybrid drive system (Fig. 3). The equipment includes a 15 kW magneto-electric motor, a lithium-ion high-voltage battery, and the necessary power and control electronics.

Figure 3: Location of the hybrid components in the ESF 2009



The vehicle is equipped with a comprehensive, seven-part safety concept, designed in particular for the high-voltage electronics system that operates at 120 V. The system includes the following features:

- Color-coded HV cables and contact protection, with generously dimensioned insulation and special plugs
- High-strength steel housing for Li-ion battery
- Cells on bed of gel and discharge ports with bursting disks
- Multiple safety interlock to automatically separate battery terminals
- Short-circuit monitoring
- Active discharging of the high-voltage system in the event of faults or fire
- Pyrotechnic tripping of the HV system in the event of an accident.

TECHNICAL DESCRIPTION OF SELECTED SYSTEMS

LED pixel headlamps for hazard light

Night vision systems are a great help for the driver: with the night vision assistant, even with oncoming traffic, drivers can still see their own lane and the right-hand edge of the roadway without any risk of dazzling other road users. Advances in camera technology and image processing now allow systems to recognize potential dangers on and immediately adjacent to the roadway. These can be specially highlighted on a suitable display to warn drivers. The preferred solution would be for drivers to receive an alert about a potential hazard directly in the traffic area, without wasting time looking at a display. This function will be called a “hazard light” in the following.

There are basically two different approaches to realize this function: (1) a type of search lamp that moves in a similar way to an active curved illumination module, or (2) a fixed headlight with electronically controlled light distribution. The second variant has been implemented in the ESF 2009, since fractions of a second are of vital importance with a “hazard light” (Fig. 4). In principle, there are also two different approaches for the non-mechanical systems: the use of a video projector [3] or similar device, or the use of an electronically addressable LED array [4].

The second approach was the option preferred in the ESF 2009. An array of this kind basically consists of a number of individual LED chips arranged in rows and columns. Approximately 40–100 LED pixels are needed to create a vehicle headlamp (depending on the desired resolution and the maximum area to be illuminated). The ESF 2009 has 96 pixels arranged in four rows, with a different number of pixels per row. Each of the 96 pixels can be dimmed in 256 steps, and can be switched on within a few milliseconds.

Figure 4: Spotlight function

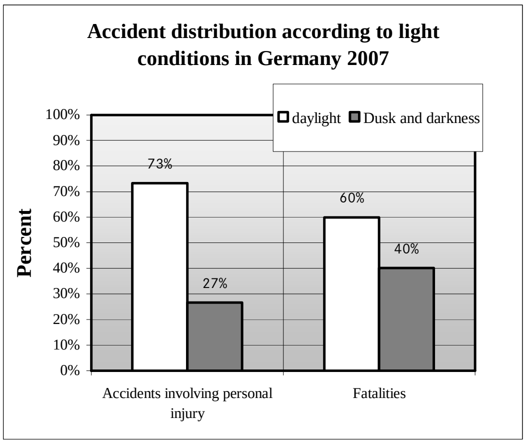
As well as the “hazard light,” it is possible to use this LED array to implement adaptive light functions, such as active curve illumination and partial high beam. In conjunction with the image evaluation, various ways of warning the driver can be tested in the ESF 2009. Simply illuminating any hazard will not be possible, since other road users must not be dazzled. In the case of pedestrians, therefore, two possible solutions would be illumination up to the waistline, or projection of a “light pointer” onto the roadway.

While most of the technical problems have now been solved, further studies are required in this area, and the legal regulation for this new function still needs to be defined.

Side Reflect – improvement in side visibility at night

Dusk and darkness pose an enormous risk potential. Over one quarter of all accidents occur under these lighting conditions. Additionally, the severity of injuries increases during these times. Some 40% of accidents involving fatalities occur at night [5] (Fig. 5).

Figure 5: Accident distribution by light conditions



The (active) lighting techniques have been steadily improved over the last few years. However, there are still many situations presenting an increased risk potential, such as an unlit vehicle that has been left at the side of a country road, or vehicles crossing an intersection without warning.

The objective of Side Reflect is to enhance the side visibility of the vehicle in order to reduce this accident risk at night. The reflective properties under diffused side light conditions are enhanced (Fig. 6). One element consisted of reflective strips on the tires (as has been standard on cycle tires for a number of years).

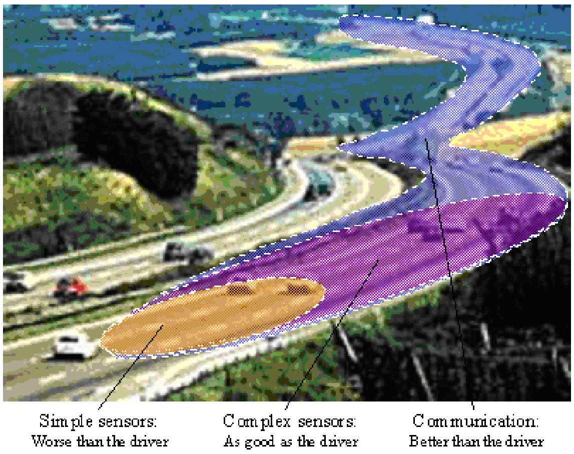
Figure 6: Improvement in side visibility with Side Reflect

An additional component that was presented by way of example in the ESF 2009 was door seals with reflective properties. Here, the external area of the door seal rubber was coated with a special film that integrates seamlessly into the vehicle design. These reflective door seals emphasize the vehicle contour for enhanced night-time visibility.

Vehicle communication

Autonomous sensor systems for hazard detection in the vicinity of the vehicle form the basis for today's driver assistance systems, which can significantly improve active safety. However, the drawback with all the standard solutions at present is that detection of the immediate environment is restricted to the field of vision. With this kind of sensor system, it is not possible to detect or locate hidden objects (vehicles), whether these are behind hilltops, curves, or buildings at inner-city intersections. In this context, vehicle communication offers the option of extending the driver's field of vision and that of the vehicle far beyond the physical range of visual detection through spontaneous (ad-hoc) networking between vehicles (Car-2-Car, C2C), and/or to the infrastructure (Car-2-I) (Fig. 7).

Figure 7: Telematic horizon



The C2C and C2I (= C2X) communication defines a cooperative system that requires the vehicle hardware configuration to be extended to include a radio communications unit (on-board unit) with GPS capability. Vehicles with the appropriate equipment then transmit information such as GPS position, speed, and direction on a cyclical basis. This information allows every receiver to put together a continuous image of the environment and monitor any changes in it.

By passing on data from one vehicle to another ("multihop communication"), the range of radio communication can be extended to areas that are not accessible for direct transmission ("single-hop communication").

The potential of C2X communications for active safety stems in part from the possibilities offered by sensor data fusion. The additional data obtained from C2X communication can improve the quality of conventional environment sensors. New assistance functions can also be realized, thanks to the continuous recording, aggregation, and evaluation of the sensor data available in the vehicle. For example, an ESP intervention might occur without the driver being aware of it when driving round a curve with a partial section that is slippery. The relevant C2X application recognizes this ESP activity and links the information with additional sensor information, such as speed, steering angle, slip/traction, outside temperature, rain sensor, etc. Based on these parameters, a suitable algorithm can detect "risk of ice" or "risk of skidding," and transmit a warning message by multihop communication (Fig. 8). When another vehicle approaches this hazard spot, the driver will receive an acoustic and/or visual warning in good time, and can adapt accordingly to the approaching hazard situation.

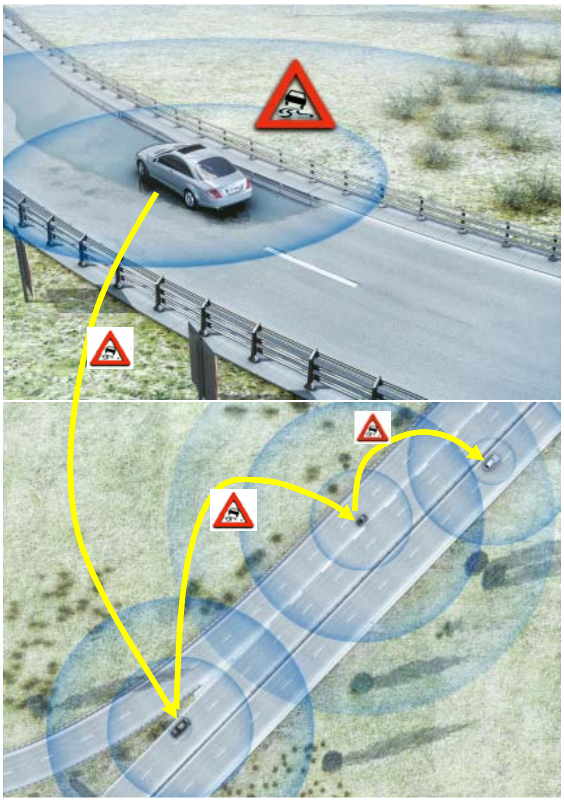
Particularly in the introductory phase of C2X systems, situations may arise where there are no communication partners within radio range. Warnings are then stored, carried further, and passed on as soon as a communication partner (vehicle or communication unit in the infrastructure) is within range (store and forward system). Traffic traveling in the opposite direction can be usefully employed in this context to transport warnings back into the target area in question. Intelligent, position-based routing algorithms ensure that, even in scenarios where there is low traffic density in the danger zone, valid warnings are not wasted, but are safely stored.

Since C2X communication is a cooperative system, its benefits and quality will increase as use of the communication systems spreads.

Rapid penetration will therefore be possible only if there is a uniform communication standard that all automakers adhere to and that is jointly defined by as many manufacturers and suppliers as possible. This will be ensured by the Car-2-Car Communication Consortium (C2CCC), and by the ETSI Technical Committee Intelligent Transportation Systems.

C2X communication, therefore, can potentially play a key role in helping to avoid accidents through automatically generated warning messages before hazards such as accident sites, vehicles left at the roadside, obstacles on the roadway, abrupt breaking vehicles, the end of a traffic jam, construction sites/vehicles, approaching emergency vehicles, etc., and in controlling the flow of traffic, all without generating any additional communication costs. However, it is less suitable for on-board autonomous system intervention (e.g. automatic braking) owing to the latency times involved, and also to system-related inaccuracies in determining position with GPS.

Figure 8: Ad-hoc communications and multihop message passing



Invisible Protection Zone, Brake Bag

The current E-Class model year 2009 features the last development stage for the time being of an automatic emergency brake system. The emergency braking function before an unavoidable collision in escalating parallel traffic reduces the speed of the resulting vehicle collision by approx. 6–8 km/h. Approximately 0.6 s before the collision, the vehicle, which is already performing partial braking, is guided into an emergency braking maneuver. A further escalation level appears impossible at present, since the vehicle has already been fully decelerated up to the slip limit. Increasing the deceleration energy through that of the wheel brake must therefore be seen as a further escalation module.

In this context, Mercedes-Benz has developed the concept of the Brake Bag. An airbag with standard driver inflator was added to the front underbody paneling of a standard S-Class vehicle. This paneling has a double-wall design, so that the airbag can be installed spread out between both body panels. Once activated, the airbag expands, supporting itself on the top side of the front integral carrier (Fig. 9). The underside is fitted with a friction lining designed to achieve optimum deceleration. It is mounted in front on the vehicle crossbar, so as to transfer the fictional forces generated by braking the vehicle on the roadway.

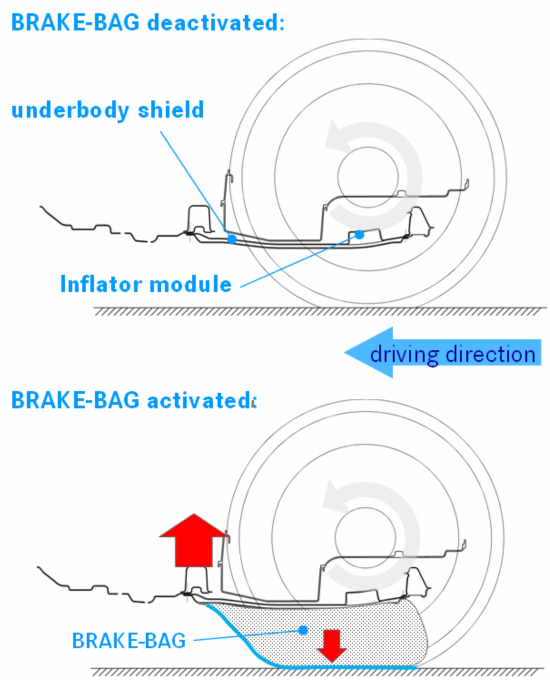
If the Brake Bag is activated in escalating oncoming traffic, i.e. after the warning that is triggered approximately 2.6 s before the time of collision, after initiating partial braking at approx. 1.6 s, and after initiation of emergency braking at approx. 0.6 s before the start of the collision, the result is a rapid and temporary increase in deceleration lasting approximately 75–100ms, with a deceleration rate of 20 m/s^2 (Fig. 10).

The increase in deceleration is primarily influenced by an elevation in the center of gravity of the vehicle as it performs the emergency braking maneuver. When the airbag expands, it momentarily raises the vehicle by approx. 80 mm. During this brief period, the thrust exerted on the friction lining of the Brake-Bag is increased by the factor of the mass acceleration times the overall vehicle mass.

This increased thrust leads to a greater rate of deceleration (Fig. 11) that can be generated with a normal wheel brake. In this context, it is important that the precise collision point is predicted as exactly as possible, since the process is reversed after a certain period, leading to a load reduction that has a negative impact on the deceleration value.

As a result of the vehicle's upward movement, the brake dive movement is also compensated for, thus improving the geometric compatibility of the braking vehicle. The deformation structures adjust to the original design level.

Figure 9: Cross-section of brake bag



The following effects can also be observed:

An influence from the seat structure on the inert mass of the occupants can also be observed, owing to the elevation of the vehicle. The value measured in tests is approx. 20 mm, which means that compression of the elastic seat foam and the convergence of the seat ramp and the bodies of the occupants result in improved coupling in the subsequent crash.

This applies in equal measure to coupling with the already tensioned seatbelt in the PRE-SAFE® phase. In the escalation to the accident, the occupant is held in position by a reversible tensioning, in preparation for the subsequent emergency braking.

Figure 10: Deceleration with brake bag

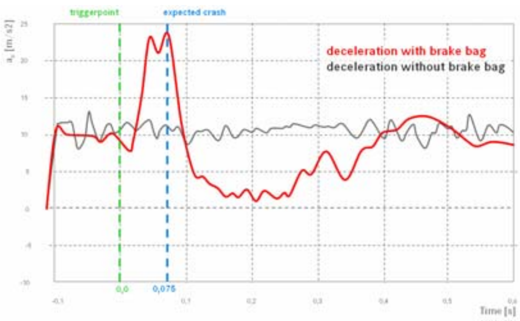
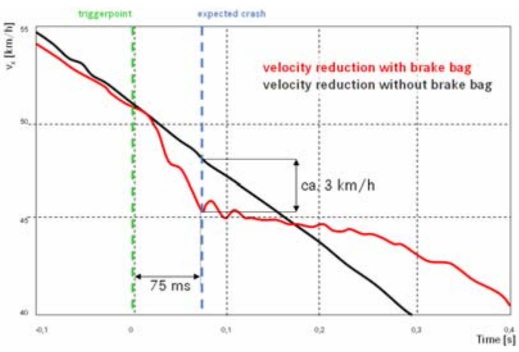


Figure 11: Reduction in speed with brake bag



The emergency braking then generates an increase to approx. 400–600 N on the belt through the inertia force imparted. The deceleration from the Brake Bag of approx. 20 m/s^2 further enhances this seatbelt pre-tensioning to approx. 800–1,200 N, thus contributing to optimize deceleration coupling even before the pyrotechnic belt tensioner is triggered.

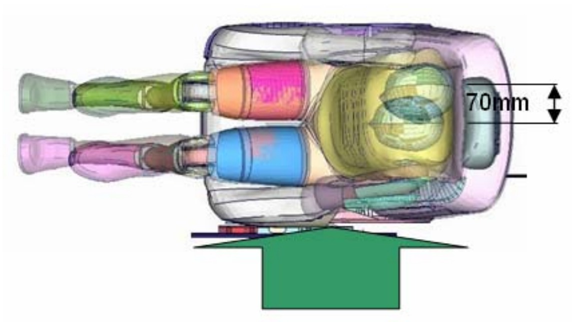
PRE-PULSE occupant safety system

Standard restraint systems can be described as only reactive occupant safety systems. For example, a generation of force and the associated energy conversion within the belt system occurs only after the occupant has traveled the necessary distance after a specific period by being thrust forward in a frontal impact. However, at this point, valuable deformation space has been used only for the vehicle deceleration, but not to decelerate the occupants. The way the airbag operates is similar to the functioning of the belt described above. Only after sufficient internal pressure has developed from precompression of the bag does deceleration (or acceleration in the case of a side impact) occur, followed by a conversion of energy to the occupant.

The crucial lever for reducing the load values in a side impact is the distance between the occupant and the door. The greater this distance, the lower the speed at which the door accelerates the occupant through the occupant protection system. At the same time, this distance is limited by the possible vehicle size and the comfort dimensions. The contact speed of the intruding door is primarily influenced by measures adopted for the body shell and the door. Here, too, there are restrictions imposed by limits on vehicle weight and the vehicle package.

Measures undertaken to date to increase side-impact protection have mainly been implemented in the vehicle itself, i.e. influencing the occupants has not been considered so far. A PRE-PULSE occupant safety system, as presented in the ESF 2009, taking the example of a side impact, uses the early information on the unavoidable collision for a preparatory energy conversion that affects the occupant. Such PRE-PULSE systems accelerate the occupant shortly after the accident event in the direction created by the collision energy (Fig. 12), and thus reduce in good time the energy delta between vehicle and occupant. The energy is not converted exclusively when an impact occurs, but instead the full energy is distributed between a light advance impact, and a reduced main impact.

Figure 12: Deflection of the occupant through forward thrusting



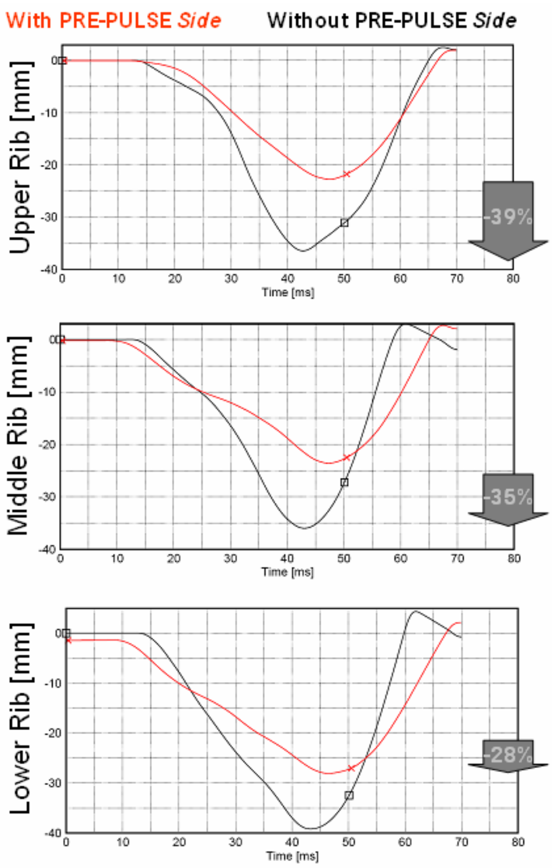
This can be simply explained using the example of a side impact.

The seat was equipped with the dynamic seat component of the multi-contour seat in order to create the PRE-PULSE effect on the occupant. This features air cushions in the “cheeks” of the driver and front seat passenger backrests, to improve lateral support on curves through inflation.

The size and inflation characteristics of these cushions were modified so that they can propel the occupant towards the center of the vehicle after a sudden pulse-type inflation. This process is reversible and can be repeated.

The movement towards the center of the vehicle increases the distance between the occupant and the door.

Figure 13: Rib deflection in load case FMVSS 214new



The side bag can now be safely deployed. The contact point between the door and the occupant occurs later with the restraint system, i.e. at a lower intrusion speed. Additionally, the occupant is already moving at a certain velocity in the direction of impact, and this velocity no longer needs to be converted through contact with the side bag and the door. Simulation tests showed a reduction in rib intrusion of 30% on average (Fig. 13).

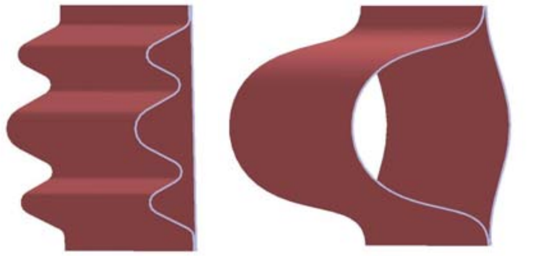
Pressurized Vehicle Components

In general, two principals of pressurized components have been investigated for front and side member applications, involving various departments at Mercedes-Benz:

- The first principle states that the components must retain the original structural characteristics they had before being pressurized. Pressure therefore needs to be carefully adjusted.

- The second principle is that the structure should expand when pressure is applied from a small cross-section to a larger one. This can offer considerable advantages, such as packaging benefits (Fig. 14), an increased moment of inertia, and an extension of the overall crash length. In addition, there are two opportunities to apply pressure and enforce the structure in general:

Figure 14: Pressure-loaded side impact protection beam. Significant increase in geometry.



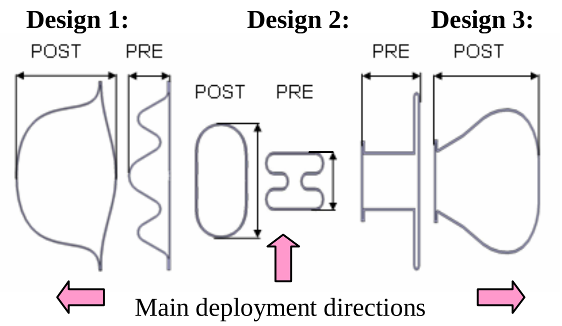
- Adding a gas generator that maintains a defined, virtually constant level of pressure over a period of time. The firing time should match the ongoing deformation of the structures involved and last between 10 ms and 20 ms for the various applications.

For an almost sealed component, high-level pressure will be available for up to 100 ms of deformation.

- Installation of a gas generator that is able to deform a component from an initial structural shape to a final one, without providing pressure for longer than is needed for deployment.

Various dynamic sub-component tests have been conducted for validation. The mean crash load was increased by 20 to 40 kN, and deformation was reduced to between 10 mm and 100 mm. With an increased mean crash load, pressurized front member components could be introduced to cover small and large-sized engines without body-in-white modifications. In addition, it seems possible to introduce new propulsion concepts that can incorporate higher component weights (batteries, hydrogen storage), without major structural modifications being necessary. A door component, the side impact intrusion bar, was investigated for a pressurized side member application. Fig. 15 shows three different designs.

Figure 15: Design studies for side impact intrusion beams.



The extension rate, which describes the rate between the deformed and undeformed cross-section shapes, came to approximately 250%, 100%, and 300%. The weight was reduced by 25%.

Figure 16: Door beam deformed/undeformed

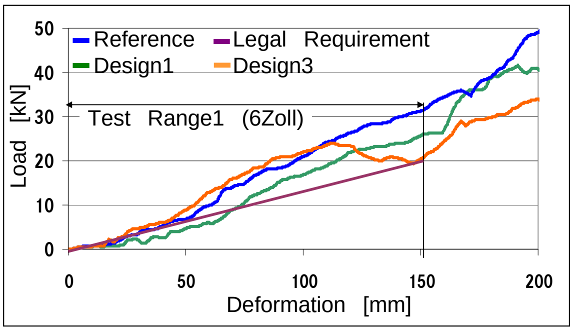
As regards safety aspects, there was an urgent need to have the main direction of deployment directed outward from the car, e.g. Design 1 (Fig. 15).

In the first development stage, the door beam was designed to fulfill FMVSS214 requirements without pressurizing. Using the tube of the gas generator as a load-carrying component, the load level increased by about 7.5 kN to 12 kN.

All undeployed designs fulfilled the FMVSS214 static requirements (Fig. 17).

If, in addition, there was pre-crash activation of the intrusion bar, which the static standard test procedure does not seem to exclude, the mean load level would rise by 6 kN.

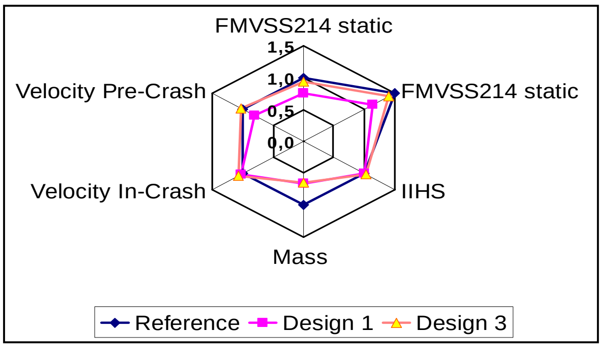
Figure 17: FMVSS214 static pole test



IIHS has been assessed in tests and simulations. It was becoming obvious that FMVSS and IIHS requirements can be achieved with reduced weight. Having lateral pre-crash sensing available, the intrusion velocity of the inner door trim was reduced by over 20%.

It has been demonstrated that the technology provides safety and weight benefits. To transfer the technology to a commercial application, however, a number of challenges first need to be met (Fig. 18). Knowing that the maximum benefits will be achieved for pre-crash applications, lateral sensing has to be established. In addition, optimized jointing, handling, and assembly concepts have to be developed. On the supplier side, there is an urgent need to come up with additional cost and weight reductions for gas generators.

Figure 18: Assessment of pressurized door components



SUMMARY

The purpose of the Experimental Safety Vehicle ESF 2009 is to illustrate new approaches aimed at improving vehicle safety. Some new, as yet unpublished approaches were selected for this. A solid foundation comes from using information on the traffic environment that is as precise and reliable as possible. Recording information using sensor beams and the networking of vehicles with the help of new communication technologies should yield further support measures in the future that will help avoid or reduce the severity of accidents.

Further milestones on the way to our vision of accident-free driving will be achieved by using innovative light technologies to improve the perception reliability of other road users, and also by improving the discernibility of the vehicle itself, particularly from the side.

Along the way, exploiting information about an imminent, unavoidable collision offers further potential for occupant and partner safety. An important component in this area is the use of the PRE-PULSE mechanism to distribute the collision energy over several impulses.

The extended coverage of the area between the occupants to protect against occupant interactions and the adaptability of the size and absorption capacity of the airbag have not been discussed in this paper, but both play an important role in accident protection in the ESF 2009.

The ESF 2009 offers an in-depth look at current development projects relating to vehicle safety at Mercedes-Benz. To an extent, it therefore also represents a risk for the company. However, it is important that experts should have the chance to discuss important new, and, in certain cases, unconventional ways of improving safety, and then develop them systematically.

The features of the ESF 2009 are intended to provide just such an opportunity.

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A SITUATION BASED METHOD TO ADAPT THE VEHICLE RESTRAINT SYSTEM IN FRONTAL CRASHES TO THE ACCIDENT SCENARIO

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ABSTRACT

The integration of active and passive safety systems is considered as a significant contribution towards further improvement of traffic safety. The present article describes an approach to integrate these systems. This is done by development of a novel control algorithm where force levels and activation times of an assumed adaptive restraint system are predefined based on the oncoming collision. Reference values for these force levels are generated in order to minimise the acceleration of the occupants.
The method takes into account the actual crash severity by a forecast of the acceleration behaviour of the passenger cell, based on prediction of collision speed, mass and stiffness of opponent and own vehicle. The prediction of mass and collision speed is not part of the present paper and currently under investigation. A forecast of the acceleration pulse is calculated by a simplified multi body model of the impact. The vehicle deformations are considered by non-linear springs with hysteresis. Their characteristics are derived from 53 crash tests published by NHTSA. The occupant of the ego-vehicle is considered also by a simplified multi body model, taking into account its mass and seating position. Optimisation algorithms determine suitable force levels and trigger times of the adaptive restraint components by minimising the acceleration of the occupant while avoiding bottoming-out of the restraint system. Currently, only straight frontal collisions with full overlap are considered. The algorithm is developed in order to provide a real-time application and is verified by detailed off-line crash simulations.
With numerical simulations several configurations with different collision severities and occupant masses were investigated. In almost every configuration significant reductions up to 90 % of the occupant acceleration were observed. The present study forms the basis of future work which includes a real-time application in a vehicle.

INTRODUCTION

Background

Active safety systems and advanced driver assistance systems (ADAS) such as electronic stability control (ESC), emergency brake assist (EBA) and lane keeping system will contribute to avoid and mitigate collisions in future [1, 2, 3].
Passive safety restraint systems are currently activated by electronic control units (ECU) that for example evaluate accelerations, roll rate and door pressure during an accident. The activation is triggered after first contact of the vehicles, in frontal crashes typically after 10 to 30 ms, which wastes ride-down distances and requires fast deployment of airbags. Yet, fast airbag deployment is aggressive to occupants, especially when they are out-of-position, for example after emergency braking or crash avoidance manoeuvres [4].
Moreover, the adaption of passive safety systems to the actual accident is mainly limited to low and high crash severity. Adaption to occupant mass and seating position provides a significant potential for reduction of injuries [5].
Especially, the integration of active and passive safety systems and the adaption of their functionality to the actual collision is considered as a significant step towards improved traffic safety [6, 7].

Objective

The present paper is based on previous work [8, 9] and describes an approach to integrate active and passive safety systems. An algorithm is developed which pre-sets force levels and trigger times of an adaptive frontal restraint system according to parameters of an oncoming collision. Reference values for these force levels are generated in order to minimise the acceleration of the occupant. Important sources for the development of the algorithm are found in [10, 11, 12].

The following section summarises the main approach of the novel approach, further details are published in [8, 9].

METHODOLOGY

The main idea of the algorithm is the prediction of the passenger cell acceleration pulse of the own vehicle (ego-vehicle). This is based on a forecast of collision speed, mass and stiffness of the colliding vehicles, which are the main input parameter of the algorithm.

The method consists of three separate modules, the vehicle model, the collision model and the occupant model. MATLAB/Simulink® software was chosen for the realisation of the complete model, due to its capability for generation of real-time codes that can be run on automotive ECUs. The structure of the Simulink model is depicted in Figure 1, which illustrates the interfaces between the modules.

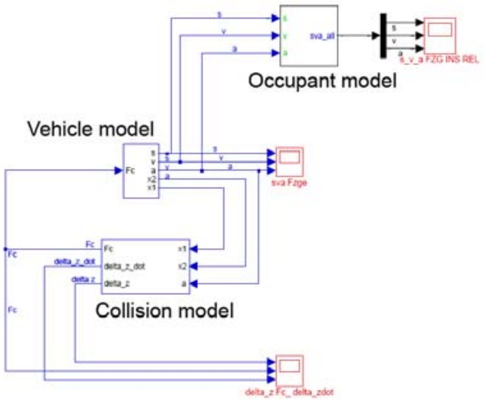

Figure 1: Structure of the Simulink model.

Prior to the impact, the vehicle model is exchanging data (state vector of ego-vehicle and collision opponent) with the collision model which predicts the acceleration of the passenger compartment. The collision model is exchanging data (predicted acceleration pulse) with the occupant model where an adaptive restraint system is minimising the occupant acceleration. Outputs of the model are force levels and activation times for an adaptive restraint system.

Vehicle Model

The vehicle model serves to predict the impact energy and delivers the input parameters (mass and collision speed) for the collision model. The module is based on state-of-the-art longitudinal vehicle dynamics modelling and includes driving resistances (air, climbing and rolling resistance), for the basic theory refer to [13].

Additionally, an Antilock Braking System (ABS) and an EBA of the ego-vehicle are integrated to include their influences on the mitigation of oncoming collisions. Therefore, rotational degrees of freedom for the wheels are modelled.

The control algorithms of the driver assistance systems were taken from literature [14, 15]. Nevertheless, serial ABS or EBA applications can be integrated any time during full vehicle system integration.

One component of the vehicle model is the collision prediction block which uses the input of an environment recognition system (such as radar, video or laser scanner) to predict the state vector (position and velocity) and mass of the collision opponent prior to collision. This block is not yet implemented and part of ongoing work. The Simulink structure of the current vehicle model is depicted in Figure 2. A detailed description of the model can be found in [8].

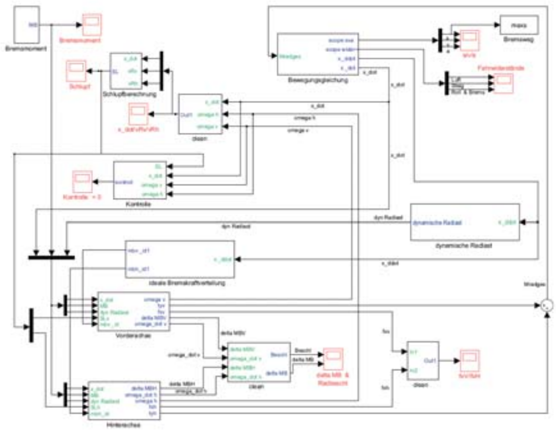

Figure 2: Simulink structure of vehicle model.

Collision Model

The collision model serves to predict the acceleration of the passenger compartment of the ego-vehicle. It consists of two rigid bodes with a single degree of freedom for each in longitudinal direction (x_{opp} and x_{ego}), see Figure 3. They represent the opponent vehicle (mass m_{opp}) and the ego vehicle (mass m_{ego}). The rigid bodies are linked together by force elements (nonlinear springs with hysteresis, F_C).

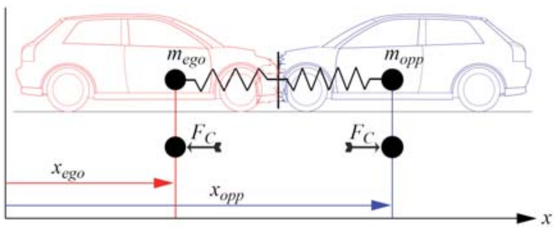

Figure 3: Scheme of collision model.

By numerical integration of the equations of motion of this model, Eq. (1), the acceleration of the passenger compartment of the ego-vehicle is calculated.

$$
\begin{aligned}
m_{opp} \cdot \ddot{x}_{opp} + F_C &= 0 \\
m_{ego} \cdot \ddot{x}_{ego} + F_C &= 0 \\
F_C &= c_{def} \cdot (x_{opp} - x_{ego}) \\
c_{def} &= f(x_{ego}, x_{opp})
\end{aligned} \qquad (1).
$$

The spring characteristics of the force elements, which describe the deformation behaviour of the vehicles in a full overlapped frontal crash, are derived from crash tests published by NHTSA [10]. A total number of 53 vehicles were analysed, for an example see Figure 4.

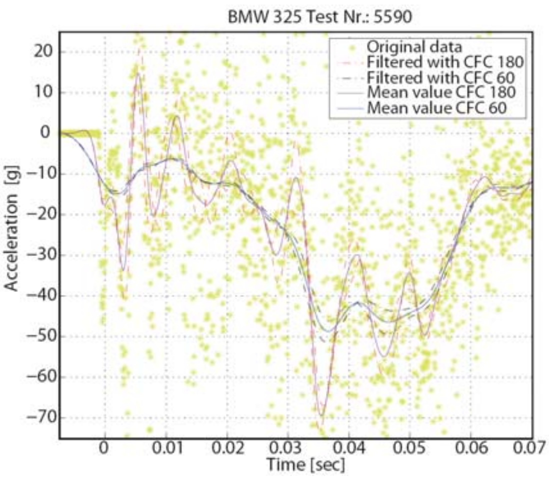

Figure 4: Example of passenger compartment acceleration [8].

The filtered data forms the basis for further analysis. In case of a frontal collision with full overlap, a method [8] was developed to combine the individual stiffness's of the opponents to one single spring F_c with discrete non-linear force-deflection characteristics c_{def}, Figure 5 and Eq. (1). The solid (red) and dashed (blue) line correspond to two different vehicles, the dot and dashed line (green) represents the combination of them.

Occupant Model

The main approach for the occupant model is the following assumption: The injury risk and severity in a vehicle accident are reduced when maximum and mean accelerations are reduced. This is especially true in low to medium crash severity where the integrity of the passenger compartment prevents intrusion-induced injuries. Modern cars are designed to withstand collision severities in frontal crash of up to 56 kph against a rigid barrier or 64 kph against a deformable honeycomb barrier with minimal intrusion into the footwell.

In the present occupant model, the occupant of the ego-vehicle is considered by a simple rigid body model, comparable to the collision model. It takes into account mass and seating position of the occupant (see Figure 6).

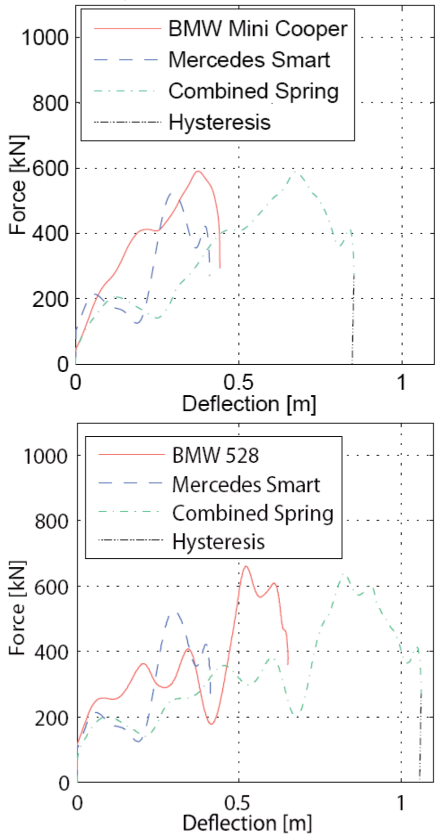

Figure 5: Two examples of the combined deformation spring [8].

In a later vehicle application these parameters have to be provided by occupant sensing systems. The equation of motion for the occupant model is:

$$
m_{occ} \cdot \ddot{x}_{occ} = F_{Air,Steer} + F_{Belt} + F_{Seat} \qquad (2).
$$

m_{occ} denotes the mass of the occupant, x_{occ} the position of the occupant, $F_{Air,Steer}$ (airbag in combination with steering column), F_{Belt} (seatbelt), and F_{Seat} (seat) the forces of the restraint system acting on the occupant, see Figure 6.

Optimisation algorithms determine suitable force levels and trigger times of the adaptive restraint system, based on the criterion of minimising the maximum and mean acceleration of the occupant (represented by the single rigid body m_{occ}). A secondary condition is the avoidance of bottoming-out of the restraint sytem, by limiting the forward motion of the occupant rigid body, $x_{occ}>0$. Within this study, genetic as well as gradient based optimisation algorithms were investigated [8].

The optimisation of the force levels and activation times of the restraint system will be the key issue for a real-time vehicle application. At the moment, putting the results of a large amount of optimisation runs into a database (characteristic diagram) is the most promising solution for real-time performance.

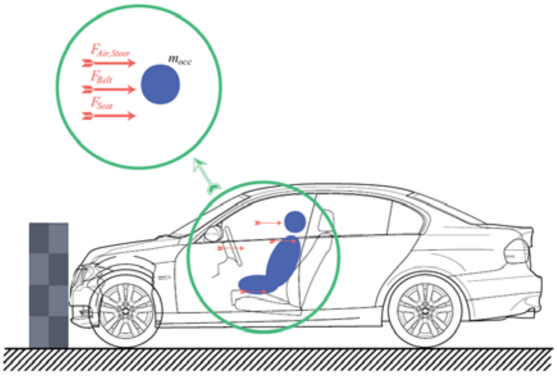

Figure 6: Simplified rigid body model of the occupant.
$F_{Air,Steer}$ describes the forces by the frontal airbag in combination with the steering column, F_{Belt} is the resulting force in lateral direction of shoulder and lap belt and F_{Seat} stands for the frictional force of the seat, [8].

The next section explains the verification of the model with numerical simulation since experimental verification of the model would require several cost-intensive full-scale crash tests.

VERIFICATION

The verification of the presented model was carried out by a detailed off-line simulation. This off-line simulation was based on a Finite-Element-Method (FEM) model of a full frontal car to car crash. A FEM model of the FORD Taurus [16] was used for simulation of the crush behaviour of ego- and opponent vehicle, Figure 7.

Figure 7: FEM model of investigated vehicle [16].
LS-Dyna FEM model of the 2001 FORD Taurus, occupant and restraint system were added.

Since this model did neither include an occupant nor a restraint system, a Hybrid-III 50 percentile male crash test dummy, a seat with 3 point belt system and a frontal driver airbag was added [17], see Figure 8.
The first step for verification was to simulate a 56 kph frontal crash against a rigid barrier with full overlap (US-NCAP crash test), see Figure 9. The validation of the model was published in [18] and is accurate within the requirements of the present study.
The acceleration, measured in a similar location as in the NHTSA data [10] was derived from the FEM simulation. Using this simulation, the acceleration and crush behaviour of the vehicle was derived in a similar manner than in the real tests published by NHTSA, see chapter methodology. This simulation forms the basis for further verifications.

Figure 8: Occupant and restraint system in the ego-vehicle [17].

Nevertheless, the car body of the FORD Taurus FEM model was reinforced in order to demonstrate a stiffer car structure which withstands EURO-NCAP frontal crash requirements with minimal intrusion to the passenger compartment in the footwell area. The reason for that was the approach of the algorithm which minimises acceleration induced injuries and not intrusion induced injuries. Also, steering wheel displacements, which decreases the available ride-down is not implemented in the collision model.

Figure 9: USNCAP frontal crash.
56 kph impact speed, full overlap, rigid barrier, 50th percentile H-III dummy.

As depicted in Figure 10, the accuracy of the predicted passenger compartment acceleration (red solid line) is remarkably high for the first 40 ms, the 70 g peak at 45 ms is filtered out through the prediction algorithm. Nevertheless the integral of this curve (velocity during the collision) fit accurately, Figure 11. For the desired application, namely pre-setting an adaptive restraint system, the accuracy is sufficient.

The next step in the verification was to perform car to car crash simulations.

The FORD Taurus was impacted at different impact speed against another FORD Taurus FEM model, (for test set-up, see Figure 12 and Table 1).

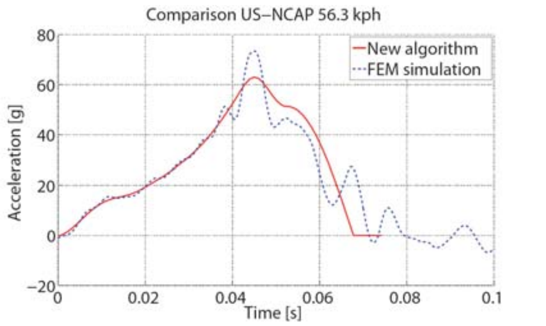

Figure 10: Comparison of passenger compartment acceleration (US-NCAP).

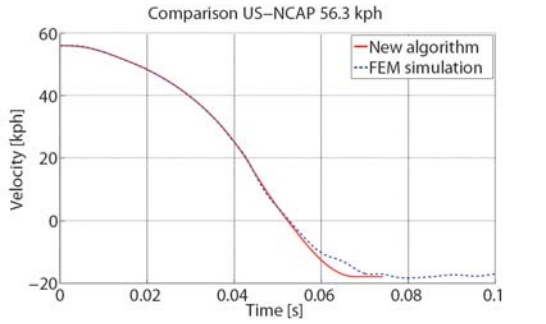

Figure 11: Comparison of passenger compartment velocity (US-NCAP).

Figure 12: car to car frontal collision (FORD Taurus vs. FORD Taurus).

The occupant and the restraint model was not verified in detail, which is part of future work. Results regarding the dummy responses only can be treated to tell qualitative trends.

Impact speeds of the ego-vehicle and the opponent car were chosen based on a hypothetical impact scenario of a frontal collision on a wet road with limited vision due to fog. The kinematics of this hypothetical collision was simulated using PC-Crash® accident reconstruction software, Figure 13. The results were forwarded as an input to the vehicle model, which calculated the impact conditions listed in Table 1. Different settings for driver assistance systems were taking into account, [17].

Figure 13: Hypothetical crash scenario simulated with PC-Crash®.

The blue vehicle on the right side is overtaking. Due to fog, the approaching red vehicle on the left side is recognized late.

Table 1.
Car to car crash simulation matrix

	Ego-vehicle	Opponent	Driver assistance
Make and model	FORD Taurus	FORD Taurus	
Impact speed Simulation 1 [kph]	52	52	None
Impact speed Simulation 2 [kph]	48	48	ABS
Impact speed Simulation 3 [kph]	31	31	ABS and EBA
Overlap [%]	100	100	
Impact angle [deg]	0	0	

Exemplarily the result from simulation 3 is depicted in Figure 14. The acceleration of the passenger compartment predicted by the collision model (red solid line) is sufficiently accurate for adaption of adaptive restraints. Single peaks as calculated by the FEM model (blue dashed line) are not predicted, since during calculation of the combined "collision" spring the input data is filtered (passenger cell acceleration).

Figure 15 illustrates the result of the velocity change in the same load case. At time 53 ms, the velocity passes the zero line. The predicted rebound velocity is higher than in the detailed crash simulation. This behaviour can be modified by the hysteresis model of the algorithm. A fine-tuning of the hysteresis parameter was not yet performed.

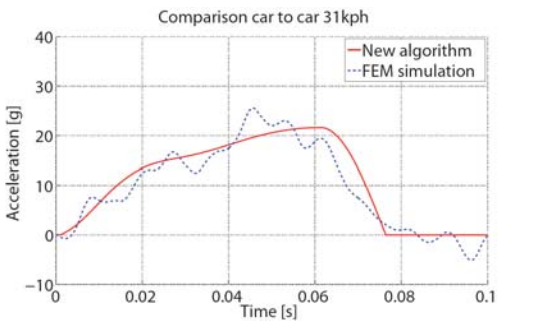

Figure 14: Comparison of FEM simulation and algorithm of collision model (acceleration).

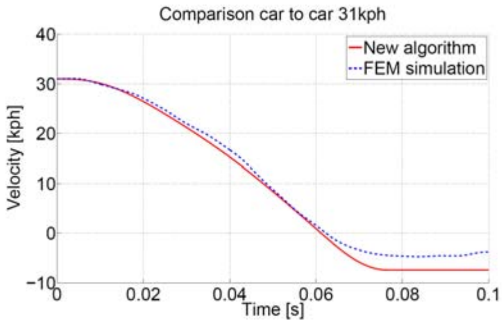

Figure 15: Comparison of FEM simulation and algorithm of collision model (velocity).

RESULTS AND DISCUSSION

The potential of the presented model was investigated in a parameter study. Different configurations with different collision severities and occupant masses were investigated. The parameters are listed in Table 2.

Table 2.
Input for parameter study

parameter	from	to
collision speed [kph]	20	54
mass opponent vehicle [kg]	800	3000
occupant weight [kg]	30	125

The collision severity ranges from low speed (20 kph) to high speed 56 kph for each vehicle. At lower speeds an adaptive restraint system will not make sense, due to low injury risk and no-fire requirements for active restraint systems. Higher speeds are not feasible for the algorithm because there is no data available for high speed crush behaviour. Additionally, at high speeds the passenger compartment will start to collapse, which would cause intrusion-induced injuries, which is not covered by the present approach.
For the mass of the opponent vehicle a range from A-segment vehicles (800 kg) up to luxury class cars (3000 kg) were investigated, which covers the majority of the passenger car fleet.
For the passenger weight, a range from 30 kg up to 125 kg was chosen in order to cover most occupants on the driver and passenger seating position.

A standard restraint system optimised for FMVSS 208 requirements forms the reference for the parameter study. As a working hypothesis, the force levels of the reference restraint system were determined with the optimisation algorithm as used for the adaptive restraint system (see section Methodology). The following load cases were used to define the reference restraint system

- "48 kph frontal collision with an unbelted 75 kg occupant"
- "56 kph frontal collision with a belted 75 kg occupant"

The fire time of the reference restraint system was set to 10 ms.

The results for the parameter study are depicted in Figure 16. In almost every configuration significant improvements up to 90 % were observed. For collisions close to the FMVSS 208 standard requirements (e.g. 54 kph closing speed and 75 kg occupant mass) the improvements are small because the non adaptive reference restraint system is already optimised for that configuration. The main improvements occur at lower severity and especially occupant masses outside of the 50th percentile (75 kg), which demonstrates the effectiveness of the integrated safety approach in real traffic conditions.

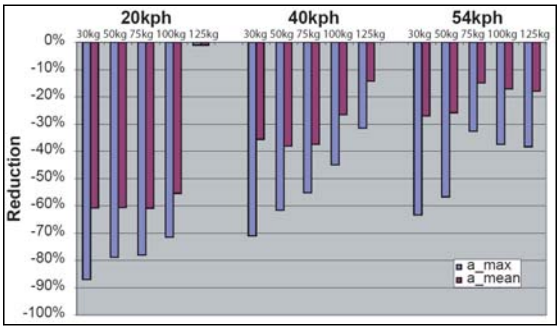

Figure 16: Reduction of the occupant maximum (a_max) and mean acceleration (a_mean) with respect to different collision speeds and occupant masses.

Since the present study assumes that make and model of the collision opponent are known, the influences of the accuracy of mass and stiffness of the opponent vehicle were analysed in a further parameter study:
Even when estimating the mass of the collision opponent based on data from a video recognition system, there is a lack of knowledge about the actual payload.
According to statistics of vehicle registrations in Austria [12], the NHTSA database [10] was searched for most likely collision opponents. 53 vehicles were investigated for that purpose. But through questionable acceleration data it was not possible to retrieve valid data for all 53 vehicles. After all, 39 vehicles with plausible acceleration data were analysed and grouped into six mass classes, as Table 3 shows.

Table 3.
Investigated Cars and Defined Mass Classes

Class	Make	Model	Mass
1	Mercedes	Smart	963 kg
1	VW	Polo	1100 kg
2	Toyota	Yaris	1245 kg
2	Kia	Rio	1352 kg
2	Mini	Cooper	1371 kg
2	Dodge	Neon	1379 kg
2	Toyota	Corolla	1379 kg
2	Ford	Focus	1394 kg
2	Honda	Civic	1394 kg
2	Ford	Focus	1398 kg
3	Toyota	Prius	1515 kg
3	Subaru	Impreza	1585 kg
3	BMW	Z4 Roadster	1630 kg
3	Honda	Accord	1673 kg
3	Saab	9-3	1705 kg
3	Subaru	Forester	1708 kg
3	VW	Jetta	1719 kg
3	Nissan	350Z	1729 kg
3	Volvo	S60	1732 kg
4	VW	Passat	1765 kg
4	Ford	Taurus	1785 kg
4	BMW	325I	1806 kg
4	Audi	A4	1820 kg
4	Volvo	S80	1820 kg
4	Saturn	Aura	1828 kg
4	Nissan	350Z	1855 kg
4	Mercedes	C300	1864 kg
4	Chrysler	Sebring	1915 kg
4	BMW	528I	1924 kg
5	Dodge	Journey	2136 kg
5	Volvo	XC90	2389 kg
5	Hummer	H3	2404 kg
5	Mercedes	ML350	2431 kg
5	BMW	X5	2458 kg
6	Audi	Q7	2582 kg
6	VW	Touareg	2600 kg
6	Toyota	Sequoia	2816 kg
6	Toyota	Tundra	2884 kg
6	Ford	F250 Pickup	3054 kg

Table 4 lists the results of the investigation of the mass influence for two different vehicles (FORD Taurus and MERCEDES C300). An occupant with 75 kg is taken into account. The closing speed is 106 kph. The parameters $a_{max,occ}$ and $a_{mean,occ}$ present the resulting loading to the occupant. Respectively, $s_{disp,occ}$ is the relative displacement, $a_{max,occ}$ the maximum acceleration and $a_{mean,occ}$ the mean acceleration of the occupant. The average acceleration of an occupant sitting in a MERCEDES C class is almost doubled when it is impacted from an 3000 kg vehicle compared to a 800 kg vehicle. When increasing the mass of the vehicle in steps of 200 kg, the average acceleration increases by approximately 1.5 g. The typical payload of a passenger car is around 300 kg [2], so the accuracy of the results are in the range of about 2 g, which has to be taken into account by the algorithm.

There where no results in the simulation of the first investigated vehicle (FORD Taurus) when colliding against a vehicle with a mass higher than 2600kg (marked with "-" in Table 2). The reason for that is that the maximum force levels of the restraint system are limited. At high impact energy levels, the occupant strikes through the airbag and contacts the dashboard.

Table 4.
Influence of Collision Opponent Mass on Occupant Loading

	Ford Taurus			Mercedes C300		
m_2	$s_{disp,occ}$ [mm]	$a_{max,occ}$ [g]	$a_{mean,occ}$ [g]	$s_{disp,occ}$ [mm]	$a_{max,occ}$ [g]	$a_{mean,occ}$ [g]
800 kg	24.1	23.17	14.90	30.3	29.43	16.70
1000 kg	40.7	23.54	16.00	52.1	30.74	18.33
1200 kg	63.2	29.13	17.22	70.0	38.02	20.25
1400 kg	74.1	32.93	18.46	87.4	45.14	21.67
1600 kg	87.5	32.93	19.37	105.5	52.49	23.61
1800 kg	87.5	32.93	20.30	116.5	57.00	24.67
2000 kg	130.3	32.93	21.12	125.8	57.40	25.93
2200 kg	158.0	32.93	21.62	133.8	57.40	27.30
2400 kg	187.8	32.93	21.98	141.4	57.40	28.02
2600 kg	221.8	32.93	22.28	149.4	57.40	28.86
2800 kg	-	-	-	161.4	57.40	29.55
3000 kg	-	-	-	173.3	57.40	30.22

For investigation of the influence of the crush zone stiffness the following approach has been chosen: All studied vehicles were classified according to their mass (Table 3).

Next the stiffness springs of these vehicles were compared and combined to an average force-deflection curve (thick line in Figure 17).

It can be seen, that according to the mass classes, the deformation characteristics of different vehicles are similar. The reason for that is that vehicles structures are designed to fulfil requirements of standard laboratory crash tests. There, only the vehicle mass has an influence on the energy that has to be absorbed by the crush zone. Restraint systems are designed to meet injury criteria of dummy responses in these specific tests.

To evaluate the influence of the stiffness a certain crash scenario (fully overlapped car to car frontal collision, masses of each vehicle 1785 kg, collision speed 108 kph, mass of occupant 75 kg) is calculated using the algorithm. The only investigated parameter is a variation of the stiffness of the crush zone according to the six classes described above. The average acceleration of the occupant scatters by approx 1 g (mean value 20.4 g). The results are shown in Table 5.

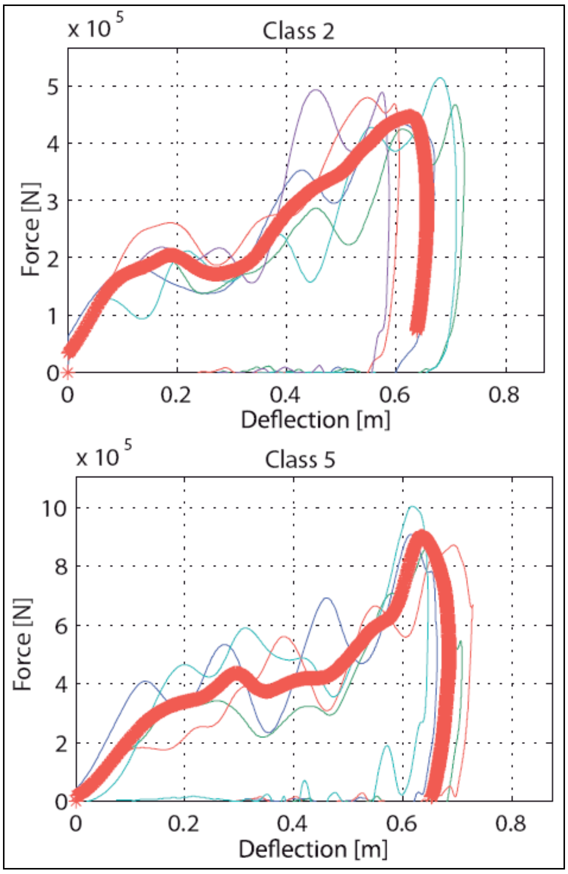

Figure 17: Examples for deformation springs with respect to different mass classes. Mass class 2 represents vehicles from 1200 to 1400 kg, mass class 5 from 2000 to 2500 kg. The thick line is the combination of the different deformation springs.

$s_{disp,veh}$ denotes the displacement of the vehicle, which is the deformation of the vehicle front in this load case. Analogue to Table 4, $a_{max,veh}$ and $a_{mean,veh}$ represent the maximum and mean acceleration of the vehicle under consideration.

Table 5.
Influence of Crush Zone Stiffness

	Occupant			Vehicle		
	$s_{disp,occ}$ [mm]	$a_{max,occ}$ [g]	$a_{mean,occ}$ [g]	$s_{disp,veh}$ [mm]	$a_{max,veh}$ [g]	$a_{mean,veh}$ [g]
Class 1	162.2	32.93	21.28	579.30	40.06	21.59
Class 2	100.4	32.93	20.23	665.50	33.64	19.88
Class 3	101.6	32.93	20.16	663.40	34.50	19.85
Class 4	108.7	32.93	20.41	653.90	39.24	20.00
Class 5	94.6	32.93	19.87	677.70	38.25	19.56
Class 6	120.4	32.93	20.52	649.90	44.74	20.22
Class 1-6	103.5	32.93	20.21	662.00	37.64	19.89

The small influence of the stiffness shows that it is sufficient to estimate roughly the mass of the opponent vehicle and to use the stiffness characteristics derived in the corresponding mass class introduced in this paper.

LIMITATIONS

As a first step, only straight frontal collisions with full overlap are considered, but basically the method can be enhanced for other impact scenarios such as rear-end collision, lateral or oblique impact. Another shortcoming is the simplification of the model in order to achieve real-time performance for a full vehicle application. Especially, it is assumed that a minimisation of occupant acceleration lowers the injury risk and severity. Detailed injury responses such as the Head Injury Criterion (HIC) cannot be assessed. The application in a vehicle, verification of the real time performance and functionality of the algorithm is part of future work.

CONCLUSIONS

An algorithm for the integration of active and passive safety systems was prepared.
The main idea is the generation of reference values for an adaptive restraint system by calculating force levels and trigger times of the different restraint components, such as belt and airbag. These were optimised with respect to maximum and mean acceleration of the occupant. The presented method consists of three separate models (vehicle model, collision model and occupant model), which are interacting. Simplified models were used in order to maintain a future real-time application.
As a first step, the model was verified with detailed FEM crash simulation models. The prediction of the passenger compartment acceleration showed sufficient accuracy for the present application.
The potential of the algorithm was demonstrated in simulations of fully overlapped frontal collision considering different input parameters:
a) Mass of colliding vehicles
b) Crush zone stiffness of colliding vehicles
c) Collision speed
d) Occupant mass of ego-vehicle
e) Seating position of occupant
These input parameters were supposed to be known, since the development of the vehicle model and the collision prediction module is still under progress.
Significant improvements up to 90 % with respect to maximum and average acceleration of the occupant could be demonstrated in different crash scenarios. The influence of mass and stiffness were investigated in order to derive requirements for the environment recognition system.

OUTLOOK

The next step will be the completion of the collision prediction module and the integration into the vehicle model. Intensive verification with driving tests and an environment recognition system will be necessary.

Further crash simulations with different FEM models and varying accident severity will be performed to verify the collision model on a broader basis and adjust some of the model parameters.
Additionally the occupant model will be verified in more detail by comparison with a validated detailed occupant simulation model and performing parameter studies.
Also applications in other load cases such as rear and side impact will be part of future work.
Next, the model will be enhanced for application a real vehicle to demonstrate a real-time application.
Finally the prediction of the opponent vehicle mass using video recognition will close the last missing link and complete the method for full vehicle integration.

ACKNOWLEDGEMENT

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POWERED TWO WHEELERS INTEGRATED SAFETY – FIRST RESULTS OF THE SIM PROJECT

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ABSTRACT

First outcomes of activities carried out in Safety In Motion EU project are hereafter described. SIM Project is aimed at identifying a suitable and comprehensive safety strategy for powered-two-wheel (PTW) vehicles, in order to avoid road accidents and/or mitigate their consequences.

Starting from the outcomes of previous accidentology activities an in-depth analysis was conducted focusing on the scenarios identified as the most frequent and dangerous for PTWs accidents. Significant accident parameters were identified and related values were analyzed. Also a technology evaluation based on state-of-the-art analysis as well as partners expertise was conducted and the effectiveness of potential benefits of safety systems was evaluated in reconstructed accident scenarios.

On such a basis a PTW safety strategy has been identified in all safety areas.

The active safety improvement is reached by actively controlling PTW stability and improving riding comfort (advanced braking and suspension systems).

In preventive safety area an HMI Information Management concept for motorbike was identified as the most effective solution for enhancing the PTW rider's awareness. Focusing on passive safety aspects, a frontal airbag fitted on motorcycle (aiming at protecting rider against the primary impact) and an inflatable wearable device (mainly for secondary impact) have been chosen to be tested either separately and jointly.

The following safety devices have been finally selected in order to be implemented and tested on vehicle prototypes:

- Active Brake System
- Stability management by traction control
- Semi-Active Suspension System
- Frontal airbag
- Inflatable wearable device
- HMI Information management concept for motorBikes (IMB)
- Enhanced HMI (ergonomic handlebar controls, wireless communication, Head-Up Display)

An integral approach to PTW safety enhancement was adopted, since all the safety devices will be implemented and tested on the same vehicle platform, the innovative PTW tilting three-wheelers Piaggio MP3.

INTRODUCTION

The background of SIM project are the findings of the MAIDS project [1] which main objectives are:

- the identification of the main factors that contribute to PTW accidents causation;
- the definition and proposal of suitable countermeasures in order to reduce the number of accidents and mitigate the consequences for the rider.

MAIDS causative factors have been categorized in three items or pillars of safety:
-Powered-two wheelers
-Human
-Infrastructure.

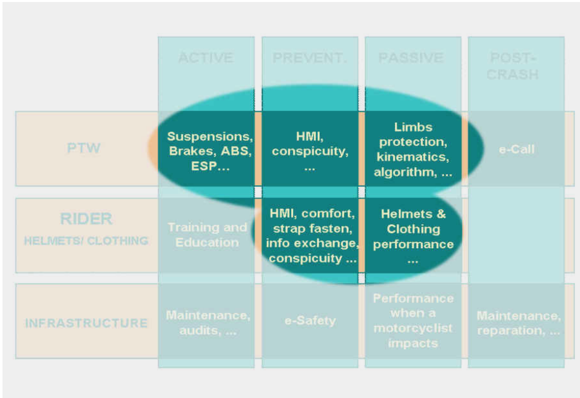

Figure 1. The Safety Matrix

The approach of SIM project is described by the Safety matrix (**Figure 1**) where the pillars of safety are crossed with the typical safety areas.
SIM project is mainly focused on **integrated safety** for **PTW**.

Even if the human factor belongs to PTW rider and vehicle driver (i.e. car, bus and truck), nevertheless SIM activities deal with this topic from PTW rider perspective in terms of protective devices (helmet and clothing) and HMI improvement.

The activities' flow within the project started with the analysis phase, based on accidentology and effectiveness evaluation of the most promising safety devices. After the safety devices have been selected, their development has been carried out for more than one year. In the last phase of the project the adopted solution will be integrated and tested into the final prototypes.

SELECTION OF PTW SAFETY STRATEGY

The SIM project has established a strong collaboration link with APROSYS (Advanced PROtection SYStems) SP4 – an Integrated Project (IP) under 6th Framework Programme of the European Commission - in order to share the knowledge gained during the first phase of SP4 concerning motorcycles passive safety [2]. As a result of this collaboration, the outcomes contained in deliverables from SP4 subproject are briefly described.

During the first phase of SP4, activities were carried out to achieve the goal of extracting information about motorcyclists' road accidents. In particular, aspects such as the following were identified:

- the most relevant accident scenarios,
- the causes of the accidents,
- the interactions between PTWs / riders and vehicles,
- the interactions between PTWs / riders and infrastructure,
- the performance of motorcyclists protective devices,
- the kinematics of the collisions,
- the most frequent riders' injuries patterns.

On the basis of the mentioned features, a number of scenarios capable to represent a wide number of casualties were identified. In a first step the National Statistics of four countries (Spain, Italy, The Netherlands and Germany) have been deeply analysed. The findings were seven main accident scenarios, describing the PTW accident occurrence as a whole, **Table 1**:

Table 1 PTW main accident scenarios

Urban Area	Non Urban Area
Moped against car in intersections.	Motorcycles against car in Intersections.
Moped against car in straight roads.	Motorcycle against car in straight roads.
Motorcycle against car in intersections.	Motorcycle. Single vehicle accidents.
Motorcycle against car in straight roads.	

In a second step the identified accident scenarios were further investigated by means of in-depths databases available within the consortium (GIDAS 2002, COST 327, NL-MAIDS, DEKRA PTW), focussing mainly on passive safety aspects.

Accident In-depth Analysis

As afore mentioned the results of APROSYS SP4 have been integrated in the SIM database analyses. The identified main accident scenarios have therefore been chosen as a starting point. Within the SIM consortium the MAIDS database, the DEKRA PTW database and the GIDAS 2002 and 2003 datasets were available for examination and, as far as the databases are of very different character and the coding regulations are oftentimes not common, several shared parameters have been identified and analysed (**Table 2**)

Table 2. Common parameter list

PTW design	Visibility conditions
PTW colour	Weather conditions
PTW user injury patterns	Lighting conditions
Accident location	Technical defects
Rider behaviour before impact	Evasive manoeuvres
Kind of collision	Kind of PTW driver reaction
Tyre conditions	Accident avoidance
Influence of tyre fault	Accident causation
Classification of skidmarks	Question of guilt
Road characteristics	PTW initial driving speed
Road condition	PTW speed of first collision
Involved parties	PTW brake system
Right-of-way regulations	

By analysing the most relevant parameters it is possible to notice that in the DEKRA database, with mostly elevated speeds outside urban areas, severe and fatal injuries play a major role. In the MAIDS database 22 riders only received first aid treatment at the scene of the accident. A total of 785 riders were treated in hospital and then released. 100 PTW riders and 5 passengers died as a result of injuries sustained in the accident. The GIDAS database shows a large number of AIS 1 and AIS 2 injuries, **Figure 2.**

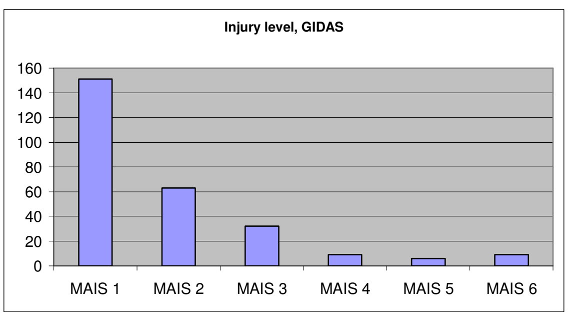

Figure 2. Injury level, GIDAS

As being representative in respect of the National Statistics in Germany, the accident site in the GIDAS database is in most cases within urban areas. The DEKRA database with its focus on severe and fatal PTW accidents shows a converse site distribution. Within MAIDS approximately two-thirds of the accidents took place in urban areas. In order to develop passive safety devices installed on the vehicle it is important to have a clear understanding of the impact kinematics. In the case of an impact against an opposing vehicle it is essential to differentiate between upright impacts and sliding impacts. In the DEKRA database most of the PTW impacts occurred in an upright driving position, **Figure 3.**

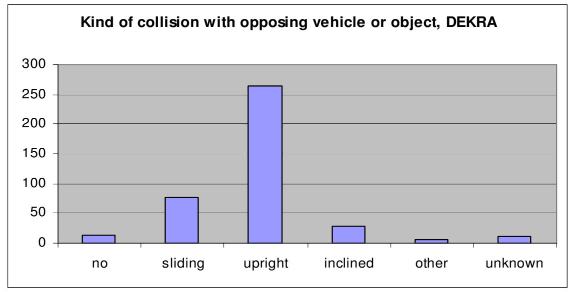

Figure 3. Kind of collision, DEKRA

In the DEKRA as well as in the GIDAS datasets the road was mainly dry. Only few cases with wet or moist road surface were recorded. In MAIDS data the roadway was found to be dry and free of contamination in 84.7% of all accidents ,wet in 7.9% of all collected cases. Ice, snow and mud were reported in 5 cases respectively and gravel or sand was reported in 2.5% of all cases. The main part of the PTW crashes occur on straight normal roads.. About half of the PTW accidents in MAIDS happen on minor arterial road or local street, according to urban area characteristics. Based on MAIDS data, roughly in 70% of the cases the PTW was travelling on a straight path. Junctions, intersections and curves – especially in rural areas – do also play an important role. As reported also in detail MAIDS data show that more than 50% of accidents happen at intersections. The different intersection types reported in MAIDS are shown in **Figure 4**.

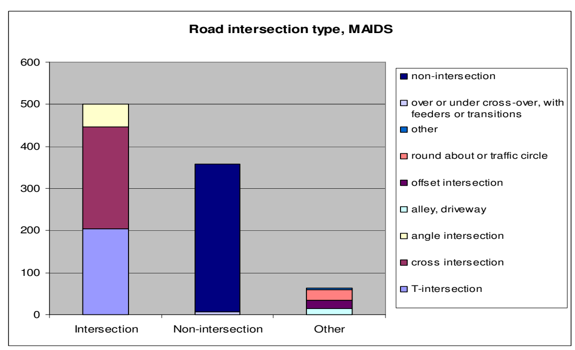

Figure 4. Intersection type, MAIDS

In the major part of the accidents the road surface is made of asphalt. MAIDS data indicates that in 56% of the cases asphalt was found in optimal condition. As expected the passenger car was in the three databases the main opposing vehicle within PTW crashes followed by PTW–PTW and PTW–pedestrian as well as PTW- truck impacts, **Figure 5**.

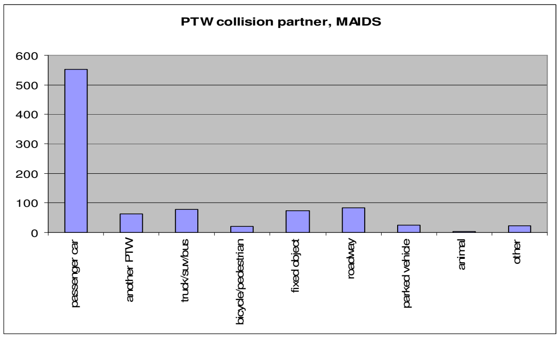

Figure 5. PTW collision partner, MAIDS

As far as the weather at the time the PTW accident happened is concerned, a distinction between clear/sunny/dry, cloudy but dry, rainless not further indicated, rain, fog/haze, hail/snow, and storm/gust of wind has been made. Most PTW accidents happened at dry weather conditions confirming the assumption that motorcycle riding is mostly a leisure activity. In the DEKRA cases were a sight obstruction at the accident scene was detectable mostly bushes or trees limited the vehicle users view. For the GIDAS database sight obstructions have been classified as being non-permanent (e.g. parked vehicles) or permanent (e.g. buildings). In 9.5% of the cases a mobile vehicle obstructed the view of the PTW rider, while in about 10% of the cases a mobile view obstruction for the OV driver was present at the time of accident. As for the light conditions most accidents happened at daytime. In Germany it is mandatory for powered two-wheelers to have the low-beam light switched on also at daylight. In most of the cases of the DEKRA and GIDAS database the PTW driver met this demand, however a not negligible amount of PTW drivers disregarded this directive, **Figure 6**.

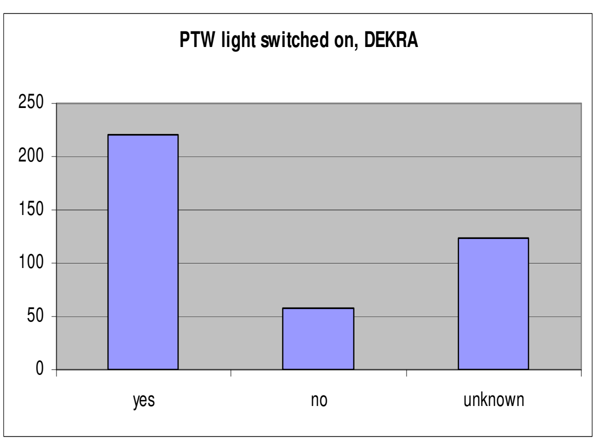

Figure 6. PTW light status

From MAIDS data, it was found that in 87.5% of the cases the main contributing factor is human related. It is divided between PTW rider (37%) and OV driver (50%). Among these a perception error of the OV driver is the most frequent event, while for the PTW rider decision and perception errors are the most relevant ones. The data in **Figure 7** indicates that a PTW rider traffic-scan error was reported in 27.7% of all cases involving an OV.

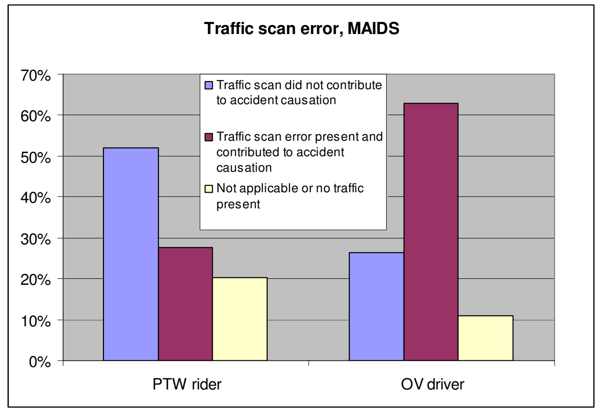

Figure 7. Traffic scan error, MAIDS

The initial driving speed bands are illustrated in **Figure 8** and **Figure 9**. In the representative GIDAS database most PTW users drove in the speed band 31–45 km/h whereas in the DEKRA database also the 61–75 km/h and the 79–90 km/h speed range is of interest. In MAIDS it was found that in roughly 45% of all cases the PTW was travelling below 45 km/h, while only in 23% of cases the travelling speed was between 46 km/h and 60 km/h. It has to be noticed that both L1 and L3 PTW legal categories are included.

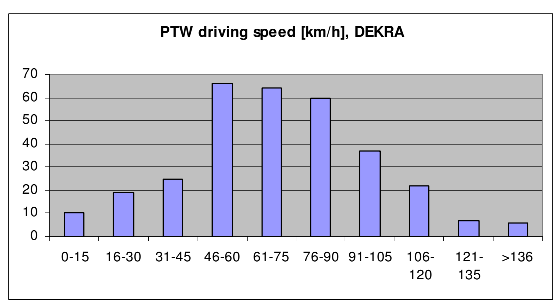

Figure 8. PTW driving speed [km/h], DEKRA

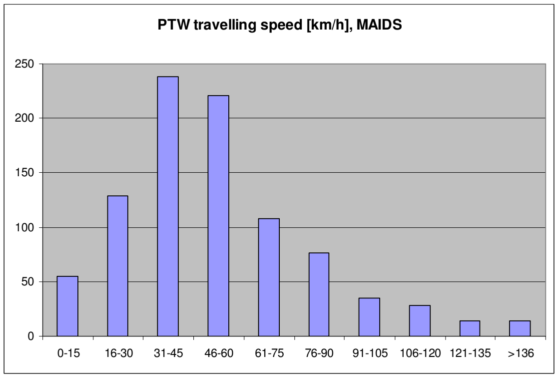

Figure 9. PTW driving speed [km/h], MAIDS

The speed of the PTW´s first collision in the DEKRA database is described in **Figure 10**. A speed reduction in respect of the initial speed is observable though not always significant.

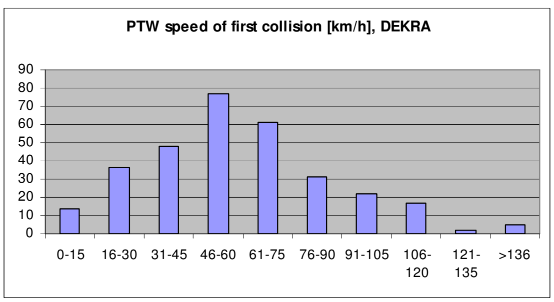

Figure 10. PTW speed of first collision [km/h], DEKRA

In the MAIDS datasets the PTW impact speed is in 63% of the cases below 45 km/h while in 17% of the cases the impact speed was found between 46 km/h and 60 km/h. In order to better understand the correlation between driving speed and first collision speed a case related speed inspection is of great help. The data was sorted in a descending order. Here, only a section in the driving speed band from 60-40 km/h is displayed, **Figure 11**. In about 50% of the displayed cases, no speed reduction prior to the first impact was detectable.

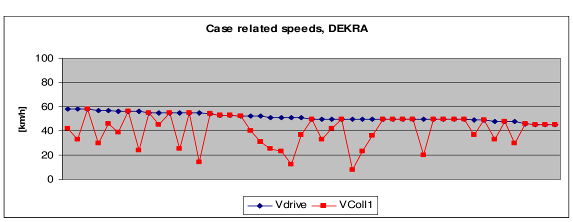

Figure 11. Case related speeds, DEKRA

For what concerning data coming from MAIDS, only cases with impact speed less than or equal to travelling speed were considered. Here, the percentage of Kinetics Energy (KE) reduction by travelling speed has been calculated. KE is defined as:

$$1 - \left(\frac{V_i}{V_t}\right)^2$$

Where Vi is the impact speed and Vt is the PTW travelling speed. In roughly 30% of these cases there was no KE reduction (with a travelling speed between 31 km/h and 45 km/h). Most of the KE reduction values (32%) is between 20% and 70% reduction in the speed range from 31-60 km/h. In most cases modern disk brakes were observed apart from a not negligible amount of drum brakes at the front wheel in the DEKRA cases. Where possible, the involved PTWs within the DEKRA and GIDAS database have been analysed in respect of anti-lock brake systems (ABS) furniture. The penetration of ABS in the motorcycle market is up to now very limited, hence only an insignificant amount of PTWs is outfitted with such systems in the investigated case collections.

Technology selection

The analysis of potential PTW and protective equipment improvement (active, passive and preventive safety devices) has been carried out starting from the literature review in PTW safety field and collecting information about state-of-the art for safety devices applied in automotive and PTW field. The state of the art of such systems is described in detail in [3].

An effectiveness evaluation has been performed on systems that can be realistically implemented on PTW based on two criteria:

- market availability and potential transfer to PTW field;
- technical feasibility (i.e. vehicle constraints).

As a result of the effectiveness evaluation a list of safety system to be installed on vehicle prototypes was defined.

Effectiveness evaluation in real accident scenarios

Starting from the previously described accident analysis and scenarios defined in **Table 1**, single cases, representative of each accident situation, have been extracted from DEKRA PTW database. The fundamental basis of the DEKRA accident database is the accumulation of written expert opinions containing the accident analyses that are drawn up by skilled forensic experts at the DEKRA branches throughout Germany. Apart from the database also the raw material (written expert opinions) is available for investigation having the advantage to extract parameters which were originally not directly implied in the database.

From the DEKRA datasets 51 cases have been selected, extracting the following parameters:

- Collision speed
- Initial speed
- Distance of falling location to collision point (if applicable)
- Braking distance (referring to the collision point)
- Mean value of braking deceleration
- Starting point of braking (referring to the collision point)
- Reaction point/reaction demand (referring to the collision point)
- Kind of reaction demand
- Road surface conditions
- Weather conditions

It is worth to be mentioned that the analysed 51 accidents have been chosen depending on reaction demand and following rider braking behaviour in order to evaluate the benefit of an advanced braking system.

Also if database analyses can simply give general insights into the accident occurrence, for more detailed data considerations it is essential to analyse case-related accident characteristics. One opportunity to face this problem is the preparation of in-depth accident reports, containing common information about the accident and the vehicles involved, sketches, vehicle kinematics, pre-crash phase calculation tables and picture documentations (**Figure 12**). From the raw data, at DEKRA 16 in-depth accident reports have been drawn up and made available to the project consortium for further examination. analyses. The whole in-depth analyses can be found in Annex A of [3].

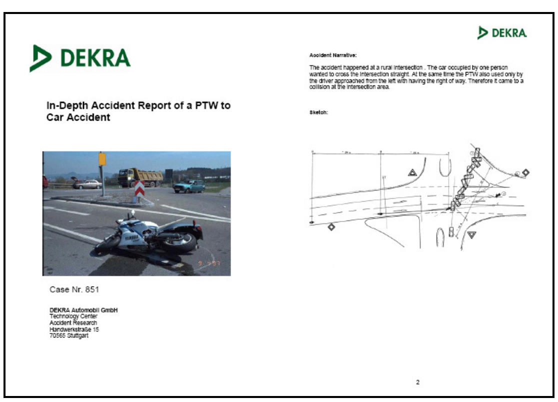

Figure 12. In-depth accident analysis example

With the data coming from the 51 cases and 16 fully reconstructed cases (DEKRA database) brake system and suspension system have been evaluated taking into account the typical “boundary” conditions of the accidents.

A different approach has been followed for the effectiveness evaluation of the passive safety devices (airbag, leg protectors, wearable devices…). that has been made starting from results of previous studies [4] and analysing 20 cases from DEKRA database in which PTW impact was against passenger car, PTW was in upright position, and the rider was severely injured or killed.

The potential benefits of HMI improvement was extrapolated mainly based on MAIDS findings that reports human factors as the main contributing accident causation factor (**Figure 13**) and according to ESoP in HMI [5].

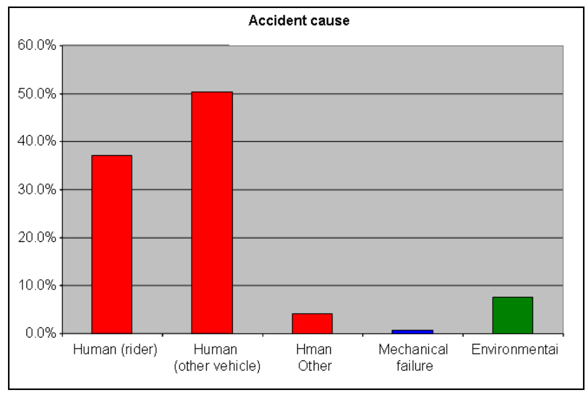

Figure 13. Accident Causes From MAIDS database.

Safety Systems Requirements

From the effectiveness evaluation, based on the partners’ expertise, system requirements for most promising solutions have been set.

The brake systems analysis on real case accident scenarios pointed out that in most cases an electronic brake system with active brake distribution could lead to accident avoidance or, at least, to a massive impact energy reduction (**Figure 14**).

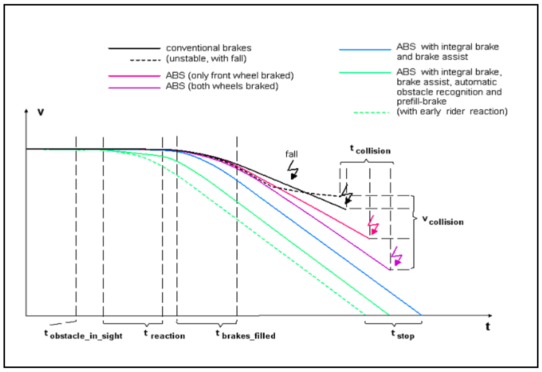

Figure 14. Performance comparison between different braking systems

To achieve that, the **advanced brake system** to be implemented in SIM prototype has to be able to independently build up pressure on each caliper, allowing active brake force distribution depending on actual grip on single wheel. By this feature it is possible to implement advanced functions for electronic brake management (e.g. rear lift off protection and brake traction control).

On the other hand the vehicle suspension must be able to adapt to the road condition and to the instantaneous brake/acceleration request, providing the highest tire adherence and force stability achievable in each situation (**Figure 15**), so assuring the maximum effectiveness respect to accident avoidance.

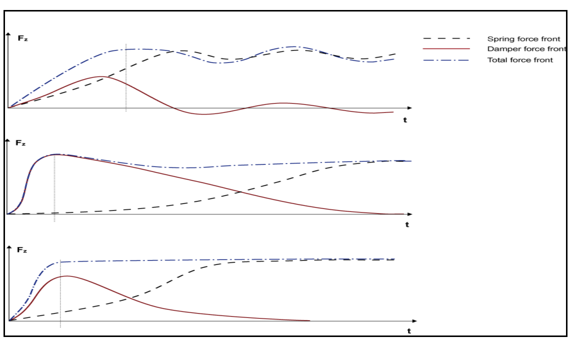

Figure 15. Damping modulation effect on tire force

In order to realize that, the SIM **suspension system** must provide a real time variable damping in order to allow instantaneous self-adaptation by means of fast electronic valves and programmable ECU for suspension management algorithms implementation.

In case the accident can not be avoided at all, a protection strategy for vehicle occupants must be investigated. Due to the highly variable rider motion during a crash event, a cooperative strategy between protective devices fitted on the vehicle and worn by the rider could be needed.

In this respect, SIM prototype must be provided at least of one specifically designed **airbag** and an inflatable wearable device **(airjacket)**.

From a technical point of view, the real challenge is the integration of the airbag in the limited spaces available on a motorcycle and the setup of an effective deployment strategy of inflatable devices.

In order to set-up the passive safety devices, extensive virtual tests coupled with a limited number of real crashes are performed both in standalone and cooperative configuration. Because of the intrinsic active safety enhancement assured by the innovative front suspension the Piaggio Mp3 (**Figure 16**) vehicle have been chosen as the ideal platform for the test of SIM advanced safety features.

Figure 16. Piaggio Three Wheeler Motorcycle (Mp3).

Active And Preventive Safety Systems

After an in-depth analysis of the most promising active and preventive safety devices, it is pointed out that the most advanced technologies could lead to a significant reduction of accidents or at least to a mitigation of eventual consequences in terms of rider injuries, for example avoiding the rider's loss of vehicle control or significantly reducing the kinetic energy at the impact. In addition to that an efficient human machine interface represents an effective preventive safety feature reducing possible distraction in riding activity.

In such vision, the following active and preventive safety devices have been selected in order to be implemented and tested taking into account the architecture and the dynamic behaviour of the vehicle chosen as technological platform for SIM prototype, the PIAGGIO MP3 motorcycle:

- Semi-Active electronic suspension system
- Traction control system
- Enhanced anti-lock braking system
- HMI management concept for motorbike
- Enhanced HMI (ergonomic handlebar controls, wireless communication, Head-Up Display)

Active safety systems

Regarding the active safety systems that are developed inside the SIM project, an electronic suspension system and an enhanced anti-lock braking system are studied and implemented.

It is noticeable that the effectiveness of braking system and traction management could be improved by integrating the suspension control system.

The suspension system for the project have been developed in order to guarantee a semi-active function. This kind of implementation requires a very fast modulation of suspension damping in order adapt the vehicle to the driving conditions but also to the driver's behaviour. In fact the characteristics are modified by using sensors to continuously detect vehicle and environmental parameters such as movement of the suspension parts, brake pressure, throttle angle and vehicle roll. The sensor signals are transferred to the suspension ECU which according to control algorithms transforms the signals into an electric signal.

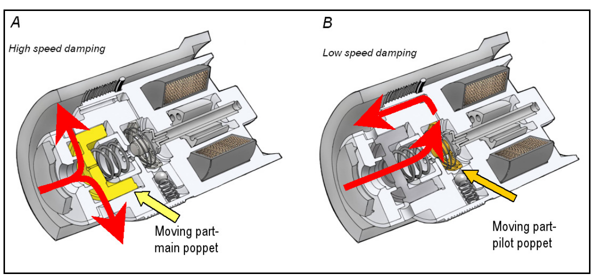

Figure 17. Continually Electronically Steered (CES) valve.

The fast damping modulation is granted by a continuously variable electronic valve specifically designed for Mp3 application (**Figure 17**).

In order to adapt the PTW suspension to the driver's behaviour, a setting switch has been used to allow the rider to choose between pre-programmed suspension behaviour (comfort, sport, normal).

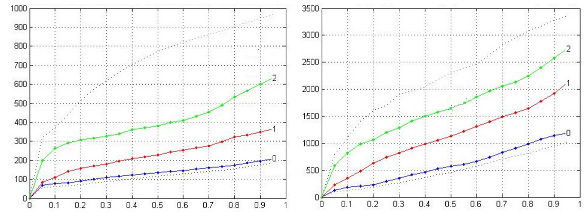

Figure 18. SIM suspensions settings.

During SIM project development an automatic safety system control is foreseen in order to maximize comfort, performance and safety. With the safety system active, the suspension is adapted to minimize braking distance, to prevent high side situations, smoothening the suspension behaviour when in fully extended or compressed state and to optimize the damping setting in order to achieve optimal stability and handling of the vehicle. In order to achieve the goal Sky-Hook and Ground Hook control algorithms will, be implemented in the dedicated suspension ECU.

Apart from the suspension system, for increasing rider stability control and preventing MP3 wheels from locking, an enhanced anti-lock braking system, based on two independent hydraulic circuits has been developed (**Figure 19**). The system is developed also in order to integrate further functionalities like FIB (Full Integral Brake) ABD (Active Brakeforce Distribution), RLP (Rear wheel Lift off Protection) and TCS (Traction Control System) able to ensure a good performance of the overall braking system.

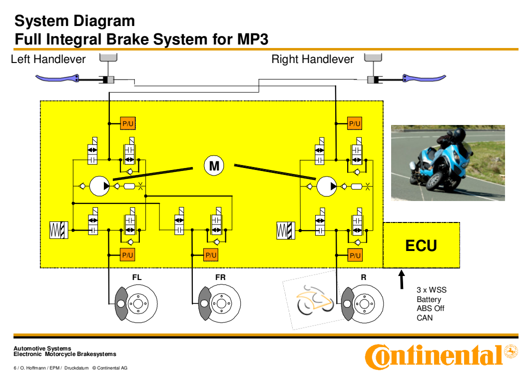

Figure 19. Electro Hydraulic scheme for SIM innovative brake system.

In order to set-up the main parameters for active safety systems management a complete vehicle model and virtual driver have been developed in virtual environment (**Figure 20**).

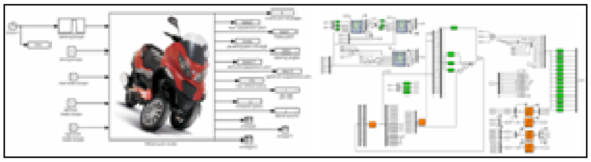

Figure 20. Mp3 virtual model with integrated active safety systems.

In such a manner, the virtual vehicle (validated with experimental tests) has been used in order to collect an extended database of simulation results with different sets of suspension characteristics and brake system logics both on flat and uneven road surfaces, also assessing the possible active systems effectiveness in terms of comfort and performances [7].

Preventive safety systems

An important role of support to active safety systems is played inside the SIM project by the preventive safety concept of HMI improvements.

The basic idea is to reduce road accidents possibility by the optimization of information flow from vehicle to rider that can greatly improve rider awareness. In order to reach this goal, a system have been developed able to redistribute the information, generally shown only in the central dashboard, to other communication channels. In this way the rider is informed about possible failures, incoming calls or navigations messages thought ad-hoc acoustic, visual and vocal signals. In such a manner the rider do not need to put off the eyes from the road, nor to take the hands away from the handlebar, remaining in the meantime focused on driving task.

HMI information management concept

The motorcycle rider receives several information referred on one hand to vehicle status and on the other hand to personal infotainment devices.

In fact, nowadays riders are interested not only to diagnosis information about vehicle functionality but also to data related to user's devices like mobile phone and PDA or to integrated applications like navigation system or media player. An easy access to this kind of information is strongly desired by the rider and so the need of communication management becomes a fundamental topic .

With the aim "to reduce the rider distraction concentrating his/her attention on the driving manoeuvres" is therefore designed and developed an HMI Information Management concept for motorBikes (IMB).

The significant information that the dashboard, the mobile phone and the navigation system provide are structured, prioritized and assessed in terms of riding safety by the IMB: the signals are handled in order to create the proper balance among the different elements of the motorbike-rider-protective equipment system.

While the output information is distributed to the rider using visual and acoustic modality, the IMB receive input commands by the rider through the vocal and the tactile modality.

Summarising, the Information Management Board picks up:

- Rider input (by voice or by handlebar controls)
- Vehicle information (like for example specific ECU malfunction, ECU settings and vehicle alerts)
- Mobile phone information including media player, SMS reader and hands-free Bluetooth
- Navigation system information

and redistributes them through the SIM enhanced HMI, that includes an additional display mounted on the handlebar and an head up display mounted in the helmet (**Figure 21**).

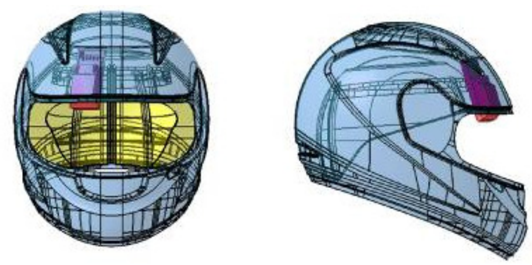

Figure 21. Helmet head up display placement.

The helmet is also equipped with a microphone and headsets wireless connected to the IMB through which the audio communication is permitted.

It is important to highlight that the SIM HMI displays does not substitute the conventional dashboard because its role is to enhance some critical messages about the vehicle status. Moreover, in order to ensure that the surrounding ambient noise is being perceived by the rider since his safety depends also on such an information, the solution with only one active earphone in the helmet is implemented.

Passive Safety Systems

In order to develop a passive safety system, the first step is related to the definition of most relevant crash scenarios used in order to evaluate its effectiveness. In [8], based on kind of injuries sustained by the rider in similar crashes and complexity of rider motion during the event, two main scenarios have been selected from ISO 13232 standard: configuration 413 and 114 (**Figure 22**).

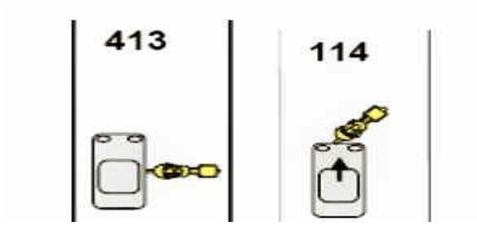

Figure 22. Crash configuration analysed in SIM project

In fact, in those configurations, previous full scale crash tests shown that a frontal airbag totally avoids the contact with the car in 431 situation drastically reducing the injuries suffered by the rider, specially in head and neck. Otherwise the ISO 114 configuration can be considered the worst case scenario on which the airbag, also if it do not cause additional damages, can not avoid the contact with the other vehicle nor the ground. For this kind of accidents where the rider separates from the PTW, the only effective protection can be provided by protective devices located on the rider garment.

Based on this analysis, the passive safety system for SIM project have been designed as a cooperative architecture composed by:

- frontal airbag system
- wearable inflatable device

In the next research and development phases, each subsystem has been tested as standalone and/or in combination with the other module in simulation environment by multibody codes (**Figure 23**).

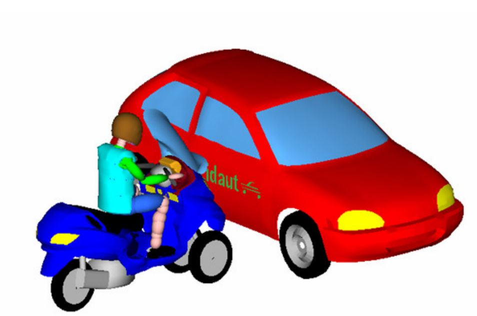

Figure 23. Multibody model for passive safety systems assessment.

In addition to multibody analysis that give a preliminary estimate of rider and dynamic and interaction with protective devices during crash sequence, a finite element model has been developed in order to obtain a more detailed simulation of energy absorption and rider injury level (**Figure 24**).

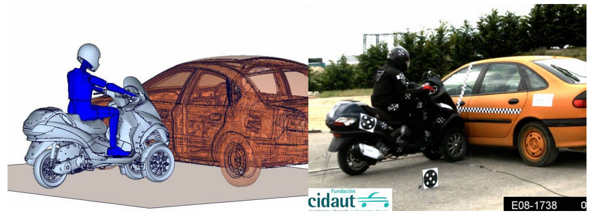

Figure 24. Mp3 FE model and simulation of 114 configuration crash test.

The FE model has been set-up by acceleration data collect on specific vehicle position during full scale tests against rigid wall performed in cooperation with Aprosys Project (**Figure 25**)

Figure 25. Mp3 full scale crash test (from Aprosys project).

As preliminary strategy, the main functionality of the airbag should be to restrain the rider (protecting/damping the rider from the primary impact), while the major benefits from the wearable module are expected in case of separation between rider and PTW (secondary impact). The effectiveness of the wearable module on the primary impact and the potential side-effects when used in combination with airbag module has also been evaluated by multibody code without harmful results.

In detail the defined PTW airbag functions are:

- To hold back the rider and avoid handlebar contact.
- To guarantee a large volume able to dissipate rider kinetic energy.
- To reduce rider forward displacement.

The wearable safety system used and tested in SIM project consists of an inflatable jacket which provides a better level of protection for the rider. The airbag jacket is expected to have more benefits for the secondary impact injuries, even if it will be tested also in combination with the frontal airbag module (**Figure 26**).

Figure 26. Rider protection air-jacket.

Using the data collected during real crash tests between PTW and passenger cars, from the accelerometers placed along the MP3, an algorithm has been programmed in order to have the decision-making ability of crash event recognition for safety systems activation. The "no fire" thresholds for the algorithm have been set by an experimental campaign of signal registration during normal vehicle operation conditions and also some "misuse" tests (e.g. potholes or drop tests). From further videos and deceleration diagrams analysis of full scale tests, the preliminary set of parameters for the activation of the passive safety system and satellite sensor position has been decided.

The frontal airbag shape and volume and inflator pressure levels have been empirically developed by static bench tests on physical prototypes in order to provide an overall energy absorption similar to the one coming into play in the real crash (**Figure 27**).

Figure 27. Frontal airbag prototype.

Final optimization of airbag prototype have been realized through sled tests that reproduce on a one axis configuration the decelerations felt by the rider during full scale crash. In such a manner it is possible to perform several set-up runs for bag, inflator and firing strategy without significant damages on vehicle structure (**Figure 28**).

Figure 28. Sled test for frontal airbag development.

CONCLUSIONS

As a whole, the PTW overall safety strategy followed in SIM project started from findings of the MAIDS project and from the current situation of PTW accidents and fatalities trends in EU roads.

The main factors that contribute to accident causation have been categorized and crossed with the safety areas (active, preventive and passive). By such an approach, the topics in which PTW safety improvement is feasible are identified for each cell of the Safety Matrix.

SIM project does not expect to cover all aspects of the Safety Matrix, however since the consortium is well-balanced in terms of industrial partners, universities and research centres and it is led by a PTW manufacturer, the efforts are focused on PTW safety improvement and PTW rider protection and comfort.

Further accident analyses were conducted on in-depth databases and results were compared with ones obtained in previous EU projects (i.e. APROSYS SP4). The outcomes are reported in [6].

In [3] the most promising safety enhanced technologies have been selected based on partners' expertise and by evaluating their effectiveness in real accident scenarios.

The safety devices to be developed and tested within the project have been selected taking into account also the real market perspectives. Summarizing SIM activities, at the end of the second year, the design and development of the active safety systems have been completed and system prototypes have been realized:

-stability management system based on a three-channel advanced braking system

-semi-active suspension system with three setting levels (normal, sport, comfort)

Also a Human-Machine Interface concept has been realized by an Information Management Board that gathers data from vehicle via CAN bus and sends ad-hoc messages to HMI display and in helmet audio speakers.

Some additional information (like RPM and speed) are provided to rider via Head-up Display integrated into the helmet housing.

Beside the great challenge represented by the implementation of rider protection system on a scooter and the strong effort needed for validation of results, passive safety devices characteristics have been selected by several simulation both in FE and multibody environment.

Currently a frontal airbag is installed on vehicle and its preliminary set-up and effectiveness evaluation has been performed by experimental sled tests.

The actuation logic of protection system has been selected and first set of parameters for firing strategy has been set-up from vehicle "misuse" tests, as well as sensor position from full scale crash tests.

To conclude, powered-two-wheelers rider safety is a complex phenomenon that requires a comprehensive approach and the aim and responsibility of SIM project can only be addressed within design and development of new products featuring advanced technologies in all field of safety, related to vehicle and rider helmet and clothing.

Nevertheless it should be underlined that road safety can be achieved in a structural way only with the support and common effort of all stakeholders, first of all road users that have to make the most out of the new technologies available today and in the foreseeable future on the market.

In such a vision the major effort of road operators should be oriented to improvement of passive safety performances of the infrastructure and in a long term, to effectively make the infrastructure cooperative with vehicles within a common communication architecture for safety and traffic management issues.

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ENHANCED AUTOMATIC COLLISION NOTIFICATION SYSTEM – IMPROVED RESCUE CARE DUE TO INJURY PREDICTION – FIRST FIELD EXPERIENCE

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ABSTRACT

This paper summarizes the initial findings from a database of crashes that involved BMW's equipped with Automatic Crash Notification (ACN) Systems in the US and Germany. In addition, first field experiences with BMW's enhanced ACN systems are reported where vehicles not only provide an initial crash notification but also transmit data describing the nature and severity of the collision event. The benefits of such a system, including the rapid recognition of potentially injured occupants based on key characteristics of each crash, are explored.

Since 2006, nearly 14,000 BMW crashes have occurred in the US involving vehicles equipped with ACN or enhanced ACN technology. Of these, 70% of occupants indicate no injury to the TSP (Telematics Service Provider) operators, 20% indicate they are injured in some way and require help while 10% provide no verbal response to the TSP call-taker. An investigation of a subsample of crashes occurring in Florida suggests that no hospital transport was necessary for 81% of the calls where no voice response occurred. Although the majority of these cases require no further care, 19% of the no voice population was subsequently transported to a hospital or trauma center for additional care. This population of occupants could benefit from an automatic call for help to a Public Services Answering Point (PSAP- commonly known as 911) that includes an estimate of the likelihood of serious injuries.

To assist in identifying crashes with incapacitating injuries, the William Lehman Injury Research Center (WLIRC) in Miami, Florida and BMW have pioneered the development of an algorithm called URGENCY. This algorithm is based on US national crash statistics and BMW internal data. The injury prediction by URGENCY permits the transmission of the earliest and best information to the PSAP. We report early observations of injury severity and location for enhanced ACN equipped vehicle crashes occurring in the US and Germany.

INTRODUCTION

When a motor vehicle crash occurs with a potential for injuries, a notification of the event and the location of the crash are critical so that rescue can be dispatched to the scene. It is also helpful for emergency dispatch to recognize the severity of the collision and the extent of injuries so that they can adequately assign personnel and specialized equipment as needed. This paper describes Automatic Crash Notification (ACN) technology that initiates this critical call for help. In addition, this study reports first field experiences with BMW's enhanced ACN systems where vehicles not only provide an initial crash notification but also transmit data describing the nature and severity of the collision event. The benefits and potential for such a system, including the rapid recognition of potentially injured occupants even in the absence of voice, are explored.

The rapid identification of occupants involved in a crash followed by definitive care in the most appropriate facility has been shown to improve injury outcomes and prevent fatality. A study by Clark and Cushing based on US data suggests a 6% fatality reduction is possible (1,647 lives in the US in 1997) if all time delays for notification of Emergency Medical Services (EMS) were eliminated even if methods for dispatch and treatment remained the same (Clark 2002). This reduction in notification time would occur with widespread implementation of enhanced ACN technology in passenger vehicles today.

Three studies conducted by the US National Highway Traffic Safety Administration (NHTSA) have explored preventable deaths to assess the effectiveness of the current trauma care system (Esposito 1992, Maio 1995, Cunningham 1995). Two of the studies concluded that 28.5% and 27.6% of fatalities occurring in their regions were preventable with improved EMS and treatment. The third study concluded that 17% of fatalities occurring in combined urban and rural areas were preventable. Delayed treatment and improper management of the injured were cited as the factors that most frequently contributed to the avoidable death. The majority of the preventable deaths occurred after arrival at a hospital. These studies suggests that opportunities exist to prevent trauma deaths not only by reducing the time from crash to hospital, but also to aid in recognizing the nature of the most serious injuries and the most appropriate medical facility to provide definitive treatment.

A recent evaluation of the US trauma system considered the effect of trauma center care on mortality outcome of patients (MacKenzie, 2006). The study estimated mortality rates for patients arriving at hospitals with one or more Abbreviated Injury Scale Level 3 injuries (AIS 3). Overall, the findings of this study suggest that the risk of death is 25% lower when care is provided in a trauma center compared to a non-trauma center. This study underscores the importance of treatment in the most appropriate medical facility.

Automatic Crash Notification Systems

BMW first introduced ACN technology in their vehicles in 1997. Other vehicle manufacturers are now equipping their vehicles with ACN as well. In the event of a moderate to high severity impact, ACN systems rapidly notify authorities that a crash has occurred, transmit the location of the crash and vehicle data. The information is first screened by an intermediate TSP like ATX or OnStar and, in the case where medical care or police assistance is required, forwarded to 911 for further assistance. ACN systems allow for verbal communication between the call-taker at the TSP and crash involved occupants in order to better evaluate the overall severity of the crash event to make appropriate decisions.

The principle components used by the ACN system are listed in Figure 1. The system is triggered using data from crash sensors used to deploy front and side airbag systems including accelerometers, pressure sensors and gyroscopic sensors. If a crash event exceeds the predetermined threshold for transmission of an ACN signal, verbal communication between the TSP and occupant occurs through a fixed microphone and the vehicle audio system.

The ACN system is a stand-alone system where there is no need for an additional mobile phone. The vehicle sends an emergency call automatically, if a crash was detected or manually by pushing the SOS button if assistance is needed.

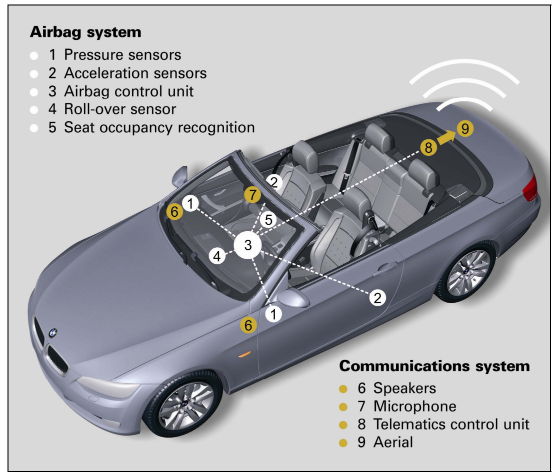

Figure 1. Airbag and communication components using the example of the 3 series convertible.

Once a call is initiated, ACN equipped vehicles transmit a notification that the crash has occurred, exact GPS position, the Vehicle Identification Number (VIN) specifying owner information and vehicle characteristics. The vehicle calls the TSP and the occupants can talk to operators with specialized training.

In 2007, BMW introduced an enhanced Automatic Crash Notification Technology. These systems collect additional crash metrics through on-board sensors that can be used as the basis for estimating crash severity and risk of injury to occupants. The additional data collected and transmitted includes the crash deltaV in the longitudinal and lateral directions for each impact event, crash type, safety belt status for front seat occupants, airbag deployment status, the occurrence of multiple impact events and the occurrence of rollover if the vehicle is equipped with rollover sensors.

Once transmitted to the BMW call center, the raw data passes through an algorithm known as URGENCY which estimates the risk of serious injuries based on crash conditions. The algorithm was first proposed in 1997 and consists of a single logistic regression model that related the risk of high severity injury to independent variables describing each crash event (Malliaris 1997). Since its initial development, URGENCY has been retrained using recent crash data, modified to more accurately treat differences in serious injury risk by crash direction and enhanced to include additional crash parameters like multiple impacts (Augenstein 2003). The algorithm estimates the risk of serious injury based on crash parameters transmitted by the enhanced ACN system. Seriously injured occupants are defined as those who have sustained one or more injuries with an Abbreviated Injury Severity (AIS) Score of 3 or higher (includes AIS 3, AIS 4, AIS 5, AIS 6 and fatally injured). This group is referred to as MAIS3+ injured and includes those who need immediate medical attention due to potentially life threatening injuries.

The URGENCY Algorithm treats crashes separately by impact type including frontal, nearside, farside, rear impacts and rollover. The algorithm was trained using 2000-2006 NASS CDS data including passenger vehicle front seat occupants over the age of 12 who are involved in planar only crashes. Model year 1998 and later vehicles only were used during model development and evaluation.

Each model was subsequently evaluated using the 2007 population of NASS CDS cases meeting the same criteria used for model training. These cases are independent of those used to train the model and were analyzed to determine the predictive value of the models for crashes estimated to be at or above the threshold for triggering the ACN system. Table 1 shows the overall ability of the models to identify or capture the MAIS3+ injured within the evaluation population (i.e. model sensitivity). Further, the table presents model specificity which indicates the models ability to capture the uninjured within the evaluation population as well. These values are presented in Table 1 for planar only crashes by crash direction.

Crash Mode	Sensitivity	Specificity
Frontal	71.2%	90.2%
Nearside	90.6%	85.7%
Farside	81.2%	88.6%
Rear	52.7%	98.2%
Overall	75.9%	90.8%

Table 1. URGENCY Algorithm capture rate within the 2007 NASS CDS crash population.

The overall predictive accuracy of the model suggests that 75.9% of injured occupants would be correctly identified using data automatically collected and transmitted by vehicles alone. In other words, an automatic call for help indicating serious injury is likely would be made for three out of four MAIS3+ injured occupants even if their crash was not observed by somebody on scene or if occupants were unable to place a call themselves. When URGENCY estimates are used in combination with verbal information gathered by the TSP or 911, occupants in need of medical attention would be rarely missed. A third opportunity to assess injury severity exists before hospital transport once EMS has arrived on scene.

Figure 2 shows the sequence of events that occurs when an enhanced ACN equipped vehicle is involved in a crash severe enough to trigger the automatic call for help. In this case the vehicle automatically sends the crash descriptors described above to the BMW Assist Center (TSP). While the vehicle is sending the data, a voice communication between the BMW Call Center and the occupants is simultaneously established. In the background the URGENCY algorithm is used to calculate the risk of serious injury and the call center is able to provide all this information, shortly after the crash, directly to the nearest Public Safety Answering Point (PSAP). If desired a conference call with the vehicle is also possible. Ideally, the PSAP would then utilize the available information to arrange appropriate rescue based on the risk of serious injuries communicated by the TSP. The additional data can then aid in the decision to dispatch either a helicopter or an Emergency Doctor or the Fire Department, and to further involve the EMS and the Police, for more accurate and proper allocation of resources.

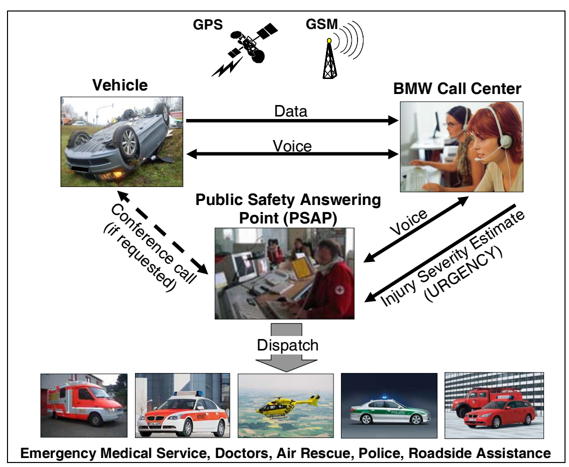

Figure 2. Flow chart of the functionality of the enhanced ACN system.

OPPORTUNITIES TO IMPROVE RESCUE USING ENHANCED ACN DATA

As discussed above, enhanced ACN systems now provide crash notification and location data along with data needed to approximate severity of the collision event. In most cases, occupants involved in crashes will respond verbally to call-taker questioning and those who require medical assistance can be easily identified. However, it is possible that occupants may not realize that they are injured shortly after a crash or they may not recognize the true extent of their injuries.

This portion of the study examined the population of BMWs in service in Florida from 2006-2008 who were involved in crashes severe enough to trigger the ACN system. The goal was to estimate: 1) the frequency of crashes where occupants suggested they were uninjured yet subsequently required hospital transport and; 2) the frequency of crashes where occupants did not respond to TSP operators yet were injured and required help. Establishing the magnitude of this population provided an indication of those who would most benefit from enhanced ACN data to be transmitted and processed remotely by the TSP and passed along to the PSAP.

Analysis of Verbal Response from Occupants

During this portion of the study, data from two primary sources were utilized. The first was the BMW Accident Research Crash database that includes a census of crashes involving ACN equipped model year 2004-2009 BMWs in service on US roadways. The dataset contains the vehicle identification number (VIN) along with GPS coordinates identifying precise crash location, and a written record of the verbal exchange between occupants and the ATX call-taker. Data is captured electronically by the communications software at the TSP. Each call-taker also enters notes documenting occupant response and information shared during the call.

Researchers reviewed each available call log to determine the nature of the crash including indications of injury, the general nature of the crash (i.e. multi-vehicle crash, rollover, etc) and the presence or absence of voice response. Cases where the ACN call log reflects no verbal response from occupants are classified as 'No voice.' In many cases, the TSP operator may hear noises in the vehicle or voices outside the vehicle yet no direct response from occupants is heard. It is suspected that some of these cases may result from occupants quickly exiting the vehicle following the crash before the TSP operator can initiate contact. In other cases, occupants may be injured such that a response is not possible or occupants may simply choose not to verbally respond. Crashes occurring in the state of Florida from 2006-2008 were retained for subsequent analysis.

The second source of data was the Florida State Crash Data from 2006-2008. This dataset contains a census of crashes where a police report was filed. In the state of Florida, the minimum criteria to file a police report include one or more fatality, any injury, alcohol involvement, or leaving scene. When a vehicle is towed from the scene, the officer uses his or her discretion in filing a report. Due to the criteria for inclusion, any crash where one or more occupant was transported to a hospital for treatment should be included within the annual file.

Findings

Table 2 shows the count of ACN crashes in the US and Florida alone in 2006-2008. The population of ACN crashes is also shown by approximate injury severity as reported verbally by occupants. A category where no voice response is provided by occupants is also included. The 'Not Reported' category includes crashes where there was verbal interaction with occupants yet no explicit statement of injury or non-injury was found in the call log. Due to the absence of this information, it was assumed that the TSP call-taker did not suspect injuries and simply neglected to enter this information into the log.

Injury Level Reported Verbally	2006-2008 Crashes	
	Count	%
All Crashes	14,008	
Uninjured	6,285	45%
Low Severity Injury	2,468	18%
Moderate or Serious Injury	288	2%
No Voice	1,467	10%
Not Reported	3,500	25%
Florida Crashes	1,338	
Uninjured	565	42%
Low Severity Injury	299	22%
Moderate to Serious Injury	26	2%
No Voice	166	12%
Not Reported	283	21%

Table 2. US ACN Crash populations for 2006-2008 cases including occupant reported injury level.

Police records from the Florida state data were merged with ACN records using the unique VIN and crash date as unique criteria for linkage. The goal in connecting the two sources is to determine the general characteristics of the crash, identify the type of information offered verbally by drivers and to characterize the type of treatment (hospital transport, trauma center transport or no transport) received by crash involved drivers. Table 3 shows the count of cases within the complete ACN dataset and the population from the Florida file.

Table 3 also shows the police reported injury severity for occupants of the BMWs involved in the crash. Injuries are coded by police using the KABCO scale. The KABCO scale was established by the National Safety Council in 1982 and is used primarily by police to classify the apparent injury severity of occupants involved in crashes. The scale includes 5 levels, where K level injuries are those where the occupant dies due to injury, A level injuries are those where the officer observed incapacitating injuries, B are non-incapacitating evident injuries, C are possible injuries and O are uninjured. The KABCO scale is a useful means to approximate injury severity yet it has been criticized as inaccurate due to the subjective assessments made by police. Data describing hospitalization was also retained, specific hospitals were identified and those where occupants were transported to a level I trauma center were flagged.

Police Reported Injury Severity	2006-2008 Crashes	
	Count	%
Florida Crashes	1,338	
K, A	57	4%
B, C	318	24%
O*	978	73%
Hospital Transport	235	18%
Trauma Center Transport	32	2%

* includes cases where no PAR (Police Accident Report) was filed.

Table 3. Police reported injury severity and level of transport for 2006-2008 BMW Crash Cases.

Two populations were explored in more detail including the population where occupants did not reported injuries the TSP call-taker and the population who did not provide a verbal response to the TSP once communications were established with the vehicle. As shown in Table 4, 848 drivers were involved in crashes occurring in Florida from 2006-2008 and verbally reported that no injury was sustained. However, police coded that 194 (23%) of these drivers sustained possible (C), non-incapacitating (B), incapacitating (A) or fatal (K) injuries. A total of 108 of these were transported to a medical care facility and 23 of those receiving medical care were transported to a trauma center.

It should be noted that the criteria for transport to a trauma center can be met in a number of ways that are assessed and established on scene by first responders. These criteria include: 1) physiologic criteria like obvious signs of injury, reduced awareness (based on Glasgow Coma Scale), low blood pressure or head injury with neurologic deficit; 2) mechanism criteria including fatality of another occupant in the vehicle, ejection or evidence of a high energy event or; 3) First responder high suspicion of injury. If a first responder permits EMS personnel to override tangible criteria and decide that trauma center is in the best interest of crash involved occupants.

Although 108 occupants were transported to some type of medical care facility based on decisions made by EMS personnel on scene, this does not necessarily prove that an injury has occurred.

Police Reported Injury Severity	2006-2008 Crashes	
	Count	%
Crashes with Voice Response but No Injury Reported	848	
K, A	23	3%
B, C	171	20%
O*	654	77%
Hospital Transport	108	13%
Trauma Center Transport	23	3%

* includes cases where no PAR was filed

Table 4. Police reported injury severity and level of transport for cases where no injury was reported by drivers (2006-2008 cases in Florida only).

Table 5 indicates that, during 166 crashes, there was no verbal response from any occupant in the vehicle following the crash. Of these, police reported that 8 (5%) drivers sustained incapacitating or fatal injuries based on their judgment. A total of 34 (20%) were coded as having non-incapacitating or possible injuries and 111 (67%) were coded as having no injury at all. Thirty one (31) crashes or 19% of no voice cases resulted in one or more hospital transports and 5 (3%) resulted in trauma center transport.

Police Reported Injury Severity	2006-2008 Crashes Count	%
Crashes With No Voice Response	166	
K, A	8	5%
B, C	34	20%
O*	111	67%
Hospital Transport	31	19%
Trauma Center Transport	5	3%

* includes cases where no PAR was filed

Table 5. Police reported injury severity and level of transport for no voice cases (2006-2008 cases in Florida only).

Opportunities to Improve Rescue Decisions

Since their first introduction in the fall of 2007 in Germany, 116 enhanced ACN crash calls have occurred. In the US, 449 enhanced ACN crashes have occurred since the spring of 2008.

To further explore the benefit of geographic data (GPS coordinates) transmitted in combination with injury severity, we analyzed the population of enhanced ACN crashes occurring in the US and Germany to date. Each crash was classified as low to moderate or serious based on their crash characteristics. GPS coordinates were reviewed to establish the geographically closest treatment facility to the crash. Subsequently, the distance along the roadway was calculated using the Google Earth mapping application. Figure 3 shows the driving distances along the roadway separating enhanced ACN vehicle crashes and Trauma Centers in Germany and the US. This plot is limited to those classified as serious based on transmitted crash data processed by the URGENCY Algorithm.

In general, the distribution of distances to a Level 1 trauma center in the US and Germany are similar with only minor differences. The percentage of crashes occurring within 20 km of a trauma center is higher in Germany compared with the US. While a larger percentage of US crashes appear to occur more than 20 km from the nearest level 1 trauma center.

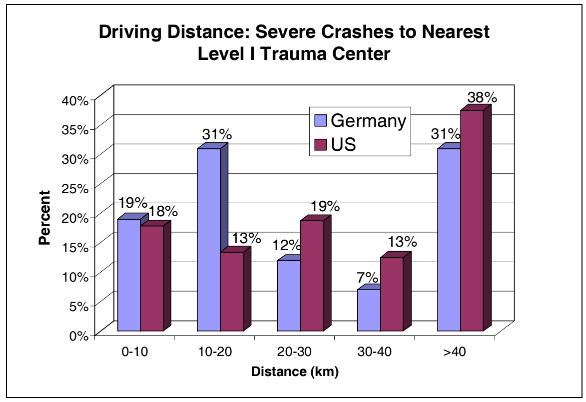

Figure 3. Driving distances from enhanced ACN vehicle crash locations to nearest Level I trauma center- US and Germany compared.

The transfer of geographic information from the TSP to the PSAP is currently done verbally. In the future, transmission of this data, accompanied by estimates of injury severity from the URGENCY algorithm, could be done electronically. Once received, the PSAP could utilize the data according to their established dispatch protocols to best select and deploy rescue resources.

Analysis of Enhanced ACN Data- First Experiences

Figures 4 and 5 compare the overall estimated injury severity for enhanced ACN equipped vehicle crashes occurring in the US and Germany with the percentage of crashes where one or more MAIS3+ injuries occurred in a vehicle. Data from NASS CDS and GIDAS from 2000-2007 were considered and the subset of crashes expected to exceed the enhanced ACN Trigger threshold were retained. These crashes include those severe enough to deploy airbags in the frontal and side direction.

As shown in Figure 4 and Figure 5, the percent of cases in the enhanced ACN crash populations in the US and Germany were more frequently classified as serious when compared with the NASS and GIDAS populations of crashes.

Since the enhanced ACN signal would be the first notification of a potentially serious crash and the first step of the rescue chain, a rather broad criteria has been established so that occupants with potentially serious injuries are unlikely to be missed. Once EMS arrives at the scene, they will conduct a more detailed, in-person assessment of crash involved occupants to make subsequent triage decisions. It should be noted that the threshold applied to these first enhanced ACN crashes is purposely set lower than that used to identify the performance of

URGENCY as shown in Table 1 to avoid missed serious injuries as the system is first introduced.

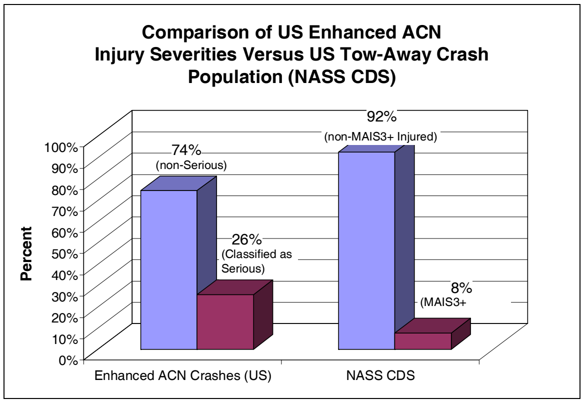

Figure 4. Comparison of injury severity from enhanced ACN data and MAIS3+ Injury Rate based on US Tow Away Crash Population

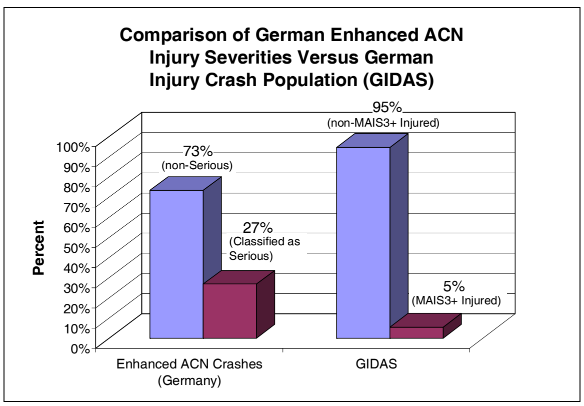

Figure 5. Comparison of injury severity from enhanced ACN data and MAIS3+ Injury Rate based on German Crash Populations

A second reason for the disparity in percentage of serious crashes between the enhanced ACN data and the US and German data, may result from differences in severity between the two populations. It is likely that the enhanced ACN crashes are more severe than the distribution of crashes in the general population. While the data shown in Figures 4 and 5 include only crashes severe enough to trigger the ACN system, it is possible that those in the enhanced ACN dataset occur at higher speeds or under more severe conditions.

DISCUSSION

This paper reports first field experiences with BMW's enhanced ACN systems where vehicles not only provide an initial notification of a crash but also transmit data describing the nature and severity of the collision event. We present an analysis of populations who could benefit from enhanced data now transmitted and identify how the application of URGENCY to estimate likelihood of serious injuries could help improve rescue care.

Usefulness of verbal data- A review of BMW ACN crash call logs suggests that verbal interactions between drivers and TSP call-takers often provides valuable information needed to make remote dispatch decisions. However, a review of logs for BMW crashes occurring in Florida from 2006-2008, in combination with a review of corresponding police reported data, revealed that some occupants who verbally indicated to the TSP they were uninjured were, in fact, transported to hospitals following on scene assessment by EMS. As shown in Table 4, 13% of drivers who initially provided no definite indication of injury indeed required hospital transport. Twenty-three of these 108 (3% of those who reported no injury) even met current criteria for trauma center transport. This suggests that serious injuries were sustained by one or more occupants in the BMW or the crash event was severe enough that EMS decided trauma center care was needed due to a high suspicion of injury.

Past research has shown that occupants, who sustain the most serious internal injuries, including those to the liver and thoracic aorta, are often unaware of their injuries until diagnosed in a hospital or before treatment is too late (Augenstein 1994, 1995, 2000; Lombardo 1993). For those where occupants report no injury, the injury severity could also be applied to confirm a lower severity crash has occurred or suggest follow-up by rescue when in fact a higher severity event is detected.

Cases with no voice response- Table 2 indicates that, in 10% of all cases and 12% in Florida, there is no verbal response from the vehicle occupants, even though there is voice communication within the vehicle by the TSP. For most, the lack of response suggests that the crash is minor and vehicle occupants have perhaps exited the vehicle to examine damage or for other reasons. In some cases, the lack of response is due to an incapacitating injury. It is particularly important to apply an injury risk algorithm to these events with no-voice response so that those in most need of care are identified and receive prompt rescue response.

Data presented here shows that, in the state of Florida from 2006-2008, 31 out of 166 cases or 19% of occupants who did not respond verbally to the TSP subsequently required hospital transport and medical attention (see Table 5). Five of these occupants ultimately received care at a trauma center. It is these occupants who may not be able to communicate the need for care who would best benefit from enhanced ACN technology. For them the vehicle based data could provide an automatic indication to the PSAP that the risk of serious injury is high and immediate rescue care is required.

Although findings are based on preliminary data with relatively low crash counts, the implications are clear. Looking at the complete US, 10% of all BMW ACN crashes had no voice response (i.e. 569 out of 5,689 in 2008). Applying findings from Florida we project that a total of 114 BMW occupants across the US each year could require subsequent medical attention although they may not provide a verbal response to TSP call-takers. Imagining such a system implemented in all passenger vehicles in the US, this automatic call for help could improve outcomes in the same way for over 15,200 drivers each year involved in moderate to high severity crashes. This estimate was derived from NASS CDS 2007 data, where 800,000 passenger vehicles were reported to be involved in a tow-away crash severe enough to trigger an ACN system if the system were available.

<u>Utility of crash location data-</u> Knowledge of crash location by dispatch in combination with the likelihood of serious injuries also presents opportunities to improve care for crash involved occupants. Figure 3 suggests that in 31% of BMW enhanced ACN crashes in Germany and 38% in the US occur further than 40 km from the nearest Level 1 trauma center. Even under ideal rescue conditions, it is unlikely that the total time from crash occurrence to definitive trauma center care (including EMS to travel to the scene, on scene care and transport) would occur within the "Golden Hour" of trauma. The "Golden Hour" of trauma care is a concept that emphasizes the time dependency of many injuries where the patient must come under restorative care during that first hour following the trauma.

For the most severe crashes, delayed deployment of additional rescue resources like extrication equipment or air transport could also significantly impact outcomes. If the automated assessment of injury severity occurred just moments after the crash using enhanced data transmitted by vehicles, deployment of such resources could occur much more rapidly than in the present system. Based on traffic conditions and location data, the decision to deploy air rescue may also be considered if appropriate conditions exist.

<u>Development of a working system-</u> Although manufacturers like BMW are now equipping vehicles with technology capable of transmitting valuable crash information to TSP's, the remaining rescue system must be enhanced to most effectively utilize the data. Mechanisms for the transfer of telematics data from one entity to another along the rescue chain are needed. This transfer may occur verbally or in electronic form as the system develops. Protocols must be enhanced so that the injury severity data is consistently treated by all involved and actionable. Currently, no criteria exists within dispatch or trauma triage protocols to process specific data elements known to effect the risk of serious injury including crash (deltaV), impact direction, number of impacts, restraint status (i.e. airbag deployment regime and belt use) and occupant age. In our opinion and those of others, a synthesized estimate of injury severity would be most useful. Finally, education is required so that 911 operators, EMS and treating physicians understand the value and correctly interpret the information to allow for real improvements in patient care.

The Centers for Disease Control (CDC) in the US has established a new triage protocol that allows for the telematics data like those transmitted by enhanced ACN Systems as criteria for increasing the level of urgent care provided to occupants exposed to a crash. Although no formal definitions have been specified for the treatment of telematics data, a medical committee established by CDC has recommended the use of an algorithm like URGENCY as the basis for recognizing crashes with high risks of serious injury and accelerating the rescue for those crashes. BMW and WLIRC will continue work with the CDC, EMS and dispatch community to define best practices to apply when this enhanced data is transmitted from the vehicle.

CONCLUSIONS

Enhanced Automatic Crash Notification Systems are now available and in service in many countries around the world and provide near instantaneous data on crash occurrence, location and severity. This data should be used by PSAP's to identify when the dispatch of rescue services is needed and the most appropriate assets to send. Enhanced ACN data, now transmitted by a growing population of BMW vehicles, can be used to optimize rescue response particularly in the absence of voice from occupants of the car.

In most cases, verbal data provided to the TSP and PSAP through the on-board communication system are valuable to dispatch in order to make rescue decisions. However, some occupants who provide a verbal response to TSP call-takers may not always accurately recognize or communicate that they are injured. A lack of voice response from occupants does not necessarily indicate a high risk of serious injury; however some occupants who may be unable to respond do require immediate medical assistance.

The data analyzed during this study represents a census of crashes involving ACN and enhanced ACN equipped vehicles in service in the US and Germany. With more than 700,000 BMW vehicles worldwide currently in service equipped with the technology, the resulting information transmitted in the event of a crash is of unprecedented value for research purposes. True population based estimates are possible using this data. When linked with other records like police reports, the information serves as a valuable resource for studying the performance of enhanced ACN systems or other safety technologies introduced within the fleet.

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Combining CIREN and NASS-CDS Data to Predict Occupant Outcomes in Frontal Crashes

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ABSTRACT

The National Highway Traffic Safety Administration's (NHTSA) Crash Injury Research and Engineering Network (CIREN) provides detailed outcome and patient care information for a sample of seriously injured case occupants involved in motor vehicle crashes. NHTSA's National Automotive Sampling System-Crashworthiness Data System (NASS-CDS) provides a population-based sample of tow-away crashes that includes both non-injured and seriously injured occupants. This study combines the strengths of CIREN and NASS-CDS to produce predictive models that relate occupant and vehicle measures to treatment and occupant outcomes.

Qualifying frontal impact cases from CIREN involving seriously injured driver and/or front outboard passengers were used to evaluate the significance of the relationship between vehicle crash/occupant parameters and hospital treatment/outcome. A subset of CIREN cases where event data recorder (EDR) information was obtained was also analyzed. Regression analyses were done to assess the significance of predicted variables with regards to the outcomes of interest. Using significant predictors, a set of functions were developed that predict the probabilities of an occupant going to the intensive care unit (ICU), experiencing invasive surgery (OR) within 12 and 24 hours of the crash, or fatality given serious injury. NASS-CDS cases meeting the same CIREN crash and occupant inclusion criteria were used to establish the probability of serious injury given a qualifying frontal impact. This study has shown that the NASS-CDS-based probability of serious injury and the CIREN-based probability of seeing various outcomes given serious injury can be combined to form models that estimate the joint probability that a case occupant involved in a qualifying frontal crash would see an outcome of interest (ICU, OR, or fatality).

INTRODUCTION

It has been shown that the risk of death is 25% lower when care is given to a seriously injured patient at a trauma center versus a non-trauma center (MacKenzie et al., 2006). Over 40% of the patients included in the study by MacKenzie et al. (2006) were injured as the result of a motor vehicle crash. A motor vehicle crash resulting in serious injury requires rapid attention by the responding emergency medical services (EMS), police or appropriate rescue agency. Through observations made at the scene, the responding agency must decide where to transport the patient and by what means. This triage of vehicle occupants involved in motor vehicle crashes is currently done on-scene using the American College of Surgeons (ACS) field triage decision scheme published in 2006 (ACS, 2006) and later supported with detailed rationale (Sasser et al., 2009) . The field triage decision scheme consists of four sections or steps: 1. vital signs and level of consciousness, 2. anatomy of injury, 3. mechanism of injury and evidence of high-energy impact, and 4. special patient or system considerations.

The National Highway Traffic Safety Administration (NHTSA) is tasked with reducing injuries and fatalities that result from motor vehicle crashes. As part of this effort, NHTSA collects and analyzes data from real world crashes. This data is used to assess injury and fatality trends. NHTSA's National Automotive Sampling System – Crashworthiness Data System (NASS-CDS) collects vehicle crash and occupant injury data from a population-based sample of tow-away crashes. The NASS-CDS data set is useful in that the injury rates seen in a particular crash mode can be weighted to estimate the overall population risk of experiencing a given level of injury in a crash configuration of interest. NHTSA's Crash Injury Research and Engineering Network (CIREN) program collects data from a convenience sample of motor vehicle crashes in which there was serious or disabling injury to at least one case occupant. Like NASS-CDS, CIREN cases involve detailed crash reconstructions in which both vehicle and occupant data are collected. Vehicle data includes, among other things, structural deformation, delta V, principal direction of force (PDOF), and restraint system types and usage. Occupant data includes, among other things, case occupant position, demographics, anthropometry, and a description of injuries and their sources. However, CIREN provides a more detailed biomechanical analysis and sourcing of the observed injuries. CIREN also provides detailed hospital care and patient outcome data that is not documented in NASS-CDS cases. Unfortunately, trends seen in CIREN data can't be extrapolated to the general population because CIREN is not a probability sample.

Step 3 in the ACS field triage decision scheme has an entry for assessing crash severity as determined by telemetry data obtained from automatic collision notification (ACN) systems. However, specific telemetry variables or predictive models are not suggested. Others have documented models using vehicle and occupant data in an attempt to predict the probability of a maximum Abbreviated Injury Scale (MAIS) (AAAM, 1998) of 3+ for a case occupant in a given crash scenario. The URGENCY Algorithm is one such model (Malliaris et al., 1997; Augenstein et al., 2001). These models emphasized the change in velocity or delta V of the vehicle that occurred as the result of the crash, but also include many other occupant and vehicle variables that can be obtained from a NASS-CDS or CIREN case. The current study used similar methods to those previously used to predict outcomes of case occupants in motor vehicle crashes. However, the current study aims to relate crash and occupant parameters to fatality and hospital outcomes. The hospital outcome data is available in CIREN, but not in NASS-CDS. The predictive model from CIREN alone can not be used to predict risks for the population at large. Therefore, the current study uses common inclusion criteria between CIREN and NASS-CDS cases to describe a population-based combined probability of the outcomes of interest.

Qualifying frontal crashes were used to complete the modeling of outcomes in the current study. These outcomes of interest include: 1. time in intensive care unit (ICU), 2. fatality, 3. ICU or fatality, 4. invasive surgery or operating room (OR) within 12 hours post crash, and 5. invasive surgery within 24 hours post crash.

METHODS

CIREN Case Analysis

The current study uses CIREN frontal crash data given the following inclusion criteria:

- Most severe event and damage from frontal collision
- PDOF of 11, 12 or 1 o'clock
- 1998+ vehicle model year
- MAIS 3+ injury cases
- Known WinSMASH (Sharma et al., 2007) delta V
- Known hospital outcomes (ICU, OR, etc.)
- Known seat belt use and airbag availability and deployment status. Unknown belt use, misused belts and cases with missing airbags were excluded
- One or fewer 25+ kph delta V events

Cases were limited to those with one or fewer 25+ kph delta V events. This limitation allowed for improved study of the association between a single frontal crash event and the resulting injury and hospital outcomes.

Two CIREN frontal crash data sets were produced. The first included all CIREN cases meeting the criteria above. The second included those where the case vehicle was equipped with an event data recorder (EDR). EDR cases did not require the existence of WinSMASH delta V, but did require a complete velocity-time history data set as obtained from the EDR for the crash event of interest. EDR cases judged to have incomplete velocity-time history data were not included in the current study. As noted previously by Niehoff et al. (2005), older models of General Motors (GM) vehicles collect between 100-150 ms of longitudinal delta V data for airbag deployment cases and in more recent model years 300 ms of longitudinal and lateral delta v data is recorded. Thus, only the longitudinal data was evaluated in the current study. Cases were limited to model year 2001+ EDR equipped vehicles from both GM and Ford Motor Company (Ford).

The aim of this study was to relate vehicle and occupant predictors to outcomes of interest. Fatality, ICU and OR were the outcomes studied. Evaluation of ICU and OR outcomes was restricted to non-fatal cases. However, a case could fall into more than one of the ICU and OR outcome categories.

This first step in assessing the relationship between the predictive variables and the outcomes studied involved completing χ^2 tests for each predictor to see if it was associated with the individual outcomes. Variables that were found to be significant at $p < 0.10$ were kept for later use in developing the multivariable probability models. Variables were grouped by vehicle and by occupant. Table 1 shows the list of predictors considered for the χ^2 tests. Many of the predictors are ones that could be collected through telemetry systems or at the crash site by the responding police or fire and rescue personnel. Others, however, would require assessment at the hospital or would come as the result of crash reconstruction. The aim of this study was the modeling of motor vehicle crash occupant outcomes using predictors that can be assessed through use of data collected via telemetry systems or those that can be assessed at the crash site by responding emergency personnel. Thus, the predictive models were limited to these variables. Though WinSMASH delta V is only obtained through crash reconstruction, it was used in the non-EDR data set of the current study as a surrogate for delta V that could be obtained via telemetry systems.

Table 1. Vehicle and occupant variables

Vehicle/Crash Predictors	Occupant Predictors
Entrapped[2]	GCS < 14[1,2]
Entrapped or No Exit[2]	GCS < 14, Tube or Sedated[1,2]
WinSMASH Longitudinal Delta V[4]	Respiration Rate < 10 or > 29[2]
WinSMASH Total Delta V[4]	Systolic Blood Pressure < 90[2]
EDR Longitudinal Delta V[1]	Triage Step 1[2]
EDR - Peak 30 ms Crash Pulse[1]	Triage Step 2[2]
EDR - Peak 50 ms Crash Pulse[1]	Triate Step 1 or 2[2]
EDR - Pre-impact Braking[1]	Triage Step 1 and 2[2]
EDR - Pre-impact Vehicle Speed[1]	BMI[3]
Barrier Equivalent Speed (BES)[4,5]	BMI Ranges[2]
PDOF[1,4]	Age[1,2]
Maximum Crush[4]	Age Ranges[1,2]
Crush Area[4]	Age > 65 Years[1,2]
Average Crush: C1 - C6[4]	Gender[1,2]
Vehicle Curb Weight[1]	Driver / Passenger[1,2]
Vehicle Curb Weight < 1500 kg[1,2]	Belt Use[1,2]
Vehicle Model Year[1]	
Certified Advanced Compliant[1]	
Airbag Deployment[1,2]	
Intrusion at Case Occupant[4]	
Intrusion - Any Position[4]	
Intrusion > 12" at Case Occupant[2]	
Intrusion > 18" in Any Position[2]	
Intrusion > 12" or > 18"[2]	

Notes:
1. Determined via telemetry systems / ACN
2. Determined at crash site or by EMS
3. Determined at hospital
4. Determined through crash investigation
5. BES described by Sharma et al. (2007)

Occupant-related predictors requiring further description include Step 1 (vital signs and consciousness) and Step 2 (anatomy of injury) of the ACS field triage decision scheme. Step 1 is positive if the Glasgow Coma Score (GCS) is less than 14, the respiration rate is less than 10 or greater than 29 or systolic blood pressure (SBP) is less than 90. Cases where the occupant was intubated or sedated were grouped separately and not considered as positive for GCS less than 14. Step 2 was positive if any of the following were true: 1. penetrating injuries to the head, neck, torso, and extremities proximal to the elbow and knee, 2. flail chest, 3. two or more proximal long bone fractures, 4. crushed, degloved or mangled extremity, 5. amputation proximal to the wrist or ankle, 6. pelvic fractures, 7. open or depressed skull fracture, or 8. paralysis. Body mass index or BMI was grouped by those occupants that had BMI less than 25, 25 – 30, 30 – 35, and greater than 35. Age was grouped as under 30 years of age, 30 – 65, and greater than 65 years of age.

On the vehicle side, maximum crush was recorded in the frontal event of interest. Average crush is the average of the crush at the six locations (C1 to C6) measured across the front of the vehicle. Crush area was defined as the product of average crush and vehicle end width. PDOF was separated into three groups; eleven, twelve and one o'clock. Intrusion was evaluated as a continuous variable for the peak values measured at the case occupant's position and for the peak value measured at any position in the vehicle. These values were also grouped by thresholds used in Step 3 of the ACS field triage decision scheme. The compliance status of the case vehicles was also evaluated based on the advanced airbag section of Federal Motor Vehicle Safety Standard No. 208 (NHTSA, 2007). Compliance status was defined as certified advanced compliant (CAC) or not CAC. Manufacturers did not begin certifying their vehicles as CAC until model year 2003.

Five EDR-based variables were assessed for EDR cases included in the current study (Table 1). Post-crash velocity-time history entries were used to calculate EDR longitudinal delta V. The velocity-time history data was also used to calculate a peak slope over both 30 and 50 ms windows. Pre-impact vehicle velocity and pre-impact braking were also collected from the EDR data when possible.

Modeling of the outcomes of interest using promising predictors ($p < 0.10$ from the χ^2 tests) was done next. First, stepwise regressions were done using only the vehicle- and crash-based predictors. Next, stepwise regression was done using only the occupant-based predictors. Finally, the overall predictive model for the individual outcome was created using stepwise regression that included the variables found to be significant in the respective vehicle- and occupant-based models. Backward and forward selection were also used to verify the results of the stepwise selection for the final model. The maximum p value allowed for entering and staying in the model was 0.10. Model fit was assessed using Hosmer and Lemeshow's Goodness-of-Fit test (Hosmer and Lemeshow, 2000). A value of $p > 0.10$ for the Hosmer and Lemeshow test signified an acceptable fit of the model.

NASS-CDS

NASS-CDS cases were queried with the same inclusion criteria used in selecting CIREN cases. The exception was that the NASS-CDS cases included all MAIS levels. The prevalence of MAIS injuries at all levels in CDS cases and the ability to produce a weighted population estimate of the data made it possible for the NASS-CDS query to provide a rate of MAIS 3+ injured case occupants given the inclusion criteria listed earlier for CIREN frontal cases. This rate or probability of experiencing a MAIS 3+ injury could be used in combination with the probability of outcomes modeled using the CIREN data to produce static models of combined probability. However, it was thought more appropriate to produce two unique predictive models for probability of MAIS 3+ injury in NASS-CDS frontal cases; one model for all qualifying model year 1998+ vehicle crash cases, one for model year 2001+ EDR cases. These two NASS-CDS models were then used in combination with the respective CIREN outcome models. The product of the NASS-CDS MAIS 3+ injury and CIREN hospital treatment models was taken to create a combined probability function that can be used to predict the likelihood of a treatment (ICU, OR) or fatality given a qualifying frontal crash.

RESULTS

For the first data set involving all CIREN cases, 482 frontal crash cases met the inclusion criteria. For the second data set involving only EDR equipped vehicles, there were 40 CIREN frontal crash cases that met the inclusion criteria. Though Ford cases were included in the sampling of EDR cases, only cases involving GM vehicles met the inclusion criteria. Of these 40 EDR cases, 33 had available WinSMASH delta V data and thus were cases that were also included in the overall set of 482 cases. The distribution of class variables for the 482 CIREN cases meeting the inclusion criteria are shown in Figures 1 and 2. Table 2 shows the mean and standard deviation for the various occupant-based continuous measures that were evaluated in the current study, grouped by all cases and by individual outcomes. Table 3 shows similar results for the vehicle-based variables.

Assessing Variable Significance

Wald χ^2 tests were completed to assess the significance of the individual predictor variables for each of the outcomes of interest. Tables A1 and A2 (see Appendix) show the Wald χ^2 values for predictors with $p < 0.10$ for CIREN frontal cases and CIREN frontal cases with EDR, respectively. Empty cells in the tables signify variables with $p > 0.10$. Variables were grouped into partitions related to vehicle crush or change in velocity, intrusion, vital signs, entrapment, age, position, belt use, gender, vehicle model year and curb weight.

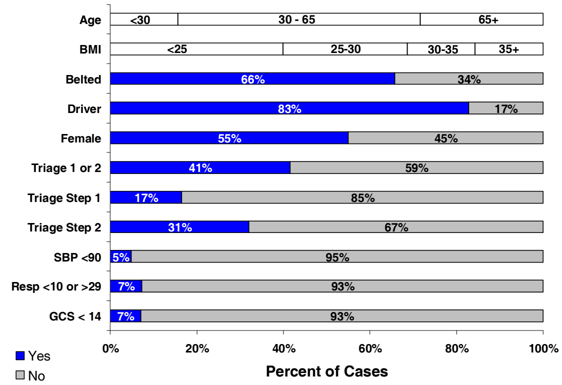

Figure 1. Distribution of occupant class variables

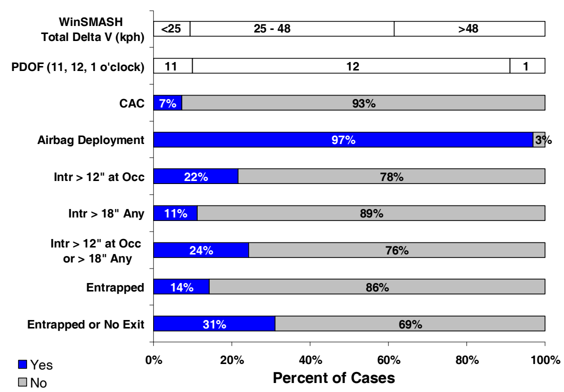

Figure 2. Distribution of vehicle class variables

Table 2. Average occupant measures for CIREN cases by outcome

				Age Yrs		BMI		MAIS		ISS		# of AIS 3+ Injuries		Total Injuries	
	Outcome	Group	N	Avg	SD	Avg	SD	Avg	SD	Avg	SD	Avg	SD	Avg	SD
All CIREN Frontals	All	NA	482	43.9	18.3	28.4	7.8	3.4	0.8	20.3	13.5	2.5	2.0	10.0	5.9
	ICU	No	304	42.0	16.6	28.5	8.2	3.1	0.4	15.0	6.7	1.8	1.1	8.1	4.0
		Yes	140	46.7	19.7	28.1	7.0	3.6	0.7	23.5	10.2	3.4	2.3	12.6	7.1
	Fatal or ICU	No	304	42.0	16.6	28.5	8.2	3.1	0.4	15.0	6.7	1.8	1.1	8.1	4.0
		Yes	178	47.1	20.6	28.4	7.2	3.9	1.0	29.2	17.1	3.8	2.5	13.2	7.2
	Fatal	No	444	43.5	17.8	28.3	7.9	3.3	0.6	17.7	8.9	2.3	1.7	9.5	5.6
		Yes	38	48.4	23.8	29.6	7.6	5.0	0.9	50.9	20.5	5.1	3.0	15.5	7.2
	OR < 12 hrs	No	230	45.7	18.7	27.8	7.9	3.2	0.5	17.2	8.2	2.1	1.4	8.9	4.7
		Yes	195	41.7	16.6	29.0	7.9	3.3	0.6	18.1	9.3	2.5	2.0	10.3	6.1
	OR < 24 hrs	No	151	47.8	19.6	28.3	8.8	3.3	0.5	17.5	7.9	1.9	1.2	8.6	4.3
		Yes	280	41.5	16.5	28.5	7.5	3.3	0.6	17.8	9.3	2.5	1.9	9.9	6.0
CIREN EDR Frontals	All	NA	40	49.8	19.7	28.2	7.1	3.5	0.8	20.7	12.0	2.7	1.8	9.8	5.3
	ICU	No	19	53.6	16.5	26.9	5.8	3.2	0.5	17.1	8.8	2.0	0.9	6.6	2.7
		Yes	19	46.0	20.8	29.6	8.5	3.5	0.8	22.3	13.1	3.0	1.9	12.4	5.3
	Fatal or ICU	No	19	53.6	16.5	26.9	5.8	3.2	0.5	17.1	8.8	2.0	0.9	6.6	2.7
		Yes	21	46.4	22.0	29.4	8.1	3.7	0.9	24.1	13.6	3.3	2.2	12.9	5.4
	Fatal	No	38	49.8	18.9	28.3	7.3	3.4	0.7	19.7	11.3	2.5	1.6	9.4	5.0
		Yes	2	49.8	42.7	27.5	2.2	5.0	0.0	40.5	3.5	6.0	4.2	20.0	.
	OR < 12 hrs	No	18	50.3	20.7	28.3	8.5	3.3	0.6	19.8	10.8	2.4	1.7	8.4	4.9
		Yes	20	49.3	17.7	28.3	6.3	3.4	0.8	19.6	12.1	2.6	1.5	10.4	5.2
	OR < 24 hrs	No	9	56.8	17.4	29.4	10.4	3.1	0.3	15.8	4.7	1.8	1.0	6.3	3.3
		Yes	28	47.4	19.4	27.9	6.4	3.5	0.7	21.3	12.6	2.8	1.6	10.7	5.2

Table 3. Average vehicle measures for CIREN cases by outcome

	Outcome	Group	N	BES		EDR Longitudinal Delta V (kph)		WinSMASH Total Delta V (kph)		WinSMASH Longitudinal Delta V (kph)		Intrusion Occupant Position (cm)		Intrusion Any Position (cm)		Max Crush (cm)		Crush Area (cm^2)		Average Crush C1 to C6 (cm)		Vehicle Model Year		Vehicle Curb Weight (kg)	
				Avg	SD	Avg	SD	Avg	SD	Avg	SD	Avg	SD	Avg	SD	Avg	SD	Avg	SD	Avg	SD	Avg	SD	Avg	SD
All CIREN Frontals	All	NA	482	43.8	17.4	-	-	45.5	17.3	44.5	17.4	16.3	16.9	21.5	19.1	65.7	29.6	5902	3233	37.6	20.2	2001.0	2.4	1465	319.2
	ICU	No	304	41.0	14.7	-	-	43.3	15.3	42.2	15.4	13.7	15.3	19.2	18.4	61.4	25.6	5353	2664	34.2	16.6	2000.9	2.4	1460	336.9
		Yes	140	47.2	19.7	-	-	48.1	19.5	47.4	19.4	21.4	18.9	25.9	19.7	71.1	31.2	6764	3818	42.3	23.6	2001.5	2.4	1494	294.1
	Fatal or ICU	No	304	41.0	14.7	-	-	43.3	15.3	42.2	15.4	13.7	15.3	19.2	18.4	61.4	25.6	5353	2664	34.2	16.6	2000.9	2.4	1460	336.9
		Yes	178	48.5	20.3	-	-	49.4	19.8	48.5	19.7	20.7	18.7	25.4	19.7	73.0	34.1	6870	3869	43.4	24.2	2001.2	2.4	1473	287.2
	Fatal	No	444	43.0	16.7	-	-	44.8	16.9	43.8	16.9	16.1	16.9	21.3	19.0	64.5	27.9	5791	3134	36.8	19.4	2001.1	2.4	1470	324.1
		Yes	38	53.3	22.2	-	-	53.9	20.7	52.6	20.6	18.1	17.8	23.8	19.6	79.9	42.9	7281	4089	47.7	26.4	2000.0	1.9	1398	249.1
	OR < 12 hrs	No	230	42.3	16.8	-	-	44.3	17.2	43.5	17.2	14.3	16.2	20.5	19.1	64.4	29.5	5642	3001	35.6	18.5	2001.2	2.4	1492	345.8
		Yes	195	43.6	16.6	-	-	45.4	16.4	44.3	16.5	18.5	17.9	22.5	19.3	64.2	26.3	5994	3295	38.1	20.3	2001.0	2.3	1455	304.9
	OR < 24 hrs	No	151	40.4	17.0	-	-	42.4	17.1	41.5	17.1	11.7	14.9	17.9	17.9	61.1	30.5	5346	3071	33.2	18.7	2001.3	2.4	1490	329.8
		Yes	280	44.4	16.2	-	-	46.2	16.5	45.2	16.6	18.3	16.8	22.7	18.8	66.7	26.2	6079	3146	38.9	19.6	2001.0	2.4	1465	323.8
CIREN EDR Frontals	All	NA	40	45.8	17.8	53.4	14.6	46.6	19.1	45.7	19.0	18.6	16.7	23.8	16.7	69.6	28.1	6115	3424	38.8	20.7	2002.8	1.6	1521	345.5
	ICU	No	19	39.7	14.9	46.2	9.2	40.4	17.4	39.5	17.3	11.6	14.8	17.1	15.2	67.3	27.0	5433	2620	34.9	15.7	2002.6	1.8	1564	366.8
		Yes	19	54.4	17.8	59.4	16.1	55.1	18.3	54.1	18.1	27.0	15.4	32.6	14.2	74.7	29.3	7112	3996	44.7	24.2	2002.9	1.5	1499	340.8
	Fatal or ICU	No	19	39.7	14.9	46.2	9.2	40.4	17.4	39.5	17.3	11.6	14.8	17.1	15.2	67.3	27.0	5433	2620	34.9	15.7	2002.6	1.8	1564	366.8
		Yes	21	52.7	18.6	59.9	15.7	53.2	19.2	52.3	19.0	24.8	16.1	29.9	15.9	71.6	29.6	6732	3980	42.3	24.2	2003.0	1.4	1483	329.2
	Fatal	No	38	46.4	17.7	52.8	14.5	47.3	19.0	46.3	18.9	19.3	16.8	24.8	16.5	71.0	28.0	6272	3440	39.8	20.7	2002.7	1.6	1531	350.8
		Yes	2	25.0	.	65.0	16.1	25.0	.	25.0	.	4.5	3.5	4.5	3.5	42.0	11.3	3122	676	19.6	0.6	2004.0	0.0	1329	157.0
	OR < 12 hrs	No	18	43.9	14.0	47.4	11.6	44.6	15.2	43.8	15.1	16.2	17.1	22.8	17.3	70.9	27.1	5949	2945	38.5	18.4	2002.2	1.2	1449	321.6
		Yes	20	48.7	20.7	57.6	15.4	50.0	22.4	48.9	22.3	22.1	16.4	26.6	15.9	71.2	29.6	6563	3885	41.0	23.1	2003.2	1.8	1605	367.3
	OR < 24 hrs	No	9	38.9	13.4	41.4	7.9	37.9	15.7	37.1	15.1	12.3	13.9	17.4	15.4	63.9	29.3	5010	3205	32.1	18.9	2002.2	1.4	1534	399.0
		Yes	28	48.0	18.5	56.4	14.6	49.8	19.4	48.7	19.4	22.1	17.2	27.6	16.4	73.3	28.3	6619	3524	41.9	21.3	2002.9	1.7	1547	336.4

There are a number of significant observations that can be made in looking at the relationships between single variables and the outcomes studied for the full set of qualifying CIREN frontal cases (Appendix - Table A1). First, delta V, whether total or longitudinal, is consistently a significant predictor of outcome. The only exception is for those with invasive surgery within 12 hours of the crash. Post-test crush measures such as peak crush, average crush, and crush area were generally even more significantly associated with the outcomes studied than delta V measures, as evidenced by higher χ^2 values for the crush measures. However, these measures may not be appropriate for on-site triage and are not available for measure through telemetry, but instead require crash reconstruction to be calculated. Thus, these crush-based variables were not included in the predictive models. The field triage decision scheme Step 1 and Step 2 measures were also consistently strong predictors, with at least one being significantly related to each of the outcomes. It was also noteworthy that intrusion at the case occupant position was always a better predictor of outcome than peak intrusion at any position in the vehicle. Step 3 of the triage decision scheme assesses whether intrusion is greater than 12 inches at the occupant position or 18 inches at any position. However, independently the 18 inches threshold for any position was not significant at $p < 0.05$ for any outcome, while the 12 inch threshold at the occupant position was significantly related ($p < 0.05$) to all outcomes other than fatality.

The CIREN EDR cases saw many fewer significant variables (Appendix - Table A2). For instance, Triage Step 1 was not significant for any outcomes and Step 2 was only significant for two outcomes. The small number of qualifying EDR cases (n=40) available is likely the cause. It was noteworthy that EDR longitudinal delta V was shown to be a stronger predictor of outcome than WinSMASH longitudinal delta V, WinSMASH total delta V and barrier equivalent speed when comparing χ^2 values. Other EDR-based variables also were significant for certain outcomes including crash pulse severity measures and pre-impact braking. Of note, pre-impact braking was significant for a reduced probability of going to the ICU. Pre-impact velocity was not found to be significant for any outcome. Regression analyses related to fatality were not done on the EDR data set given only two fatal cases out of the 40 EDR cases included in the study.

Those variables with the highest Wald χ^2 value were selected for use in the predictive modeling for the outcomes of interest as described in the next section. For instance, there were many cases for the respective outcomes in which total delta V and longitudinal delta V were both significant predictors. For these instances, the predictor with the maximum χ^2 value was used. There were also cases where a predictor such as crush area or average crush had a larger χ^2 value than delta V or max crush. However, as noted earlier, the emphasis of the current study was to produce models with predictors that can be assessed at the crash scene or via telemetry.

Predictive Modeling – All CIREN Cases (n=482)

Stepwise regressions were done in combination with forward and backward selection of variables to establish models of treatment given injury. The threshold for both entering and staying in the model was $p < 0.10$. Table 4 shows the results for the final models produced for each of the five groupings of outcomes of interest. The significant predictors and their respective maximum likelihood estimates, Wald χ^2, p values, point estimates and 95% confidence intervals are shown. The Hosmer and Lemeshow Goodness-of-Fit tests found good fit for all models with p values greater than 0.1 in all cases.

Most variables were directionally associated with the outcomes of interest as would be considered logical. Delta V, intrusion and the field triage decision scheme vital sign (Step 1) and injury (Step 2) measures all were consistent in that, when significant, they were associated with an increased likelihood of the outcomes studied. In contrast, seat belt use was associated with a lower probability of the respective outcomes when it was a significant predictor. One exception was the over-65 age group. This group predicts an increase in probability of fatality, but a reduced probability of OR. Of all injured body regions, OR was most significantly associated with lower extremity injuries ($\chi^2 = 21.5$, $p < 0.0001$), but was also significant for not having AIS 3+ spine injuries ($\chi^2 = 8.8$, $p < 0.01$). Conversely, spine injuries were found to be significantly associated with being over 65 ($\chi^2 = 20.6$, $p < 0.0001$) while lower extremity injuries were found to be significantly associated with those under age 65 ($\chi^2 = 5.4$, $p < 0.05$). While it is not possible to assess injury probability or risk in CIREN, these relationships within the injured population help explain why the elderly group was less and not more likely to have invasive surgery within 24 hours of a crash. A reduced ability of the older population to endure invasive surgery soon after a traumatic event may also contribute to a lower probability of OR within 24 hours for the elderly population.

The models provide the maximum likelihood estimates for the intercept (Q_i) and for the significant predictors (Q_1, $Q_2 \ldots Q_n$) that can be used to predict the probability (P_{CIREN}) of the outcome of interest per the following equations. X_1 to X_n would represent the values for the respective predictors for a given case.

$$P_{CIREN} = \frac{1}{(1+e^{-L})} \qquad (1)$$

$$L = Q_i + Q_1 X_1 + Q_2 X_2 \ldots . Q_n X_n \qquad (2)$$

Table 4. Model results for all qualifying CIREN frontal cases

Outcome	Predictor	Predictor Values[1]	-2 Log L	Maximum Likelihood Estimate	Wald $\chi2$	Pr > $\chi2$	Odds Ratio [95% CI]	Model Fit[2]
ICU	Intercept		463.9	-283.000	8.451	0.0036	NA	0.7719
	Intrusion > 12" at Occ.	1=yes, 0=no		-0.477	12.080	0.0005	0.385 [0.225 - 0.660]	
	Vehicle Model Year	Continuous		0.141	8.404	0.0037	1.151 [1.047 - 1.267]	
	Occ. Age - Years	Continuous		0.023	12.279	0.0005	1.023 [1.010 - 1.036]	
	Triage Step 1	1=yes, 0=no		-1.031	41.819	< 0.0001	0.127 [0.068 - 0.238]	
	Triage Step 2	1=yes, 0=no		-0.292	5.671	0.0173	0.558 [0.345 - 0.902]	
ICU or Fatal	Intercept		498.3	-1.703	12.031	0.0005	NA	0.8772
	Longitudinal Delta V (KPH)	Continuous		0.020	8.238	0.0041	1.020 [1.006 - 1.034]	
	Intrusion > 12" at Occ.	1=yes, 0=no		-0.307	4.885	0.0271	0.541 [0.314 - 0.933]	
	Occ. Age - Years	Continuous		0.026	16.676	< 0.0001	1.026 [1.013 - 1.039]	
	Triage Step 1	1=yes, 0=no		-1.056	47.553	< 0.0001	0.121 [0.066 - 0.220]	
	Triage Step 2	1=yes, 0=no		-0.287	5.985	0.0144	0.564 [0.356 - 0.892]	
Fatal	Intercept		116.6	-4.848	22.616	< 0.0001	NA	0.9319
	Total Delta V (KPH)	Continuous		0.032	3.964	0.0465	1.033 [1.000 - 1.066]	
	Entrapped or No Exit	1=yes, 0=no		1.095	4.111	0.0426	8.941 [1.076 - 74.307]	
	Age > 65 Years	1=yes, 0=no		-0.698	4.937	0.0263	0.247 [0.072 - 0.848]	
	Belted	1=yes, 0=no		1.380	16.649	< 0.0001	15.812 [4.198 - 59.553]	
	Triage Step 1	1=yes, 0=no		-0.996	14.715	0.0001	0.136 [0.049 - 0.377]	
OR within 12 hrs	Intercept		562.3	-2.154	1.061	0.3030	NA	0.7116
	Age > 65 Years	1=yes, 0=no		0.294	3.856	0.0496	1.801 [1.001 - 3.242]	
	Occ. Position	Driver=1, Pssgr=0		-2.632	3.541	0.0599	.0591 [0.341 - 1.022]	
	Triage Step 1	1=yes, 0=no		-0.244	2.798	0.0944	0.614 [0.346 - 1.087]	
	Curb Wt < 1500 kg	1=yes, 0=no		-0.190	3.333	0.0679	0.684 [0.454 - 1.028]	
	Entrapped or No Exit	1=yes, 0=no		-0.211	3.505	0.0612	0.656 [0.422 - 1.020]	
	Intrusion > 12" at Occ.	1=yes, 0=no		-0.222	2.859	0.0908	0.383 [0.383 - 1.073]	
OR within 24 hrs	Intercept		515.6	0.802	17.064	< 0.0001	NA	0.9398
	Age > 65 Years	1=yes, 0=no		0.405	7.959	0.0048	2.246 [1.280 - 3.941]	
	Triage Step 2	1=yes, 0=no		-0.254	4.291	0.0383	0.602 [0.372 - 0.973]	
	Curb Wt < 1500 kg	1=yes, 0=no		-0.285	6.808	0.0091	0.565 [0.368 - 0.868]	
	Entrapped or No Exit	1=yes, 0=no		-0.312	6.313	0.0120	0.536 [0.330 - 0.872]	
	Intrusion > 12" at Occ.	1=yes, 0=no		-0.416	6.981	0.0082	0.435 [0.235 - 0.807]	

Notes:
1. All class level predictors modeled as 0 vs. 1.
2. Hosmer and Lemeshow Goodness-of-Fit: Pr > $\chi2$

Predictive Modeling – CIREN EDR Cases (n=40)

Stepwise regressions were also done for the 40 EDR cases using the significant variables documented in Table 5. Only two significant multi-variable models were produced using the EDR data. EDR delta V was positively associated with an increase probability of seeing all outcomes studied. Only the ICU and ICU or fatal models included additional significant ($p < 0.10$) predictors other than EDR delta V after completing stepwise, backward and forward selections. A model was not created for fatal cases given there were only two fatal cases in the EDR data set.

NASS-CDS

Given the same inclusion criteria as used in collecting CIREN frontal cases for the current study, a population-based estimate of the rate of MAIS 3+ injury for all qualifying model year 1998+ vehicles was found to be 2.1%. The same estimate for model year 2001+ GM vehicles, which corresponds to the cases included in the CIREN EDR analysis, was found to be 2.2%. Regression analysis produced two models, one for all qualifying 1998+ model year vehicles and one for 2001+ model year EDR equipped GM vehicles (Table 6). These models predict the probability of MAIS 3+ injury given the frontal crash inclusion criteria used. They can be used in combination with the CIREN-based models to produce a combined probability for the outcomes evaluated in the current study.

Combined Probability Models

A population-based probability of outcomes of interest given a frontal crash meeting the inclusion criteria of the current study can be formulated as the product of the risk of sustaining an MAIS 3+ injury (P_{CDS}) as established from the NASS-CDS data and the probability of outcome ($P_{CIR.EN} = P(ICU|MAIS3+)$). The formula (A1) and sample calculation for probability of MAIS 3+ injury (A2) and ICU given MAIS 3+ injury (A3) are located in the appendix.

Table 5. Model results for all qualifying CIREN EDR frontal cases

Outcome	Predictor	Predictor Values	-2 Log L	Maximum Likelihood Estimate	Wald $\chi2$	Pr > $\chi2$	Odds Ratio [95% CI]	Model Fit[1]
ICU	Intercept		28.6	-5.123	4.241	0.0395	NA	0.8768
	Intrusion > 12" at Occ	1=yes, 0=no		-1.043	3.938	0.0472	0.124 [0.016 - 0.975]	
	Triage Step 1	1=yes, 0=no		-1.582	7.103	0.0077	0.042 [0.004 - 0.433]	
	EDR Delta V (KPH)	Continuous		0.107	5.173	0.0229	1.113 [1.015 - 1.221]	
ICU or Fatal	Intercept		15.5	-14.688	5.277	0.0216	NA	0.7692
	EDR Delta V (KPH)	Continuous		0.320	5.427	0.0198	1.377 [1.052 - 1.801]	
	Pre-impact Braking	1=yes, 0=no		2.243	3.872	0.0491	88.827 [1.018 - >999.999]	
	Triage Step 2	1=yes, 0=no		-3.033	5.564	0.0183	0.002 [<0.001 - 0.359]	

Notes:
1. Hosmer and Lemeshow Goodness-of-Fit: Pr > $\chi2$

Table 6. Model results for MAIS 3+ injury in NASS-CDS frontal cases

	Outcome	Predictor	Predictor Values	-2 Log L	Maximum Likelihood Estimate	Wald $\chi2$	Pr > $\chi2$	Odds Ratio [95% CI]
All 1998+ Vehicles	MAIS 3+	Intercept		470193.1	-7.383	505.226	< 0.0001	NA
		Age	Continuous		0.031	27.474	< 0.0001	1.032 [1.020 - 1.044]
		Delta V (MPH)	Continuous		0.158	323.608	< 0.0001	1.171 [1.151 - 1.191]
		Airbag deployed , not belted	1=yes, 0=no		1.044	29.269	< 0.0001	2.841 [1.946 - 4.147]
		Belted, no airbag deployment	1=yes, 0=no		0.981	1.857	0.1730	2.668 [0.650 - 10.948]
		Gender	1=male, 0=female		-0.536	15.423	< 0.001	0.585 [0.448 - 0.764]
All 2001+ GM EDR Vehicles	MAIS 3+	Intercept		49098.2	-540.300	5.647	0.0194	NA
		Age	Continuous		0.023	6.592	0.0102	1.024 [1.006 - 1.042]
		Delta V (MPH)	Continuous		0.181	39.042	< 0.0001	1.198 [1.132 - 1.268]
		Model Year	Continuous		0.266	5.326	0.0210	1.305 [1.041 - 1.635]
		Airbag deployed , not belted	1=yes, 0=no		1.499	13.677	0.0002	4.475 [2.023 - 9.903]
		Belted, no airbag deployment	1=yes, 0=no		-31.080	135.690	< 0.0001	<0.001 [<0.001 - <0.001]
		PDOF - 1 o'clock	1=yes, 0=no		-2.375	14.023	0.0002	0.093 [0.027 - 0.322]
		PDOF - 11 o'clock	1=yes, 0=no		-0.386	1.199	0.2735	0.680 [0.341 - 1.356]
		Gender	1=male, 0=female		-0.937	7.172	0.0074	0.392 [0.197 - 0.778]

CONCLUSIONS

This study shows an example in which NASS-CDS and CIREN data sets can be used together to project probability of certain outcomes in frontal crashes. The CIREN data analysis of all qualifying frontal cases produced models using numerous vehicle- and occupant-based variables and for all outcomes of interest showed good model fit as evaluated using the Hosmer and Lemeshow Goodness-of-Fit test. All of the models included at least two occupant and two vehicle or crash-based variables. Modeling of EDR cases, where fewer cases where available, produced models for two of five outcomes studied.

Many typical factors generally thought to be positively associated with severity of injury such as delta V and intrusion proved to consistently be related to the treatment and injury outcomes evaluated in the current study. Additionally, measures currently used in the ACS field triage decision scheme related to vital signs and injury also proved to be significant predictors. There were exceptions where factors that may logically be thought to produce a positive relationship related to the treatment outcome in fact had a negative outcome. The prime example was age and invasive surgery where being over 65 years old reduced the likelihood of a case occupant needing invasive surgery in the first 12 or 24 hours following a crash. This exception could be explained in either of two ways. First, the older population tends to sustain more spinal injuries and fewer lower extremity injuries, compared to younger patients. However, the majority of injuries treated in the OR are lower-extremity injuries. Second, older occupants may require a greater period of time to stabilize before invasive surgery.

EDR delta V was shown in the 40 cases studied to be significantly associated with outcome. The 30 and 50 ms pulse evaluations were also significant predictors of outcome, but in no instance were they better than EDR delta V. The 50 ms window is associated with the acceleration severity index (CEN, 1998), which was also not found to be a better predictor of injury as compared to delta V by Gabauer and Gabler (2007). In single predictor logistic regressions, EDR delta V was a better predictor of the outcomes studied than WinSMASH delta V. However, both WinSMASH- and EDR-based delta V were shown to be significant predictors of motor vehicle crash occupant outcome. Future study with a larger data set of EDR cases should be done to further assess the predictive performance of all EDR-based variables including delta V, braking and pre-impact speed.

Prior studies have proposed the need to combine telematics data from ACN systems with the URGENCY Algorithm for improving the emergency response for potentially seriously injured motor vehicle crash victims (Augenstein et al., 2001; Augenstein et al., 2003; Augenstein et al., 2005; Augenstein et al., 2006; Augenstein et al., 2007; Champion et al., 2003; Champion et al., 2005). The URGENCY Algorithm predicts a probability of MAIS 3+ injury for motor vehicle crash victims through the application of regression models developed using various vehicle, crash and occupant data. The current study has shown that similar techniques can be used to combine a probability of MAIS 3+ injury with the probability of invasive surgery within 12 or 24 hours, time spent in ICU or fatality. However, unlike the URGENCY Algorithm, the CDS-based models produced in the current study were limited to frontal crashes.

Study Limitations

Study limitations include the fact that only frontal cases involving 1998+ model year vehicles were included in the analysis qualifying CIREN cases. Similar methods of producing models combining the probabilities of MAIS 3+ injury in CDS with probabilities for outcome in CIREN could be done for other crash modes and groupings of vehicle model years. The majority of AIS 3+ injuries occur in frontal crashes, making analysis of this crash type a good starting point. While the model year 1998 break point was chosen to coincide with second generation or depowered frontal airbags and to allow for sufficient quantity of cases for analysis.

This study was also limited in that only 36 of 482 cases analyzed were for vehicles that were certified to the advanced airbag requirements of FMVSS No. 208 (NHTSA, 2007). Thus the relationships between crash and occupant variables and outcome presented here may not extend to new CAC vehicles. Manufacturers did not begin certifying their vehicles as CAC until the 2003 model year. The average model year evaluated in the current study was 2001±2.4.

In addition to differences in FMVSS No. 208 compliance, there are other differences in vehicle content that would differentiate the average vehicle in this study from the average vehicle available new for purchase today. The Insurance Institute for Highway Safety (IIHS) provides another example of how different a model year 2001 vehicle may be versus a current vehicle. Brumbelow (2007) showed that only 50% of 2001 model year vehicles tested were "good" performers in the IIHS's frontal offset crash condition, whereas, over 90% of tested model year 2007 vehicles were considered "good" performers. So, one possible difference between earlier model vehicles that did not rate as "good" in IIHS evaluations versus current models that do is that earlier vehicles could be expected on average to have greater intrusion into the occupant compartment and a "softer" crash pulse as compared to a similarly sized "good" performing vehicle. This could translate to a different distribution of injuries for newer vehicles that would have less intrusion into the occupant compartment, but possibly a "stiffer" crash pulse.

The CIREN MAIS 3+ injury cases used in the current study may have a different distribution of vehicle/crash and occupant variables than a set of NASS-CDS MAIS 3+ injury cases obtained using the same vehicle- and crash-based inclusion criteria. For starters, all CIREN case occupants went to a level I trauma center. Thus, on average, the ISS, MAIS, and crash measures such as delta V are likely to be higher in CIREN than NASS-CDS. However, there is no reason to believe that CIREN would be biased in a way that would alter the relationships between outcomes of interest and the significant predictors documented in the current study.

Future Study

Although the models produced show good fit based on statistical measures, future work will be required to assess the sensitivity and specificity of the respective models. Receiver operating characteristic (ROC) curves will be produced for this purpose. Future work should also compare the NASS-CDS-based models for predicting probability of MAIS 3+ injury from the current study versus those of the URGENCY Algorithm. The URGENCY Algorithm comprehends multiple impact directions. Thus, direct comparison of the predictive capabilities of URGENCY Algorithm versus the current CDS-based models may not be appropriate given the restrictions on case types used in the current study per the inclusion criteria. However, the methods used in the current study could be expanded to produce combined probability models for multiple impact scenarios (front, side, rear and/or rollover, e.g.).

Future work could also involve improved grouping or filtering of outcomes. This could include filtering of outcomes by the occurrence of more serious or compelling Abbreviated Injury Scale (AIS) 3+ injuries to further improve the predictive capability of the models by refining the relationships between the types of injuries sustained and the possible vehicle and occupant predictors. For instance, CIREN data provides additional detail beyond the AIS coding to document whether an AIS 3 long bone fracture was open or closed or whether an AIS 3+ internal organ or vessel injury required invasive surgery. Looking at the relationship between occupant and vehicle/crash predictors and these more compelling injuries may provide additional insight into the predictors that could be used in the triage of motor vehicle crash victims. Additionally, there may be other significant predictors or means by which to refine or re-group the predictors from the current study to further improve the predictive capabilities of the individual models.

The current study has modeled and found significant many of the variables used in the ACS field triage decision scheme. However, related to telemetry data field in Step 3 of the field triage decision scheme, future study of EDR cases in CIREN would require a larger set of data to better study the relationship between the outcomes of interest from the current study and EDR variables such as delta V, 50 ms crash pulse, pre-impact braking, and pre-impact vehicle speed.

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APPENDIX

Table A1. Results of binary logistic regression tests for all CIREN cases

		Data Source				Occupant Outcome									
						ICU		Fatal		ICU or Fatal		OR < 12 hrs		OR < 24 hrs	
	Variable	ACN	Crash Site / EMS	Hospital	Crash Investigation	χ^2	p	χ^2	p	χ^2	p	χ^2	p	χ^2	p
Vehicle & Crash Data	Entrapped		x			3.1	0.0780	-	-	-	-	3.0	0.0843	-	-
	Entrapped or No Exit		x			4.0	0.0462	3.9	0.0488	-	-	6.3	0.0118	10.9	0.0009
	WinSMASH Long. Delta V				x	8.7	0.0032	8.5	0.0035	14.1	0.0002	-	-	4.6	0.0325
	WinSMASH Total Delta V				x	7.8	0.0052	9.2	0.0024	13.3	0.0003	-	-	5.1	0.0244
	BES				x	12.6	0.0004	11.6	0.0007	19.5	< 0.0001	-	-	5.7	0.0166
	PDOF	x			x	-	-	-	-	-	-	-	-	-	-
	Maximum Crush				x	11.2	0.0008	8.8	0.0030	16.1	< 0.0001	-	-	4.0	0.0451
	Crush Area				x	17.8	< 0.0001	6.7	0.0098	22.2	< 0.0001	-	-	5.2	0.0225
	Average Crush: C1 - C6				x	15.9	< 0.0001	9.5	0.0021	21.8	< 0.0001	-	-	8.3	0.0039
	Vehicle Curb Wt	x				-	-	-	-	-	-	-	-	-	-
	Vehicle Curb Wt < 1500 kg	x	x			-	-	-	-	-	-	2.9	0.0898	5.0	0.0261
	Vehicle Model Year	x				5.3	0.0210	7.3	0.0070	-	-	-	-	-	-
	CAC[1]	x				-	-	ID[1]	ID[1]	-	-	-	-	-	-
	Airbag Deployment[2]	x				-	-	ID[2]	ID[2]	-	-	-	-	-	-
	Intrusion at Case Occupant				x	18.8	< 0.0001	-	-	18.4	< 0.0001	6.0	0.0140	15.2	< 0.0001
	Intrusion - Any Position				x	11.3	0.0008	-	-	11.5	0.0007	-	-	6.5	0.0111
	Intrusion > 12" at Case Occ		x			17.6	< 0.0001	-	-	19.4	< 0.0001	7.0	0.0081	13.0	0.0003
	Intrsusion > 18" in Any Position		x			3.2	0.0730	-	-	3.2	0.0721	-	-	-	-
	Intr. > 12" at Occ or > 18" Any		x			13.7	0.0002	3.4	0.0634	16.6	< 0.0001	6.4	0.0112	13.0	0.0003
Occupant Data	GCS < 14	x	x			20.6	< 0.0001	23.5	< 0.0001	23.8	< 0.0001	-	-	-	-
	GCS < 14, Tubed or Sedated	x	x			41.9	< 0.0001	35.8	< 0.0001	53.1	< 0.0001	-	-	-	-
	Respiration Rate <10 or >29		x			2.8	0.0959	11.6	0.0007	6.3	0.0122	4.6	0.0321	-	-
	Systolic Blood Pressure < 90		x			15.8	<0.001	5.9	0.0153	17.5	< 0.0001	2.9	0.0877	-	-
	Triage Step 1		x			44.7	< 0.0001	17.8	< 0.0001	53.7	< 0.0001	4.2	0.0406	-	-
	Triage Step 2		x			8.8	0.0031	-	-	10.8	0.0010	3.1	0.0799	7.9	0.0050
	Triage Step 1 or 2		x			25.4	< 0.0001	7.5	0.0061	32.3	< 0.0001	3.9	0.0487	5.0	0.0249
	Triage Step 1 and 2		x			20.0	< 0.0001	4.2	0.0398	20.3	< 0.0001	6.0	0.0141	4.1	0.0435
	BMI			x		-	-	-	-	-	-	-	-	-	-
	BMI Ranges	x	x			-	-	-	-	-	-	3.4	0.0652	-	-
	Age	x	x			6.7	0.0097	-	-	8.5	0.0036	5.2	0.0229	12.1	0.0005
	Age Ranges	x	x			-	-	6.5	0.0105	3.2	0.0738	4.1	0.0442	13.5	0.0012
	Age > 65 Years	x	x			5.1	0.0244	5.3	0.0209	8.4	0.0037	3.6	0.0588	12.2	0.0005
	Gender	x	x			-	-	3.9	0.0486	-	-	-	-	-	-
	Driver / Passenger	x	x			-	-	-	-	-	-	3.9	0.0496	-	-
	Belt Use	x	x			-	-	18.4	< 0.0001	-	-	-	-	-	-

Notes:
1. Only two fatals on certified advanced compliant (CAC) vehicles
2. Only 15 non-deployments in 482 cases. This resulted in quasi-complete separate in some analyses.

Table A2. Results of binary logistic regression tests for CIREN EDR cases

		Data Source				Occupant Outcome							
						ICU		ICU or Fatal		OR < 12 hrs		OR < 24 hrs	
	Variable	ACN	Crash Site / EMS	Hospital	Crash Investigation	$\chi2$	p	$\chi2$	p	$\chi2$	p	$\chi2$	p
Vehicle & Crash Data	Entrapped		x			-	-	-	-	-	-	-	-
	Entrapped or No Exit		x			3.2	0.0742	-	-	-	-	-	-
	EDR - Long. Delta V	x				6.4	0.0112	6.1	0.0135	3.2	0.0730	3.7	0.0545
	EDR - 30 ms pulse	x				4.0	0.0463	-	-	-	-	-	-
	EDR - 50 ms pulse	x				4.8	0.0282	3.2	0.0748	-	-	-	-
	EDR - Avg Decel Gs	x				4.9	0.0267	5.5	0.0194	-	-	3.2	0.0745
	EDR - Pre-Impact Veh Speed	x				-	-	-	-	-	-	-	-
	EDR - Pre-Impact Braking	x				3.5	0.0627	4.0	0.0445	-	-	-	-
	WinSMASH Long. Delta V				x	4.3	0.0384	3.5	0.0621	-	-	2.8	0.0932
	WinSMASH Total Delta V				x	4.3	0.0376	3.5	0.0623	-	-	2.9	0.0870
	BES				x	5.3	0.0219	4.4	0.0370	-	-	-	-
	PDOF	x			x	-	-	-	-	-	-	-	-
	Maximum Crush				x	-	-	-	-	-	-	-	-
	Crush Area				x	-	-	-	-	-	-	-	-
	Average Crush: C1 - C6				x	-	-	-	-	-	-	-	-
	Vehicle Curb Wt	x				-	-	-	-	-	-	-	-
	Vehicle Curb Wt < 1500 kg	x	x			-	-	-	-	-	-	-	-
	Intrusion at Case Occupant		x			7.1	0.0077	5.8	0.0163	-	-	3.3	0.0698
	Intrusion - Any Position				x	7.4	0.0064	5.5	0.0188	-	-	4.1	0.0431
	Intrusion > 12" at Case Occupant		x			6.5	0.0109	5.3	0.0209	-	-	3.7	0.0528
	Intrsusion > 18" in Any Position		x			-	-	-	-	-	-	-	-
	Intr. > 12" at Occ or > 18" Any		x			7.9	0.0050	6.5	0.0107	-	-	4.3	0.0389
Occupant Data	GCS < 14	x	x			-	-	-	-	-	-	-	-
	GCS < 14, Tubed or Sedated	x	x			-	-	-	-	-	-	-	-
	Respiration Rate <10 or >29		x			-	-	-	-	-	-	-	-
	Systolic Blood Pressure < 90		x			-	-	-	-	-	-	-	-
	Triage Step 1		x			-	-	-	-	-	-	-	-
	Triage Step 2		x			3.9	0.0495	3.0	0.0852	-	-	-	-
	Triage Step 1 or 2		x			-	-	-	-	-	-	-	-
	Triage Step 1 and 2		x			-	-	-	-	-	-	-	-
	BMI			x		-	-	-	-	-	-	-	-
	BMI Range	x	x			-	-	-	-	-	-	-	-
	Age	x	x			-	-	-	-	-	-	-	-
	Age Ranges	x	x			-	-	-	-	-	-	-	-
	Age > 65 Years	x	x			-	-	-	-	-	-	-	-
	Gender	x	x			-	-	-	-	-	-	-	-
	Driver / Passenger	x	x			-	-	-	-	-	-	-	-
	Belt Use	x	x			-	-	-	-	2.9	0.0863	3.0	0.0854

Combined Probability Equations:

$$P(ICU) = P(AIS3+) * P(ICU \mid AIS3+) \qquad \text{(A1)}$$

$$P(AIS3+) = \frac{1}{(1+\exp^{-(-7.383+0.031*X_1+0.158*X_2+1.044*X_3+0.981*X_4-0.536*X_5)})} \qquad \text{(A2)}$$

Where X_1 to X_5 represent the respective predictors as ordered in Table 6.

$$P(ICU \mid AIS3+) = \frac{1}{(1+\exp^{-(-283.0-0.477*X_1+0.141*X_2+0.023*X_3-1.031*X_4-0.292*X_5)})} \qquad \text{(A3)}$$

Where X_1 to X_5 represent the respective predictors as ordered in Table 4.