Development of a safety impact estimation tool for advanced safety technologies

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ABSTRACT

In order to develop and deploy advanced safety technologies, it is important to estimate effectiveness based on the system function or performance. Although various types of safety impact methodology (SIM) have been proposed to date, few SIMs can be applicable for actual system effectiveness estimation. In this study, a universal SIM (T-SIM) was developed and its validity was confirmed against field data. T-SIM uses the number of fatalities and casualties (fatal and nonfatal injury) that are expected to be prevented by the technologies rather than just collision/avoidance ratio because some of the safety technologies, such as a collision mitigation system, can reduce the impact speed by brake application and thus may help reduce the number of fatalities and casualties. T-SIM consists of two parts: (1) accident pattern classification and (2) effectiveness estimation for each system. In the first part of the T-SIM, accident data from the National Automotive Sampling System - General Estimates System (NASS-GES) and Fatality Analysis Reporting System (FARS) were categorized by such variables as type of accident (e.g., head-on) and relation to the intersection. The categorized accident patterns enable users to choose the accidents for which the technologies may be effective. By using the same accident pattern database, users also can compare the effectiveness of different safety systems. In the second part of the T-SIM, accident patterns applicable to a particular safety system are selected from the categorized patterns. A driver-model and a vehicle-model can be applied, which allows users to examine the effect of system parameters and configurations. Through the validation process using a Electronic Stability Control (ESC) system as an example of advanced safety technologies, the estimated effectiveness by T-SIM was compared with that reported by a study based on field data [2]. Although the accident databases are different, statistical analysis showed the effectiveness estimated by T-SIM is not significantly different from that by the field study and it was confirmed that the T-SIM can be used to estimate the effectiveness of other advanced safety technologies. Then the T-SIM was applied for a Pre-Collision System for the effectiveness estimation and further improvement. It was estimated that a PCS has high potential for reducing fatalities and casualties of rear-end accidents. In addition, it was also estimated that the PCS could be improved by changing such system parameters as warning, brake-assist and automatic brake timings.

INTRODUCTION

Various kinds of safety technologies such as Electronic Stability Control (ESC) system and Pre-Collision System (PCS) have been developed in order to help reduce traffic accidents. It is important to estimate effectiveness for the development and deployment of a safety system. However, it could take at least several years to accumulate sufficient accident data in order to investigate the effectiveness of such systems in the field. Therefore, the development of a methodology that can estimate the effectiveness of a safety system in advance is useful.

A safety impact estimation methodology (SIM) is a tool to estimate the benefit of safety systems, for example, by the number of fatalities, casualties (fatal and non-fatal injuries), or accidents that may be prevented by introducing an active safety system into the market. Safety impacts can be measured in various ways (e.g., [1], [2], [4], [5], [8]); therefore, a wide variety of SIM tool designs may be possible. We believe, however, that such numbers as fatalities and casualties reduction should be used as the output of the SIM tools for active safety systems. Some recent safety systems can reduce the impact speed by utilization of the electronic throttle control and/or brake application. Therefore, a safety impact estimation methodology should also consider the estimated reduction in fatalities and injuries resulting from the reduced impact speed, rather than only estimating a crash-avoidance ratio. If those numbers can be identified by a SIM tool, engineers and researchers can assess a system's effectiveness.

Before using a SIM tool to estimate the potential safety impact of an active safety system, the accuracy and reliability of the SIM tool should be confirmed with real field data. Accident databases such as FARS and NASS-GES are good examples of field data that can be used to confirm the validity of the SIM tool. However, as mentioned earlier, it may take more than 10 years to collect enough field data in order to have sufficient data for validation of the tool. In addition, even when some field data are available, it does not necessarily mean that the data from the field can be used for accurate validation of the SIM tool. Field data, which are collected based on past systems, may not include sufficient details of the crashes to allow for sufficient analysis into the applicability of the characteristics and configurations of the active safety systems that will be deployed in the future. Therefore, it is important to confirm the validity of the SIM tool by comparing the SIM output and the safety impact achieved by an active safety system that has already been available in the market for a long time. The SIM can be validated if the SIM output is confirmed to be similar to the findings from accident statistics.

It is also important to identify the users of a SIM tool when evaluating its usefulness. An effective SIM tool should provide good feedback to engineers and researchers who are responsible for the development of active safety systems and their deployment strategies by showing not only the effectiveness of a potential active safety system but also the changes in effectiveness when the system parameters are modified. Therefore, the SIM tool should allow users to modify system parameters, such as the system operating speed range, to examine the impact of those changes. In addition, it is important to design the SIM tool to be as user-friendly as possible to produce accurate and reliable outputs without requiring extensive user training.

SIM Development Approach

The goal of this study was to develop a universal SIM tool:

- That uses real field data (FARS and NASS-GES data) to estimate effectiveness of safety systems,
- Whose accuracy is validated by comparing the SIM outputs with the effectiveness achieved by an existing system in the field, and
- That allows engineers and researchers to examine the effect of modifying system parameters and configurations when developing an active safety system.

Therefore, our goal was to develop a systematic process to estimate the ratio (and the numbers) of fatalities and casualties expected to be prevented ("effectiveness") based on the data from FARS and NASS-GES databases. Although each accident is unique and an almost infinite number of accident types are possible, they are also usually classified into several categories. We believe that it would be helpful for engineers and researchers to provide such categories as "rear-end crashes" and "head-on crashes" and for the users to be allowed to select the categories when analyzing probable causes for an accident and considering the possible countermeasures. But this categorization should be done using a systematic methodology.

Toyota's SIM (T-SIM)

Figure 1 shows the comparison between typical SIMs and the T-SIM concept.

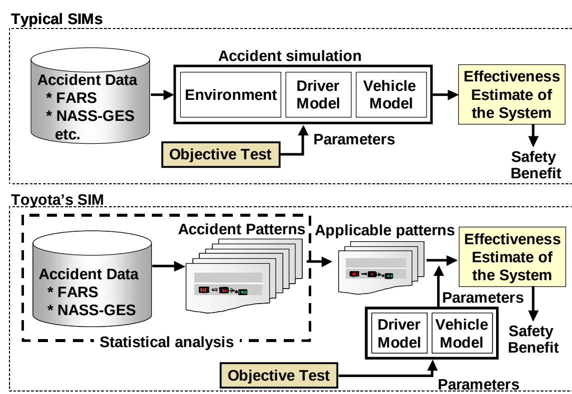

Figure 1. Comparison of T-SIM and typical SIMs

Typical SIMs are usually developed and tuned for a specific system, i.e., a SIM for Forward Collision Warning System (FCWS), a different SIM for ESC system, and so on. For each system, accident cases to which the system is applicable are selected from accident databases. Driver- and vehicle-model parameters are determined based on objective tests and detailed accident data (e.g., National Automotive Sampling System - Crashworthiness Data System

(NASS-CDS) and naturalistic driving data from driving recorders. System benefit is calculated from the accident simulation using the selected accident cases and the models.

However, there are some concerns associated with the approach. Firstly, it may result in creation of a number of complicated inflexible SIM tools. It is important for development engineers of active safety systems to have flexibility in adjusting parameters and system boundaries when designing effective systems. If multiple incompatible tools have to be used to compare two different systems, engineers will face a major challenge in designing integrated safety systems. Secondly, it is not easy to understand accident situations in such statistical data as NASS-GES and FARS and therefore it may be difficult to determine if a safety system can be effective for those accidents. Thirdly, such detailed data as NASS-CDS and naturalistic driving data can be used to determine if the system is applicable to those accidents; however, only a small number of detailed data are currently available and there is some uncertainty regarding whether the data are a good reflection of the national population. Fourthly, it is necessary for a better estimation to simulate accidents accurately; however, parameters for the simulation are given from small numbers of objective tests and/or detailed data. Finally, since this type of SIM is usually made for a specific system, users need to repeat nearly the entire process in order to build another SIM for each specific system.

On the other hand, our basic approach is to construct a universal SIM tool based on the standard sets of accident patterns with adjustable parameters. This type of SIM allows development engineers to select applicable accident patterns when creating a system concept. During the engineering exercise, engineers can adjust system boundaries, such as the operating speed range, to see the boundaries' impact on safety benefits.

The T-SIM consists of two parts: one part is the classification of accident patterns of NASS-GES and FARS database, which can be used for various kinds of systems. The other is the selection of the applicable patterns to a specific system from the categorized patterns and the application of a driver-model and a vehicle-model to estimate the system effectiveness.

The main benefits of the T-SIM are:

1. The classification will operate to allow the user to address a particular purpose; therefore, the T-SIM users can easily understand for what kind of accidents a safety system can be effective.
2. The T-SIM users do not need to conduct the accident analysis when they try to estimate effectiveness of a different safety system.
3. It is possible to compare the effectiveness of different systems in the same condition by using the same accident database of the T-SIM.

Accident Pattern Classification

Categorization of Data Elements

As the first step of developing standard sets of accident patterns, NASS-GES and FARS data were categorized into several groups. The "occupant" data set is used for both NASS-GES and FARS. Table 1 shows the results of these categorization efforts.

For multi-vehicle crashes, it is important to distinguish them into culpable party and counter party. A culpable party is the vehicle that has mainly contributed to the occurrence of a particular accident. For example, in a rear-end accident, if the driver of the following vehicle was inattentive and did not see the preceding vehicle slowing down, and collided into the preceding vehicle, the following vehicle is the culpable party because the contribution of this striking vehicle to the accident is greater than the preceding struck vehicle. To determine which vehicle was culpable we examined each vehicle's role (i.e. striking or struck), drivers' distraction, travel speed and vehicle maneuver prior to critical event.

The grouped vehicles are limited to three categories in order to reduce the number of combinations: automobiles, motored cycles, and other vehicles. Automobiles include all passenger vehicles (automobiles, automobile derivatives, utility vehicles, all kinds of trucks and buses).

Each item in the "grouped categories" can be considered one similar group of accidents (head-on collision between automobiles at an intersection with a traffic signal) therefore can be used as the basis for creating standard accident patterns. Their combinations (type of accident, culpable party, counter party, location, and traffic control) generate 486 sets of standardized accident patterns.

After minor cases (with less than 0.025% of all fatalities or less than 0.025% of all casualties) and unclear cases (vehicle involved in crashes and/or location of crash are unknown) are eliminated; only 98 patterns remain. In total, these 98 patterns can represent approximately 85% of all accident cases therefore it is reasonable to believe these 98 patterns can be used to represent a large percentage of the accident patterns in the United States (Table 2).

Table 1. Categorization of NASS-GES and FARS Accident Cases

	Grouped Categories	2005 NASS-GES Variables	2005 FARS Variables
Type of Accident	Multi-Vehicle Crashes Head-on; Angle; Rear-End; Sideswipe Same Direction; Sideswipe Opposite Direction; Rear-to-Rear Single Vehicle Crashes Pedestrian; Pedal Cyclist; Rollover/Overturn; Guardrail; Concrete Traffic Barrier; Post, Pole or Support; Culvert or Ditch; Curb; Embankment; Fence, Wall; Tree; Animal; Parked Motor Vehicle or Other Motor Vehicle not in Transport; Bridge Structure; Other Fixed Object; Other Object not Fixed; Other Non-Collision	#40 IMP Manner of Collision #37 IMP First Harmful Event	#25 Manner of Collision #24 First Harmful Event
Culpable Party	Automobile; Motored Cycle; Other Vehicle	#158 Imputed Body Type	#110 Body Type
Counter Party	Automobile; Motored Cycle; Other Vehicle	#158 IMP Body Type	#110 Body Type
Location	Intersection Related; Non-Junction; Other Location	#45 IMP Relation to Junction	#26 Relation to Junction
Traffic Control	Traffic Signal; Stop, Yield, School Zone Sign; No Controls	#48 IMP Traffic Control Device	#35 Traffic Control Device

* IMP: Imputed

Table 2. Coverage of Extracted 98 Standard Accident Patterns

Type of Accidents	Number of Standard Accident Patterns	Coverage (Casualties, NASS-GES)	Coverage (Fatalities)
Automobile x Automobile	22	86.3%	94.7%
Single Vehicle (excluding Pedestrian and Pedal Cyclist)	41	85.4%	91.7%
Automobile x Motorcycle	11	68.3%	82.6%
Motorcycle x Automobile	14	78.1%	82.6%
Automobile x Pedal Cyclist	5	81.9%	88.7%
Automobile x Pedestrian	5	93.1%	86.2%
Total	98	85.8%	83.5%

Selection of Parameters for Effectiveness Estimation

The next step was to examine the parameters (conditions) that can contribute to the number of accidents. The following NASS-GES and FARS data elements are identified as accident parameters (Table 3).

For each of these 98 patterns, the parameters and data counts are extracted from NASS-GES and FARS. The extracted data will be used as the database to calculate safety impacts. We are developing an interface tool to identify applicable accident patterns and adjustable accident parameters when estimating safety impacts of future active safety systems.

When examining NASS-GES and FARS databases, one would discover that there are many cases where vehicle travel speed is reported as “unknown.” We examined the linear correlation between “Posted Speed Limit” and “Vehicle Travel Speed.” After normal distributions were confirmed, linear regression models were created and applied to generate estimated vehicle travel speeds based on the posted speed limits (Figure 2).

Table 3. Categorization of NASS-GES and FARS Accident Cases

Parameters for Effectiveness Estimation	2005 NASS-GES Variables	2005 FARS Variables
Culpable Party's Travel Speed	#120: Travel Speed #46: Imputed Speed Limit	#127: Travel Speed #30: Speed Limit
Damage Area	#74: General Area Damage	#135: Impact Point – Initial
Traffic-Way Flow	#15: Trafficway Flow	#28: Trafficway Flow
Pre-Crash Vehicle Control	#138: Precrash Vehicle Control	-
Corrective Action Attempt	#137: Corrective Action Attempt	#151: Crash Avoidance Maneuver
Roadway Alignment	#36: Imputed Roadway Alignment	#31: Roadway Alignment
Roadway Surface Condition	#47: Imputed Roadway Surface Condition	#34: Roadway Surface Condition
Atmospheric Condition	#49: Imputed Atmospheric Condition	#39: Atmospheric Condition
Light Condition	#30: Imputed Light Condition	#38: Light Condition
Driver Distraction by #1	#182: Driver Distracted by #1	-
Driver Related Factors #1	-	#229: Driver Related Factors #1

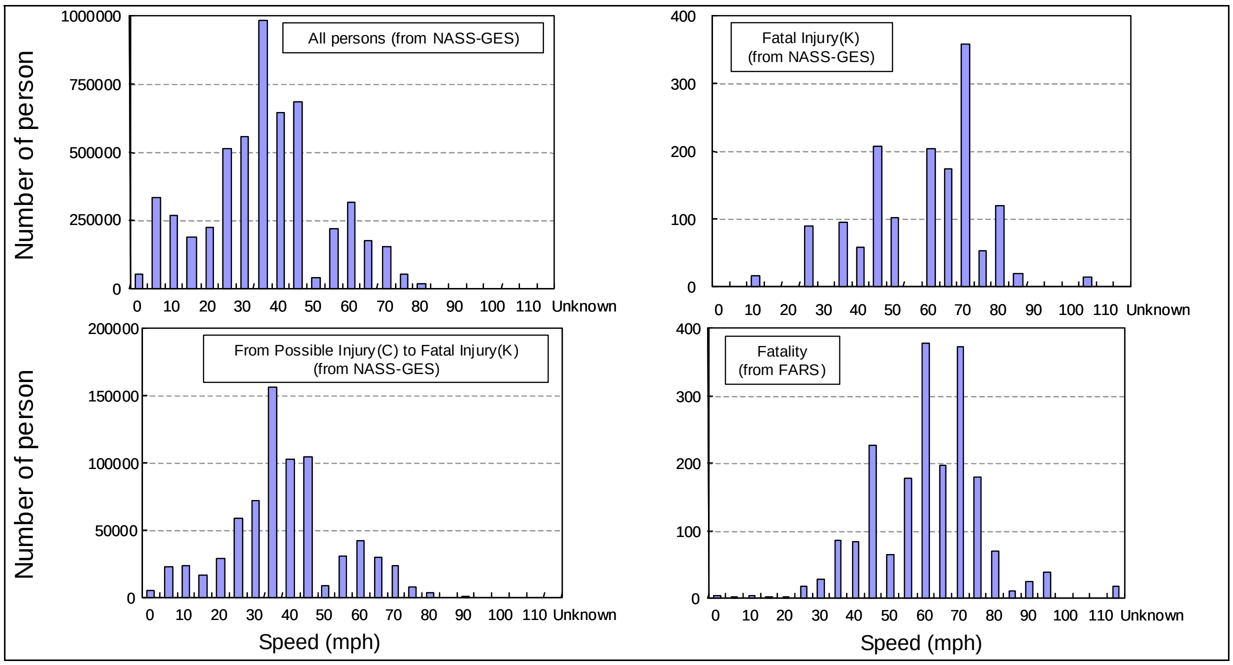

Figure 2. Estimated Vehicle Traveling Speeds

SIM Validation Approach

<u>T-SIM Application to ESC for its validation</u>

The validity of the T-SIM was examined with existing field data. There are sufficient accident data in the field for ESC systems because they were already introduced into the market for a wide range of vehicles for several years. One of the benefits of the T-SIM is that it can be used not only for a particular system but also for a wider range of active safety systems. Therefore, it was decided to validate the T-SIM concept by comparing the data produced by the T-SIM for ESC and the effectiveness of ESC identified in field studies conducted by NHTSA [2].

In the NHTSA report, it was identified that the effectiveness of ESC by comparing accident frequencies of identical and/or similar vehicle models with and without ESC.

In the report, analyses were conducted based on field data of FARS and state accident data from 1997 to 2004. We used the NASS-GES database to compare the results with the state data files because those databases are thought to be comparable. Since the ranges of the years of the databases in the T-SIM and the NHTSA report are different, we compared the distributions of an accident type in those two ranges of years as a check for similarity and found that the databases are comparable.

Identification of Influential Parameters

To examine the validity of the T-SIM, we first identified the functionalities of a typical ESC system. A typical ESC system is designed to activate the vehicle chassis control system to help avoid vehicle loss of control and help allow the driver to regain control when s/he has lost control. There are two types of control loss: front-wheel skid (drift off) and rear-wheel skid (spin).

In this SIM validation step, two operating conditions for ESC were considered to estimate the effectiveness: (A) ESC works at the speed equal to or more than 10 mph, and (B) ESC works to help prevent skidding. The operating condition (A) is defined from the system setting, and the effect of ESC on preventing skidding in condition (B) is mentioned in the previous studies ([6], [11]) and was also confirmed by our ground test [10].

It is natural to consider that there may be some other factors that may affect ESC activation. The "roadway surface condition" is a good example. Table 4 shows the number of persons involved in accidents by "pre-crash vehicle control" and "roadway surface condition" categories. This table was made from the database with the 98 accident patterns. Although "skidding laterally" occurred more often (29%) in the "Snow or slush" condition than that in other conditions (3% in "Dry," 12% in "Wet," 23% in "Ice"), there are still a larger number of accidents that happened even when the vehicle was under a "tracking" condition (54% in "Snow or slush," 87% in "Dry," 70% in "Wet," 40% in "Ice"). In other words, even in the "Snow or slush" condition, a large amount of accidents occurred in the "tracking" condition. Similar phenomena are also observed in other roadway surface conditions. It indicates that the roadway surface condition may seem to have an association with the number of "skidding" accidents, however the influence is secondary. Since typical ESC systems are designed to function when the vehicle is "skidding," whether the vehicle is skidding or not is the primary effect on ESC activation. Therefore it is appropriate to use only the "pre-crash vehicle control" condition as the variable when examining the effectiveness of ESC.

Table 4. Number of persons involved in accidents by "Pre-crash Vehicle Control" and "Roadway Surface Condition" categories

Roadway surface condition / Pre-crash Vehicle Control	Dry	Wet	Snow or slush	Ice	Other /Unkown	Total
Tracking	232806	52573	15315	5515	604	306815
Skidding longitudinally	14195	6729	4507	4660	19	30110
Skidding laterally	8552	8707	8092	3201	0	28551
Other	0	0	0	0	0	0
Other vehicle loss of control (specify)	0	591	0	0	0	591
Precrash stability unknown	11543	5944	299	552	0	18337
Total	267096	74545	28213	13928	623	384405

Estimated effectiveness by the T-SIM and the effectiveness reported by NHTSA

The NHTSA report estimated the effectiveness of ESC for passenger cars (PCs) and light trucks and vans (LTVs) separately. To examine the appropriateness of the T-SIM, however, we have divided our vehicle category into these two categories, PCs and LTVs, in order to match the NHTSA report. This was done solely for the purpose of examining the validity of the SIM tool.

The effectiveness of ESC estimated by the T-SIM and that by a previous report are shown in Figures 3 (for fatal crashes) and 4 (for various crashes). In these graphs, the bars on the left side of each accident type show the effectiveness of ESC for PCs, and the bars on the right side show that for LTVs, extracted from the NHTSA Technical Report [2].

The diamond (blue) dotted level lines indicate estimated results by the T-SIM calculated under the conditions of (A) ("culpable party's travel speed" is over 10 mph) and (B1) ("skidding laterally"), and the square (red) dotted level lines indicate estimated results calculated under the conditions of (A) and (B2) (both "skidding laterally and "skidding longitudinally").

In the NHTSA report, all crash involvements refer to all types of fatal crash involvements for the FARS database and not only fatal but also non-fatal crash involvements (i.e., property damage, possible injury, non-incapacitating and incapacitating injury) for the state data files (see page 19 of the NHTSA report). In the T-SIM, we used fatalities of the FARS database and "All Persons" data (Fatal injury (K), Incapacitating Injury (A), Nonincapacitating Evident Injury (B), Possible Injury (C), and No Injury (O)) in the NASS-GES database for the purpose of comparison.

In general, it can be said that the effectiveness values estimated by the T-SIM are reasonably comparable to the effectiveness reported in the NHTSA report because most of the estimated effectiveness for preventing fatal accidents fit within the confidence bounds.

Then, chi-square statistics were applied for the estimated effectiveness of the crash types (e.g., "all run-off-road," rollover") by the T-SIM and that by the previous report. In this statistical analysis, the stated effectiveness in the NHTSA report was treated as the expected frequency and the effectiveness estimated by the T-SIM was treated as the observed frequency.

Overall, a significant difference was not seen when the confidence bounds in the NHTSA report are taken into account. Through the validation process of the effectiveness of ESC systems, it was confirmed that the T-SIM is able to estimate the effectiveness of the safety system. Therefore, the T-SIM can be used as a tool to estimate the effectiveness of other safety systems by modeling a driver-model and a vehicle-model for the systems.

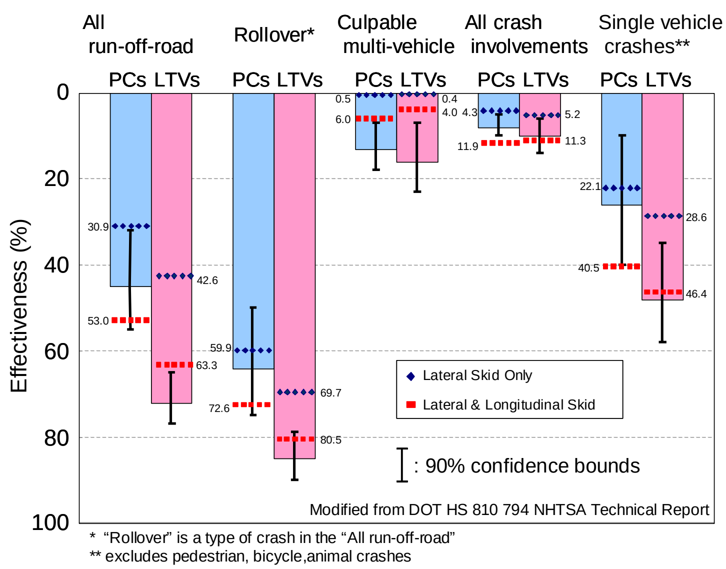

Figure 3. Effectiveness Estimation Results in Fatal Crashes by Vehicle Type

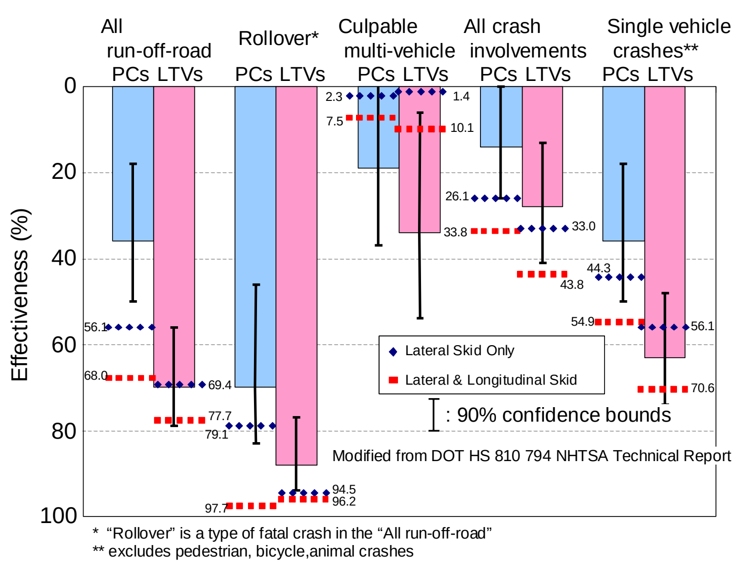

Figure 4. Effectiveness Estimation Results on Various Crashes by Vehicle Type

Effectiveness estimation of a Pre-Collision System

Among all accidents of light vehicle crashes, rear-end collisions is the most frequent, accounting for 29% of all crashes [8]. In order to reduce fatalities and casualties by the rear-end collisions, a Pre-Collision System (PCS) has been developed [3]. A PCS constantly monitors a vehicle and/or obstacle ahead with a front-mounted sensor (e.g. a millimeter-wave radar sensor), prepares the brake-assist for increased braking and finally applies automatic braking in order to mitigate the impact of collision when the system's computer determines that a frontal collision is unavoidable. Many countries are going to promote to spread the PCS.

For the effectiveness estimation and further improvement, the T-SIM was applied for a PCS. The driver model was developed from a driving simulator test. The driver-parameters such as subjects' response time to the warning, system response time, and reduction speed were collected using our driving simulator [7] from about 100 subjects. The vehicle model was made from objective tests using an actual vehicle.

It was estimated that a PCS has high potential for reducing fatalities and casualties caused by rear-end collision. In addition, the PCS system parameters such as warning, brake-assist and automatic brake timings were changed to study what parameter is the most effective and it was estimated that the PCS could be improved by modifying those parameters.

Conclusion

In this study, our goal was to develop a universal SIM tool (T-SIM) that is accurate and functional in estimating effectiveness of various safety systems.

The validity of the T-SIM was confirmed by comparing the estimated effectiveness using the T-SIM and an analysis reported by a previous study. Through the validation process of the effectiveness of ESC systems, it was confirmed that the T-SIM is able to estimate the effectiveness of the safety system.

One of the advantages of the T-SIM is that it can be used not only for ESC but also for a wider range of active safety systems. For the effectiveness estimation and further improvement, the T-SIM was applied for a PCS. The driver- and the vehicle-models were built from objective tests. It was estimated that a PCS has high potential for reducing fatalities and casualties of rear-end accidents. In addition, it was also estimated that the PCS could be improved by changing such system parameters as warning, brake-assist and automatic brake timings.

This is just the beginning of the study for the T-SIM and there is still a lot of work ahead of us; however, we believe that our T-SIM will be able to contribute to improve understanding of the effectiveness of advanced technology safety systems in helping to reduce crashes, and therefore, to improve vehicle safety.

Acknowledgement

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NEW APPROACH OF ACCIDENT BENEFIT ANALYSIS FOR REAR END COLLISION AVOIDANCE AND MITIGATION SYSTEMS

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ABSTRACT

In Germany approximately 12% of all accidents with persons injured and approximately 20% of all material damage accidents are caused by cars in rear end collisions. As a consequence, Bosch is introducing collision avoidance and mitigation systems for rear impact scenarios. Warning, brake support, and autonomous emergency braking are part of Bosch's Advanced Emergency Braking Systems which address such accidents. This study determines the benefit of these assistance and safety systems and estimates the collision avoidance capability considering the driver's behavior. By analyzing representative accidents with injuries from the GIDAS (German In-Depth Accident Study) database, a high potential for collision warning and avoidance systems was determined. For the first time in such a study, this analysis considers the effects of different driver reactions due to warning, braking support, or autonomous braking with respect to the possible driver behavior. For this, a calculation method was developed and used for evaluating the accidents automatically. Both accident avoidance and average speed reduction was determined for different driver types, warning strategies and applications. From the results, an avoidance ratio of 38% for Predictive Collision Warning up to 72% for Automatic Emergency Braking, of all rear-end accidents can be expected for a realistic driver. Therefore it is estimated that 3 out of 4 accidents with severe injuries could be avoided based on the Emergency Brake Assist function and assuming a 100% installation rate. The potential to reduce collision speed in non avoided accidents is calculated on an average basis and is determined to be between 25% and 55% for the realistic driver. The results in the analyses show the high efficiency of the Bosch AEBS functions in avoiding accidents or mitigating injuries by reducing collision speed and should encourage the introduction of Advanced Emergency Braking Systems across a wide range.

INTRODUCTION

Since active safety systems have become more popular over the past few years, they are now an integral part of new vehicles. The vehicle stability control system ESP® (Electronic Stability Program) is considered to be a representative example of these active safety systems. ESP® supports the driver in nearly all critical driving situations in which an unstable driving condition might occur. By automatically braking individual wheels the system helps to prevent skidding and keeps the vehicle stable. This results in fewer single vehicle accidents with high severity. A large number of international studies by well-known automobile manufacturers and independent institutes have proven the effectiveness of ESP® in reducing the number of accidents. For example Baum *et al* [1] stated ESP® would save 4000 lives per annum assuming a 100% penetration of ESP® for all passenger cars within the European Union (EU25). Furthermore approximately 95.000 injuries would be prevented in such accident scenarios. In the US even up to 9.500 lives and 252.000 injuries per annum could be saved or prevented respectively by a vehicle stability control system like ESP®. Such high avoidance potential could reduce the share of accidents against fixed objects significantly. Figure 1 gives an overview of all accidents with casualties by kind of accident for three different countries.

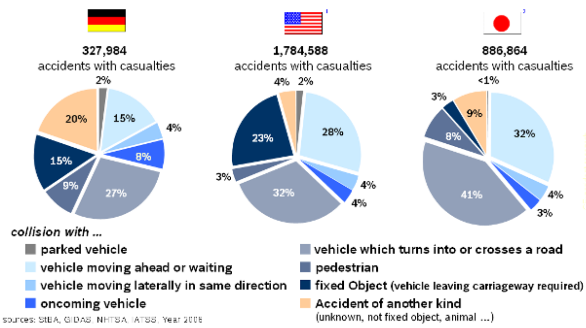

Figure 1. Accidents with casualties by kind of accident [3], [4], [5]

As a result, other types of accidents come to the fore. As shown in Figure 1, a high share of accidents are rear-end collisions against a leading vehicle. With a fraction of 15% of all accidents in Germany, 28% in the US and even 32% in Japan, these accidents cover a high quantity of accidents with casualties. Approximately 4 out of 5 accidents are caused primarily by a passenger car, whereas the remaining accidents are caused primarily by trucks.

In fact, accidents with only property damage are neglected typically, hence their relevance and potentials are underestimated. Together with Allianz Zentrum für Technik (AZT) - a leading specialist in damage analysis and prevention - we established that approximately 1.1 Million rear-end crashes per annum in Germany occur. This database consists of accidents caused by a passenger vehicle wherein either a police report or individually regulated insurance claim was filed [6]. Such collisions occur mainly at lower speeds but with higher frequency. In summary, a higher need for collision avoidance systems is given. Aside from ESP®, Bosch also provides a family of driver assistance and safety functions which are part of the Advanced Emergency Braking Systems (AEBS). The idea behind AEBS is scalable functionality - from driver warning over optimized braking support to a fully autonomous braking system. To estimate long term effects within the development process, the scope of all functions is a proven benefit within the real world according to their functional specifications.

Real world accidents have to be taken into account to evaluate this benefit. Up to now, other studies considered only one part of the aspects above. For example autonomous braking systems were part of the study from Schittenhelm [7]. He quoted that 20% of all passenger vehicles which caused rear-end collisions would be avoided by the Distronic plus and the Brake Assist System (BAS). Based on semi-autonomous braking and additional braking support by increasing brake pressure, this analysis does not consider any driver reactions due to acoustic or tactile warning strategies. From this point of view it seems to be a more conservative estimate regarding the benefit of predictive safety systems.

In harmony with this concept, the goal of this study is to evaluate the benefit of the Advanced Emergency Braking Systems functions from Bosch using the German In-Depth Accident Study (GIDAS) database. A driver model was developed which considers driver behavior and reaction in order to gain the function's benefit not just based on functional characteristics. As an outcome two major results were obtained - firstly the accident avoidance potential and secondly the reduction of injury severity.

METHODOLOGY

The analysis is based on data from the GIDAS project [8]. Since 1999, accidents with injuries were surveyed within Germany around the region of Hanover and Dresden. Approximately 2000 accidents per year were reviewed and deemed to be valid as representative for accidents with injuries in Germany. For each accident, approximately 3000 details are collected and provided within a database for further analysis. Along with the vehicle damage and personal injuries, information from prior to the accident also is obtained based on the fact that each accident is reconstructed in detail. Therefore, physical information regarding the pre-, during- and post- post crash phase is available and essential for the analysis of safety systems as AEBS. For this study, 9323 reconstructed accidents with injuries were used. By selecting collisions with significant characteristics, it was ensured that only relevant accidents were taken into account for the AEBS benefit calculation. In this study only passenger vehicles causing rear-end collisions are considered. Thus rear end collisions against a motorcycle caused by a passenger car are also included. Furthermore, accidents were also taken into account wherein a passenger car as the primary cause has had a frontal impact against an opposing vehicle. Hence 1103 relevant accidents (12%) remain from 9323 GIDAS accidents. Those accidents define the so called field of effect. In other words these are the accidents that could be influenced positively by any of the AEBS functions. For Germany, this data represents approximately 39.000 accidents with injuries per annum. In the next step the benefit for each AEBS function is determined by considering driver behavior, functional characteristics and additional system assumptions.

It is apparent that by integrating different driver and sensor characteristics, a complex handling for each accident within the benefit estimation results. Due to this, a tool was developed which allows the handling of sensor parameters, driver reactions and additional system values in a more simple way. By using the Matlab environment from MathWorks™ it is now possible to determine the benefit for a wide range of AEBS functions easily. Modifications within the driver model and functional applications are now easy to handle and it is open for the integration of new applications.

DRIVER MODEL

The effect of predictive collision avoidance systems is directly linked to the driver's reaction. It is evident that a critical situation will be handled in a better way if the driver reacts immediately after warning with a braking intervention. This is also true for autonomous braking systems because the efficiency increases with the braking support of an active driver. For this reason, a driver model was developed and integrated to estimate the driver behavior and reaction.

In the first step, the driver reactions were analyzed in real accident situations. For each accident within the field of effect, deceleration and brake distances were evaluated and classified into three categories. Figure 2 shows the distribution of the classified drivers. 31% of the drivers did not show any (brake) reaction which is assigned to driver type I. Compared to this, 49% of the drivers brake but with less braking performance due to late reaction or light deceleration - this type of driver is categorized as driver type II. Finally 20% of the drivers - driver type III - brake with maximum deceleration but with delayed reaction. Weather and road surface conditions were taken into account.

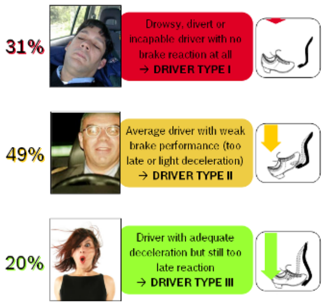

Figure 2: Distribution of the driver behavior for three classified driver types from GIDAS accidents

The question arises why the classification is so important. The reason for classification is that the real braking performance is considered in the functional activity.

In addition to that, Bosch's Advanced Emergency Braking Systems identify the driver's activity to adopt its warning strategy according to his driving behavior. For a less active driver, the warning time is set up earlier relative to a more active driver who reacts faster and therefore the warning strategy could comprise a later warning. The reason for this is clear: Less active drivers need more time to recognize the situation and to employ any brake intervention. Another advantage of this strategy is to minimize false alarms which results in a higher system acceptance and as a result, a higher benefit of the system. As Wilhelm in [9] stated the probability that the driver will subjectively assess the system poorly for providing false warnings rises with the quantity of warnings which preceed his own normal personal brake timing. In the benefit analyses, this is considered by separating inactive from active drivers using weighting factors for the benefit calculation. For instance, if a driver was classified as driver type I (no (brake-)reaction) in the real GIDAS accident it is more likely that this is an inactive driver in the real world. For this reason we set the activity level to 30% for these cases. In other words the status "inactive driver" was set to 70% for all drivers classified as driver type I. For driver type II and driver type III other distributions were used. These values were consolidated in other studies, internal investigations, and expert knowledge.

Depending on a driver's activity level and relative closing velocity, the warning strategy is adapted. The strategy of the Bosch AEBS functions consists of two warning levels. The first level is an acoustic signal, whereas the next level uses a brake jerk to alert the driver. The time delay between first and second level is variable with respect to the driver's activity level. In the calculation, it is also considered that in the real world some drivers will not show any reaction based on simply an acoustic or tactile warning. This is likely due to inattention caused by alcohol, drowsiness or other inactivity. Figure 3 shows the warning level process in a simple way.

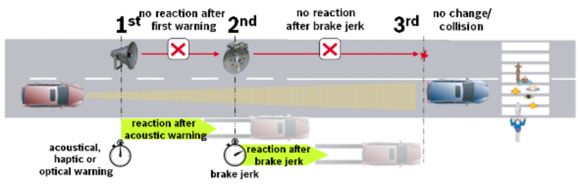

Figure 3: Two-level warning strategy depending on drivers activity and relative closing velocity

Finally, for the driver model it is necessary to know how and in what way the driver reacts after each warning. For this, three driver categories with different behaviors are defined. In Figure 4, the three classes are shown. It was distinguished between a realistic-, lethargic and best-case driver with different reaction times and deceleration levels respectively. Based on [10] and [11] such a driver population is expected whereas the realistic driver has a higher share with mean reaction time and deceleration compared to lethargic and best-case driver with poor reaction and low deceleration or fast reaction and higher deceleration respectively. It is furthermore assumed that the lethargic and the best-driver represent the borderline of the distribution as seen in Figure 4.

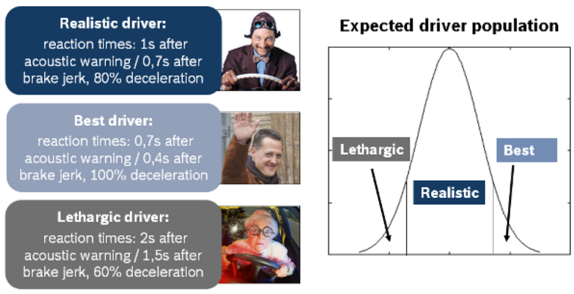

Figure 4: Classes of different driver behaviors

After all in Figure 5 the whole driver model is shown as it is realized for the benefit calculation of the AEBS functions. However it is recognizable how driver type, driver activity, warning strategy and driver behaviors are integrated and work together. As mentioned before, there are different reactions expected if an acoustic or tactile warning is given from the system. It is apparent that for different safety systems these kinds of reaction vary. For the purpose of the AEBS function evaluation we proceed on the assumptions that a share of 10% will still show no reaction after warning. Another share of 50% will react after the acoustic warning and 40% of the drivers will react after the brake jerk was activated.

Based on the distributions stated above for each driver behavior, a single result is calculated by taking the real deceleration (real driver type), driver's activity, and proposed reaction after warning into account.

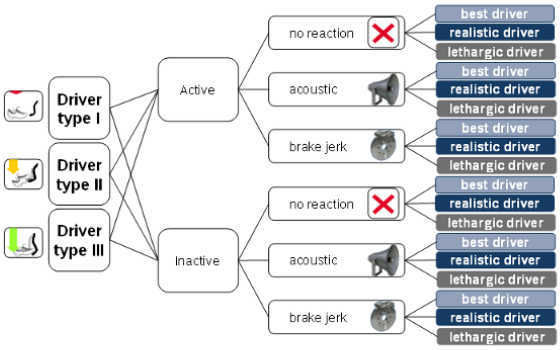

Figure 5: Driver model

The overall benefit is calculated afterward by weighting each single result depending on the driver type which is in focus, i.e. realistic driver.

AEBS FUNCTIONS AND MODE OF ACTION

The main objective of the Bosch AEBS functions is collision avoidance by driver warning. This also includes those cases wherein the driver shows no reaction. In such cases, the system intention is to prompt the driver to react by pushing the brakes. If reaction time was too late or poor brake pressure was measured, an earlier brake intention or a more powerful braking respectively would be the target of the AEBS functions. This is shown in Figure 6.

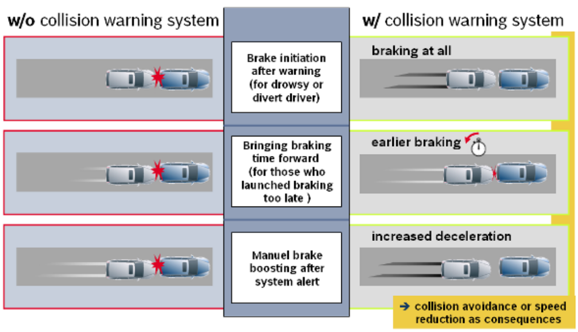

Figure 6: Potential benefit of collision warning systems

The Bosch AEBS functions use radar technology to detect a potential collision object. The sensor is placed on the front end of the car and monitors the frontal field of the vehicle. If a critical situation is detected indicated by potential opposing obstacles and high closing velocities the system will run through different levels of warning strategies. These strategies again depend on closing velocity and driver behavior. As mentioned above, aside from acoustic warning a tactile warning is given which is realized as a brake jerk. This functionality is called Predictive Collision Warning (PCW) and is part of the Bosch AEBS family.

It is clear that this function can be extended to a target braking function. The system calculates in advance the deceleration which is necessary to avoid any collision but still does not interfere. The target braking will be activated if the driver pushes the brakes. Based on the pre-calculation the optimized deceleration is controlled. If a collision is unavoidable the maximum deceleration will be set for injury mitigation. This function characteristic is helpful for driver type II as seen in Figure 2 due to the fact that their deceleration level was too low. Together with warning and target brake this function is called Emergency Brake Assist (EBA).

As can be seen in the real world (Figure 2), there is still driver type I which shows no (brake-) reaction. To be consistent, the next level of functional characteristic is an autonomous brake initiation. The Automatic Emergency Braking (AEB) function from Bosch fulfills these requirements. This is realized by a multistage intervention. At a very early stage the first level sets a deceleration of 0.3g. Depending on reaction and the ongoing situation, a second level is selected. Finally if a collision is unavoidable 0.5s prior to impact, a maximum brake deceleration will be initiated. It is expected that a driver of driver type III will react eventually due to the multiple interventions and will be prompted to brake on his own. However, comparing EBA and AEB, increased development effort, system costs and foremost liability risks for the autonomously acting AEB have to be taken into account.

BENEFIT ESTIMATION

In order to avoid false alarms, the warning strategy uses different warning times depending on relative closing velocity, classification of the driver as active or inactive, as well as the initial speed of the vehicle itself. It is apparent that the variety of different accident scenarios tend to be complex if they were to be analyzed in detail. Nevertheless to gain the benefit for each function, the collision speeds are recalculated by taking driver reaction (GIDAS) and hypothetical driver reaction (driver model) into account. Furthermore, time of braking as well as deceleration level will be established by fusion of functional intervention and driver initiated braking. In the end, the collision speed is calculated by numerical integration. As a result for all AEBS functions, the total quantity of accidents avoided as well as the calculated speed reduction is received. A 100% penetration with AEBS functions of the (Ego-) vehicles is assumed. Figure 7 shows the results for avoided accidents for the three different driver types. The benefit calculation is based on a production level application for the PCW and EBA function and an application close to production level for the AEB function. These are optimized in terms of warning strategy and not for maximum benefit. Therefore more efficiency could be possible by other parameter applications.

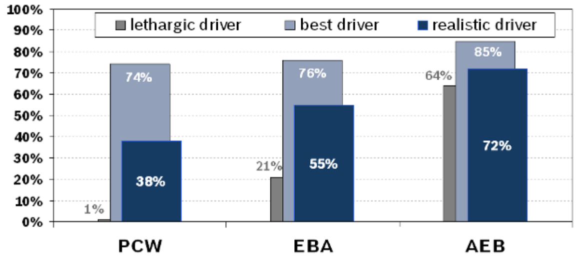

Figure 7: Accident avoidance potential of AEBS functions in rear-end crashes for different driver types

For the Predictive Collision Warning system (PCW) an avoidance benefit of approximately 38% is obtained assuming a realistic driver.

For the Emergency Brake Assist (EBA) function with the target braking, the benefit raises to more than half (55%) of the accidents in the field of effect. This is a remarkable result for a non autonomous function like EBA.

For the full scale characteristic like the Automatic Emergency Braking (AEB) function, 72% of the accidents can be avoided. This is not surprising due to the fact that in an early stage, a braking intervention is initiated if no reaction of the driver is detected by the system. As a consequence, collision speed is reduced significantly and accidents can be avoided.

Focusing on the different driver types in Figure 7, the influence on the accident avoidance potential for the different functions show significantly different potential. Regarding the collision warning functions (PCW) the potential varies from 1% to 74% for a lethargic driver and the best driver respectively. These deviations are caused by different reaction times after warning - 2s reaction time for a lethargic driver and 0.7s reaction time for the best driver. It is apparent that a lethargic driver with poor reaction times and less deceleration does not avoid a collision by means of a pure warning system alone. The analyses show that in real accidents braking was initiated after collision. In comparison to lethargic- and realistic drivers the best driver is able to avoid more accidents due to fast reaction and high deceleration level.

By looking at the level of automation, another important result is recognized. For the AEB function the difference between lethargic and best driver is 21%. This small gap results in the early activation of the AEB function if no reaction is detected by the system. Hence the biggest benefit of this function is realized for lethargic drivers.

If these results were transferred to accidents at injury level we obtain the effects as shown in Figure 8 taking a realistic driver behavior into account. The first bar shows the distribution of severity level for all rear-end crashes in the field of effect. While the amount of 1% for fatal accidents is low, the remaining accidents are shared between accidents with severe and slight injuries. The distribution herein shows a share of 10% for accidents with severe injuries and 89% for accidents with slight injuries.

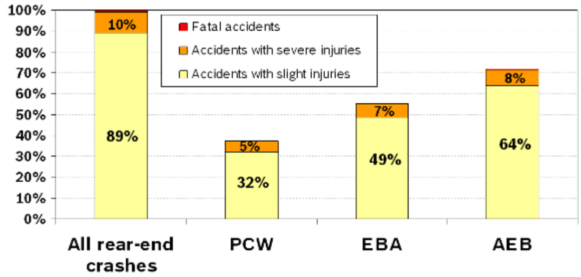

Figure 8: Distribution of avoided injuries by the AEBS functions in avoided rear-end crashes for a realistic driver

The benefit received from the AEBS functions leads to two major conclusions:

- The relations for all considered functions (PCW, EBA and AEB) stay the same regarding all severities for the rear end-crashes.
- The benefit increases enormously by increasing the automation level of the safety system.

For example, the quantity of reduced accidents with severe injuries has a share of 7% for EBA function. With respect to all rear-end crashes with severe injuries about 3 out of 4 accidents are avoided. Furthermore, every 2nd accident with slight injuries is avoided compared to all accidents with slight injuries in rear-end crashes. A prediction regarding fatal accidents is not made due to the lower share within this accident type for the field of effect used. If 39.000 relevant accidents with injuries are considered, in 2006 for Germany the following reduced number of accidents with severe and slight injuries will be avoided (Table 1).

	PCW	EBA	AEB
Accidents w/ slight injuries	12500	19100	25000
Accidents w/ severe injuries	2000	2700	3100

Table 1: Estimated number of reduced accidents with injuries by the AEBS functions for Germany

Furthermore it must be kept in mind that there are still benefits given from the AEBS functions due to accident mitigation by taking the reduced collision speed into account. This is part of the following discussion.

Along with the high accident avoidance potential, the benefit of AEBS functions is especially established in the reduced collision speed. In Figure 9 the average reduction in collision speed is shown for each AEBS function and for different driver types.

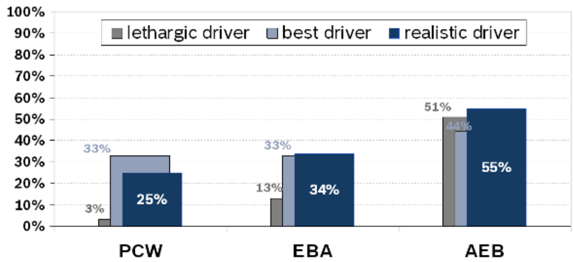

Figure 9: Average Reduction in Collision Speed of AEBS Functions for not avoided rear-end crashes

The average reduction in collision speed is determined based on accidents with reduction in speed and accidents with unchanged course. Therefore, all avoided accidents are excluded. For the realistic driver, a collision avoidance function based on warning only, like PCW, can on average reduce speed by 25%. By an EBA-function (warning + brake boost), the collision speed can be reduced on average by almost 34%. This share even increases to 55% for the AEB function.

It is apparent that minor variations occur regarding different driver types within one functional characteristic. Due to the fact that the best-driver brakes immediately with maximum deceleration this share is less when compared to that of lethargic- or realistic driver

Regarding the collision warning functions (PCW), the potential varies from 3% to 33% for a lethargic driver and the best driver respectively. Again the major difference in reaction time and deceleration level results in a different benefit.

This deviation will be reduced if the automation level is increased. For unavoided accidents, the EBA function reduces the collision speed by about 34% for a realistic driver. Even a higher reduction is given for the AEB function (55%).

It is expected that the significant reduction in collision speeds will have a considerable positive effect on the injury severities. Ongoing work aims at a comparison of the injuries in real crashes with the injury severities in the same accident with the intervention of a collision avoidance/mitigation system. A statistical model for predicting injury severities is currently being generated with SAS[1]. Hereby, a logistic regressions model is setup as a convenient statistical approach for predicting specified injury severities.

With a logistic regression model, the probability of suffering a specified injury severity or not can be estimated. Based on univariate and multivariate frequency and correlation analyses of cars in the field of effect of AEBS functions, variables are selected which have a significant influence on suffering a specified injury severity in a crash.

Two regression models will be identified. The first model[2] provides the estimation of the probability for suffering minimally "slight injuries." With the second regression model[3] the probability of having minimally "severely injured" car occupants after crash will be estimated.

COMPARISON TO LEGAL REQUIREMENTS

As proposed in the NHTSA review for the New Car Assessment Program (NCAP) from July 2008 [12], new test requirements will be introduced for Forward Collision Warning (FCW) systems. Currently there are three test scenarios defined although two scenarios are in focus of the discussion:

- 1st scenario: Subject vehicle approaches a stopped principle other vehicle at 45mph (72.5kph). The system must give a warning 2.7s prior to collision.
- 2nd scenario: Subject vehicle follows principle other vehicle at 45mph (72.5kph). The other vehicle starts braking. The system must give a warning 2.4s prior to collision.
- 3rd scenario: Subject vehicle at 45mph (72.5kph) encounters a slower principle other vehicle with speed 20mph (32.2kph). The system must give a warning at 2.1s prior to impact.

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[1] Statistical Analysis System
[2] Significant Hosmer-Lemeshow test (0.86), $R^2=0.62$, c-Statistics=0.89
[3] Significant Hosmer-Lemeshow test (0.11), $R^2=0.15$, c-Statistics=0.78

The systems in use must fulfill the velocity range which is specified between 30kph and 80kph. Furthermore, it has been claimed that the FCW systems do not necessarily have to work at night and under rainy conditions. As a matter of fact the AEBS functions from Bosch fulfill the requirements. Moreover the speed range is specified through the entire test range and above. Additionally, the Bosch system also works in misty or rainy conditions at both day and night. It is apparent that the systems can be compared to each other. Due to the early and fixed warning times specified in the NCAP requirements it is assumed that more false positive alarms will be given from such a collision warning system. A false positive alarm hereby is defined as a warning given to driver which does not address a potential accident scenario and should be classified as not relevant. Therefore it is more probable that a driver will switch off the system if there is an alarm in a non critical event. As a result, the FCW functionality would be inactive and not available in case it is required. This is why the Bosch AEBS functions use a more flexible warning strategy. The strategy minimizes positive false alarms and a higher acceptance by the driver is realized due to its familiarity and reliability. Nevertheless a comparison of the FCW and the Bosch PCW function was done by setting the requirements for FCW as stated above. In other words for example, accidents which occurred at night are not considered in the benefit calculation for the FCW function. The results are shown in Figure 10 and Figure 11 for the avoided accidents and the average reduced collision speed respectively. The calculation was done for all driver types defined before.

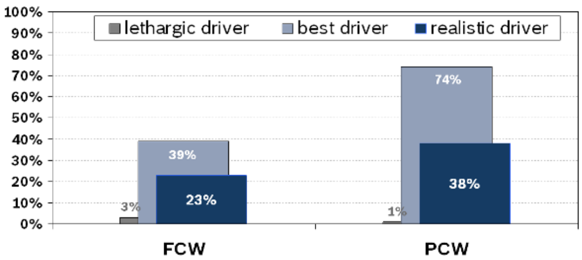

Figure 10: Comparison of FCW vs. PCW in rear-end crashes, Fraction of avoided accidents

As seen in Figure 10 the results show a decreasing benefit if the minimum requirements for FCW functionality were fulfilled. The difference between FCW and the Bosch PCW function for a realistic driver was estimated to be 15%. The same situation is shown in Figure 11 for the average reduction of collision speed. Approximately 16% difference is estimated between FCW and PCW for the realistic driver.

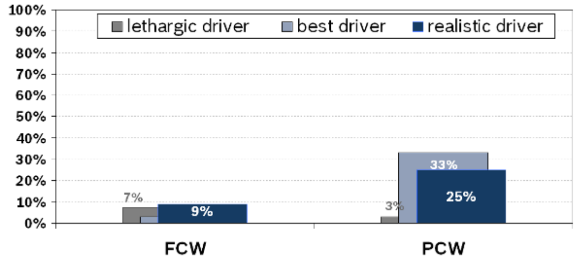

Figure 11: Average reduction in collision speed for not avoided rear-end crashes

CONCLUSIONS

- The study considers 1103 rear-end accidents with injuries from 9323 GIDAS accidents as representative for Germany.
- The analysis is based on three specified applications from the Bosch Advanced Emergency Braking Systems. The PCW and EBA functions are based on production level application whereas the AEB function is based on a market level application. The optimization strategy was to ensure a reduced number of positive false alarms taking maximum avoidance potential into account. Other application settings are also possible by optimizing the accident avoidance.
- A high accident avoidance potential for rear-end collisions is given from the Bosch Advanced Emergency Braking Systems. The share of avoided accidents for a realistic driver was calculated for the PCW system to be 38%, for EBA system to be 55% and for the AEB system to be 72% respectively.
- The efficiency of collision warning systems like PCW depends on driver behavior and on reaction time. The variations are from 1% to 74% for the lethargic and the best-driver respectively.
- An increased system automation level - from PCW, EBA to AEB - reduces the driver influence on the one hand significantly and increases the accident avoidance potential on the other, in particular for lethargic drivers. However, comparing EBA and AEB, increased development effort, system costs and foremost liability risks for the autonomously acting AEB have to be taken into account. Therefore an optimum benefit over cost ratio is expected for the EBA function.
- The number of avoided accidents with severe injuries is estimated to be approximately 2700 rear-end accidents in Germany annually. Furthermore, the amount of avoided rear-end accidents with slight injuries is estimated to be approximately 19100 accidents. Hereby the EBA function for a realistic driver is considered and a 100% installation rate.

- If an accident is unavoidable, the AEBS functions will reduce the collision speed significantly. For the PCW function an average reduction of collision speed is encountered for 25% of unavoided accidents. For the AEB function a rate of even 55% was determined.
- The Bosch Advanced Emergency Braking System functions operate over a wide velocity range, even at night and under rain or bad weather conditions.
- By fulfilling NCAP requirements for FCW systems, accident avoidance potential is reduced from 38% for the PCW system to 23% for the FCW system assuming a realistic driver.
- Furthermore, by fulfilling NCAP requirements for FCW systems, a significantly decreased benefit is determined for the average reduced collision speed for unavoided accidents. For the realistic driver a decrease from 25% to 9% is given based on the PCW function compared to the FCW function respectively.
- A high probability for positive false alarms is expected and hence less acceptance by the driver without variable warning strategy. This strategy should be individually controlled by a driver classification system and taking the relative closing velocity into account.

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Increased safety and reduction of congestion by using driver assistance technology; dream or reality?

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Paper Number 09-0408

ABSTRACT

As accidents with trucks have a large influence on traffic flow, a large pilot on the effect of driver assistance systems was kicked off in July 2008 in the Netherlands. The primary goals of the pilot are to assess the potential for improving safety and maintaining traffic flow.
The potential contribution of driver assistance systems to these objectives will be determined with 2550 trucks from about 100 transport companies. Each truck is equipped with one assistance system and a registration unit for monitoring driving and vehicle behaviour.

Driver assistance systems used are: Lane Departure Warning, Forward Collision Warning, Directional Control, Adaptive Cruise Control, Rollover Control and Black Box with Feedback. The latter system was developed especially for this project. Based on continuous measurements, the driver receives a daily report on his "safe and congestion preventing" driving behaviour. So far, drivers and transport companies are very positive on this system.

When closing the pilot halfway 2009, it will be concluded what the effects are of these systems on traffic safety and congestion. The conclusions will be based on proving ground tests, simulations and measurements from the pilot, like:

- Average speed, speed variations, accelerations, etc.
- Time-to-Collision over a time span, headway (time)
- Warnings and actions by the systems

Effects on traffic flow will be quantified based on changes in driving behaviour and based on expected reductions of accidents. This pilot will deliver unique, statistical data on the actual effectiveness of a range of driver assistance systems.

The project is performed in a close cooperation between TNO, the Dutch Ministry of Transport, Public Works and Water Management, Connekt and Buck Consultants. Currently, the focus is on the Netherlands, but it is investigated how to interpret the results for Europe.

INTRODUCTION

During rush hour, large parts of the Netherlands are suffering from traffic jams. Especially the areas around the major cities are congested. Besides this, there are on many spots increasing congestion problems during the rest of daytime. The Dutch infrastructure is relatively vulnerable for incidents. A well know example of incidents which can paralyse large areas of motorway traffic for hours is the case of the heavy vehicle roll over accident, occurring about thirty times a year on a motorway and about one hundred times on other roads, often close to motorway areas.
Figure 1 shows the locations of rollover accidents with heavy vehicles, in 2006, on Dutch motorways.

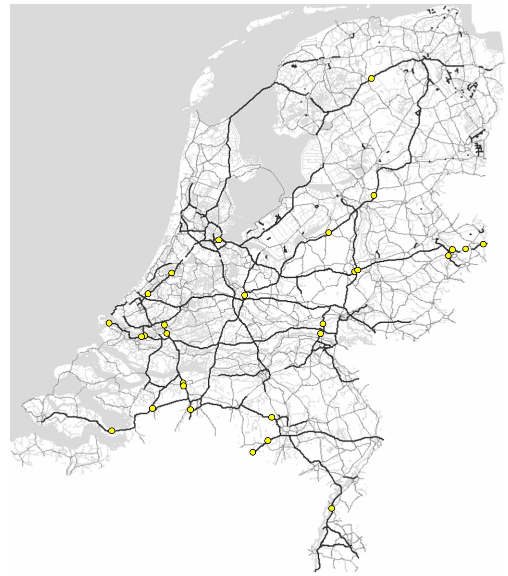

Figure 1. Locations of rollover accidents with heavy vehicles on Dutch highways, 2006

This situation is affecting of course the daily life of many commuters, but also has increasing negative economical and environmental effects. The Dutch Ministry of Transport, Public Works and Water Management has considered this situation with growing concerns and launched the so-called FileProof Programme in 2006.

At the start of FileProof, ministree employees, local governments, private citizens, business, interest groups and knowledge institutions provided a host of creative ideas on the topic. This host consisted of about 3000 ideas, which were evaluated by a group of experts, resulting in a wide programme of about forty projects. These projects all aim at short-term solutions for traffic congestion, ranging from changing driver attitude and improved road signs to implementation of Accident Prevention Systems in (heavy duty) vehicles.
It can be seen that the projects also have different objectives from increasing regular traffic flow to a more fluent level, up to the reduction of occasional traffic jams.

This paper focuses on the Accident Prevention Systems (APS) project. Determining the effects of these systems on safety and traffic flow, as well as determining the effectiveness of the systems, needs to be done in a joint effort of theoretical work and major experimental work. For this last part, a so-called Field Operational Test is an appropriate instrument which also is being applied in this APS project.

The project described here contains the most comprehensive Field Operational Test (FOT) conducted so far, on Accident Prevention Systems in heavy duty vehicles.

The objectives of this project are divided into these aspects:

1. Assess the impact of large-scale implementation of accident prevention systems on traffic circulation and traffic safety
2. Gain insight into the effectiveness of the various systems with respect to lorry traffic safety.

The APS project is conducted with full support of many Dutch transport companies and by the relevant transport interest groups.

BASICS OF THE METHODOLOGY

The Dutch Ministry of Transport, Public Works and Water Management wanted to be able to measure real-life effects of the Accident Prevention Systems, rather than purely simulation results or theoretical answers. Furthermore, a boost of the implementation of APS in the heavy vehicle fleet was considered to be highly desirable, hoping it would increase also road safety. Therefore, a FOT turned out to be a very appropriate instrument. In starting an FOT, it is best to learn from previous experiences as it is a complicated instrument. Within the EU project FESTA [1] a FOT was defined as:
A study undertaken to evaluate a function, or functions, under normal operating conditions in environments typically encountered by the host vehicle(s) using quasi-experimental methods.

It is important to note the wording "to evaluate" in this definition. Many aspects of a system can be evaluated, ranging from technical aspects to e.g. influencing the actual driving behaviour.

In an FOT effects can be studied in real traffic conditions, rather than under pre-defined circumstances. That would be the case in laboratory testing or driving simulator testing. Though, while working in an FOT, one has to be careful with comparing measured data from several participating vehicles. Without proper reference data (measured in vehicles without APS) the benefits and effects of the in-car systems cannot be properly assessed. Furthermore, one should compare only results from similar situations. External factors like weather type, traffic condition, GPS location, time of day and road type must be taken into account.

In an early stage of the project, traffic simulations were performed to determine the number of vehicles and the period during which the measurements should be done. Statistical power analyses were conducted, using Monte Carlo simulations. This made it possible to take into account the two underlying variables; the number of vehicles in each test group (per APS) and the measurement duration. In traditional power analysis methods (e.g. Cohen [2]), this combination is not accounted for in a straightforward manner.
In the end, it was recommended that the number of vehicles in each group should be 400, while the measurements should ideally run over about 8 months. All vehicles should have a data collection unit on board, to measure basic input for later analysis. Parameters to be measured would be e.g. vehicle speed, time to collision, time to line crossing, location (GPS), time and accelerations. Furthermore, participating vehicles have at most one working APS onboard.

One group of vehicles should have only a data collection unit on board, no active APS. This group is the reference group. It is essential to have a group like this. Without it, the actual effects of the APS cannot be truly determined.

SYSTEMS

An early study in the starting phase of the project looked into the support systems to be used in the FOT. Basic issues here were the needs on the Dutch roads, availability of systems, working principle and expected benefit and effectiveness of the system. Furthermore, it was tried to pick systems with different principles of work and different types of potential accident scenarios in which the APS should be effective (head-tail accidents, side accident, single sided accidents). It was also decided to have a mixture of systems only informing the driver, and systems which actually perform actions. Also the moment in which the systems become active differs for the systems chosen (see Figure 2).

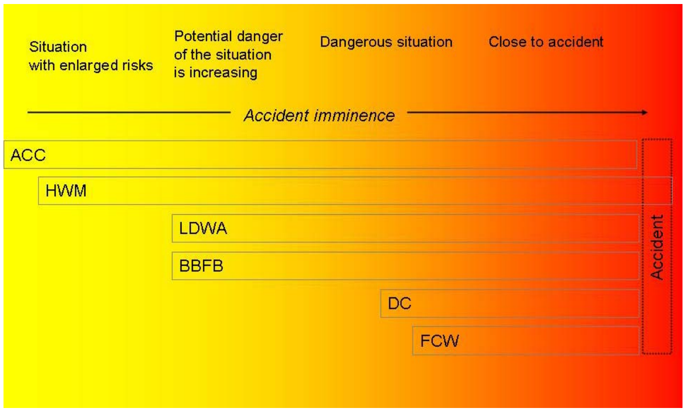

Figure 2. Accident imminence and activation of APS

There are some reference groups in the project. The trucks in the reference groups all are equipped with the same data collection unit as all other trucks.
Based on the pre-study [3, 4], the following systems were selected to be included in the FOT.

1. HWM + FCW (Headway Warning and Monitoring + Forward Collision Warning). The system used in the FOT combines the two functionalities into one module. HWM warns whenever the time headway to the preceding vehicle becomes too short. The headway is determined by using a combination of the vehicle speed and the distance to the preceding vehicle. The FCW warns the driver when the time to collision becomes smaller than a certain threshold value. Within the FOT, the driver cannot switch off the HWM/FCW system.

2. LDWA (Lane Departure Warning Assist). This assist warns the driver when he is unnoticed leaving his lane (i.e. indicator lights are not used during or close to a lane departure). This is done based on a time to line crossing criterion, determined by a camera. Also this system cannot be switched off by the driver in the FOT.

3. ACC (Adaptive Cruise Control). ACC intends to maintain the speed as programmed by the driver, but also tracks down preceding vehicles. The headway towards these vehicles is kept to a safe value. The test drivers in the FOT can switch on and off the ACC as they wish. ACC is most often used during long distance travels in uncongested traffic.

4. DC (Directional Control). DC is an autonomous system, taking action when the vehicle does not properly respond to steering actions or starts sliding. Its actions normally are performed by braking at selected wheels. DC can be combined effectively with ROC (Roll Over Control), which is an algorithm that also uses the brakes when the vehicle tends to roll over.

5. BBFB (Black Box FeedBack). This is a new system, developed especially for this FOT. This system is described in the next section.

The HWM/FCW and the LDWA can be built into (heavy duty) vehicles during the vehicle's commercial life time, as they are available as retrofit systems. This essentially speeds up the large-scale introduction of these systems. The BBFB functionality is a newly developed functionality of a kind of fleet management system which also is available as retrofit toolkit. For heavy vehicles equipped with a relatively new version of the hardware of the fleet management system, a remote software update is sufficient to equip existing vehicles with the BBFB functionality.
The ACC, DC and ROC are only available as ex factory systems. To get these systems in the FOT, also truck OEMs were involved in the project set up.

Figure 3 shows the ordering of these systems in subprojects, including the number of trucks in each group. In total, 2550 trucks are involved in the project.

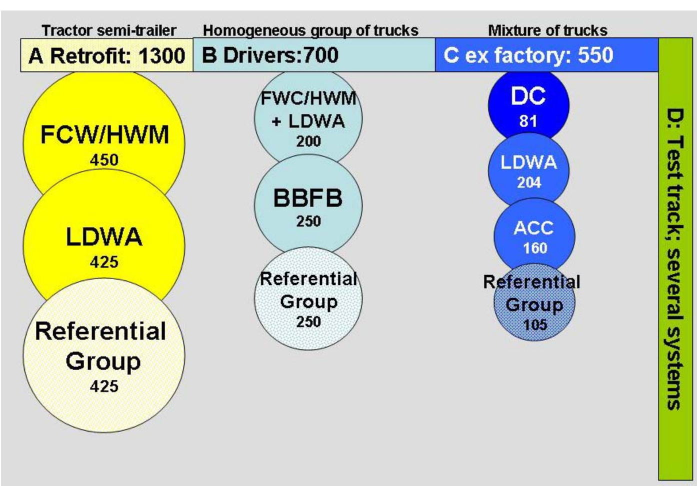

Figure 3. Groups of trucks in the FOT, including numbers

As can be seen from this figure, there are four subprojects. SP A has a focus on retrofit systems, which are being installed on the participating trucks. SP B focuses on actively influencing the driver's behaviour, including the development and use of the new Black Box FeedBack functionality. SP C works on ex factory systems, more cooperation with OEMs is taking place here. The sample groups are some smaller here as it turned out to be necessary to interfere with the actual production process which is not easily done.
SP D focuses on proving ground tests, going into issues which cannot be determined in tests on public roads. Work on SP D Track tests will be discussed in one of the later sections.

BLACK BOX FEEDBACK (BBFB)

At the moment the project was initiated, there were no systems commercially available which inform the driver on his actual driving behaviour. It is expected such system will raise driver awareness on effects of driving behaviour. This can lead to improved driving behaviour and a more effective traffic flow. Therefore, TNO developed in cooperation with the company CarrierWeb a new type of Accident Prevention System, the so-called Black Box FeedBack. This system is based on CarrierWeb's fleet management system, using its existing hardware and interface.
Figure 4 shows an example of the output the driver receives.

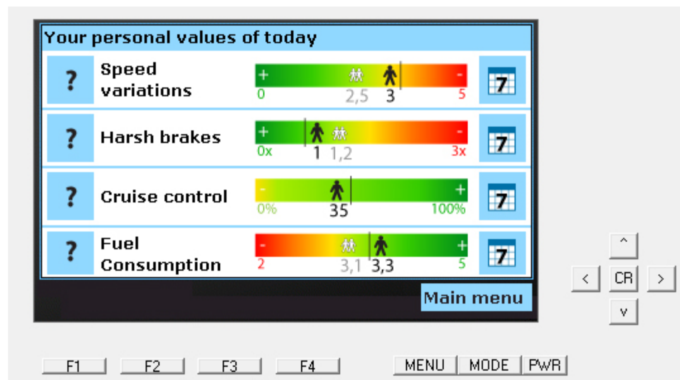

Figure 4. BBFB screen output to the driver on his daily performance

The fleet management system has a connection to the vehicle CAN. Through this connection data are transmitted to the new BBFB software. Amongst the data collected within the BBFB functionality are the vehicle speed, date, time, vehicle ID, driver ID (driver has to log on to the system, and receives personal driving information), acceleration parameters (positive and negative), fuel rate usage, distance driven, number of brakes events and GPS location.

The feedback to the driver includes amongst others:
- Speed fluctuations
- Harsh breaks
- Cruise control usage
- Fuel usage

The driver receives per variable information and explanation of his results of the last day and of the last few weeks. He can compare his results with his own long term average, but also with the long term average of his colleagues. This feature is added on specific demand by a selection of drivers in the test group.

Figure 5 shows the functional principle of the BBFB system.

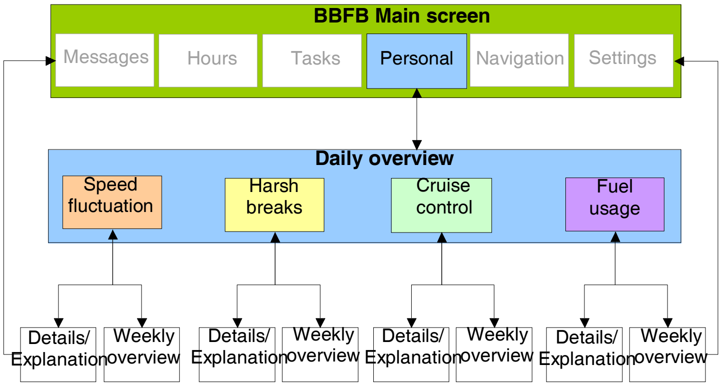

Figure 5. Functional overview of the BBFB system [5]

Feedback to the driver is presented:

- Automatically when the driver indicates that he is having a break
- Automatically when the driver logs off.
- Never while driving (where 'driving' is defined as speed > 5 km/u)
- Upon request

NOT ON THE ROAD, PLEASE

There are some items which could not be tested with large groups of vehicles e.g. due to the increased danger level or the costs.

For systems like DC and ROC, the risk towards roll over during daily transport activities had to be assessed. To do this properly, an extensive sensor system would have to be installed on the truck. This cannot be done for hundreds of trucks as in the full FOT due to high costs of sensors and long installation times. Instead, one truck was fully equipped and used extensively. There were two types of tests in which this specific truck was used: user tests and proving ground tests.

User tests

For the user test, the fully equipped truck was used by several transport companies for one or two weeks in regular transport activities. The participating companies had different types of transport activities.
An important part of the measurement equipment is the so-called RPAS module, a vehicle state estimator for trucks to assess rollover risk, developed and patented by TNO. The concept of the RPAS module is shown in Figure 6.

RPAS determines the rollover threshold value of any truck combination using data from only a few sensors that can be installed easily. The system can be used as an autonomous unit in which the sensors are incorporated and it is generally installed on the trailer. As the rollover propensity of tractor semi-trailer is mainly determined by the loading of the trailer, the internal algorithm is developed to adapt the critical roll value shortly after the load of the trailer has changed. In the user test the algorithm has been applied for post-processing of recorded data.

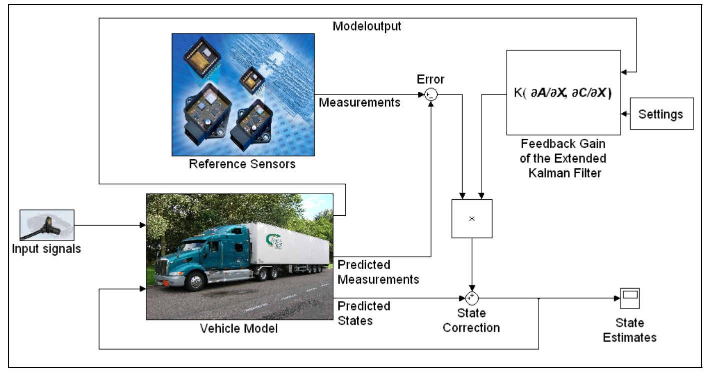

Figure 6. RPAS state estimator concept [6]

During the user test, no emergency situations occurred but nonetheless some interesting observations were made. On the proving ground it was assessed that for this particular vehicle the DC system activates at a rollover risk level of about 55% of the rollover threshold value. During three trips (more than 100 were recorded) the rollover risk marginally exceeded 55%, and during the event with the highest recorded rollover risk (61%) the DC actually was activated. As expected the rollover risk achieves significant values for the loaded truck only. For the unloaded truck the maximum rollover risk during trips never exceeded 45%.

A detailed analysis was made into the situations where rollover risk was relatively high using e.g. recorded GPS coordinates. The largest rollover risk is generally found for cloverleaf motorway junctions and on motorway entrances and exits.

Figure 7 shows the location where the DC intervention occurred during the 7400 km User test.
The rollover risk is indicated in Figure 8 together with measured vehicle speed, steering angle and lateral acceleration.

Figure 7. Cloverleaf with highest measured level of roll over risk and DC intervention.

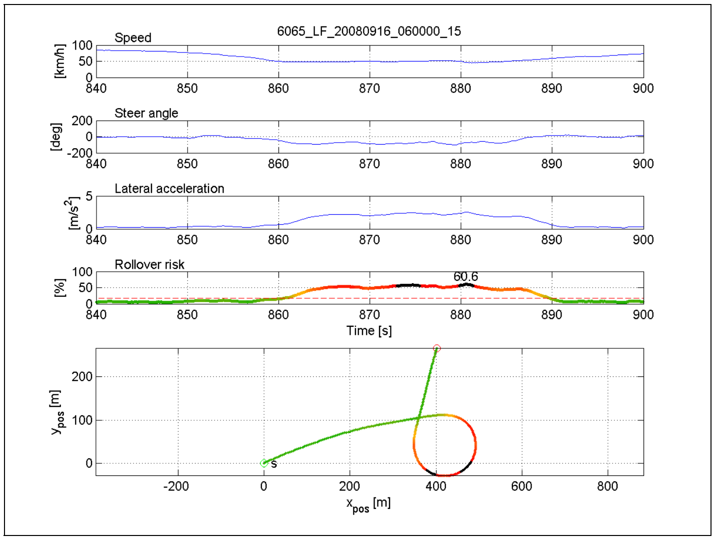

Figure 8. Measured values of speed, steer angle, lateral acceleration and rollover risk for the trip recording with DC intervention

For the occurrence of high levels of roll over risks the vehicle payload is the most influencing factor. Secondly, there is a strong relation with road infra structure, and finally the recordings have also shown that the maximum level of rollover risk is dependent on the driver. In all cases however the drivers maintained sufficient margin towards the rollover threshold so it can be concluded that in general they have a true perception of the vehicle safety levels.

Proving ground tests

On a proving ground, it is possible to go to the limits of vehicle operation. In controlled situations, one can get very close to an accident situation, while still being able to avoid it at a very late moment. Furthermore it is possible to repeat experiments with exactly the same conditions, thus testing several Accident Prevention Systems under the same circumstances.

On the proving ground, experiments were performed with roll over systems, ACC, FCW and LDWA. The test truck was a fully loaded tractor semi-trailer, which was equipped with many data acquisition systems (including the RPAS module). The truck was e.g. approaching a “target vehicle”. The FCW or ACC should in time warn the driver or undertake action, both for moving target vehicles as well as for a non-moving target. The systems were also tested on their ability to make a distinction between a vehicle and road furniture.

Furthermore other tests were performed, like:

- Driving in a constant circle, with increasing speed. Thus, near-critical levels of roll over were achieved.
- Driving in a circle with decreasing diameter, like in slip road situations.
- Braking while driving in a curve.
- Changing lanes, including extreme avoidance maneuvers.
- Line crossings including corrections.

HOW TO COME TO CONCLUSIONS

The FOT is planned to run until the end of June 2009. Only then, a full data set will be available for final analysis. The data from the 2550 test trucks will be combined with data from the track tests, the user test and results found in literature. Of course, data has to be properly collected and combined to have a solid basis for conclusions on the effects of APS on traffic flow and traffic safety.
From the overall project, some intermediate conclusions have been found:

- The preparations for a FOT like this are easily underestimated. The number of partners, the technical requirements and data acquisition are key issues for the success of a FOT.
- There is a huge enthusiasm for the project from the side of transport companies. They made large parts of their fleet available, which did cost them a considerable amount of time.
- For unloaded trucks, the measured level of roll over risk was always below 45%.
- During a majority of working days a moderate level of roll over risk are obtained with a loaded vehicle (45-55% risk level). Drivers normally assess the risk level in time and properly.
- The Black Box Feedback gives drivers information that makes them more aware of their driving habits.

Last but clearly not least: never underestimate the effect of daily life of drivers to your test…….or how lunch packaged in aluminum foil can strongly affect measurements!

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RECONSIDERING ACCIDENT CAUSATION ANALYSIS AND EVALUATING THE SAFETY BENEFITS OF TECHNOLOGIES: FINAL RESULTS OF THE TRACE PROJECT

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ABSTRACT

The objectives of the EU-funded project TRACE (TRaffic Accident Causation in Europe, 2006-2008) are the up-dating of the etiology of road accidents and the assessment of the safety benefits of promising technology-based solutions.

The analyses are based on available, reliable and accessible existing databases (access to which has been greatly facilitated by a number of partners highly experienced in safety analysis, coming from 8 different countries and having access to different kinds of databases, in-depth or regional or national statistics in their own country).

Apart from considerable improvements in the methodologies applicable to accident research in the field of human factors, statistics and epidemiology, allowing a better understanding of the crash generating issues, the TRACE project quantified the expected safety benefits for existing and future safety applications.

As for existing safety functions or safety packages, the main striking results show that any increment of a passive or active safety function selected in this project produces additional safety benefits. In general, the safety gains are even higher for higher injury severity levels. For example, if all cars were Euro NCAP five stars and fitted with EBA and ESC, compared to four stars without ESC and EBA, injury accidents would be reduced by 47%, all injuries would be mitigated by 68% and severe + fatal injuries by 70%.

As for future advanced safety functions, TRACE investigated 19 safety systems. The results show that the greatest additional safety gains potential are expected from intelligent speed adaptation systems, automatic crash notification systems, and collision warning and collision avoidance systems. Their expected benefits (expected reduction in the total number of injured persons if the fleet is 100% equipped) are between 6% and 11%. Safety benefits of other systems are more often below 5%. Some systems have a very low expected safety benefit (around or less than 1%).

INTRODUCTION

The EUropean Council for Automotive Research (EUCAR) launched in 2001 an initiative to develop a systemic approach to the problem of road safety: **Integrated Safety**. The idea was to revisit the Safety problem with a holistic System Approach. In 2008, a few projects (AIDE, PREVENT, EASIS, APROSYS, SAFESPOT, CVIS, WATCH-OVER, etc.) have already produced methodologies and results. Just a few of these research integrated projects or sub projects (i.e. Aprosys, Prevent-Intersafe) called for prior accident analysis in order to start further tasks (development of models, simulations, technologies, demonstrators, tests, etc.) on a thorough understanding of the real-world problems. Consequently, this knowledge is sometimes considered as a missing plinth.

Simultaneously, an eSafety Forum was established by the European Commission DG Information Society in 2001 as a joint platform involving all road safety stakeholders. The Forum adopted twenty-eight recommendations towards the better use of Information and Communication Technologies (ICT) for improved road safety. But, even though former research in accident causation and impact assessment produced a tremendous amount of knowledge, the exact nature of the contribution that ICT can make to road safety could not be determined because consistent EU-wide accident causation analysis was not sufficiently available to gauge this impact. Consequently, the first of these recommendations sought to consolidate analyses from existing accident and risk exposure data sources for a better understanding of the causes and circumstances of road accidents and to determine the most promising and/or effective counter measures. The second recommendation called for the establishment of a common format for recording accident data to develop an information system covering all EU Member States.

Simultaneously, The EU was funding an important project, SafetyNet (The European Road Safety Observatory), which particularly aims at making consistent accident data collection protocols in several EU countries and at constituting an accident databank on injury and fatal accidents.

But the project had just started in 2004 and would provide neither accident data, nor accident analysis in the short term. Moreover this project did not aim at identifying relevant methodologies to evaluate the effectiveness and efficiency of safety systems based on technology. To try to overcome these problems in the short term, one of the e-safety Working Group (Accident Analysis) examined available data sources which were known to them.

The analysis confirmed the hypothesis of the working group that although many information sources already existed, they were not enough as they currently exist to provide Europe with the analysis it needs because the picture obtained was a mixed one. Some data sources were never designed for the purpose of coordinated analysis and therefore have little potential. Some others have their main focus on passive safety, biomechanics or traumatology and do not give much insight into the *causes* of the accidents they contain. Others have considerable potential.

Based on this qualitative analysis of existing sources the working group recommended to the eSafety Forum that existing sources could nevertheless help to give a better understanding on accident causation and to evaluate (at least partially) the effectiveness of some on-board safety functions, if shared analysis mechanisms are employed to interrogate the different data sources and share the results.

The TRACE proposal was born. It was submitted to the EU in 2005, with two main objectives:

- The determination and the continuous up-dating of the **etiology**, i.e. causes, of road accidents and the assessment of whether the existing technologies or the technologies under current development address the real needs of the road users inferred from the accident and driver behavior analyses.

- The identification and the **assessment** (in terms of saved lives, injuries mitigation and avoided accidents), among possible technology-based safety functions, of the most promising solutions that can assist the driver or any other road users in a normal road situation or in an emergency situation or, as a last resort, mitigate the violence of crashes and protect the vehicle occupants, the pedestrians, and the two-wheelers in case of a crash or a rollover.

This current paper gives a synthesis of the principal striking TRACE outcomes. It is therefore a non-comprehensive summary of what is available in the 32 technical and scientific reports that TRACE has generated. The reader is highly encouraged to look at the technical reports for a more in-depth inquiry into TRACE objectives, challenges and achievements.

The paper is split up into 3 chapters. The first one ‘Methodologies’ briefly reports about methodologies developed in TRACE with regards to human factors analysis and statistics. The second one ‘Accident Causation’ reports about the first objective of the project, whereas the third one ‘Evaluation’ reports about the second objective.

Please see [27] for further information regarding the project structure of TRACE and the involved partners.

METHODOLOGIES

Human Factors

Accident causation can seem misleadingly simple, nearly obvious. It is thus often assumed that there is one cause or one road user responsible for an accident and that it would just take determining that cause or this responsible road user, suppressing the first and punishing the second, to prevent the accident occurring. Maybe such a view had reached a relative validity in the old times of the driving system when monolithic defects were easy to diagnose. However, it is less and less proving to be efficient as the system is continuously improving on the basis of research and developments addressing the different components involved. The problem is that, more and more, a cause becomes a cause only if it combines with several other hidden ones, and the so considered 'responsible road user' is more and more the heir of the influence of these combination of factors intervening in the driving interactions. Road safety of the 21st century has become a matter of complexity, apart from some residual extreme cases showing

atypical accident patterns (e.g. involving big holes on the road, breakdown of the car brakes, aberrant drivers' behaviours). In order to keep improving safety, it has become essential to study this complexity. And the more we will gain in safety, the more thorough research works will be necessary to go on progressing.
The European TRACE project is turned towards developing a better understanding of accident causation, in order to reach the definition of more appropriate preventative measures, involving notably electronic safety functions.. Along this objective, Work Package 5 'Human Factors' of this project has been designed to contribute to the development of a deeper analysis of the difficulties encountered by the human component, the road user, in order to promote an improving of the driving system which is put at his disposal. The work done in TRACE WP5 has led to several operational grids of analysis, in line with theoretical models, which offer a means to progressing the understanding of the human role in accident generation, and in the methods allowing a better diagnosis of the causes of human errors, violations, and exceeding capacity. The underlying concept behind these grids is oriented toward a 'safe system model', keeping in mind that the purpose of any device dedicated to a human use should be conceived and built in a way of neither being problematic nor dangerous for its users. So should be the driving system.
In a first step, a grid has been created for analysing the operational difficulties that human beings can find in driving, potentially resulting in accidents [16]. This grid delineates so-called 'Human Functional Failures' (HFF) representing the weaknesses and limits in adaptive capacity of the human functions (perception, comprehension, anticipation, decision, action) to which drivers appeal in order to drive efficiently. And as far as an accident is not intentional for anyone (otherwise it is no more an accident) each HFF is considered as the result of a malfunction characterizing the driving system as a whole. It is a symptom which manifests a wrong interaction between a road user and his driving task environment. Human failure should not be considered – which is often the case - as the cause of the accident but rather as a weak link in a malfunction chain, this chain being necessary to find out if any efficient solution is thought to be defined. Thus, once a human functional failure is diagnosed, it still has to be defined which factors and which contexts have originated it.
The problem with many accident causation coding systems currently used across Europe is that they do not separate the 'errors' (or human functional failures) from the 'factors' which lead to these failures. The second step of the methodological work consisted in building a grid allowing the determination of all the elements (factors) - would they be referring to the road layout, the vehicle parameters, the driver or the traffic surrounding - that could originate or favour a Human Functional Failure, not confusing these factors with their consequences [17]. A complementary grid also provides a classification of 'pre-accident driving situations' in which human failures occur. These pre-accident driving situations are built from a combination of: 1- the types of driving tasks (e.g. overtaking, crossing, turning), 2- their location (e.g. intersection, straight road, roundabout) and 3- the potential conflicts met in the situation (e.g. pedestrian crossing, oncoming vehicle, car door opening). The precise characterisation of these pre-accident situations in accident studies allows definition of the circumstances in which road users find difficulties.
A third step of this methodological work consisted of providing a method allowing the aggregation of similar accident processes on a multidimensional level (a scenario) [18]. The method consists in building typical scenarios of human failure production, integrating the elements studied in the previous steps. The Typical Human Functional Failure Scenarios represent the regularities which can be found in the process governing similar accidents. They are expressed under the shape of chains which connect a pre-accident situation, explicative elements involved, a consequent human functional failure and a resultant critical situation leading to a crash configuration. But a main difficulty in the determination of all these detailed variables is the necessity to base them upon in-depth accident data performed by specialists in the different domains. In order to allow accidentologists using data that doesn't fulfil these ideal conditions (i.e. in-depth, involving psychologists), we have defined the most frequent scenarios found in the study of a large sample of in-depth accident cases, on which to base in order to recognize the overall process on a 'family air' basis, which can be done from less in-depth data.
A last methodological work performed in TRACE WP5 is differentiated from the previous ones in its more prospective purpose. It was aimed at enlarging the classical view on driving behaviour determinants by incorporating the social and cultural dimensions as further upstream factors of human functional failures. Factors such as culture, social status or specific social group membership have an identifiable influence on individual behaviour. It presents a scheme of analysis built upon the notion of 'social spheres' [19]. This scheme is aimed at showing the relative influence of the different layers ('spheres') of socio-cultural variables that are located outside the individual

sphere and which can potentially have a latent or manifest influence on the production of an accident. The integration of such socio-cultural background variables in the analysis of human failure production has the potential to increase the understanding of the accident causation process and to find additional means to fight against. These aspects should notably be taken into account when dealing with driving aids, so as to appropriately answer the needs and constraints coming from different drivers' social groups.

The different deliverables of WP5 have been provided to progress the search for understating accident causation and its underlying and upstream determinants. As such they contribute to the European TRACE project objectives of promoting a scientific knowledge on accident causation, so as to better defining the safety measures able reducing it. In this respect, the overall point of WP5 is to remind that the road user is the core of the driving system, and human performance the measure of its effectiveness. That is why possible human failures must be studied in-depth, their causes and producing contexts clarified in order to put forward the most efficient measures able at harmonizing human travelling behaviour inside the traffic system. The methods proposed regarding as 'Human Factors' allow a more integrative approach inside accident research in Europe. This is being done in numerous studies conducted in TRACE operational work packages, addressed to the different road user groups (elderly drivers, PTW, passenger cars, gender issue, etc.), to the main identified driving situations (intersection, specific manoeuvres, degraded situations, etc.) and to the most involved factors (vigilance, attention, experience, infrastructure, etc.). These different studies increase the understanding regarding human factors in accident causation and the necessity to develop a safe system well addressed to human needs. And the 'human factors' methods put forward in TRACE WP5 will be useful and constructive when considering the building of a comprehensive European road safety observatory.

Statistical Analysis Methodologies

The overall objectives of TRACE WP7 ‘Statistical Analysis’ have been twofold:

- to improve statistical methodology for diagnosis of road safety problems and evaluation of promising technological solutions
- to provide methodological advice and statistical services to other TRACE work packages.

In its empirical part, the TRACE project exclusively relies on *existing* European data on traffic safety. Thus, statistical methods for collecting accident and exposure data have not been treated. Rather, quantitative methods serving the following purposes have been investigated:

- methods for improving the usability of existing accident and exposure databases
- methods for traffic accident causation studies
- methods for accident and injury risk studies
- methods for safety functions effectiveness evaluation and prediction.

WP7 has also provided traffic safety researchers with a statistical expansion method for addressing accident causation issues at European level accounting for the fact that accident and exposure data availability varies substantially between the countries.

In all these areas the scientific work under WP7 has developed operational statistical models in the conceptual framework of general “systemic” theories of the accident generating process. Emphasis was put in WP7 on careful selection, adaptation and application of appropriate classical and newer implementation-ready methods from the various fields of the statistical sciences. For all results both scientific rigor for the statistical community and accessibility for empirical accident researchers had to be achieved. The principal aim of WP7 was to provide best practice examples of high-quality traffic safety research using up-to-date statistical methods.

Improving the usability of existing accident databases. The purpose of this activity has been to enable traffic safety researchers to make best possible use of existing European accident and exposure databases [21]. Therefore, the task has covered methods to overcome typical accident and exposure data quality problems like missing values, missing variables and biases due to selective data collection.

Under certain conditions data quality problems of the types listed above can be overcome using appropriate statistical methods: imputation methods for treating data with missing values, data fusion methods for supplementing missing variables and weighting and expansion methods for reducing biases due to selectivity of sampling in in-depth studies have been studied.

Frequently, researchers need to address accident causation issues at the European level in situations where no complete empirical data is available. Therefore, an expansion method for creating synthetic tables at EU level, by combining detailed data from regional studies or national sources with coarser structural information on traffic accidents in Europe as a whole under an appropriate statistical model, has been developed.

Analysis methods for accident causation studies. It is obvious that accident causation analysis is a matter of importance in TRACE. In order to provide appropriate methodological support to the operational work packages, this task deals with analysis methods for accident causation studies. Emphasis lies on exploratory or hypothesis-generating methods, as confirmatory or hypothesis-testing methods of accident and injury risk analysis [23].

First, a theoretical framework for causal analysis in accident causation research has been proposed and problems linked with establishing causal relationships have been discussed. Then, in view of the huge volume of many accident databases, some data mining tools have been investigated which are highly relevant for accident experts. Specific 2D graphical representations (self-organizing maps) of the different risk factors can provide, at a glance, a qualitative understanding of possible accident causes. In a subsequent step, information theoretic methods (mutual information ratio) can be used to quantify more precisely the impact of each single factor. By automatic learning, a function can be constructed to forecast, for instance, accident severity given a set of pre-selected factors.

In addition, nonparametric statistical methods which do not require any model presumptions have been examined and applied to measure the relationship between injury risk and potential determining factors.

Analysis methods for accident and injury risk studies. In studies of traffic accident causation, researchers frequently aim to assess risk factors for accident involvement and accidental injury. Consequently, this task provides the operational work packages of TRACE with appropriate methodological tools from accident and injury epidemiology [22].

As different types of accident and exposure databases are encountered in the TRACE project, special emphasis is placed on study designs which fit to the available data sources. Among other things, it has been shown how to conduct accident causation studies using easily accessible routine accident and exposure data under different study designs such as, for instance, the case-control design. Analysis methods for accident causation studies relying exclusively on accident data (concept of induced exposure) have also been critically examined. The tailor-made statistical tools treated in this task enable accident researchers to identify whether there is a relationship between a set of potential risk factors and accident involvement or accidental injury.

In order to make the statistical concepts and methods easily accessible also to researchers who are not experts in statistics and/or epidemiology, numerous examples and detailed empirical case studies have been integrated in the technical reports.

Evaluation of the safety benefits of existing safety functions: statistical methodologies. The aim of this task has been to develop and improve quantitative methods for ex post evaluation of the effects of specific in-vehicle safety functions. Appropriate analytical approaches have been investigated for this purpose. The methods developed under this task have been extensively applied in TRACE WP4 “Evaluation” [24].

The scientific work deals with statistical methods for evaluating safety features which are already on the market. The methods - exclusively relying on empirical traffic accident data - are not only suitable for the evaluation of individual safety devices but may also be applied to assess any combination of passive and active safety features. It is shown in detail how to compute accident avoiding effectiveness as well as injury avoiding and injury mitigation effectiveness taking account of confounding factors where necessary. The methodology is demonstrated on real-world data examples.

Concluding remarks. Basically, the scientific work carried out under TRACE Work Package 7 “Statistical Methods” has dealt with the following two questions:

- How can statistical methods contribute to improve our empirical knowledge on traffic accident causation in Europe?
- How can statistical methods contribute to identify safety systems suitable for traffic accident prevention and accidental injury mitigation?

The application of statistical methods in the field of traffic safety has a long tradition. Thus, it was clear from the outset that among the statistical sciences especially the discipline of *epidemiology* offers a wide variety of concepts, methods and models that can be applied either directly or after some proper adaptation to answer the above research questions.

- Study of the *incidence* of accidents and of the frequency distribution of accident characteristics is essentially a descriptive exercise. This, however, does not mean that only the methods of descriptive statistics are relevant. As accidents and accidental injuries occur randomly, analytical methods based on probability models, e.g. models and methods of sampling theory are needed already at this stage.
- Research on the *determinants* of road traffic accidents can best be conducted under an epidemiological framework providing the accident researcher with suitable study designs and analysis tools. Study of determinants considers the *aetiology* of accidents and accidental injury. In this context, of course, a distinction has to be made between potential and proven aetiological agents. Especially when

using routine data on traffic participation and accident involvement the empirical findings referring to risk factors for accident involvement may be largely descriptive and should not be over-interpreted in a causal sense.

- Likewise, assessment of the *effectiveness* of innovative safety systems already launched onto the market must also observe the methodological principles developed in epidemiology. Ex post evaluation of new safety systems should especially utilize the methodological principles developed for observational studies where it is difficult or even impossible to find a control group in the classical sense. As has been shown in the TRACE Reports, proper epidemiological model building is essential if meaningful conclusions on the effectiveness of single or multiple safety functions are to be drawn.

As can be seen, statistical methods in general together with specific concepts established for high-quality epidemiological research are indispensable tools both for establishing accident causation factors and for evaluating safety systems aiming at accident prevention and injury mitigation.

In the TRACE reports, a large number of classical and newer statistical methods, including methods from the field of artificial intelligence, have been investigated and explored for use in accident causation studies and safety system assessment. As can be expected, these methods differ in their degree of suitability for accident research purposes. In the conclusions, this aspect is addressed. In addition, it is always clearly stated whether or not the method under consideration is accessible to traffic safety analysts not specializing in statistics or should better be applied by statistical experts only.

Not surprisingly, one comes to the conclusion that high-quality research on traffic accident causation presupposes correspondingly high methodological standards. These standards, of course, can best be ensured in interdisciplinary teams involving experts from statistics and epidemiology. The TRACE project serves as a good example of this.

Data

Work Package 8 was the data provision work package of the TRACE Project [25]. The analysts working in the other Work Packages were able to request data from designated data providers. The objective of Work Package 8 was not to produce a database of harmonised data. It was to provide suitable aggregated data (crosstabulations) from existing individual databases that analysts could consider in answering the specific research questions of the Work Packages.

The main features and achievements of the work of Work Package 8 are summarised below.

An effective Data Exchange Methodology that is both understandable and suitable has been put in place, allowing TRACE to make the best use of existing data.

Participants in Work Package 8 have successfully prepared large, complex sets of data tables for the analysts in the Operational Work Packages of TRACE.

- At least 940 requested tables, in 83 worksheets, as part of 23 data requests have been handled.
- Approximately 3,700 tables of data have been prepared and returned to analysts. The concept of counting data packages and monitoring effort has had to evolve and be reshaped as the project developed but the volume of data exchange is as large, if not more, than originally planned.
- In light of an expected lack of risk exposure data, analysts have been provided with a tool to understand and access a wide range of data already published.

Recommendations for future European data gathering activities are made, along with support to current initiatives from a TRACE perspective:

- Continuing harmonisation of variables and definitions, for descriptive, in-depth and exposure data. This would allow both easier data provision and analysis.
- Development of a Pan-European accident classification coding system. Accident classification is an important step in both understanding accident causation and evaluating the potential of new safety systems.
- Harmonisation of accident causation coding systems. Any proposed systems should be tested against the broad and in-depth questions posed in the TRACE tasks.
- Development of European field operational tests. An understanding of human interaction with new vehicle technologies (both for safety and comfort) will allow a much fuller evaluation of the potential effect of such devices on safety.
- Development of European risk exposure data. Greater availability and depth of risk exposure data would allow a new perspective on the analysis of accident causation.
- Further development of the CARE database and interface. More countries would allow a better European context, and further development of the interface would give more flexibility when examining specific accident scenarios.

ACCIDENT CAUSATION

Current knowledge needs to be structured and linked to specific research angles and analysed according to specific methodologies to avoid misunderstanding and to allow a clear view of what accident causation is. Therefore, TRACE had three different research angles to cover accident causation issues:

- The **Road user approach**: it allows identifying specific causation factors for specific road users.
- The **Types of situation approach**: as the road user can be confronted with different driving situations, that can develop into different emergency situations, that deserve specific analysis regardless of the road user type.
- The **Types of factors approach**: factors can be identified and observed according to social and cultural factors, factors related to the trip itself and factors related to the driving task.

These 3 approaches are developed according to three different kinds of analyses:

- A macroscopic statistical analysis aimed at describing the main problems.
- A microscopic analysis aimed at describing the accident mechanisms with the use of in–depth data.
- A risk analysis aimed at quantifying the risk factors in terms of risk, relative risk and, where possible, attributable risks.

TRACE produced a lot of research outputs combining these three approaches and these three types of analysis. We are reporting below only the main findings [1, 2, 3, 4, 5, 6, 7, 8].

Types of factors

A variety of theories on accident causation exists and up until today no synthesis has emerged [5]. Theories and models reflect peoples' views on reality to explain complex relations in simplified ways. The motivation lies in the belief that every accident can be prevented, if the causes for this accident can be eliminated. Accident Models help to understand the occurrence of traffic accidents and give answers to questions on how and why accidents happen, where and when they take place, and who is involved, and furthermore to find according preventive measures.
Epidemiological studies can reveal risk factors for crashes that increase the chance for an accident to occur or the chance for someone to cause, or just be involved in an accident. Additionally, in-depth accident research identifies factors that contributed to a specific accident and are able to explain the occurrence of the accident. This is done by applying causality to certain factors that led to the accident. Most in-depth accident databases provide a list of factors, from which the investigator can choose the factors that contributed to the accident. Some investigation classifications code key events or triggering factors, in addition to also considering the most important factors, or the last factors, that finally caused the accident in the causal chain in time, respectively.
Of course, usually one factor cannot cause an accident. Most often a combination of contributing factors, forming a sufficient cause, leads to the accident [5, 16].
In the model, the classification of accident related factors is two dimensional. One dimension is expressing the time (accident process) by levels, and the other dimension reflects the origin from where a factor stems from (from a "traditional view") by components. Generalised examples are used in the table 1 to visualize the classification of factors.

Table 1. Classification of accident related factors

Levels and Components	Background factors	Trip related factors (task 3.3)	Driving task associated factors (task 3.4)
Environment	Modes of Transport, Climate	Road characteristics	Road and light condition
Vehicle	Vehicle fleet, safety standards	Vehicle type and maintenance status	Vehicle condition and performance
Human	Transportation politics, Socio-demographic characteristics (task 3.2)	Physical and mental state	Actual behaviour and performance

The analysis showed that already on a random choice of cases, a lot of sociological and cultural factors are found, that influence the following acts, behaviours, vehicles involved in the accident etc. But, of course it is not possible to explain every accident in sociological terms. And this is not wanted from a prevention point of view, which in modern society of course tries to protect the individuals but also tries to give responsibility back to the individual. It is however, necessary to know the underlying reasons for some factors found on a trip or even driving task level. Sociological and cultural factors are just one component of the background factors, although strong interactions between those factors and environmental and vehicle related factors on a background level can be expected.

It has been possible to identify not only the most 'typical' characteristics of accidents where trip related or driving task-related factors are involved but also to identify the main reasons for what went wrong in the accidents where these factors and their associated characteristics, are present.

After screening literature and accident databases to find, define and classify relevant factors, the results from methodological WP's were also taken into account to decide how to proceed. It was decided to especially analyse accidents where the following factors contributed by statistical database analysis and some of the factors also by in-depth case analysis: alcohol, vigilance, experience, vehicle condition, road condition and layout, attention, sudden health problems, speed (including 'inappropriate speeding' and 'illegal speeding'), and technical defects.

Factors are regarded to be relevant either by risk increase or by high prevalence as contributing to accidents. After screening literature and accident databases to find, define and classify relevant factors on the trip and driving task level, the results (methods) from methodological WP's were then applied to accidents caused by the relevant factors.. Following factors were analysed by statistical database analysis and by in-depth case analysis applying the WP5 human functional failure analysis: alcohol, vigilance, experience, vehicle condition, road condition and layout, attention, sudden health problems, speed (including 'inappropriate speeding' and 'illegal speeding'), and technical defects.

According to the different methods and databases used the results are manifold when analyzing accident causation from a factors point of view. One interesting result e.g. is that an alcohol related accident is predominantly found for pedestrians and/or cyclists in the UK, Germany and the Czech Republic, whereas in Spain, Italy, and France all road user groups are affected. Another example for the results is the notion that if a young driver (<25years) is involved in a driving accident with frontal impact on a rural road with a speed limit between 60 and 100km/h in winter and nighttime, then it is very likely that the road condition and layout contributed to this accident. And the next example stems from the functional failure analysis for alcohol related accidents: Whereas the primary active road user (the one inducing the accident situation) often is the impaired one showing loss or restrictions in consciousness and ratio, for the opponent often visibility (of the active road user) plays an important role in contributing to the accidents occurrence. The failures of "Expecting a non-priority vehicle not to undertake a manoeuvre in intersection" or "Road user surprised by a pedestrian (or two-wheeler) on approach" shows a tendency for the fact, that the primary active road user (here: the alcoholised one) performed unforeseeable actions that were not possible to see (visibility) or predict from the opponents point of view and the accidents therefore hardly to avoid.

In general it has been possible to identify not only the most 'typical' characteristics of accidents where trip related or driving task-related factors are involved but also to identify the main reasons for what went wrong in the accidents where these factors and their associated characteristics, are present.

Types of users

TRACE WP1 (Road Users) addressed the analysis of the different accident causation mechanisms of each of the road user groups (passenger car occupants, powered two wheelers, van, bus and trucks occupants, pedestrians and pedal cyclists, elderly people and gender related crashes). Some of the findings for passenger car occupants are reported below, after having given a look at the general statistics of mortality (figure 1), which show that other road users are also of high interest in terms of mortality and accident process. Other findings for the other types of users are available in the TRACE reports [1, 2].

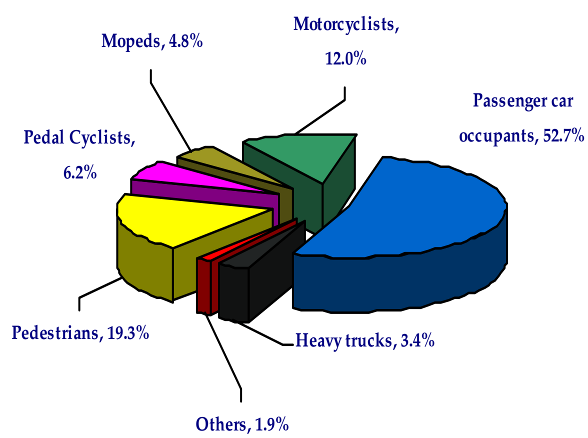


Figure 1. Distribution of Road Fatalities on the European Roads (Source: ERSO).

Passenger Car Drivers. When examined from the angle of human functional failures, it can be noted that cars drivers are particularly prone to perception errors, this category of failures being observed in 35.7% of the cases that compose the studied sample.

The most frequently identified pre-accident situations are spread between the driving ‘Stabilized’ situations and the tasks to perform when managing intersection crossings (‘Going ahead on a straight road’ 15.2% and ‘Crossing intersection with a priority vehicle coming’ 12.7% are the most frequent pre-accident situations observed in the sample).

The study of explanatory elements also brings information on the way functional failures occur. Several elements come out (‘Atypical manoeuvres from other users’, ‘Road over familiarity or monotony of the travel’, Choice of too a high speed for the situation’, etc.), but it can be seen that again the distribution of the elements is wide-spread.

These results shed light to the interest of looking at the data in a more relevant way than the overall one, so specificities can emerge more clearly. Two categories of crashes have been studied: Single cars accidents and cars vs. other road users.

When analysed separately, the drivers of the single car accidents sample feature a specific profile. Firstly because their accident happens when the task to perform is quite simple: the pre-accident situations are always related to stabilized situations and more specifically to guiding the vehicle on the carriageway (either or straightway road or during curve negotiation).

Additionally, the human functional failures associated to those drivers are typical of losses of control. Here are found, in 40 % of cases , handling difficulties (associated with attention impairment or external disturbance such wet carriageway or wind blast).

The losses of psycho-physiological capacities are also found in the same proportions (38.7%) as being the cause of the single car accident. This loss is mainly due to psychotropic intake (alcohol for the major part of the drivers) but the drivers falling asleep account for 15.4% of those accidents.

At last, in 1 case out of 5, the drivers have had troubles to perform a correct evaluation of a road difficulty. Those losses of control are related to changes in road situations in almost 1 case out of 4 but the layout is not the only element that should be underlined here. The majority of factors are endogenous, that is associated to drivers' states or their conditions of task realization. What is found as having an influence on the losses of control are: in one third of the cases, the alcohol intake; the speed chosen by the drivers (36.7%); the level of attention allocated to the driving task; and at last the level of experience of the road users, either concerning their driving knowledge, the familiarity they have of their vehicle or of the location of the accident.

All these explanatory elements have a role when combined with each other until the drivers fail to perform the task, although quite simple, as if this particular association of parameters was having influence on the most rooted abilities developed in driving activity, the skill-based ones. On the other hand, the accident mechanisms observed for the group of multi-vehicles collisions are various. First in the tasks to realize: they cover many pre-accident situations and concern stabilized situations as well as intersection crossing of specific manoeuvres. This heterogeneity is also found in failures and explanatory elements. It is then with the help of the typical generating failure scenario that light is brought on the specificities of this population.

Perceptive failures are central in these kinds of accidents and they reveal the multiplicity of the problems encountered by the drivers when they interact with others:

- Visibility constraints are decisive in almost 6% of the accidents cases, especially when they prevent the drivers from detecting the atypical manoeuvre of the other road users.
- The search for directions and the monitoring of potential conflict with others are the causes of monopolisation of the driver's attention, leading him to not detect the relevant information.
- A low level of attention devoted to the driving task has also impact on the detection of the other, especially if the task to perform is familiar and if the environment is dense and the traffic important, or if the driver is lost in his/her thoughts.

Misleading indications are also at the origin of some 'Processing' distortions. A same indication sometimes having several meanings and being then ambiguous, the driver undertakes the wrong manoeuvre regarding the other's behaviour.

The wrong expectations concerning the others' manoeuvres are also very represented in this sample of passenger cars drivers. Although those manoeuvres are sometimes difficult to anticipate, the rigid attachment of their right of way status that the drivers develop is generally at the core of the scenarios putting forward those 'Prognosis' failures and scenarios.

Types of situations

TRACE identified four specific groups of situations covering the majority of the real-world driving situations:

- Stabilized Traffic Scenarios concerning every normal driving situation that can become risky due to specific failures (e.g. guidance errors) or sudden conflict situations with other road users.
- Specific Manoeuvre Scenarios including accidents due to scenarios created by performing specific driving manoeuvres (e.g. overtaking, U-turning, car-following, joining a carriageway, etc.).
- Degradation Scenarios gathering accidents concerned with the presence of factors which degrade the road way, the environment (fog, heavy rain) and trigger accidents.

- Intersection Scenarios that concern every situation occurring at or close to an intersection.
Examples of analysis concerning the three first situations are given below. Intersection scenarios are reported in a separate paper .

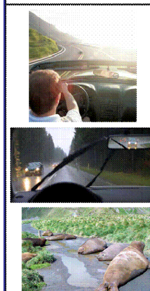
Stabilized situations. These situations represent 49% of the total number of situations in EU27 and 33% of the total number of injury accidents in Europe (estimation relying on results coming from Spain, UK, France, Greece and Czech Republic). The main results regarding the identification of the causes are the following:

In-depth analysis	Collision with a pedestrian	Lane departure/ run-off accident	Accident with more than one vehicle
Key events	Pedestrian has a recognition error, crossing or invading the road illegally. Also, the pedestrian made an error recognition and low level of attention	Speeding Decision error Alcohol impairment Low level of attention Environmental perturbation Complex or difficult site, narrow road	Opponent error: Speeding Opponent car decision error Stabilized car decision error Stabilized error: Not keeping safe distance Stabilized state: Low level of attention
Human Functional Failures	Detection: The passenger car driver was surprised by the pedestrian non visible	Diagnosis stage: The passenger car driver has an erroneous evaluation of the bend in a context of playing-driving and of an although known bend. Handling stage: Guidance interruption consequently to attention orientation towards a secondary task	Handling stage: The stabilized vehicle sudden encounter of an external disruption. Loss of psycho-physiological capacities consequently to a failing asleep or ill-health from the opponent vehicle. Detection: Late detection of the slowing down of the vehicle ahead
Risk factors (increase)	Straight sections Pedestrian gender (male)	Driver gender: male Bad weather conditions Single carriageway road Sharp curve Night lightning	Slight curves Bad weather conditions Night lightning Double carriageway road

Specific manoeuvres. These situations represent 7% of the total number of situations in EU27 and 24% of the total number of injury accidents in Europe (estimation relying on results coming from Spain, UK, France, Greece and Czech Republic). The main results regarding the identification of the causes are the following:

	Overtaking	Turning left	U-turning	Changing lane
Key events	1. Internal conditions of the task: a. Incorrect driving manoeuvre b. Poor evaluation / anticipation 2. Driver behaviour Looked but did not see			
Contributing factors	1. Inadapted speed 2. Careless, reckless or in a hurry 3. Risky driving 4. Excessive speed	1. Automatic driving 2. Global time constraint 3. Risky driving 4. Mobile mask	1. Risky driving 2. Global time constraint 3. Low level of attention 4. Careless, reckless or in a hurry	1. Restlessness 2. Risky driving 3. Alcohol / drugs 4. Inadapted speed
Human functional failures	1. Decision 2. Action 3. Diagnosis	1. Perception 2. Decision 3. Diagnosis	1. Perception 2. Decision 3. Diagnosis	Not available
Counter-measures	-To adapt the speed to the situation and to the legal limit speed -Collision warning system -Collision avoidance system -Inter-vehicle communication system -Lane changing assistance -To respect laws -ESC/TCS	-Inter-vehicle communication system -To respect laws -To help the driver to see	-Blind spot monitoring -Inter-vehicle communication system -To respect laws	-Inter-vehicle communication system -Alcohol and drug preventio -To adapt the speed to the situation and to the legal limit speed

Degradation situations. The accidents in degraded conditions (in dark and/or bad weather conditions only) represent 35% of the total number of injury accidents in EU27, 46% of the overall fatalities (3% of the casualties in degraded situation) and 39% of severely injured (14% of the casualties in degraded situation). The main results regarding the identification of the causes are the following:

	Key events	Human fucntional failures
	❑ "Risk taking" was the most commonly identified factor group within degraded lighting, degraded weather and degraded road surface ❑ "Distraction" was also a commonly occurring factor group within carriageway hazards, along with "visibility impaired" ❑ "Psychological condition", "distraction", "road condition", "visibility impaired' were also prevalent.	❑ The presence of degradation in general mainly led to either failures in detection (i.e. the degraded situation restricted the road user's visibility) or failures when taking action (i.e. the degradation directly affected the road user's control of their vehicle, such as when manoeuvring around a bend). ❑ Accidents where degraded lighting was a cause mainly led to failures in detecting a conflict ahead, ❑ In accidents where degraded road surfaces were a cause, the road user experienced a failure when trying to keep control of their vehicle ('taking action') ❑ Both degraded weather and hazards were found to lead to a failure in two ways, either in detection (visibility restricted) or when taking action (keeping control of vehicle)

EVALUATION

The second principal aim of TRACE was to investigate the impact of advanced safety functions on reducing several types of injury crashes involving passenger cars or restricting (mitigating) crash consequences (so-called safety benefits). WP6 provided at the beginning of the project a list of the most promising safety functions that address current and future accident types on European roads.
The evaluation has been performed from two different perspectives:
- Assessment of the potential proportion of injury accidents that could be avoided and of the potential proportion of injury accidents whose severity could be reduced, for safety functions, of passenger cars, not already on the market (this is the so-called *a priori effectiveness*).
- Assessment of the actual proportion of injury accidents that could be avoided and of the actual proportion of accidents whose severity could be reduced, for safety functions, of passenger cars, already on the market (this is the so-called *a posteriori effectiveness*) once the cars are equipped with existing functions.

A Priori Effectiveness

Different methods have been applied and different data used [9, 10, 11, 12]. The allocation of the safety functions to different methods is presented in table 2.
These different methods are presented extensively in the TRACE reports. It is also argued why different methods were necessary and why, given the low effectiveness of some safety functions, it is assumed

that the discrepancies between the methods are not introducing too much bias in the comparison of the results.

Table 2. Safety functions selected for evaluation and method used for evaluating the safety benefits

#	Safety System	Method			
		"Target population" method	Effectiveness evaluation	Unit HARM	Neural Networks
1	Tyre Pressure and Monitoring	X			
2	Lane Keeping Support	X			
3	Lane Changing Support	X			
4	Cornering Brake Control	X			
5	Traffic Sign Recognition	X			
6	Intersection Control	X			
7	Intelligent Speed Adaptation		X		
8	Blind Spot Detection		X		
9	Alcolock Key			X	
10	Advanced Automatic Crash Notification			X	
11	Night Vision			X	
12	Collision Avoidance				X
13	Predictive Brake Assist				X
14	Dynamic Suspension				X
15	Drowsy Driver Detection System				X
16	Advanced Front Light System				X
17	Rear Light Brake Force Display				X
18	Collision Warning				X
19	Advanced Adaptive Cruise Control				X

The target population method (calculating only the proportion of crashes addressed by the function) is used only for cases where this population is low and does not imply a full calculation of effectiveness. Neural Networks are used to investigate the impact of primary safety functions on restriction of accident consequences. The proposed approach investigated the effectiveness of several safety functions on different accident configurations, by estimating the influence of each safety function on different accident parameters. The evaluation is performed in terms of assessment of the potential proportion of accidents whose severity could be reduced, for each safety function. Other methods are chosen according to the function under study, availability of data and relevance of the method. Full definitions of the functions are described in the TRACE reports. We are just reporting here their generic titles which are sufficient to understand the concept but not to understand how they work.

The main results coming out from the analysis are presented in table 3. This table shows the overall effectiveness evaluation results for the selected nineteen (19) primary safety systems for *passenger cars* that have been studied in TRACE. In table 3 the safety systems effectiveness is presented in terms of:

- **Fatalities saved**: The percentage of fatalities that could be saved by the safety function if the fleet is 100 % fitted with this particular function.
- **Serious injuries saved**: The percentage of serious injuries that could be saved if the fleet is 100 % fitted with this particular function.

It should be noted that, in this table, the absence of calculated values in fatalities saved for some of the safety systems occurs because these values have not been calculated (and thus are not available) and does not suggest that those systems do not provide any benefits in terms of fatalities saved. Additionally, it should also be noted that in some cases the percentage of the effectiveness in terms of fatalities saved is higher than the corresponding percentage in terms of serious injuries saved. However, this does not imply that more fatalities (in absolute numbers) than serious injuries would be saved, since in most accident configurations the number of injuries is much higher than the number of fatalities.

The results show that the greatest additional safety gain potentials are expected from intelligent speed adaptation systems, automatic crash notification systems, and collision warning and collision avoidance systems. Their expected benefits (expected reduction in the total number of injured persons) are between 6% and 11%. Safety benefits of other systems are more often below 5%. Some systems have a very low expected safety benefit (around or less than 1%).

Table 3. Potential safety benefits of safety systems

Safety System	Safety Function	Effectiveness (%)	
		Fatalities Saved	Serious Injuries Saved
Intelligent Speed Adaptation (**)	Drive Safe	17	11
Advanced Automatic Crash Notification (***)	Rescue	10,8	-
Advanced Adaptive Cruise Control	Drive Safe	-	11
Collision Avoidance	Drive Safe	-	9,1
Collision Warning	Drive Safe	-	6,6
Traffic Sign Recognition (*)	Drive Safe	-	5,8
Lane Keeping Assistant (*)	Drive Safe	-	5,7
Night Vision	Visibility	3,5	4,8
Blind Spot Detection (*)	Drive Safe	2,5	4
Lane Changing Assistant (*)	Drive Safe	-	3,1
Alcolock Key(***,#)	Drive Safe	6	3
Drowsy Driver Detection System	Drive Safe	-	2,9
Intersection Control (*)	Drive Safe	-	2,3
Cornering Brake Control (*)	Braking Systems	-	2,3
Tyre Pressure Monitoring and Warning (*)	Drive Safe	-	1,3
Rear Light Brake Force Display	Visibility	-	0,8
Advanced Adaptive Front Light System	Visibility	-	0,6
Predictive Assist Braking	Braking Systems	-	0,2
Dynamic Suspension	Handling/Kinematics	-	0

** The potential magnitude (target population) of the effectiveness has been calculated*
*** The numbers are for the 'Driver Select' ISA configuration which has been estimated as the most effective*
**** Results based on non-European data*
 # For the Alcolock Key the results for the mode "All newly registered vehicles (First full year)" with effectiveness 25% is used which gives the highest results but it is above the average performance of Alcolock key
N/A Not Applicable
- Value not available

A Posteriori Effectiveness

The first task of this part was to select the safety applications to be studied. Depending on the availability of crash data and also considering the actual low penetration rate of active safety functions, we have selected for evaluation the Electronic Stability Control (ESC) and the Emergency Brake Assist (EBA) systems.

As for the passive safety systems, newer cars are designed to offer good overall protection. Car structure, load limiters, front airbags, side airbags, knee airbags, pretensioners, padding and non aggressive structures in the door panel, the dashboard, the windshield, the seats, the head rest also participate in supplying more protection. The whole package is then very difficult to evaluate separately, one element independently from the others. We have then decided to consider that we would evaluate in TRACE the safety of the whole package, this package being, for the sake of simplicity, the number of stars awarded at the Euro NCAP testing.

The challenges were to compare the effectiveness of some safety configuration SC I with the effectiveness of some safety configuration SC II [14, 24]. A safety configuration (SC) can be understood as a package of safety functions.

Ten comparisons have been carried out and the evaluations presented in table 4 are now available [15].

The evaluation of the potential safety benefits of existing safety functions is expected to be carried out at the EU25 or EU 27 level. It would mean that:

- either the relevant data is available at that level and the above-mentioned analysis is done with the European data
- or the relevant data is not available at the EU level and the analysis is done with the data available in a selection of countries, the results being *expanded* at the EU level with an appropriate technique.

The relevant data is actually not available at the EU level. We have then chosen to conduct the analysis with the French data and try to expand the results at the EU level if possible.

As explained and discussed in the TRACE reports, the data relevant for such an analysis is a macroscopic accident dataset in which we can get information about vehicles involved in crashes (and especially their equipment) and about the crash and the impact configurations. We chose to use the French Injury Crash census.

Table 4: Evaluation of the effectiveness of existing safety package

	Reduction in injury accidents (accident avoidance)	Reduction in all injuries & fatalities	Reduction in severe injuries and fatalities
Safety benefit of EBA given that the car has four stars (Euro NCAP).	-3.2%	7.8%	14.6%
Safety benefit of ESC given that the car has four stars and an EBA.	5.2%	10.3%	16,8%
Safety benefit of ESC given that the car has five stars and an EBA.	3.2%	10.7% (*)	23.4% (*)
Safety benefit of the fifth star given that the car has four stars and an EBA.	6,4%	8,3%	N.A.
Safety benefit of the fifth star given that the car has four stars, an EBA and an ESC.	19.3% (*)	33,8% (*)	35,1% (*)
Safety benefit of EBA and ESC given that the car has four stars.	18,6%	36,3% (*)	42,3%
Safety benefit of EBA and a fifth star given that the car has four stars.	28,2% (*)	36% (*)	37,5% (*)
Safety benefit of ESC and a fifth star given that the car has four stars and an EBA.	22% (*)	38,6% (*)	37,1% (*)
Safety benefit EBA, ESC and a fifth star given that the car has four stars.	47,2% (*)	67,8% (*)	69,5% (*)
Safety benefit of a fifth star and removing an ESC given that the car has four stars, an EBA and an ESC.	2,1%	N.A.	N.A.

* Statistically significant

The French accident national database gathers all information on every injury road accident occurring all over France during a year. This database only focuses on accidents in which at least one road user sustains injuries. No property-damage accident is registered in this database. The information is collected by the Police forces on the scene of the accident. On the basis of the police report, usually used for forensic purpose, they also have to fill in a statistical form called BAAC (Bulletin d'Analyse d'Accident Corporel) bringing together all the characteristic of the accident.

Among all the vehicles within our injury accidents database, a selection has been made in order to retain only crashed vehicles that were pertinent for the analysis.

Firstly, we selected French vehicles whose model year stands between 2000 and 2006. We restricted our analysis to four and five star vehicles, excluding three stars vehicles. It was useless to keep vehicles with model years prior to year 2000 since considerable improvements have been brought to car crashworthiness since the late nineties and the additional benefits of newer passive or active safety devices must be compared to vehicles built just prior to these improvements and not a long time ago.

We also selected cars fitted with ABS since this is now standard equipment.

The presence of EBA and ESC in the car also had to be stated. The vehicles with optional equipment were not taken into account, as we could not be sure if the safety function was really on board. There were some special cases where the optional equipment has been considered as if it was not present on the vehicle (ESC equipment for the Megane for instance since the equipment rate for some vehicles was known to be very low).

We must explain that the injury severity codification was changed in 2005 in France (the split between slight and serious injuries changed towards a split between slight and hospitalized injuries). There is not any evident correlation between the new and the former classification. It becomes impossible to aggregate data of accidents occurred before 2005 with those concerning accidents from 2005 on, at least if the analysis deals with injury severity. Therefore, we had to perform our analysis on the accident cases that occurred in 2005 and 2006.

The last selection concerned the use of the seat belt and the seating position in the vehicle; only the belted driver and front passenger were selected for the analysis.

Available in our sample were 15 466 four star vehicles and 4 610 five star vehicles.

The main striking results coming out from the analysis are what we call the '*overall effectiveness*' of the selected safety systems with breakdown by injury severity levels (table 4). This 'overall effectiveness' represents the percentage of reduction in injury accident and injuries that would be observed if all cars would be fitted with the system(s) under consideration, compared to cars of a reference group. Reference groups are not always the same, the less equipped reference group being 4 star cars without EBA, without ESC.

This overall effectiveness is derived from the *specific effectiveness* which is the effectiveness of the safety configurations which applies only to accident types or impact types for which the safety systems are designed for.

The main outcome of this analysis is that any increment of a passive or active safety function selected in this analysis (5 stars, Emergency Brake Assist, Electronic Stability Control) produces additional safety benefits. In general, the safety gains are higher for higher severity levels [15]. For example, if all cars were five stars fitted with EBA and ESC, compared to four stars without ESC and EBA, injury accidents would be reduced by 47.2%, all injuries would be mitigated by 67.8% and severe + fatal injuries by 69.5%.

The results are very positive and encouraging, showing great potential for the generalization of the selected safety applications and validating the choices made so far by the various stakeholders who have been pushing the installation of safety technologies in the passenger cars for years.

CONCLUSION

Apart from considerable improvements in the methodologies applicable to accident research in the field of human factors, statistics and epidemiology, allowing a better understanding of the crash generating issues, the TRACE project quantified the expected safety benefits for existing and future safety applications.

- As for existing safety functions or safety packages, the main striking results show that any increment of a passive or active safety function selected in this project produces additional safety benefits. In general, the safety gains are even higher for higher injury severity levels. For example, if all cars were five stars and fitted with EBA and ESC, compared to four stars without ESC and EBA, injury accidents would be reduced by 47%, all injuries would be mitigated by 68% and severe + fatal injuries by 70%.
- As for future advanced safety functions, TRACE investigated 19 safety systems. The results show that the greatest additional safety gains potential are expected from intelligent speed adaptation systems, automatic crash notification systems, and collision warning and collision avoidance systems. Their expected benefits (expected reduction in the total number of injured persons) are between 6% and 11%. Safety benefits of other systems are more often below

5%. Some systems have a very low expected safety benefit (around or less than 1%).

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The views expressed in this work belong to the authors and are not necessarily those of the UK Department for Transport or Highways Agency, who made the UK data available to the Vehicle Safety Research Centre at Loughborough University for the TRACE project.

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BENEFIT ESTIMATION OF ADVANCED DRIVER ASSISTANCE SYSTEMS FOR CARS DERIVED FROM REAL-LIFE ACCIDENTS

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Paper Number 09-0317

ABSTRACT

Advanced Driver Assistance Systems (ADAS) are today becoming increasingly common in the market. The safety potential of these systems has been evaluated using different approaches in several studies. In order to quantify the effects of ADAS on accidents described by insurers` claim files, German Insurers Accident Research has performed a comprehensive study. The database used for the study was a representative excerpt from the German Insurers' data, covering 2,025 accidents. Statistical methods were used to extrapolate these accidents up to 167,699 claims.

The conclusions of the analyses are as follows: a Collision Mitigation Braking System (CMBS) which is able to gather information from the environment, to warn the driver and to perform a partial braking maneuver autonomously (CMBS 2), could prevent up to 17.8 % of all car accidents with personal injuries in the data sample. The theoretical safety potential of a Lateral Guidance System, consisting of Lane Change Assist and Lane Keeping Assist, was determined to be up to 7.3 %.

Hence, a car fleet equipped with CMBS 2 and Lateral Guidance could avoid up to 25.1 % of all car accidents in the data sample. This theoretical safety potential is based on the assumptions that 100 % of the car fleet is equipped with these systems and the driver reacts perfectly when warned.

DATABASE

German Insurers Accident Research (UDV) is a department of the German Insurance Association (Gesamtverband der Deutschen Versicherungswirtschaft e.V. - GDV) and has access to all the third party vehicle insurance claims reported to the GDV. For 2007, these amounted to 3.4 million claims, of which 2.6 million were claims involving cars. For the purposes of accident research, the UDV set up a database (referred to as the UDB), taking a representative cross-section (years 2002-2006) from this large data pool. The data collected is conditioned for interdisciplinary purposes for the fields of vehicle safety, transport infrastructure and traffic behaviour. The contents of the claim files from the insurers form the basis of the UDB. The depth of information provided by the UDB is significantly higher than that of the Federal German statistics [1] (see Figure 1). It is comparable with GIDAS [2, 3], although some attributes are less meaningful because no analysis is carried out at the scene of the accident. Around 1,000 new cases are added to the UDB each year.

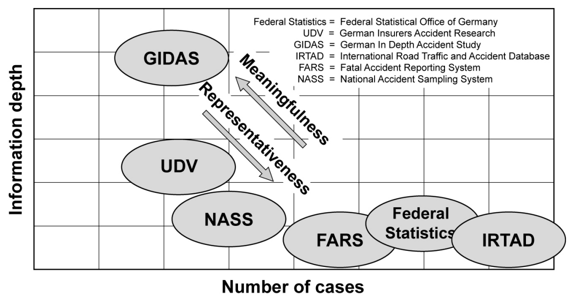


Figure 1. The UDV database compared with other accident databases.

Data set and representativeness

Only third-party vehicle claims involving personal injury and at least € 15,000 total claim value have been taken into account for the GDV accident database. Cases involving only damage to property and less serious accidents involving personal injury (total claim value < € 15,000) are not included in the UDB. Each year, a random sampling method [4] is used to collect stratified random samples that take into account the type of traffic involvement, the damage sum class and the time of year as stratification variables. Case-dependent extrapolation factors allow the sample in the UDB to be extrapolated to the target population of all claims in Germany. This ensures that the statements with respect to the safety potential of driver assistance systems refer to a representative sample of all claims dealt with by German insurers.

This current study is based on a total of 1,641 car accidents, which were extrapolated to a total of 136,954 cases. All types of traffic involvement were taken into account as the collision parties for the car (cars, trucks, buses, motorcycles, bicycles and pedestrians) as well as single car accidents. Single car accidents are, however, underrepresented, as cases in which there is no injury or damage to a third party are not brought to the attention of GDV.

METHOD

Analysis of the safety potential was carried out using a multi-step-approach (see Figure 2). Starting from the accident data stored in the UDB ("A – UDB database"), the accidents involving cars were selected in a first step ("B – Data pool"). In a second step, key aspects of the course of the accidents and groups of ADASs were defined ("C – Relevance pool 1") that could be expected to exert a positive influence on the key aspects of the accidents that had been derived (e.g. Intelligent Braking Assist, Lateral Support). In a third step, the system characteristics were derived for generic ADASs. Different stages of development of the systems were defined and evaluated ("D – Relevance pool 2"). It was of no significance for the analysis whether it is currently already possible to implement the technical system characteristics and whether the systems under consideration are already available on the market. It was also not the intention to carry out a comparison of specific products.

Fourthly, the theoretical safety potentials of the defined generic ADASs were determined by systematic case-by-case analysis ("E – Calculation of the theoretical safety potential"), and driver behaviour and HMI layout were additionally considered in the fifth step. ("F – Calculation of the achievable safety potential").

The cases were analyzed using the "What would happen if..." method. The prerequisite for this is that none of the vehicles involved in the accidents that were analyzed were fitted with an ADAS. This approach considers the course of the accident as it happened in reality and contrasts it with the course of the accident as it would have been with ADAS (see also [5]). This makes it possible to determine the influence an ADAS would have had on the course of the accident if all the cars had been fitted with the ADAS under consideration. Although a comparison between "cars with ADAS" and "cars without ADAS" would have been theoretically possible, this was not done,

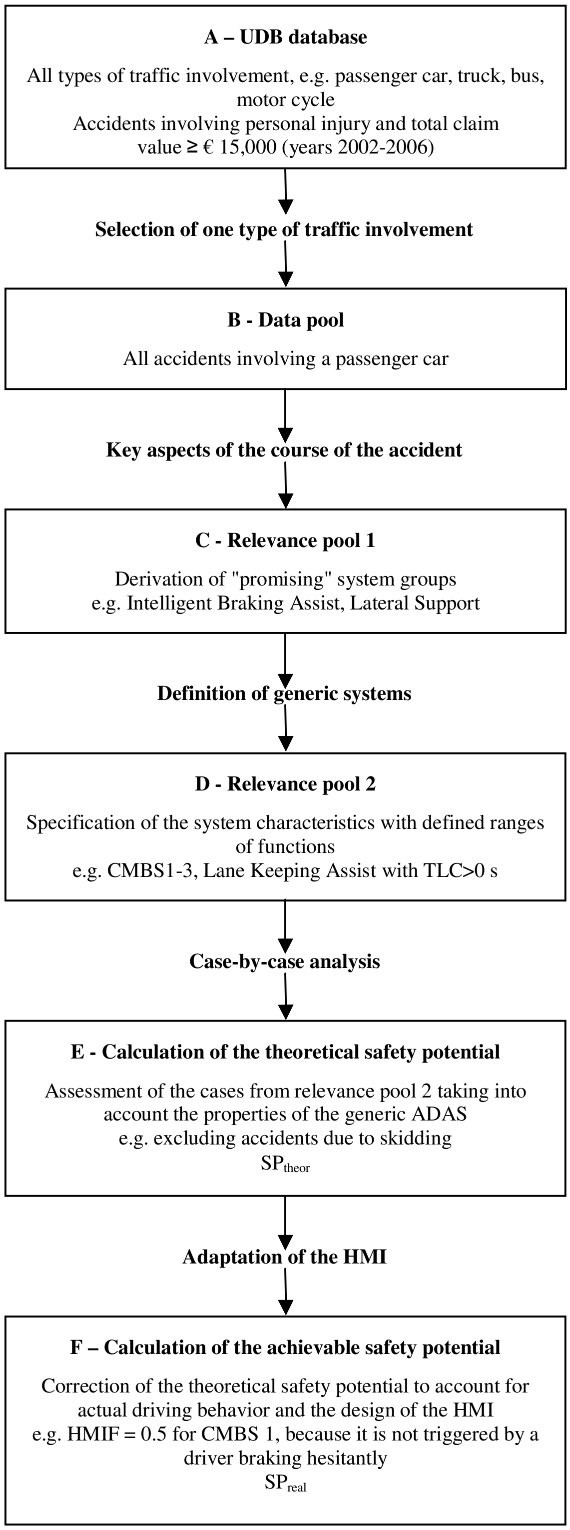


Figure 2. Multi-step-approach where A ≥ B ≥ C ≥ D ≥ E ≥ F with respect to the size of the data pool.

on the one hand because there are still too few cars fitted with modern ADASs in the overall total (and involved in the accidents) and on the other because it was not intended to compare specific products [6, 7].

The method of investigation selected initially assumes that a driver reacts ideally to the warnings issued by the system, which is generally not the case in reality. This means that the theoretical safety potential calculated in step four of the method represents an upper limit that is unlikely to be achieved under real driving conditions. Taking adequate account of driver behaviour is a huge challenge in accident research, in particular in the context of ADASs. The problem is approached in different ways in the various studies. Thus, it is for instance possible to divide drivers into groups and to characterize these groups with specific attributes such as braking behaviour [8]. A different approach was adopted in this study: In order to provide a quantitative description of the influence of the systems and their various development stages on driver behaviour, existing expertise based on the most recent information was used. The index derived from this ("HMIF") takes account of the following parameters: driver reaction, behaviour adaptation, and the design of the human-machine interface [9]. The HMIF can take a value between 0 and 1. This is multiplied by the theoretical safety potential in order to determine the safety potential that can be achieved when the aspects mentioned above are taken into account.

$$SP_{real} = HMIF \times SP_{theor}$$

$HMIF$ – Human Machine Interface Factor where $HMIF \in \{0...1\}$

SP_{real} – achievable safety potential

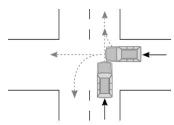
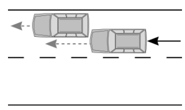
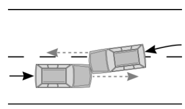
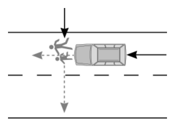
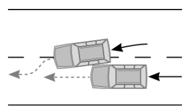
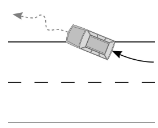
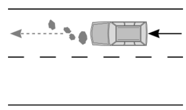
SP_{theor} – theoretical safety potential

A value of HMIF=0 means that there is only a theoretical safety potential that cannot, however, be exploited in practice because of poor interface design. One example would be an optical collision warning system that directs the driver's attention into the vehicle instead of onto the road. A value of HMIF=1 means that the potential that can be achieved in theory and in reality are identical. An example of such a system is the Electronic Stability Program (ESP): When the ESP intervenes, the driver's attention is not distracted, neither is there a risk of any negative behaviour adaptation associated with a different driving style.

APPLICATION OF THE METHOD TO SELECTED SYSTEMS

Using the method described, the car accidents in the UDB (n=1,641) extrapolated to n=136,954 were categorized on the basis of the attribute "kind of accident" and ordered by the frequency with which the different types occurred (see Table 1). The "kind of accident" attribute describes the directions in which the vehicles involved were heading when they first collided on the carriageway, or, if there was no collision, at the time of the first mechanical impact on a vehicle [1].

Table 1.
Most frequent accident scenarios for car accidents from the data pool

Most frequent accident situation ($n_{data\ pool}$=136,954) [100 %]		**Proportion**
(1) Collision with another vehicle which is turning into or crossing a road		34.5%
(2) Collision with another vehicle - moving forwards or waiting - which is starting, stopping or is stationary		22.2%
(3) Collision with another oncoming vehicle		15.5%
(4) Collision between vehicle and pedestrian		12.1%
(5) Collision with another vehicle moving laterally in the same direction		6.9%
(6) Leaving the carriageway to the right or left		6.3%
(7) Collision with an obstacle in the carriageway		0.1%

The list of typical accident scenarios in Table 1 can be used for preliminary selection of sensible ADAS groups (see Table 2). This list does not, however, provide the theoretical safety potential of generic ADASs. Instead, it is possible to identify potential promising ADAS groups in accordance with the stated methodology (relevance pool 1).

Table 2.
Ranking of possible ADAS groups on the basis of the data pool

ADAS group	Accident situation addressed	Data pool
Intelligent Braking Assist	(1) (2) (7)	56.8 % (n=77,775)
Rear-end collisions and all situations where the directions of travel of vehicles cross each other		
Pedestrian/Bicyclist Detection Assist	(1) (4)	46.6 % (n=63,865)
Also possible: All other situations where pedestrians/bicyclists interact with vehicles		
Junction/Intersection Assist	(1)	34.5 % (n=47,243)
Addresses all situations where the directions of travel of vehicles cross each other		
Lateral Support	(3) (5) (6)	27.7 % (n=37,895)
Covers situations where drivers leave the lane unintentionally or intentionally, e.g. overtaking and blind spots		

This reveals that intelligent braking systems that are, among other things, able to prevent rear-end collisions would be able to address the great majority of the accidents in the database, followed by an assistance system able to prevent accidents with vulnerable road users (pedestrians and cyclists). This study, however, only investigates intelligent braking systems and lateral support systems.

Collision Mitigation Braking Systems (CMBS)

Collision Mitigation Braking Systems are able to positively influence specific accident scenarios (see tables 1 and 2) [6]. For this study, three different development stages of a CBMS were investigated with the aim of revealing sensible directions in which development can be pursued and to assess these in terms of safety potential. The system properties selected have a direct impact on the accidents in which any influence can be exerted (see Table 3 to Table 5). To comply with the methodology, steps must be taken to ensure that the vehicles in the data pool are not fitted with a CMBS. This could not, however, be guaranteed in all cases for CMBS 1.

The first development stage of a CMBS (CMBS 1) virtually corresponds to the traditional braking assist systems as required in passenger cars by the pedestrian protection directive [13] that has been approved. The second stage already has the capability of collecting environment information and is able to detect double-track vehicles driving in front. On the systems currently available on the market, this is done almost exclusively with radar sensors. The third development stage describes a system that as yet does not exist in the form presented. As such, the system is based on the functionality provided by the second stage and is also able to detect potential collision parties crossing from the side. The system is not restricted to the detection of double-track vehicles. Instead, all motorized vehicles as well as pedestrians and cyclists are detected.

Table 3.
System properties and derived database attributes for the first development stage of a CMBS (CMBS 1)

CMBS 1	
System description	**Application to the UDB**
- Enhancement of the braking force up to the blocking threshold in the event that a driver initiates an emergency braking maneuver but does not actually carry it out	- Only those accidents in which the driver braked and in which the driving and collision speeds are known - The "case car" is the vehicle on which the primary impact is at the front
- Maximum deceleration that can be achieved: 9.5 m/s² (dry road surface); 7 m/s² (wet road surface)	- Sub-categorization of the accidents by the state of the road surface (dry/wet)
- No detection of the environment	- All accident scenarios

Taking account of the system characteristics of the CMBSs described in Table 3 through Table 5 we arrive at the case material collated in Table 6. Only cases from relevance pool 2 are used to determine the

Table 4.
System properties and derived database attributes for the second development stage of a CMBS (CMBS 2)

CMBS 2	
System description	**Application to the UDB**
- As for CMBS 1 plus:	
- Forward detection of the environment (sensor-independent)	- Rear-end collisions with double-track vehicles
- Detection of double-track vehicle driving in front (not stationary)	
- Speed range: 0-200 kph	All accidents in which the driving speed of the "case car" is known and:
- warning at TTC 2.6 s, i.e. 2.6 s before the calculated collision with the vehicle in front	
- automatic partial braking at 0.6 g by the system if there is no reaction from the driver at TTC 1.6 s	- the driver has not braked
- if the driver has reacted, a modulated braking maneuver or an emergency braking maneuver is performed	- the driver has braked

theoretical safety potential. Case-by-case analysis is used to determine those accidents from relevance pool 2 that could have been avoided by CMBS 1, CMBS 2 or CMBS 3. An analogous approach is used for all the other systems under investigation (see Table 8 and Table 11).

Taking CMBS 2 as an example, we shall explain the procedure used to form the individual pools: Starting from a data pool with 65,328 car accidents, all rear-end collisions are selected. These then form relevance pool 1. In a following step, these cases are further restricted on the basis of the specified system characteristics (see Table 4). For CMBS 2, this means that only rear-end collisions with moving, double-track vehicles are taken into account (relevance pool 2). This pool is finally used for case-by-case analysis.

Table 5.
System properties and derived database attributes for the third development stage of a CMBS (CMBS 3)

CMBS 3	
System description	**Application to the UDB**
- As for CMBS 2 plus:	
- Forward and lateral detection of the environment (sensor-independent)	- All accident scenarios
- Detection of all types of road users including pedestrians and stationary objects/obstacles	
- Automatic maximum braking by the system at TTC 1 s in the sense of a modulated braking maneuver	- All accidents in which the driving speed of the "case car" is known

Table 6.
Relevant extrapolated accident data for the three development stages of a CMBS

	Data pool	**Relevance pool 1**	**Relevance pool 2**
CMBS 1	52,226	29,365	14,318
CMBS 2	65,328	23,640	7,409
CMBS 3	83,524	46,628	46,628

There are significant differences between the CMBSs with respect to the HMIF: The HMIF for CMBS 1 is 0.5. The most important reason for this is that today's systems are parameterized for normal to sporty drivers. This does not account for apprehensive or hesitant drivers who would be in particular need of the system. This was confirmed by trials in a driving simulator, where the braking assist system only registered as having triggered in 47 % of cases [10].

In the case of CMBS 2 and CMBS 3, the HMIF is 1, since no behaviour adaptation is to be expected.

Lateral Guidance Systems

Overtaking accidents, accidents in the context of changing lanes and departure from the carriageway form a further important group of accidents (see Table 2). A Lane Keeping Assist system and a Lane Change Assist system were assessed for these accidents. The latter was divided into two subsystems: One system warns of oncoming traffic when overtaking and the second system warns of vehicles approaching from behind in the blind spot during a deliberate overtaking or lane change maneuver.

Table 7.
System characteristics and derived database attributes for the Lane Keeping Assist system

<table>
<tr><th colspan="2">Lane Keeping Assist system</th></tr>
<tr><th>System description</th><th>Application to the UDB</th></tr>
<tr><td>- Capturing of the lane marking(s) using sensors and cameras (range: approx. 50 m)</td><td rowspan="5">- Accidents caused by inadvertent departure from the carriageway (e.g. as a result of inattention, distraction, overtiredness)
- The "case car" is the vehicle with the reference number 01 (party responsible for the accident)</td></tr>
<tr><td>- Detection of an impending inadvertent departure from the lane by comparing the current direction of travel with the course of the current lane</td></tr>
<tr><td>- Active between 10 kph and 200 kph</td></tr>
<tr><td>- Warning issued to the driver at TLC > 0 s (Time to Lane Change, speed-dependent)
- No intervention in the steering by the system</td></tr>
<tr><td>- Function is maintained even in bends provided that the radius is at least 200 m</td></tr>
<tr><td>- Function is only available if at least one lane marking is available</td><td>- Assumption: At least one lane marking was present in all the accidents investigated</td></tr>
<tr><td>- Detection of all types of markings except overlaid lines (e.g. in the vicinity of roadworks)</td><td>- Accidents in the vicinity of roadworks are not taken into consideration</td></tr>
<tr><td>- Coupled to the indicator unit, i.e. the system is deactivated when the indicator is switched on</td><td>- Accidents resulting from a deliberate lane change maneuver are not taken into account</td></tr>
</table>

Lane Keeping Assist - The functions of the Lane Keeping Assist system investigated here are based on systems already available on the market.

Taking account of the system characteristics described in Table 7, we arrive at the accident data shown in Table 8.

In the case of the Lane Keeping Assist system, relevance pool 1 is formed by the key aspect of the accident "departure from the lane/carriageway". For relevance pool 2, accidents in the vicinity of roadworks and in tight bends, etc. are filtered out, as it cannot be guaranteed that the system will function reliably in such cases. The case-by-case analysis was carried out on relevance pool 2 (7,207 cases).

Table 8.
Relevant extrapolated accident data for a Lane Keeping Assist system

	Data pool	**Relevance pool 1**	**Relevance pool 2**
Lane Keeping Assist system	136,954	17,848	7,207

An HMIF of 0.5 was determined in [9] for deriving the achievable safety potential of a Lane Keeping Assist system. The reason for this is that a low magnitude haptic warning tends to be selected in order to prevent frequent false warnings from being perceived as a nuisance. Acoustic warnings on the other hand are not sufficiently specific and direction-dependent acoustic warnings do not deliver any additional benefit [9].

Lane Change Assist - A variety of studies and statistics [1, 11] provide evidence that rural roads represent the greatest safety problem in Germany with respect to fatal accidents. In this context, accidents involving oncoming traffic are conspicuous. In such situations, an Overtaking Assist system providing support to the driver would be desirable. However, such a system (see Table 9) is currently not available [12]. Theoretically, it would also be conceivable to implement a system such as this using car-to-car communication. Although such systems currently belong to the future, it nevertheless makes sense to analyze the safety potential, because it can provide insights into future development priorities.

Table 9.
System characteristics and derived database attributes for the Overtaking Assist system

<table>
<tr><td colspan="2">Overtaking Assist system</td></tr>
<tr><td>System description</td><td>Application to the UDB</td></tr>
<tr><td>- Monitoring of the area in front of the vehicle at a significant distance (assumption: at least 300 m; sensor-independent)</td><td rowspan="3">- Collisions with oncoming vehicles during overtaking (using accident types in the magnitude of hundreds and the attribute "direction of travel, vehicle 1"/"Collision with vehicle 2 which ...")

- The "case car" is the vehicle with the reference number 01 (party responsible for the accident)</td></tr>
<tr><td>- Detection of oncoming double-track vehicles and motorcycles</td></tr>
<tr><td>- Calculation of the theoretical collision time using the speeds and distance between the vehicles (without taking into account the course of the road, e.g. humps)</td></tr>
<tr><td>- Warning issued to the driver when the indicator is set if the overtaking maneuver is judged to be critical</td><td>- Assumption: The driver had set the indicator for each overtaking maneuver</td></tr>
</table>

The Overtaking Assist system described in Table 9 was not assessed on the basis of the HMIF because there are currently no concrete, scientific findings with respect to such a system.

For the Blind Spot Detection system (see Tables 10 and 11), relevance pool 1 was formed by the key aspect of the accident "lane change", in other words those accidents in which a collision occurred when changing lane (7,403 cases). For relevance pool 2, only those accidents were taken into account, for example, in which the party changing lane was hit from the rear or side and was driving at least 10 kph. The accident material meeting this criterion is given in Table 11.

The HMIF for a Blind Spot Detection system is assumed to be 0.8 in accordance with [9]. The reason is that the system assumes that the driver looks in a particular direction, which does not always happen. This applies, for instance, for systems designed with a flashing signal on the wing mirror.

Table 10.
System characteristics and relevant accident data for a Blind Spot Detection system

<table>
<tr><td colspan="2">Blind Spot Detection system</td></tr>
<tr><td>System description</td><td>Application to the UDB</td></tr>
<tr><td>- Monitoring of the areas behind and to the side of the vehicle</td><td rowspan="2">- Collisions with approaching vehicles when pulling out or with overtaken vehicles when pulling in again (accident types in the magnitude of hundreds)

- The “case-car” is the vehicle with the primary impact to the rear or to the side (right or left)</td></tr>
<tr><td>- Detection of approaching double-track vehicles and motorcycles that are between 20 kph slower and 70 kph faster.</td></tr>
<tr><td>- System active as of 10 kph</td><td>- Accidents caused by changing lanes from stationary are not taken into account</td></tr>
<tr><td>- Warning issued to the driver when the indicator is set and when an approaching vehicle or motorcycle is in the blind spot area</td><td>- Assumption: Indicator is set on each overtaking maneuver</td></tr>
</table>

Table 11.
Relevant extrapolated accident data for a Lane Change Assist system

	Data pool	**Relevance pool 1**	**Relevance pool 2**
Overtaking Assist system	136,954	7,403	2,222
Blind Spot Detection system	136,954	7,403	3,582

RESULTS

This current study on the safety potential of selected ADAS systems is based on a total of 1,641 car accidents. Extrapolated to the total claims on the insurers, this corresponds to a total of 136,954 cases. Depending on the question being investigated and the ADAS under consideration, this number of cases is reduced because the information required is not always 100 % present in the database. For instance, in order to determine the safety potential of CMBS 1, only those cases are considered where it is known whether the driver braked before the collision, which means that all the accidents in which it is not possible to determine whether the driver braked must be filtered out. The same principle applies to the other ADASs considered here. This aspect is reflected in Tables 12 through 14.

A multi-step-approach was used for each ADAS under investigation (see Figure 2). Considerable differences in the magnitude of the safety potential can be observed for longitudinal guidance systems (CMBS 1-3) and lateral guidance systems.

Collision Mitigation Braking Systems (CMBS)

Table 12 indicates the fundamentally high safety potential for CMBS systems. It can be seen that even CMBS 1 has a significant positive impact on the accident situation. The configuration of the generic CMBS 1 corresponds to the braking assist system that will become mandatory when the pedestrian protection directive takes effect [13]. In this case, the achievable safety potential SP_{real} differs considerably from the theoretical safety potential SP_{theor}. Nevertheless, even if this is taken into account, it would be possible to avoid SP_{real}=5.7 % of all car accidents.

It can also be clearly seen that a significantly higher safety potential can be expected in future. If we assume that the generic CMBS 2 corresponds to the CBMS already available on the market, SP_{real}=12.1 % of all car accidents in the database could be avoided if 100 % of cars were fitted with the system.

On the basis of all the rear-end collisions in the database (n=23,640), the resulting safety potential is 28 % for CMBS 2.

Table 12.
Extrapolated numbers of accidents and theoretical and achievable safety potential of CMBSs

	Data pool [100 %]	**Relevance pool 1**	**Relevance pool 2**	**SP_{theor}**	**SP_{real}**
CMBS 1	52,226	29,365	14,318	5,960 **11.4%**	**5.7%**
CMBS 2	65,328	23,640	7,409	4,213 (6.4%) **17.8%**	(6.4%) **12.1%**
CMBS 3	83,524	46,628	46,628	24,027 (28.7%) **46.5%**	(28.7%) **40.8%**

It can be expected that systems in the more distant future would closely resemble the characteristics of the CMBS 3. Such systems can be understood as "Junction/Intersection Assist systems". If vehicles were fitted with CMBS 3 type systems, SP_{real}=40.8 % of all car accidents could be avoided. Toyota have already presented initial attempts at such systems with their Front-side Pre-crash detection system [14].

Lane Keeping Assist

Systems that warn a driver when leaving a lane are becoming increasingly common in modern vehicles. Against this background, the safety potential determined here is extremely relevant, especially as the design of the generic Lane Keeping Assist system investigated here approximately corresponds to current systems. The achievable safety potential of a Lane Keeping Assist system is SP_{real}=2.2 % (see Table 13). As with the CMBS 1, this case clearly shows the considerable influence the human-machine interface has in respect of system design.

On the basis of all the accidents in the database resulting from inadvertent departure from the lane (n=17,848), the resulting safety potential for a Lane Keeping Assist system is SP_{real}=16.8 % (SP_{theor}=33.6 %).

Table 13.
Extrapolated numbers of accidents and theoretical and achievable safety potential of a Lane Keeping Assist system

	Data pool [100 %]	**Relevance pool 1**	**Relevance pool 2**	**SP_{theor}**	**SP_{real}**
Lane Keeping Assist system	136,954	17,848	7,207	6,005 **4.4%**	3,003 **2.2%**

Lane Change Assist

Blind Spot Detection systems are also already available in many new vehicles. The design of the system investigated here approximately corresponds to that of currently available systems. The achievable safety potential SP_{real} is 1.4 % (see Table 14).

If the avoidable accidents (n=1,826) are considered in relation to all accidents where the driver deliberately changed lane (relevance pool 1, n=7,403), this results in a safety potential of SP_{real}=24.7 %.

Table 14.
Extrapolated numbers of accidents and theoretical and achievable safety potential of a Lane Change Assist system

	Data pool [100 %]	Relevance pool 1	Relevance pool 2	SP_{theor}	SP_{real}
Overtaking Assist system	136,954	7,403	2,222	1,583 **1.2%**	------
Blind Spot Detection system	136,954	7,403	3,582	2,282 **1.7%**	1,826 **1.4%**

The Overtaking Assist system is intended to provide an insight into the future. The safety potential determined shows that despite the considerable technical outlay required to implement the function, only a relatively low theoretical safety potential of SP_{theor}=1.2 % can be expected.

However, if the avoidable accidents (n=1,583) are considered in relation to all accidents where the driver deliberately changed lane (relevance pool 1, n=7,403), this results in a safety potential of SP_{theor}=21.4 % for the Overtaking Assist system.

Human factor issues

This study underscores the importance of taking the human-machine interface into account when designing the system. It is only possible to derive realistic safety potentials when this aspect is taken into account. If this factor is ignored, any potential that is determined can at best be seen as an estimate. One of the challenges that will face accident researchers generally in the future will be to reveal solutions for integrating the aspect of HMI in analyses of safety potential.

CONCLUSIONS

After the ESP, CMBSs are the systems that deliver the greatest safety potential in the field of active safety. They should therefore be fitted to the car fleet as soon as possible. In Europe, a first step has been taken in the right direction with the Regulation concerning type approval requirements for the general safety of motor vehicles [15, 16].

Hence, a future car fleet equipped with CMBS 2 and Lateral Guidance (Lane Keeping Assist, Overtaking Assist and Blind Spot Detection systems) could avoid up to SP_{theor}=25.1 % of all car accidents in the data sample. Methodologically, it is correct to add up these safety potential figures, as they arise from independent subsets of accident data.

The study also reveals a further issue: Above all in first-generation systems, it is crucial that the human-machine interface is taken into account. Significant contributions to improving safety can be achieved even with systems that are already on the market (CMBS 1, Lane Keeping Assist systems and Blind Spot Detection systems): If all cars were fitted with these systems, SP_{real}=9.3 % of all car accidents in the current database could have been avoided.

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Situation-Interpretation as a key enabler for cost-effective and low-risk driver assistance systems with high collision mitigation capabilities

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Abstract

In the area of safety-oriented driver assistance systems there is a trend to increase the accident mitigation capabilities by adding or strengthening autonomous system reactions. However, this also increases the potential for involuntary accidents in the case of malfunction. Due to product liability regulations these high risk functions require an increased development effort as well as more reliable sensor platforms, which drive up their costs.

The accident mitigation capabilities of autonomously acting systems can also be achieved by an alternative strategy avoiding the high risk system reactions. The key is an early and reliable warning giving the driver time to react to the situation, combined with functions supporting the driver in his reactions, e.g. emergency braking.

Early system reactions with low false activation rates can only be achieved by an advanced understanding of the traffic situation and an interpretation of the driver's actions in this context. To achieve this, the traditional approach of assessing the criticality of one potential collision object is extended towards observing and assessing multi-object scenarios. An analysis of accident statistics shows that in a high percentage of accidents the multi-object constellation provides additional information enabling early criticality assessments of the traffic situation. Using this information, the driver can be supported in an optimal way by an early, low-risk system reaction.

This approach is the key for the vision "safety for everybody", i.e. providing cost-effective collision mitigation functions with high collision mitigation capabilities to the mass market.

1. Risk Assessment

In the area of safety-oriented driver assistance systems there is a trend to increase the accident mitigation capabilities by adding or strengthening autonomous system reactions. The functions have to satisfy safety-standards like e.g. the ISO 26262 demanding for a risk and hazard analysis.

The approach to assess the "criticality in case of malfunction" of e.g. a fully autonomous emergency braking function used at Bosch is a model-based so-called objectified danger and risk analysis. In this, the effect of a false triggering of a specified autonomous emergency braking function is simulated on the basis of real traffic data, e.g. distances and relative velocities between vehicles. The analysis shows that the more velocity an autonomous braking function can reduce in a short time, the higher their damage potential is, i.e. the more often and the more severe rear-end accidents are caused.

The ISO 26262 demands that functions with high damage potential must satisfy a low rates of malfunction. Technically this is possible by means of the following measures: robust and therefore in tendency expensive sensors or sensor clusters (i.e. sensor-costs with respect to the function portfolio they cover); development processes and hardware that comply with ISO 26262 damage-potential rating (aSIL) standards; extensive endurance test drives to proof the compliance with false activation rates demanded by safety analysis.

In contrast, a concept putting the responsibility for triggering an autonomous intervention to the driver results in much lower demands on the false activation rates. Crucial for the category of the functions which warn and then assist the driver is that they are only activated if besides the environment sensors the activities of the driver also indicate a critical situation. This reduces the requirements to the reliability of situation interpretation by the environment sensors and the in tendency costly measures listed above are not necessary. These functions are state of the art. However, their effectiveness – i.e. the accident prevention capabilities - can be greatly increased if the warning is set to an earlier point in time giving the driver more time to react; because of the possibility of evading or a full stop, the driver has more effective methods for accident prevention than an autonomously braking system with restricted deceleration. This all is possible without an increase of the damage potential of the function.

In a generalized manner it can be summed up: The stronger and potentially more risky the intervention of an autonomous function, the more expensive the development, safeguarding and hardware of the function. In most situations though an early warning with driver assisting functions without risky autonomous interventions is similarly or more effective and can be realized on the basis of a cheaper sensor. By means of such economical systems, so the vision, access to a safety-oriented driver assistance is to be made possible for every road-user.

2. Increasing Benefit by Situational Interpretation

Key of the realization of a cheap but effective driver assistance function covering the front collision case is the realization of an early warning, i.e. an early and reliable criticality-assessment of the traffic situation. The dilemma that an earlier warning to a critical traffic situation typically also drastically increases the false warning rates is well known. To achieve an earlier warning at constant false-alarm level the following strategy is chosen:
For situational interpretation additional information arises from the observation of the traffic situation of third party road-users. If critical situations are detected for third party vehicles, a behavior deviating from the normal case is to be expected from them. For example, if a faster vehicle approaches a slower vehicle on the left lane, the probability increases that the fast vehicle will pull out onto the lane of the own vehicle and that as a result there will be a critical situation for a third party vehicle. This simple example shows that functions which only use one "target object" are restricted in the quality of the criticality assessment as a result of their principle.
Basis of the analysis of the benefit of multi-object scenarios is a detailed accident analysis of the GIDAS-accident database in individual case representation. Observed are accidents in longitudinal traffic (GIDAS-accident type 6) and accidents while turning off (GIDAS-accident type 2). Altogether, the area of effect of a driver assistance function reacting to frontal and parallel traffic therefore is approximately 20% of the complete incidence of accidents. The accidents within this area of effect were analyzed and classified according to the additional information available by additional objects. For two of classes, the additional benefit by evaluation of the multi-object information is discussed in the following. The information in percentages relates to the area of effect of approximately 20 %.

Case 1: In 9.3 % of the accidents, the preceding vehicle brakes strongly while there is oncoming traffic on the left lane. If only the "target object" is observed, the driver assistance system as a matter of principle has the problem of the decision between evading and braking. This is correspondent to the second problem of decision (warning dilemma) discussed in section 2. But when there is oncoming traffic, overtaking respectively evading can be excluded as a sensible option for action for the driver at the time of warning. This is the basis to realize an earlier and more reliable system assessment / reaction is possible.

Case 2: In 10.5 % of the accidents, the preceding vehicle drives against a slower object and brakes strongly. In principle, radar based driver assistance systems can detect pre-preceding vehicles. Before the actual target object becomes "a problem" in this example because of its strong braking, it is possible to discern a critical traffic situation for the preceding vehicle by observing its fast approach to the vehicle in front of it. The hypothesis that the preceding vehicle will brake or evade to prevent the accident is self-evident. On the basis of this interpretation, the behavior modeling for the preceding vehicle can be adjusted to already warn the driver with this before it is even possible to detect the danger by means of the state of the "target object". The described situation is especially important for a driver, because his view on the pre-preceding vehicle is obstructed. The driver assistance system however has its radar measurement and therefore an advantage in information compared to the driver.

3 Summary

By the assessment of multi-object scenarios, an earlier and more reliable criticality assessment of a traffic situation is possible for many frontal accidents. This can be used to distinctly increase the effectiveness of low-risk driver assistance functions. By combining early driver warning with driver assisting functions, it is possible to reach, relating to the total number of frontal accidents, the effectiveness of functions with strong autonomous intervention. The argument is essentially based on the experience that with "target object based" driver assistance systems, the obscurity about how a situation will progress increases drastically with growing temporal range of prediction, and that this can be moderated by the additional involvement of multi-object information.

The early warning approach illustrated by Bosch offers the advantage that it is possible to forego the use of complex, expensive and strongly autonomously intervening systems. The great benefit combined with the low price is the basis of the vision to make safety oriented driver assistance functions with high effectiveness available to the mass market.

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TESTING AND VERIFICATION OF ACTIVE SAFETY SYSTEMS WITH COORDINATED AUTOMATED DRIVING

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ABSTRACT

Although more and more virtual development methods are used for testing and verification of active safety systems, there is still a need for extensive testing of the overall system in a *real* environment. The quantitative validation requires a wide range of different parameters to be controlled – most systems require adjustments of the speed of a „vehicle under test“ and a „target vehicle“ as well as their relative positioning in distance and angle. Using human drivers these parameters are only adjustable by performing a multitude of tests with statistically distributed results. Automatically driven manoeuvres offer the chance for a directed adjustment of all relevant parameters, requiring fewer tests, thereby creating a much more efficient testing operation. The technological challenge and control task is that two vehicles pass each other precisely at a predefined time and speed. Being able to control this, even tests which could not be performed up to now due to safety risks for the drivers, will be possible.
The presentation reports on a common project of Daimler with Anthony Best Dynamics (ABD) and TU Graz, which resulted in a system using coordinated automatically driven vehicles. The need for precisely driven manoeuvres , resulting specifications for the testing methodology of coordinated path-controlled vehicles, and the challenges of its realisation will be explained. The resulting testing environment, hardware solutions and the methods for planning of safe testing trajectories will be illustrated. Results of the achieved accuracy are presented. A view on the role of this type of testing among other testing methods for precrash systems completes the paper.

MOTIVATION AND GOALS

The introduction of active safety systems has a significant impact on testing methods for vehicles: the testing procedures do not only require to bring the vehicle itself into a predefined driving state, but they also need to place the vehicle into a specific location on the road, or even other traffic members into a given relation to the vehicle under test. For example, testing of lane departure warning and avoiding systems requires the control of the vehicle’s position with respect to the lane markings; testing of adaptive cruise control or of crash avoidance systems needs two or more vehicles with a predefined relative speed and precisely controlled timing.

A huge amount of the work for ensuring the functional performance of the systems is done in the virtual domain, in which a lot of experiments with parameter variations can be designed to test the algorithms. But still there is a need to verify the sensor and system performance finally in the real world, especially under critical borderline conditions. Using human drivers, the testing of such conditions is time consuming (because the conditions cannot easily be reached by a single test), or it could even be dangerous for the drivers to test crash-prone situations. With this goal several systems have been proposed to bring the vehicle under test exactly and safely into those conditions, for example [1], [2] and [3].

The coming generation of active safety systems with automatic collision avoidance will call for even more testing because of higher and quantitatively measurable reliability requirements, partially derived from the coming ISO 26262 standards. This was the reason for Daimler to develop a flexible and efficient testing methodology for precisely performing testing manoeuvres, which should be applicable to all kinds of traffic situations as the testing environment.

CLASSIFICATION OF TESTS AND SPECIFICATIONS

A detailed analysis of the testing manoeuvre catalogs of current and future active safety systems was performed to analyse the exact requirements for such a system. It revealed several categories with different reasons for more precision (see fig. 1):

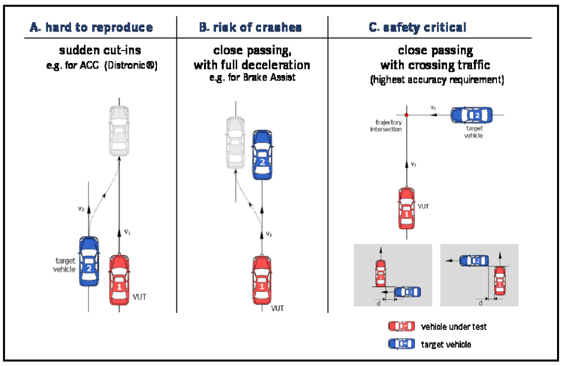

Figure 1. Manoeuvers with precision requirements.

A) manoeuvres which are hard to reproduce
B) manoeuvres which often lead to minor accidents
C) manoeuvres which are too dangerous for human drivers

It turned out that a large share of those categories could be improved significantly by a system which would drive a vehicle automatically along a predefined path under strict timing conditions; several vehicles need to be coordinated with exactly the same time base. Especially the typical "no fire" situations of crash avoidance systems ("close passings") could be tested this way very efficiently.

The accuracy requirements for the vehicle guidance system were specified as follows: Passing of any moving or stationary target should be possible with a distance of 20cm; this leads to requirements of a path following error of less than ±10cm in lateral direction. The longitudinal precision needed depends upon speed; a precision of ±40cm at a speed of 20m/s (72km/h) is equivalent to reaching any track point within a time tolerance of ±20ms (see figure 2). This time tolerance restriction is a requirement which can be generalized to other speeds.

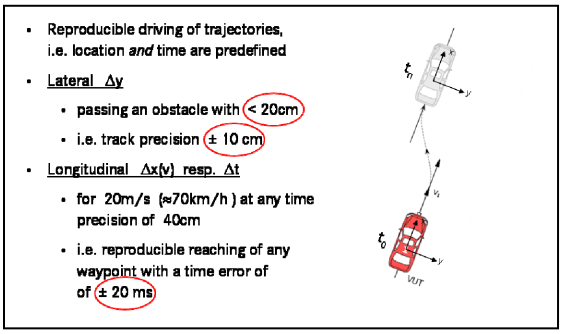

Figure 2. Requirements for driving accuracy.

There were further requirements for the design of the system: The automatic guidance must be capable of handling at least driving speeds in urban environments (70km/h), with the potential to reach higher speeds as well. It should be possible to install the system into any vehicle, in order to test vehicles in any phase of the development program. Traffic situations of up to 4 coordinated vehicles will be needed, and all the situations should be simulated before the real testing. Safety of personnel and equipment has highest priority; dangerous manoeuvres should be performed without a diver in all vehicles in the test. Finally, the system should be applicable on any test track.

TECHNICAL CHALLENGES AND SOLUTIONS

A large portion of the specifications could already be met by a "path following" control system, based on steering and pedal robots, developed by ABD. The system can automatically follow a predefined path, the actual position being measured by an Inertial Measuring Unit (IMU) backed up by a Differential Global Positioning System (DGPS) to ensure long term accuracy in the cm range. The system could be used to perform path following in a mode with a driver in the car, but also in a driverless mode with a safety controller and emergency brake actuators as necessary additional components. Figure 3 shows the implementation of the driving robots in a Mercedes test vehicle.

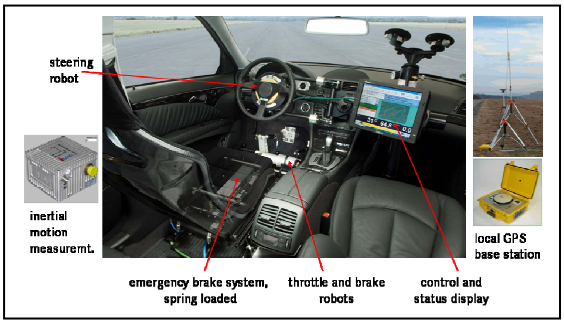

Figure 3. Driving robot integrated in test vehicle.

The challenge for the coordinated driving concept is to control a single vehicle not only laterally, but also longitudinally with high accuracy. Besides this, two or more vehicles should be able to perform precisely synchronized manoeuvres. This could be accomplished using ABD's system by implementing a trajectory control (i.e. ensuring lateral and longitudinal positioning *and* timing) based on GPS-time for each single vehicle, which is accurately available on all vehicles as an output of the DGPS system [4].

Planning of the trajectories needed much more care than for path following of a single vehicle: traffic situations are planned in detail with predefined trajectories for every vehicle. Each vehicle should know in advance what to do at any time instant, with some freedom to react in different variants depending on the actual situation. In order to avoid accidents, the test manoeuvres can be simulated in advance, considering even deviations from the planned path in case of loss of control due to unforeseeable factors.

All vehicles are controlled from a common base station; from here the operator starts the test manoeuvres via a WLAN network, the actual position and speed error is supervised, and the test can be interrupted at any time - if necessary. A thorough safety concept was designed to ensure safe operation and shut-down procedures. Figure 4 shows the base station with two test vehicles.

Figure 4. Base station and two test vehicles.

REACHED PRECISION AND REPRODUCIBILITY

In order to reach a precise trajectory control, the parameters of the system have to be adjusted carefully. However, the system is quick to configure and only requires basic information to be entered for the vehicle, such as maximum brake pedal force, and geometric information for the location of the IMU with respect to the wheelbase. A predictor model for the vehicle dynamics is not used and instead the necessary precision is achieved entirely using PID control with feedback from the IMU. The control parameters are easily derived from a set of simple open-loop driving tests. Once the parameters are set for a vehicle class, the controlled operation of the vehicle leads to very reproducible performance of the trajectory control.

Figure 5 shows a measuring set up for verification of lateral and longitudinal control accuracy. It consists of several strip-switches which close a contact when pressed down by the vehicle tire; the staggered position of the strip-switches allows for lateral resolution of 1 cm, while the timing of closing the different contacts is used for longitudinal verification.

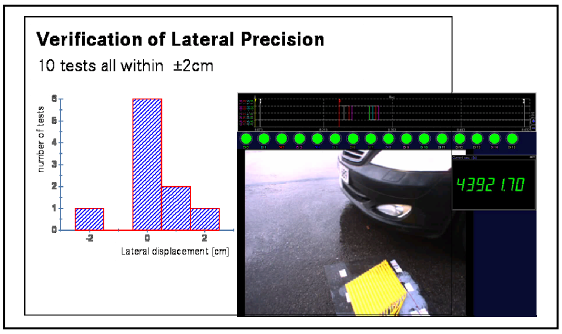

Figure 5. Lateral precision.

The absolute accuracy of the trajectory control in straight line driving has proven to be quite high. Typically, the lateral path following error was measured to be in the range of ±2cm, the longitudinal time error in the range of ±10ms (equivalent to a distance error of ±20cm at a speed of 20m/s). Indeed, if there is sufficient time to stabilize in the steady state condition, the longitudinal error is normally significantly less than this. In dynamic manoeuvres a lateral error of ±10cm and a distance error in the range of ±1m were found; however, the reproducibility of the same manoeuver was similar to the steady-state accuracy . Thus, the dynamic deviation can be considered and compensated in critical sections of the trajectories.

One important feature is the reproducibility of stopping to a point with rather high deceleration. Figure 6 shows the results of the verification measurement; all endpoints of this test were within a circle of 10cm. In summary, the system allows for very precise trajectory control of the vehicles, as long as the manoeuvers stay away from the physical limits of vehicle dynamics.

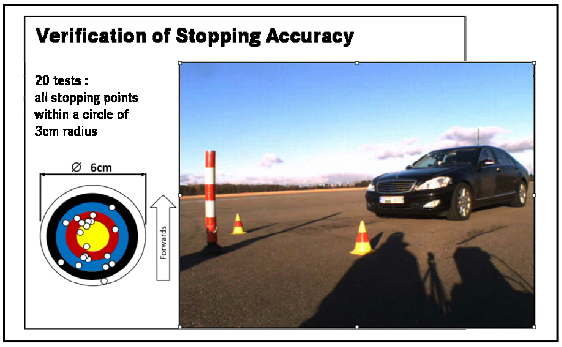

Figure 6. Precision of stopping point

PLANNING AND SIMULATION OF TESTS

For planning of the trajectories of several vehicles, a manoeuvres planning tool is implemented There are several methods to plan a trajectory of a vehicle: the simplest method is to record the track which a human driver has driven; this trajectory can be used as a template for repeated automatic driving of the same trajectory. A second method is to construct a trajectory from basic elements (see figure 7). The tool allows combining straight tracks, curves, lane changes, sinusoidal segments, slaloms, or spirals; and speed profiles for every section can be planned to provide exact timing. In "critical sections", defining maximal tolerances for lateral and longitudinal error sets the thresholds for controlled interruption of the test. It is also possible to define sections, in which the path following system allows for certain freedom of the vehicle control, i.e. acc speed control, emergency braking or lane keeping support.

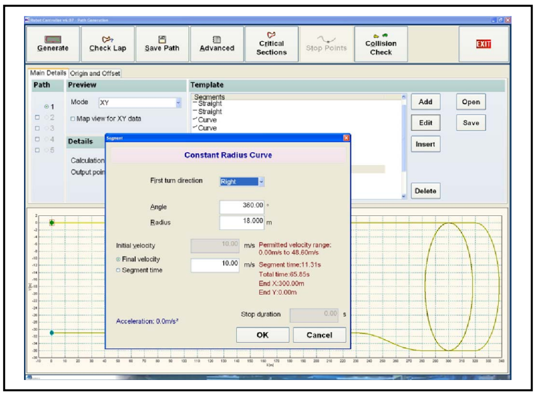

Figure 7. Planning tool.

Planned trajectories can be saved, retrieved and modified. This way, a set of manoeuvers for covering a parameter variation test can be built. Finally, this results in a database of easily repeatable verification procedures for an assistance or active safety function.

Once the trajectory is planned, the simultaneous manoeuver of several vehicles can be simulated in order to verify that the relative vehicle motion will be as intended. The resulting tracks are visualized as overlay to calibrated aerial photographs or maps of test areas; this way it can also be verified that the paths stay on the available surfaces. The simulation checks for physical limits and for expected dynamic deviations from the planned trajectory.

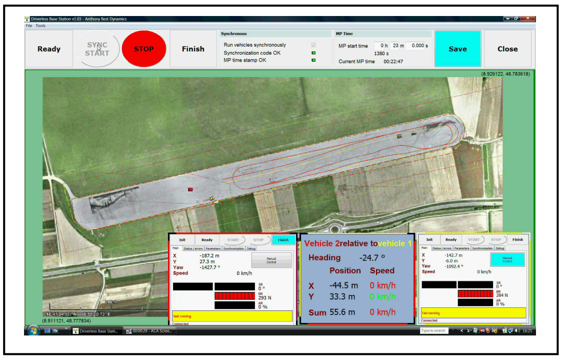

Figure 8. Simulation of a test.

SAFE OPERATION

Safe operation was one of the main challenges of the system design; it was laid out with highly reliable respectively redundant components. Nevertheless the position information might degrade at any time, and other failures could happen unexpectedly.

When a driver is in the car, he needs to keep a contact switch closed for automatic control; he can always interrupt the manoeuvre by releasing the contact, and he regains full control of the vehicle as in conventional test driving situations. This mode of operation can be used to perform traffic scenarios where the main focus is on improving repeatability or accuracy.

For safety critical scenarios, the vehicle is operated in the driverless mode. Figure 9 shows the safety components and their interaction with the other vehicle components for this mode. The safety controller verifies continuously the integrity of the system by monitoring of watchdog signals, the communication channels and other safety relevant states. If one vehicle should operate outside of predefined limits (but is still controllable), the safety controller initiates a *controlled shut down procedure* for all vehicles. This procedure will also be activated in case of a communication loss, and it can be triggered manually by the operator in the base station.

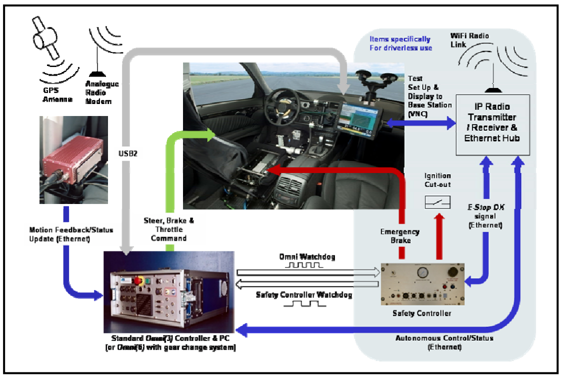

Figure 9. Control and safety components.

In case of a complete loss of control (e.g. steering or brake robot failure), or after pushing the *emergency stop* button by the operator, the safety controller activates a spring loaded safety brake system. The emergency stop will also be activated if the vehicle should leave the predefined limits of the test field.

Controlled shut down procedures are necessary because emergency braking of all vehicles in the test could lead to disastrous results: a planned trajectory with close passing of vehicles could end in a crash. To avoid this, for each point of the planned trajectory and for each vehicle, settings for steering and pedal robots in two time slots are planned in advance. The result of this shut down procedure is simulated for the whole test manoeuvre in order to verify a safe shut down, whilst also considering the possible tolerances.

The simulation is based on “PC-Crash”, a standard program for crash simulation [5]; the concept and implementation was the task of the *Vehicle Safety Institute*, Technical University of Graz. Figure 10 shows an example, how shut down procedures may be defined and verified for a close passing manoeuvres in an intersection scenario; although the traces of the possible shut down procedures seem to intersect, this definition is safe due to the given timing constraints.

By defining the controlled shut down procedures adequately, “safe” places on the test track can be set up for objects (like cameras, traffic signs, etc.), which should not be hit even in the case of deviations from the planned trajectory.

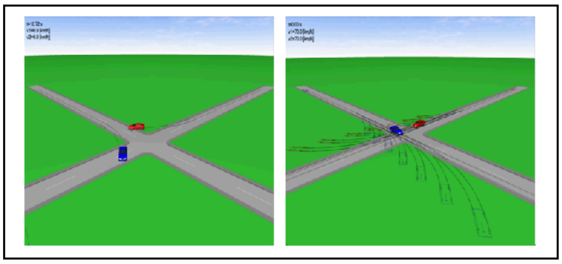

Figure 10. Example for safe vehicle traces for controlled shut down procedures

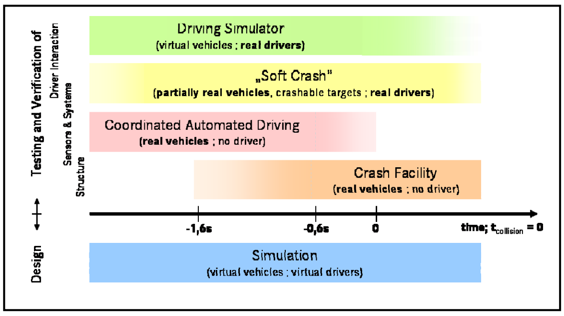

Figure 11. Validation of pre-crash systems with complementary testing methods.

CONCLUSIONS

The presented method using *controlled automated driving* of test vehicles can fulfill the specifications and has proven the potential for efficient and safe verification of assistance and active safety systems. Test procedures can be performed much more precise and repeatable than with human drivers; the risk of crashes is significantly less than with human drivers even in very close passing manoeuvres.

This way, the compliance with specifications of assistance and active safety systems can be verified efficiently; the comparison of different sensor configurations or software versions can be done with less experiments. Manoeuvres at the borderline between “system must react” and “system should not react” can be tested precisely by controlling the relative absolute position and speed of several vehicles in a traffic configuration.

As shown in figure 11, this method has its place in a set of complementary verification methods. While simulation is used for system design in a completely virtual world, the driving simulator focuses on the behaviour of real drivers, and the crash facility focuses on the structural aspects of real vehicles. Crashes with soft targets allow the checking of systems and the driver’s interactions around the time of crash, but some questions were still left open. The performance verification of *real* sensors in interaction with control algorithms in *real* traffic situations up to points very close to a crash is the realm of controlled automated driving.

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A FORWARD COLLISION WARNING (FCW) PERFORMANCE EVALUATION

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ABSTRACT

This paper describes tests performed by the National Highway Traffic Safety Administration (NHTSA) to evaluate the forward collision warning (FCW) systems installed on three late model passenger cars. NHTSA defines an FCW system as one intended to passively assist the driver in avoiding or mitigating a rear-end collision via presentation of audible, visual, and/or haptic alerts, or any combination thereof. The test maneuvers described were designed to emulate the top three most common rear-end pre-crash scenarios reported in the 2004 GES database.

FCW system performance was quantified by specifying the average time-to-collision (TTC) between the subject vehicle (SV) and principle other vehicle (POV) at the time of the SV's FCW alert.

BACKGROUND

During the summer of 2008, the National Highway Traffic Safety Administration (NHTSA) performed an evaluation of the forward collision warning (FCW) systems installed on three late model passenger cars. All tests were performed by researchers at the agency's Vehicle Research and Test Center (VRTC), located on the Transportation Research Center, Inc. (TRC) proving grounds in East Liberty, OH.

NHTSA defines an FCW system as one intended to passively assist the driver in avoiding or mitigating a rear-end collision. FCW systems have forward-looking vehicle detection capability, provided by technologies such as RADAR, LIDAR (laser), cameras, etc. Using the information provided by these sensors, an FCW system alerts the driver that a collision with another vehicle in the anticipated forward pathway of their vehicle may be imminent unless corrective action is taken. FCW system alerts consist of audible, visual, and/or haptic warnings, or any combination thereof.

At the time the work discussed in this paper was performed, the number of US-production light vehicles available with FCW was very low, with only three vehicle manufacturers offering such systems on limited variants of certain vehicle makes and models. So as to best evaluate the current state of FCW technology implementation, sample offerings from each of these vehicle manufacturers were procured: a 2009 Acura RL, 2009 Mercedes S600, and a 2008 Volvo S80. Although each of these vehicles present the driver with auditory and visual alerts, the manner in which these cues were presented differed, as shown in Table 1.

Table 1.
FCW Alert Modality

Vehicle	FCW Alert	
	Visual	Auditory
Acura RL	Message on instrument panel	Repeated beeps
Mercedes S600	Icon on instrument panel	Repeated beeps
Volvo S80	HUD using up to two sequences of red LEDs	Repeated tones

THE REAR-END COLLISION CRASH PROBLEM

When determining what kinds of tests would be appropriate for use in FCW evaluation, work performed by the agency's Automotive Rear-End Collision Avoidance System (ACAS) project [1], the Integrated Vehicle-Based Safety Systems (IVBSS) and Crash Avoidance Metrics Partnership (CAMP) programs [2,3], and research by the Volpe Center (part of DOT's Research and Innovative Technology Administration) [4] was reviewed. Based on 2004 General Estimates System (GES) statistics, a summary performed by Volpe shows that overall, approximately 6,170,000 police-reported crashes of all vehicle types, involving 10,945,000 vehicles, occurred in the United States. These statistics also indicate that overall, all police-reported light-vehicle crashes resulted in an estimated cost of $120 billion, and functional years lost (a measure of harm) totaled approximately 2,767,000 [5]. These societal harm measures were based on the GES crash sample and did not incorporate data from non-police-reported crashes.

Using the 37 crash typology described in [5], Volpe identified that many of these crashes involved rear-end collision scenarios. Of the 37 groupings used to describe the overall distribution of pre-crash scenario types, the Lead Vehicle Stopped, Lead Vehicle Decelerating, and Lead Vehicle Moving at Lower Constant Speed crashes represented in the 2004 GES database were found to be the 2nd, 4th, and 12th most common crash scenarios overall, respectively, and were the top three rear-end pre-crash scenarios. Note that in 50% of Lead Vehicle Stopped crashes, the lead vehicle first decelerates to a stop and is then struck by the following vehicle, which typically happens in the presence of a traffic control device or the lead vehicle is slowing down to make a turn. Tables 2 through 4 presents summaries of these rear-end pre-crash scenarios, ranked by frequency, cost, and harm (expressed as functional years lost), respectively.

Based on the crash frequency, cost, and harm data presented in Tables 2 through 4, NHTSA decided use of test maneuvers designed to emulate these real-world crash scenarios would provide an appropriate way to evaluate FCW performance. Building on the efforts put forth by the ACAS and IVBSS programs, NHTSA researchers subsequently developed three objective test procedures to perform the work described in this paper. The objectives of this work were twofold: (1) identify the time-to-collision (TTC) values from the time an FCW alert was first presented to the driver, and (2) refine the test procedures, as necessary, to enhance the accuracy, repeatability, and/or reproducibility by which the FCW system evaluations could be performed.

Table 2.
Crash Rankings By Frequency (2004 GES data)

Scenario	Frequency	Percent
Lead Vehicle Stopped	975,000	16.4
Lead Vehicle Decelerating	428,000	7.2
Lead Vehicle Moving at Lower Constant Speed	210,000	3.5

Table 3.
Crash Rankings By Cost (2004 GES data)

Scenario	Cost ($)	Percent
Lead Vehicle Stopped	15,388,000,000	12.8
Lead Vehicle Decelerating	6,390,000,000	5.3
Lead Vehicle Moving at Lower Constant Speed	3,910,000,000	3.3

Table 4.
Crash Rankings By Functional Years Lost (2004 GES data)

Scenario	Years Lost	Percent
Lead Vehicle Stopped	240,000	8.7
Lead Vehicle Decelerating	100,000	3.6
Lead Vehicle Moving at Lower Constant Speed	78000	2.8

TEST METHODOLOGY

Overview

The tests described in this paper were designed to evaluate the ability of an FCW system to detect and alert drivers of potential hazards in the path of their vehicles. Three driving scenarios were used to assess this technology. In the first test, a subject vehicle (SV) approached a stopped principle other vehicle (POV) in the same lane of travel. The second test began with the SV initially following the POV at the same constant speed. After a short while, the POV stopped suddenly. The third test consisted of the SV, traveling at a constant speed, approaching a slower moving POV, which was also being driven at a constant speed. For the sake of brevity, these three tests will be referred to as the "Lead Vehicle Stopped," "Decelerating Lead Vehicle," and "Slower Moving Lead Vehicle" tests, respectively, for the remainder of this paper.

The tests were each performed on the TRC skid pad, a 3600 ft (1097 m) long flat (0.5 percent upwards longitudinal slope, with a negligible cross slope) concrete roadway comprised of seven paved lanes. The pavement of the skid pad lanes used for the FCW evaluations was in good condition, free from potholes, bumps, and cracks that could cause the subject vehicle to pitch excessively. Each lane was approximately 12 ft (3.7 m) wide, and was delineated with solid white pavement lines. All tests were performed during daylight hours with good visibility (no fog, rain, or snow) and very windy conditions were avoided (wind speeds ranged from 0 to 17 mph during the testing timeline). The ambient temperatures present during test conduct ranged from 63 to 83 ºF (17 to 28 ºC).

A 2008 Buick Lucerne was used as the POV for all FCW tests discussed in this paper. The vehicle, as shown in Figure 1, was selected to represent a "typical" mid-sized passenger car. Use of an artificial representation was considered (e.g., an inflatable or foam car), but ultimately not deemed necessary for three reasons: safety considerations, test consistency, and test complexity.

Figure 1. Buick Lucerne (POV) and Mercedes S600 (SV) during an FCW test performed on the TRC skidpad.

The evaluations discussed in this paper were intended to evaluate when FCW alerts occurred. As such, SV-to-POV collisions were not expected. For an FCW to be effective in the real-world, it was believed there would be sufficient time from (1) when an FCW alert was presented to the driver to (2) when the driver would be able to comprehend the alert and take some corrective action to avoid a crash. A professional test driver was used to pilot the SV, and was aware of what actions would be taken by the POV during each trial. This, and the fact there was sufficient room to maneuver around the POV in the case of an aborted trial on the test pad, gave reason for NHTSA researchers to believe the tests could be safely performed with a "real" POV.

NHTSA researchers also believed it would be best to perform each of the three tests series with a common POV. Each test scenario contained a unique interaction between the SV and POV. By not using the same POV for all tests, researchers were concerned that scenario-based performance comparisons could be confounded by differences in how the FCW systems may have perceived the different POVs. Evaluating artificial test targets, with a radar return signature comparable to that of the "real" POV, was outside of the scope of the project.

Use of an artificial POV would have introduced significant test complexity for some tests. Although NHTSA presently owns a full-size inflatable balloon car intended for used in collision avoidance/ mitigation testing, two of the three test scenarios described in this paper required the POV accurately and consistently travel in a straight line at speeds up to 45 mph. Additionally, the "SV approaches a decelerating POV" tests required the POV achieve and maintain a set deceleration magnitude. Development of a new artificial test apparatus able to accommodate these demands was outside of the scope of the project.

Instrumentation

Table 5 provides a summary of the instrumentation used during NHTSA's FCW evaluations. The POV and each SV and were equipped with instrumentation and data acquisition systems. All analog data was sampled at 200 Hz. For the SV, vehicle speed, lateral and longitudinal position (via GPS), range to POV (via radar), yaw rate, and FCW alert status data were recorded. In the case of the Mercedes S600, FCW alert output from the high speed controller area network (CAN) also was collected using equipment discussed in the next section. For the POV, vehicle speed, position, brake pedal travel, and longitudinal acceleration data were collected. Signal conditioning of these data consisted of amplification, anti-alias filtering, and digitizing. Amplifier gains were selected to maximize the signal-to-noise ratio of the digitized data.

For both vehicles, vehicle speed was directly recorded as an analog output from a stand-alone GPS based speed sensor and calculated from the output of a second GPS system; that which provided the position data later used to determine TTC. The GPS data produced by the second system were sampled at 10 Hz, and were differentially corrected during post-processing. All data (analog and GPS-based data from the SV and POV) were then merged into a single data file per trial for the ease of subsequent data analysis.

Redundant vehicle speed sensors provided two functions. First, the stand-alone GPS-based speed sensor provided the drivers of the SV and POV with accurate real-time vehicle speed information. The GPS system used to provide position data did not have this capability. Second, during merging of the analog and differentially corrected GPS data files for an individual trial, use of common speed information from two independent sources improved the synchronization accuracy.

Table 5.
Instrumentation Used During FCW Evaluation

Type	Output	Range	Resolution	Accuracy
Differentially-Corrected GPS Data	Vehicle speed	0.5 – 125 kph* (0.3 - 77 mph)	0.01 kph* (0.001 mph)	0.1 kph* (0.06 mph)
	Longitudinal position of SV and POV	N/A	5 cm (2 in)	< 10 cm (4 in) absolute; 1 cm static
	Lateral position of SV and POV	N/A	5 cm (2 in)	< 10 cm (4 in) absolute; 1 cm static
Radar-Based Headway	Distance between SV and POV	1 – 100 m (3-300 ft)	0.5 m (1.6 ft)	+/- 5% of full scale
Rate Sensor	Yaw rate	+/- 100 deg/s	0.004 deg/s	+/- 0.05% of full scale
Accelerometer	Longitudinal acceleration	+/- 2 g's	+/- 10μg	+/- 0.05% of full scale
Brake Pedal Travel	Linear brake pedal travel	0 – 5 in	+/- 0.001 in	+/- 1% of full scale
Data Flag (FCW Alert)	Signal from FCW system that indicates if the FCW warning was issued	0 – 10V (optional: could be a binary flag from CAN Bus)	N/A	Output response better than 10 ms
Vehicle Dimensional Measurements	Location of GPS antenna, vehicle centerlines, and two bumper measurements	N/A	1 mm (0.05 in)	1 mm (0.05 inch)

*Values for the stand alone vehicle speed sensor used to provide output to the dashboard display and for data synchronization. The GPS-based vehicle speed ultimately used for TTC calculation, was derived using vehicle position and time data.

Table 5 provides a summary of the instrumentation used during NHTSA's FCW evaluations. Note that in addition to this equipment, the driver of the SV was also presented with real-time range-to-POV data produced with a laser-based distance measuring system to facilitate accurate conduct of the Decelerating Lead Vehicle tests. The output of the laser-based system was not recorded.

FCW Alert Monitoring

When activated, the FCW systems discussed in this paper provided the SV driver with auditory and/or visual alerts. Recording when these alerts first occurred was of great importance since this information would later be used to calculate the TTCs for each test scenario, the objective measure by which FCW performance was quantified. The methods used to record the FCW alerts differed from vehicle to vehicle, as shown in Table 6.

Table 6.
FCW Alert Monitoring Methods

Vehicle	Monitor
Acura RL	Auditory cue only (monitoring the visual display deemed too invasive)
Mercedes S600	High-speed CAN bus output (monitoring the visual and/or aural cues deemed too invasive)
Volvo S80	1. Low severity HUD 2. High severity HUD 3. Auditory alert (direct tap) 4. Auditory alert (via microphone)

<u>Volvo S80</u>

The Volvo S80 was the first vehicle evaluated, and its FCW alerts were monitored the most comprehensively (i.e., to provide an indication of how best to evaluate the subsequent vehicles). The auditory alert originated from a piezoelectric speaker installed behind the instrument cluster. Visual alerts were presented via a heads-up display (HUD) comprised of multiple LED clusters. These clusters provided two levels of illumination, where the system's perceived risk of a collision would dictate whether some or all of the HUD LEDs would be illuminated.

To monitor the status of the auditory alert, the leads of the piezoelectric speaker were directly tapped, and their output (i.e., the signal sent to the speaker) was recorded. Additionally, an external microphone was positioned near the speaker, and its output recorded. This was to allow researchers to examine the feasibility of using a less invasive method of capturing the FCW speaker output, a practical consideration for future NHTSA test programs.

To monitor the status of the FCW HUD, the dash-mounted LED circuit was removed and tapped. Additionally, five photocells were placed over the HUD to record when and how many LEDs were illuminated during each FCW alert. Conceptually similar to the use of the microphone being used to monitor the piezoelectric speaker output, use of the photocells allowed researchers to examine the feasibility of using a less invasive method of capturing the FCW HUD illumination. Figure 2 provides an output comparison of the FCW HUD taps, photocells, audible alarm tap, and microphone during a Lead Vehicle Stopped test performed with the Volvo S80.

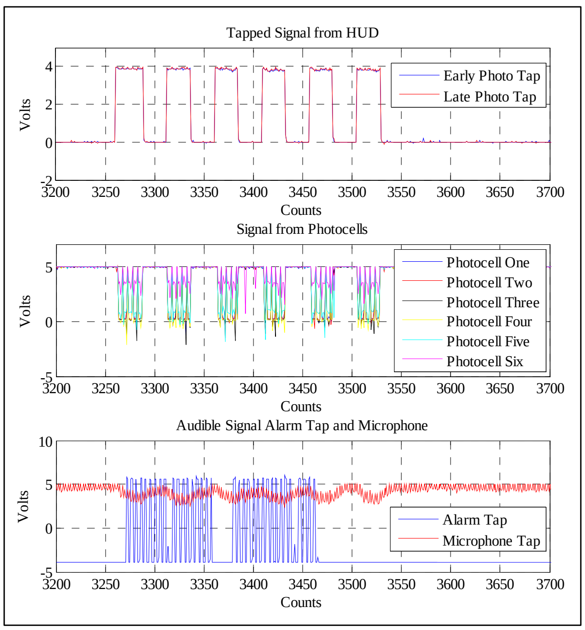

Figure 2. Outputs of the FCW warning light taps, photocells, audible alarm tap, and microphone during a test performed with the Volvo S80.

Of particular interest was the response time and signal-to-noise ratio of the microphone and photocells. For the tests described in this paper, each FCW alert presented both levels of HUD illumination, accompanied by the audible alert. Illumination of both LED clusters occurred at the same instant; the auditory alert was found to occur 20 to 65 ms later. Indication of an HUD-based alert provided by photocell output typically lagged that provided by the direct tap by 5 to 15 ms. The signal-to-noise ratio of the microphone output used to monitor the piezoelectric speaker was poor, and was affected by signal noise bleed through. As such, results from the microphone-based outputs were not considered during data analysis.

Based on comparison of each technique used for monitoring the Volvo S80 FCW alerts, the authors concluded use of the outputs provided by the direct tap of the HUD were the most appropriate. Subsequent TTC calculations for this vehicle were therefore based on the instant HUD illumination was first detected.

<u>Acura RL</u>

The Acura RL auditory alerts originated from a piezoelectric speaker installed behind the instrument cluster. The visual alert was presented via a multi-function display located in the center of the instrument cluster, where the message "BRAKE" was shown at the time of the alert. Subjective impressions from the SV test driver indicated the visual and aural cues were presented simultaneously.

Based on a combination of test feasibility and consideration of observations made during the Volvo S80 evaluation, the FCW alert detection methods used for the Acura RL was simplified. To monitor the status of the auditory alert, the leads of the piezoelectric speaker were directly tapped, and their output was recorded. For previously-stated reasons, an external microphone was not used to provide a redundant measure of this speaker's output. The visual FCW alert status was not recorded during evaluation of the Acura RL. Since the vehicle's message center was used to present the driver with information beyond just FCW alerts, use of photocell-based monitoring was not appropriate. In other words, absolutely discerning an FCW alert from some other display was not possible with this method. Researchers did not have a way to decode CAN-based FCW data for the Acura RL.

Since it was the only FCW alert information recorded, data from the piezoelectric speaker tap was used to calculate the TTC values for the Acura RL; considered at the instant speaker output was detected. Figure 3 provides an example of these data.

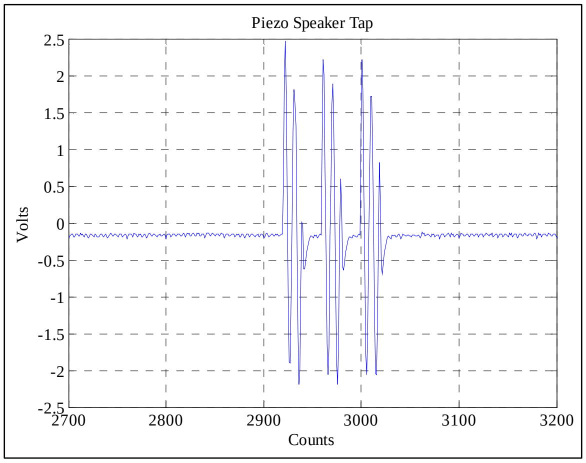

Figure 3. Alert outputs recorded during an FCW test performed with the Acura RL.

Mercedes S600

The Mercedes S600 auditory alert originated from a piezoelectric speaker installed behind the instrument cluster. Visual alerts were presented via a small icon on the instrument cluster. Although a direct tap of either alert would have provided information necessary to calculate TTCs, accessing the respective circuits would have requiring much of the dash be disassembled. Given the high cost of the vehicle, and since it was acquired via a short term lease, researchers sought to identify a less invasive means to monitor the FCW alert status.

NHTSA researchers were able to identify the FCW indicator status data via the S600 CAN bus (see Figure 4). After interfacing with the appropriate connector, the CAN data was fed into a NHTSA-developed programmable board designed to isolate and monitor the FCW status, and to output it as an analog signal to the vehicle's data acquisition system. Accessing the vehicle's CAN was necessary since the FCW alert status was not accessible via the OBD II connector.

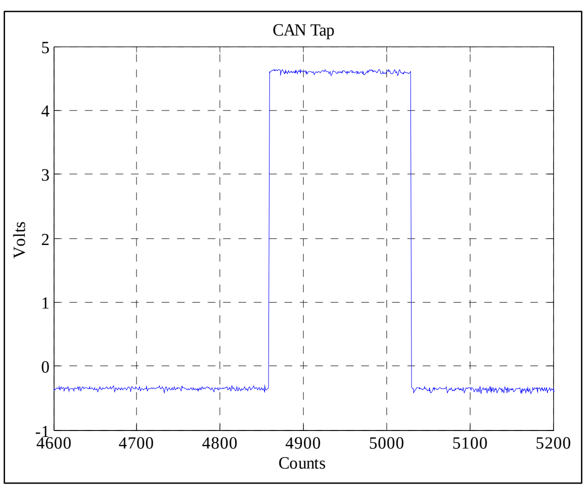

Figure 4. FCW alert status accessed via the CAN during a test performed with the Mercedes S600.

Since it was the only practical way by which the FCW alert recorded, data from the CAN was used to calculate the TTC values for the Mercedes S600 (i.e., the instant a message commanding the FCW alert was detected). Figure 4 provides an example of these data.

SV-to-POV Proximity

Accurate measurement of SV and POV position over time was of great importance for the tests described in this paper. In each scenario, the distance between the vehicles (i.e., the headway) at the time of the FCW alert was used in the calculation of the respective TTC values. Additionally, the ability of the SV to maintain and/or establish the appropriate headway to the POV and the vehicles' lateral lane positions were considered during the pre-brake validity assessments performed for the Decelerating Lead Vehicle and Slower Moving Lead Vehicle tests.

Although the most accurate SV and POV positions were ultimately derived from differentially corrected GPS data, two supplemental methods were also used: (1) via a forward-looking radar, and (2) via a laser-based range measurement sensor. Both supplemental units were attached to the front bumper of the SV, as shown in Figure 5.

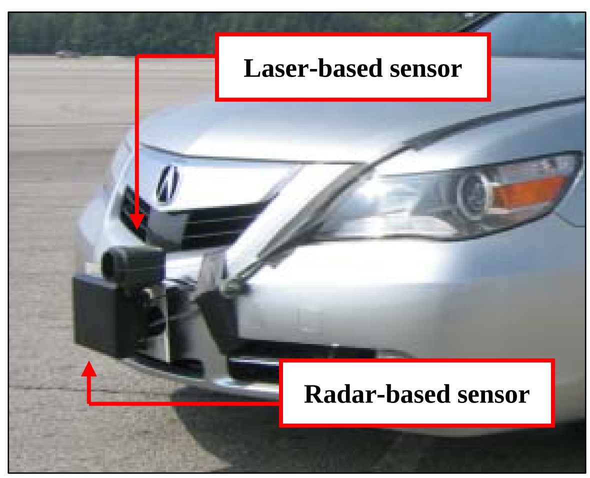

Figure 5. Instrumented test vehicle (Acura RL shown). Note bumper-mounted distance measuring equipment.

The reasons for using the supplemental distance measuring equipment were two-fold. First, to benchmark radar-based range performance against that of the GPS. This was to assess whether the radar-based system could provide an acceptable alternative to, or substitute for, differentially corrected GPS for future NHTSA tests requiring such data. Second, the laser-based range measurement provided real-time headway information to the SV driver. Such information was essential for conduct of the Decelerating Lead Vehicle tests, and not available from the GPS or radar-based measurement systems.

Programmable Brake Controller

The Decelerating Lead Vehicle tests required the POV establish and maintain moderate deceleration with minimal overshoot and variability. Since repeatably accomplishing this with even a skilled test driver is difficult, a programmable brake controller was used for these tests, as shown in Figure 6. Although this controller was expected to offer researchers the ability to command a desired deceleration, such functionality could not be realized during the tests described in this paper. Alternatively, a feedback loop that applied and maintained a constant brake pedal displacement was used. The combination of this feedback loop, and maintaining a consistent amount of time between trials[1], ultimately produced POV deceleration within the tolerances specified by the Decelerating Lead Vehicle validity criteria described later in this paper.

Figure 6. Programmable brake controller used during the Decelerating Lead Vehicle tests.

[1]Maintaining a consistent amount of time between trials was found to contribute to consistent within-series POV brake temperatures. This resulted in more consistent POV deceleration.

Test Maneuvers

Although there were three unique test scenarios discussed in this paper, a number of common validity requirements were imposed on the individual trials so as to perform the tests as objectively as possible.

1. The SV vehicle speed could not deviate from the nominal speed by more than 1.0 mph (1.6 kph) for a period of three seconds prior to the required FCW alert.

2. SV driver was not allowed to apply any force to the brake pedal before the required FCW alert occurred

3. The lateral distance between the centerline of the SV, relative to the centerline of the POV, in road coordinates, could not exceed 2.0 ft (0.6 m).

4. The yaw rate of the SV could not exceed ±1 deg/sec during the test.

5. Since each SV was equipped with an automatic transmission, all tests were performed in "Drive"

Subject Vehicle (SV) Encounters a Stopped Principle Other Vehicle (POV)

These tests are also known as "Lead Vehicle Stopped" trials. To perform this maneuver, the POV was parked in the center of a travel lane facing away from the approaching SV, oriented such that its longitudinal axis was parallel to the roadway edge, as shown in Figure 7.

The SV was then driven at a nominal speed of 45 mph (72.4 kph), in the center of the lane of travel, toward the parked POV. The test was taken to begin when the SV was 492 ft (150 m) from the POV, and concluded when the subject vehicle's FCW alert was presented. To assess FCW alert variability, performing seven valid tests was desired.

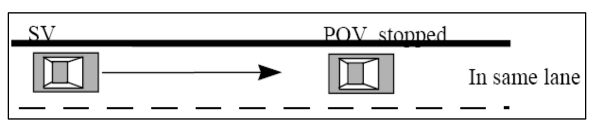

Figure 7. Lead Vehicle Stopped crash scenario.

Subject Vehicle (SV) Encounters a Decelerating Principle Other Vehicle (POV)

These tests are also known as "Decelerating Lead Vehicle" trials. To begin this maneuver, the SV and

POV were driven in the center of same travel lane at a speed of 45 mph (72.4 kph). After driving with a constant headway distance of 98.4 ft (30 m), the driver of the POV suddenly applied the brakes in a manner intended to establish constant deceleration of 0.3 g within 1.5 seconds. For this test series, the individual trials were taken to begin 3 seconds prior to the initiation of the POV braking, and concluded when the subject vehicle's FCW alert was presented. To assess FCW alert variability, performing seven valid tests was desired. Figure 8 presents the decelerating lead vehicle crash scenario.

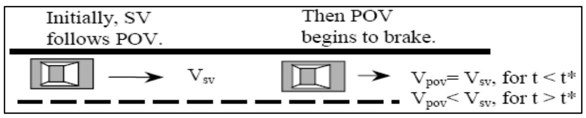

Figure 8. Decelerating Lead Vehicle crash scenario.

In addition to the previously mentioned validity requirements, the Decelerating Lead Vehicle test scenario includes the following parameters:

1. The initial POV vehicle speed could not deviate from the nominal speed by more than 1.0 mph (1.6 kph) for a period of three seconds prior to the initiation of POV braking.

2. The POV deceleration level was required to nominally be 0.3 g within 1.5 seconds after initiation of POV braking. The acceptable error magnitude of the POV deceleration was ± 0.03g, measured at the time the FCW alert first occurred. An initial overshoot beyond the deceleration target was acceptable, however the first local deceleration peak observed during an individual trial was not to exceed 0.375 g for more than 50 ms. Additionally, the POV deceleration was not permitted to exceed 0.33 g over a period defined from (1) 500 ms after the first local deceleration peak occurs, to (2) the time when the FCW alert first occurs.

3. The tolerance for the headway from the SV to the POV was required to be ± 8.2 ft (± 2.5 m), measured at two instants in time: (1) three seconds prior to the time the POV brake application was initiated, and (2) at the time the POV brake application was initiated.

Subject Vehicle (SV) Encounters a Slower Principle Other Vehicle (POV)

These tests are also known as "Slower Moving Lead Vehicle" trials. To begin this maneuver, the POV was driven in the center of a travel lane at a speed of 20 mph (32.2 kph). Shortly after the POV had established the desired test speed, the SV was driven in the center of same travel lane at a speed of 45 mph (72.4 kph), approaching the slower-moving POV from the rear. For this test series, the individual trials were taken to begin when the headway from the SV to the POV was 492 ft (150 m), and concluded when the subject vehicle's FCW alert was presented. To assess FCW alert variability, performing seven valid tests was desired. Figure 9 presents the decelerating lead vehicle crash scenario.

Figure 9. Slower Moving Lead Vehicle scenario.

As was the case for the Decelerating Lead Vehicle test scenario, the Slower Moving Lead Vehicle trials also required the POV vehicle speed not deviate from the nominal speed by more than 1.0 mph (1.6 kph) for a period during the test.

TEST RESULTS

General Observations

Performing the three tests scenarios proved to be quite straight-forward, however there were some important observations made during their conduct.

First, these tests do not lend themselves to some of the variability-reducing steps presently used by other track-based tests presently performed by NHTSA (i.e., dynamic rollover or electronic stability control testing). For example, cruise control could not be used to maintain the SV test speed. Many of the sensors used by the FCW systems discussed in this paper were shared with the vehicles' respective adaptive cruise control (ACC) systems. For at least two of the maneuvers, the decelerating and slower-moving POV tests, ACC interventions would not be expected to allow the combination of pre-FCW alert headway distances and tight SV and POV vehicle speed tolerances be realized and/or maintained.

Maintaining SV speed also required the driver to use careful throttle modulation using small, smooth inputs. Prior to actually performing the FCW tests, discussions with vehicle manufacturers indicated some systems monitor the driver's throttle inputs, and that use of abrupt throttle inputs could cause an FCW system to suppress the alert NHTSA was interested in evaluating. The rationale for such suppression involves a desire to achieve the high consumer acceptance, with the logic being that if the driver is deliberately commanding a sudden throttle input, they are providing an indication of being alert, capable of making good driving decisions, and that providing an FCW alert (an alert intended to primarily benefit inattentive drivers) may not be appropriate.

For the previously-stated reasons, the driver of the SV was also required to make small, smooth steering corrections to maintain lane position. NHTSA researchers were cautioned that use of abrupt or coarse changes in steering position, even with small magnitudes, could also result in FCW alert suppression. Evaluating whether these concerns were relevant to the test vehicles described in this paper, or attempting to determine the minimum throttle and/or steering input magnitudes necessary to evoke FCW alert suppression was not performed in this study, but may provide an interesting area for future research.

Maneuver Results

Subject Vehicle (SV) Encounters a Stopped Principle Other Vehicle (POV)

Since the POV was stationary for the entire test, the Lead Vehicle Stopped trials were the simplest to perform. The TTC for this test, a prediction of the time it would take for the SV to collide with the POV from the time of the FCW alert, was calculated by considering two factors at the time of the FCW alert: (1) distance between SV and POV at the time of the FCW alert ($s_{sv,initial}$) and (2) the speed of the SV ($v_{sv,initial}$). The corresponding TTC values were simply computed using Equation 1:

$$TTC_{Test1} = \frac{s_{sv,initial}}{v_{sv,initial}} \qquad (1)$$

Table 7 provides a summary of the TTCs calculated with data collected from tests that satisfied all validity criteria. In the case of the Volvo S80, the full suite of seven valid tests was not realized after data post processing (SV speed at the time of the FCW alert was too high for some tests). For this vehicle, the mean and standard deviations were based on five trials.

Generally speaking, and despite the prohibition of cruise control and tight allowable tolerances, the experimenters were able to successfully execute the tests without issue. That said, the Lead Vehicle Stopped tests did call to attention to two important details regarding test conduct. First, it appears the absence of a POV rear license plate was capable of influencing the FCW effectiveness for at least one vehicle used in this study. Second, although conduct of the maneuver was free of incident, some safety concerns were raised.

Table 7.
Lead Vehicle Stopped TTC Summary

Trial	Acura RL	Mercedes S600	Volvo S80
1	1.63	2.24	2.08
2	1.84	2.32	2.64
3	1.62	2.29	2.28
4	1.94	2.30	2.68
5	1.74	2.31	2.57
6	1.83	2.27	n/a
7	1.46	2.33	n/a
Ave	**1.72**	**2.29**	**2.45**
Stdev	**0.16**	**0.03**	**0.26**

During a brief pilot study comprised of Lead Vehicle Stopped tests, no license plate was installed on the rear of the POV. This was not intentional; it simply happened that since the vehicle was only being driven within the controlled confines of a proving ground, it was not so-equipped. When the Volvo S80 was evaluated in this condition, an FCW alert was not presented during three of the ten pilot tests. Seeking to understand whether the manner in which the tests were performed may have influenced the test outcome, NHTSA researchers considered a variety of experimental refinements. One such consideration was installing a license plate on the rear of the POV, since it was more representative of how the POV would be seen in the real world, and would provide a vertical metallic surface capable of being more easily detected with forward-looking radar (used to provide range and range rate data to the respective FCW systems). With the rear license plate installed on the POV, each of the valid Lead Vehicle Stopped tests performed with the Volvo S80 produced an FCW alert.

Due the low sample size of the tests performed during pilot testing, it is unclear whether the presence of the POV license plate can be absolutely attributable to the Volvo S80's apparently improved FCW performance. However, the fact remains there was at least some evidence suggesting this was the case, and that inclusion of the rear plate on the POV does indeed enhance the face validity of the test scenario. Therefore, all subsequent tests were performed with the rear license plate installed on the POV, including those of the two other test scenarios.

Subject Vehicle (SV) Encounters a Decelerating Principle Other Vehicle (POV)

Given the tight tolerances and careful choreography required by these tests, the Decelerating Lead Vehicle tests were generally the most challenging to perform. Use of the dashboard mounted headway display in the SV, and maintaining a consistent amount of time between trials, improved the efficiency these tests could be performed with. However, since the actual range between the vehicles (calculated with GPS data), and the actual deceleration produced by the POV throughout the maneuver (corrected for pitch angle) could not be calculated until these data had been output after post-processing, obtaining an acceptable number of valid trials required repeated test series for some vehicles.

The TTC for this test, a prediction of the time it would take for the SV to collide with the POV from the time it initiates braking, was calculated by considering three factors at the time of the FCW alert: (1) the speed of the SV ($v_{sv,initial}$), (2) the speed of the POV ($v_{pov,initial}$), and (3) the deceleration of the POV (a_{pov}), as shown in Equation 2. Note: To simplify calculation of the TTC for Test 2, the deceleration of the POV was taken to remain constant from the time of the FCW alert until the POV comes to a stop (i.e., a "constant" deceleration rate assumed).

$$TTC_{Test2} = \frac{-(v_{pov,initial} - v_{sv,initial}) - \sqrt{(v_{pov,initial} - v_{sv,initial})^2 - 2 * a_{pov} * s_{sv,initial}}}{a_{pov}} \quad (2)$$

Table 8 provides a summary of the TTCs calculated with data collected from tests that satisfied all validity criteria. In the case of the Mercedes S600, the full suite of seven valid tests was not realized after data post processing (the headway between the SV and POV at the onset of POV braking was found to be too short). For this vehicle, the mean and standard deviates are based on three trials.

Table 8.
Decelerating Lead Vehicle TTC Summary.

Trial	Acura RL	Mercedes S600	Volvo S80
1	2.30	2.23	3.17
2	2.16	2.34	3.06
3	2.44	2.27	2.95
4	2.21	n/a	3.08
5	2.38	n/a	3.08
6	2.28	n/a	2.92
7	2.13	n/a	3.19
Ave	**2.27**	**2.28**	**3.07**
Stdev	**0.11**	**0.05**	**0.10**

Subject Vehicle (SV) Encounters a Slower Principle Other Vehicle (POV)

Although they were more involved than the Lead Vehicle Stopped tests, the Slower Moving Lead Vehicle tests were generally quite simple to perform. That said, these tests can use considerable real estate if the POV is given an excessive head start before the SV driver begins their approach toward the POV. To maintain a constant POV speed, researchers used the vehicle's cruise control.

The TTC for this test, a prediction of the time it would take for the SV to collide with the POV from the time it initiates braking, was calculated by considering two factors at the time of the FCW alert: (1) the speed of the SV ($v_{sv,initial}$) and (2) the speed of the POV ($v_{pov,initial}$). Equation 3 was used to calculate the TTC for the Slower Moving Lead Vehicle tests.

$$TTC_{Test3} = \frac{s_{sv,initial}}{v_{sv,initial} - v_{pov,initial}} \quad (3)$$

Table 9 provides a summary of the TTCs calculated with data collected from tests that satisfied all validity criteria. In the case of the Volvo S80 the full suite of seven valid tests was not realized after data post processing. For this vehicle, the mean and standard deviates were based on three trials.

Table 9.
Slower Moving Lead Vehicle TTC Summary.

Trial	Acura RL	Mercedes S600	Volvo S80
1	1.97	2.42	2.05
2	2.13	2.43	2.80
3	2.00	2.39	2.99
4	2.02	2.37	n/a
5	1.93	2.37	n/a
6	1.98	2.35	n/a
7	2.06	2.40	n/a
Ave	**2.01**	**2.39**	**2.61**
Stdev	**0.07**	**0.03**	**0.50**

The slower moving lead vehicle test procedure required the SV and POV speeds remain constant for at least 3 seconds prior to the LDW alert. For the Volvo S80 these criteria resulted in most tests being deemed non-valid (the desired speeds were achieved too late). Increasing the pre-brake speed tolerances and/or the amount of time the vehicles were required to remain constant before the alert occurred would have increased the number of valid trials for this test condition. Had they not been deemed non-valid for minor speed infractions, each of the five Volvo S80 trials would have produce TTCs ranging from 2.40 to 3.03 seconds.

Headway Calculation Comparison

TTC values calculated with distance measurements from the radar-based range measurement equipment and differentially corrected GPS are provided in Table 10. All TTC values presented in this table used the same vehicle speed and, in the case of the Decelerating Lead Vehicle tests, deceleration data; only the distance measurements used in the calculations differed.

Whether use of the radar-based equipment would provide an acceptable alternative to, or substitute for, differentially corrected GPS for future NHTSA tests requiring such data ultimately depends on what precision is required. Use of the less accurate radar-based distance measurements resulted in TTC values 5.0 to 12.5 percent longer than those more accurately derived with differentially corrected GPS data. This error was close to the radar manufacturer's sensor accuracy specification of 5 percent, as previously shown in Table 5.

CONCLUSION

Forward collision warning (FCW) system functionality is of great interest to NHTSA. Given the prevalence of rear-end collisions in the crash data, and the high societal costs they impose, better understanding how advanced technologies may be able to mitigate these crashes is an agency priority. This paper has provided details of how NHTSA evaluated the FCW performance of three contemporary passenger cars using three test scenarios designed emulate the most commonly occurring rear-end crash scenarios. Specifically, the time-to-collision (TTC) values, predictions of the time it would take for the SV to collide with the POV from the time of the FCW alert, associated with each vehicle/scenario combination was calculated.

Although performing the tests described in this paper was generally straight-forward, some details pertaining to FCW monitoring and test conduct were challenging. The processes used to accurately monitor the FCW alert status was somewhat intrusive for the Acura RL and Volvo S80, and required cooperation with the vehicle manufacturer for evaluation of the Mercedes S600. Adhering to the tight SV-to-POV headway and POV deceleration requirements of the Decelerating Lead Vehicle tests

Table 10.
Comparison of GPS and Radar-Based TTC Values.

Vehicle	Lead Vehicle Stopped				Decelerating Lead Vehicle				Slower Moving Lead Vehicle			
	GPS	Radar	Difference		GPS	Radar	Difference		GPS	Radar	Difference	
			(sec)	(%)			(sec)	(%)			(sec)	(%)
Acura RL	1.72	1.90	**0.17**	**10.0**	2.27	2.43	**0.16**	**7.0**	2.01	2.18	**0.16**	**8.1**
Mercedes S600	2.29	2.44	**0.14**	**6.3**	2.28	2.56	**0.28**	**12.5**	2.39	2.59	**0.20**	**8.4**
Volvo S80	2.45	2.59	**0.14**	**5.5**	3.07	3.23	**0.16**	**5.0**	2.61	2.82	**0.21**	**7.8**

was demanding. To maximize efficiency when performing these tests, the authors found that providing the SV driver with accurate real-time headway information (e.g., via a dashboard-mounted display, etc.) and use of a programmable brake controller in the POV was helpful. To obtain accurate vehicle-to-vehicle range information, use of highly accurate GPS-based position data of the SV and POV was found to be very effective.

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METHOD TO ASSESS THE EFFECTIVENESS OF ACTIVE PEDESTRIAN PROTECTION SAFETY SYSTEMS

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ABSTRACT

The effectiveness analysis assesses the benefit of future safety systems in terms of collision mitigation or collision avoidance based on real life accident data. The safety systems are evaluated by case-by-case analyses based on in-depth accident data (e.g. GIDAS). For this purpose an innovative simulation environment was developed that recreates the technical specification of the proposed system consisting of function algorithm, sensor, and actuators. Therefore results of component tests and complete system tests are included into the simulation. The accidents from the database are varied in the simulation by applying stochastic methods, guaranteeing the validity of the results from a statistical viewpoint. In addition to technical parameters such as a reduction in collision speed, the evaluation also includes a reduction in collision probability. Furthermore, when evaluating the functions a distinction is made between controlled and regulated actions. For each type a special simulation technique is used, which on the one hand is a purely offline analysis of previously simulated data and on the other hand an online or in-the-loop simulation. In order to be able to consider driver reactions on defined warning strategies realistically, it is essential to integrate a driver behaviour model into the simulation. To determine the driver behaviour, studies with probands are conducted using a new simulator technology. The test scenarios for these proband studies are based on accidents of the internal Audi accident research unit (AARU) database. In order to convert the technical evaluation parameters of the accident, e.g. collision speed, to injury severity, injury-risk-functions are required. To sum up, a new method of assessing the effectiveness of integrated safety systems will be presented, which incorporates new simulation techniques, driving experiments and real life accident data to assess a well-founded evaluation of integrated safety systems.

INTRODUCTION

The requirements arising from pedestrians' safety legislation and consumer ratings have intense effects on the today's vehicle development. The design of the vehicle and the technology of the front end especially depend strongly on these measurers and induce trade-offs during the vehicle development process. Further passive measures lead to an increasing vehicle weight or cars being built higher and consequently to higher emissions. Besides secondary collisions of the pedestrians e.g. with the road are not covered by passive measures. Studies based on real accident data proved that systems enhancing the driver's braking are considerably more effective in pedestrian accidents. These studies lead to the definition of phase 2 regarding pedestrian legislation in the European Community which prescribes the installation of a brake assist system in new cars since November 2009 in combination with reduced passive measures compared to the original proposal of pedestrian legislation phase 2. Consequently a first step in resolving the conflicts of aim described above has been carried out.

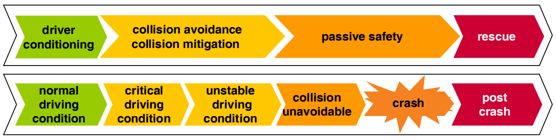

Figure 1: Chronological sequence of a normal driving condition until collision [3]

A further reduction of accidents and injuries of pedestrians can be achieved by using integrated safety systems. These systems consist of sensor systems, functional algorithms and actuating elements in addition to passive safety measures. These integrated systems are also effective during the pre-crash phase, e.g. a critical or unstable driving situation, compared to passive measures which are only effective when the collision has already happened (Figure 1). Studies of accident data have shown that a high percentage of accidents result from incorrect driving behaviour, so that integrated safety systems can help to avoid or mitigate the collision during the pre-crash phase and account for reaching the goal of a further reduction of injuries or fatalities in road traffic accidents. To quantify the effectiveness of these integrated systems on real accident data, new methods of evaluation are necessary. In this article a method for an effectiveness analysis of integrated safety systems is presented and exemplified on the use case for pedestrian safety. [3], [8], [9], [10]

DEVELOPMENT PROCESS AND EFFECTIVENESS ANALYSIS

Development process of integrated safety systems

The development process of integrated safety systems consists of three main steps that are passed through iteratively. These three steps are function definition, testing and effectiveness analysis (Figure 2). The function definition comprehends the development of the functional algorithms, triggering strategies and the design of actuating elements. The testing includes an assessment of all system components or the total system itself in a realistic environment. Further, the effectiveness analysis contains the benefit assessment of collision avoidance and collision mitigation regarding a definite system component or the total safety

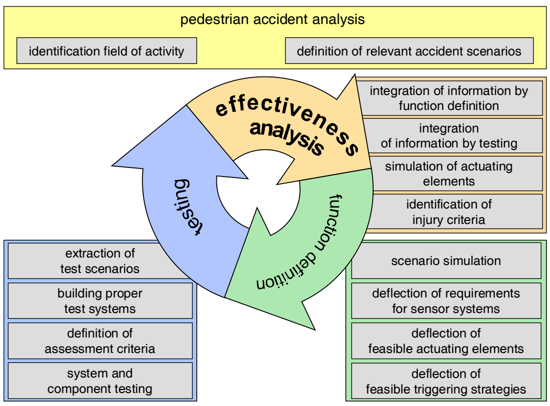

Figure 2: Function development process of integrated pedestrian safety systems [7]

system. The evaluation is accomplished for different abstraction levels based on real world accident data by a case by case analysis. The effectiveness analysis includes the influencing variables established from the testing and the function definition (Figure 3). Only with the integration into the development process is it assured that all results of the other development steps are included and a requirement based system development regarding the total system effectiveness in real world road accidents is enabled.

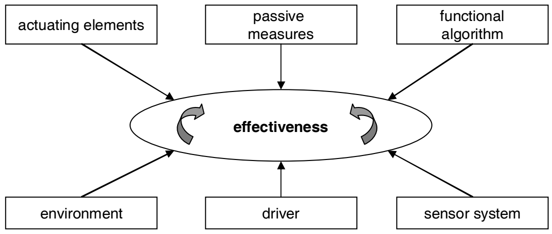

Figure 3: Influencing variables on the effectiveness of integrated safety systems [6]

Method to evaluate the benefit of integrated safety systems

To integrate the effectiveness analysis in the development process consisting of the function definition and testing a new method is presented here (Figure 4). This method allows an assessment of the integrated safety system taking into account all relevant influencing variables (Figure 3) and thus provides a realistic forecast of the system's effectiveness in real world accident scenarios.

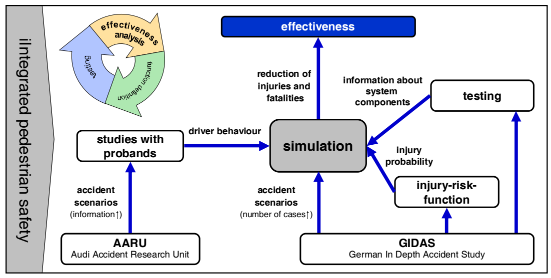

Figure 4: Method to evaluate the benefit of integrated safety systems

To achieve this goal the information from studies of probands, component testing and the injury criteria are combined in the central block of the simulation. Testing means the analysis of system components or their interaction in a realistic test environment or the real world. These include e.g. the testing of sensor systems, functional algorithms or different braking actuating elements. A particular challenge describes the driver integration. For this reason the driver reactions to various warning strategies were identified with the help of studies with probands. The cognitions from component testing and studies with probands are integrated into the simulation in form of models in order to achieve a realistic total system model. The goal is to assess the benefit of integrated safety systems in real world accidents. Because of that all process steps are based on real accident data, which are taken from different databases. Here information of the accident databases of the AARU (Audi Accident Research Unit) and the project GIDAS (German In Depth Accident Study) are integrated. In the sequel to this article the central block of the simulation and the system design based on saved injuries or fatalities are explained.

Levels of system evaluation

The goal of an integrated safety system is to protect the pedestrian (Figure 5). The strategy to achieve this goal consists of collision avoidance and collision mitigation which depends on the effectiveness of the subsystem components and their interaction with each other. An objective assessment of the system's effectiveness requires the consideration of all influencing variables (Figure 3). The actuating elements which are represented as e.g. braking systems or driver warnings are directly influencing the collision course. These are just preceded by the passive measures and their effect on the occurred collision. To activate the actuators only at specified situations, the triggering is computed by functional algorithms acquiring information from the environment or vehicle internal sensor systems.

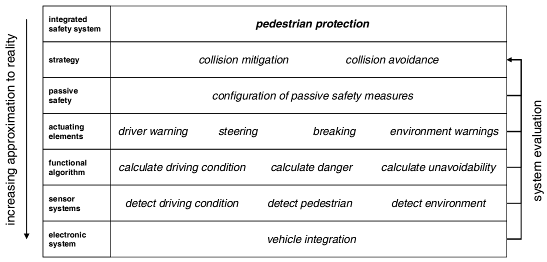

Figure 5: Levels of system evaluation

The complex interaction of the system components and the impact of changing subsystem parameters regarding the effectiveness cannot be analysed without a structured assessment. The simulation method enables the calculation of the effectiveness for individual system components or combinations from the strategic point of view. That means the assessment is carried out on different levels of system modelling always against the strategy level (Figure 5). In the process the approximation to reality increases with the number of subsystem components included (Figure 5). With this approach an identification of the relevant subsystem parameters or the subsystems themselves influencing the effectiveness is possible. The assessment results can be quantified based on both technical and injury parameters. A technical parameter to quantify the achievement of objectives for pedestrian safety for example is the collision speed. Parameters describing the injuries can be defined by the number of seriously injured pedestrians or fatalities. The effectiveness of a safety system can be quantified as the difference between the technical or injury based results of two system configurations. This implies high performance models of the system components. Possible specifications of a level-based system evaluation are shown in Figure 6. Different system modelling states can be identified e.g. model, ideal or not relevant.

	system components characteristics					
levels of evaluation	actuating elements	functional algorithm	sensor system	driver	passive measures	environment
evaluation level I	model	ideal	-	ideal	model	model
evaluation level II	model	ideal	ideal	ideal	model	model
evaluation level III	model	model	ideal	ideal	model	model
evaluation level IV	model	model	model	ideal	model	model
evaluation level V	model	model	model	model	model	model

Figure 6: Exemplary specifications of a level-based system evaluation

The influencing factors of passive measures are always implemented as a model. Without consideration of these an evaluation of integrated safety systems is not possible, because these systems consist of a combination of passive and active measures. The environment parameters are also implemented as a model for every accident scenario. An idealisation of the environment parameters would be possible, but assuming e.g. limiting friction for every accident scenario, the effectiveness analysis would no longer relate to real world accident data. In the first step of a total system evaluation, only the subsystem consisting of actuating elements is conducted as a model. The other components have an ideal behaviour or are not relevant. Assuming the functional algorithm as ideal, the actuating elements are always triggered to the specified point of time to collision. This evaluation step is independent of the pedestrian detection by the sensor system. On this level of evaluation the requirements to the actuating elements can be deviated, because only the influence of this subsystem component is considered. If the result of this evaluation step is indicating little benefit, a substantiated decision continuing the system development based on these actuation elements is possible. The addition of further modelled subsystem components are just leading to a decreasing effectiveness. In a second evaluation step an ideal sensor system can be comprised. An ideal sensor system could be characterised by range or angle of aperture and systematic effects like cycle time or lines of sight obstruction. In this case the actuating elements would be triggered if the addressed object is located in the sensor system's field of vision. During further steps evaluating the total system components, these are integrated step by step as a model. Every evaluation step enables an identification of the relevant subsystem parameters reducing the effectiveness and structured optimization loops. Because of that the subsystem models require a high quality deviated by real world testing and validation as the simulation itself. Because of that the accident simulation program PC-Crash [11] is used to model and simulate the accident scenarios. To integrate braking systems, pressure or deceleration gradients are used. The functional algorithm is integrated by a Simulink/Stateflow application development system. Considering realistic models of the sensor system, models characterising the sensor system technology are included and also validated by real world measurements. Driver integration constitutes a particular challenge because driver reactions on defined warning strategies strongly diversify and depend on the situation triggered there. Therefore the driver is included as a probabilistic model gaining from studies with probands. These studies are carried out with the simulation and testing method Vehicle in the Loop [1].

SIMULATION

Generating accident scenarios

Analysing the effect of safety systems on the collision course through case by case studies requires runnable simulation scenarios based on real world accident data. In the first step the original course effecting the collision must be reconstructed. For this purpose the kinetic quantities of the vehicle and pedestrian, the impact location and the environment at the place of collision have to be modelled in detail. By this means, runnable accident scenarios according to a real world accidental database are preserved. Equipping the vehicle with a virtual integrated pedestrian safety system, the influence of this system on the original collision course can be analysed during the next evaluation steps. The creation of simulation scenarios in general, results from defining basic scenes that are parameterised with defined values of an accident database (Figure 7).

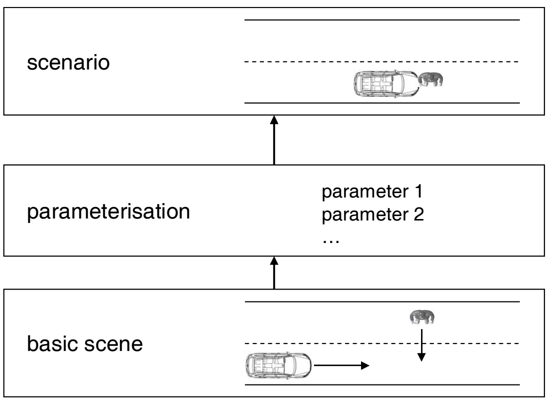

Figure 7: Generation of accident scenarios from basic scenes

One the one hand, values of the GIDAS accident database are used to parameterise the basic scenes. In this way runnable real world accident scenarios are created. On the other hand a multiplicity of fictitious single cases is generated by using stochastic parameters to set the basic scenes (Figure 8). Both methods generate a collection of single scenarios whereby the GIDAS

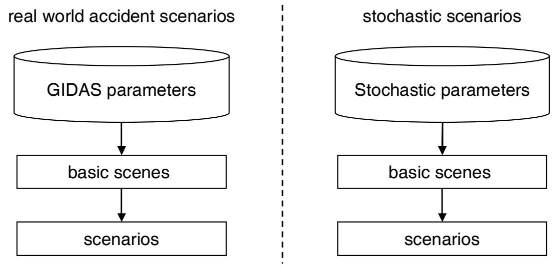

Figure 8: Different simulation databases

cases always effect a collision. The cases built on stochastic parameters also include non-collisions. So these cases must be processed for further evaluations e.g. separation of the collision from non-collision scenarios. As an essential difference to the import of original GIDAS scenarios, the stochastic method generates accident scenarios not included in GIDAS and also apparently unimaginable ones.

Sensor equivalent accident scenes

An effective generation of runnable case by case accident scenarios requires a new approach to achieve a high level of detail with a similar high level of atomization. That's why sensor equivalent accident scenes (SEAS) are created (Figure 9). These scenes can be derived from the specific feature that different accident scenarios often deliver an equivalent view for the sensor system. The sensor system's view is influenced by several environment parameters e.g. road design and layout, approximation direction of the pedestrian or lines of sight obstructions. By combination of these criteria, sensor equivalent accident scenes can be deviated by assigning the single accidents from the database to these.

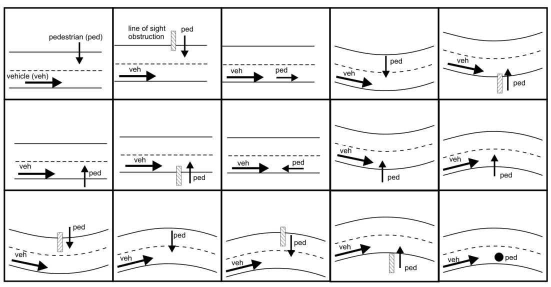

Figure 9: Examples of sensor equivalent accident scenes

For example there is no difference for a sensor system assuming a rectilinear motion of the vehicle, whether the pedestrian approaches from the left side at a crossroad, straight road or other intersections as long as no information of the characteristic environment features provided by the sensor system are pulled up for situation classification. Sensor equivalent accident scenes can roughly be grouped in straight road and turn or intersection accidents. Straight road accidents comprehend pedestrians crossing at intersections as long as there is no turning off by the vehicle. Sensor equivalent scenes for turn accidents include collisions occurring on a non rectilinear trajectory of the vehicle or at turning off. Every sensor equivalent accident scene for single accidents from the database is assigned to comply with the sensor system's view of the SEAS by using several parameters of the GIDAS accident database. One of these variables is represented by the type of accident *UTYP*. An explicit interpretation of the collision course by the accident type on its own is not possible. For that reason other parameters are comprised. These are for the vehicle *RICHT* defining the direction the vehicle moved in before the collision. Further *RICHTVU* describing the vehicle's line passed through before collision and the parameter *RICHTUE* defining the design and layout of the road at collision [2]. Combining these three parameters, the design and layout of the road can be suggested. Adding the accident type, the collision course is defined explicitly. Using only the accident type to classify a sensor equivalent accident scene, accidents that never happened that way were allocated to a SEAS type, which indirectly effects a falsification of benefit assessment in further evaluation steps.

Semi-automatic generation of accident scenarios

For the creation of runnable accident scenarios two approaches are applied. On the one hand, all straight road accidents are reconstructed semi-automatically by using basic scenes derived from sensor equivalent accident scenes. For that reason, several basic scenes have to be created and parameterised by values of the GIDAS database.

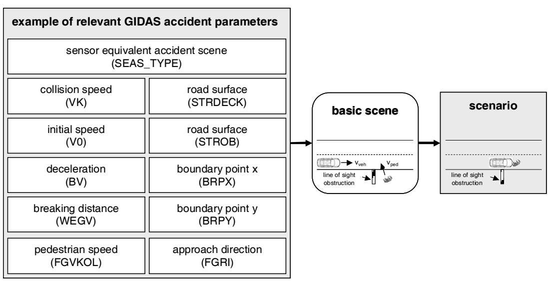

Figure 10: Generating accident scenarios

On the other hand, the remaining SEAS for turning accidents have to be modelled manually. The generation of straight road accidents is carried out automatically by comprising further parameters of the GIDAS database exceeding the allocation to sensor equivalent accident scenes. The additional values have to be selected according to an explicit definition of the collision and in the same manner that the effectiveness of an integrated safety system can be evaluated. A summary of exemplary parameters needed to be imported to set the straight road basic scenes is shown in Figure 10. Combining the vehicles' and pedestrians' kinetic quantities and the acknowledgment for the exact impact location of the pedestrian at the vehicle, an explicit modelling of the collision course is possible by calculating the basic positions of vehicle and pedestrian out of the parameters from the GIDAS database as described before. The exact position of the line of sight obstruction for the GIDAS accident can only be extracted by the sketch of the accident. For this reason the position for the line of sight obstruction in the accident scenario is set manually. Information about the road surface or other environment parameters is retained for system evaluations in further steps. For example, the road surface affects the transferable braking decelerations individually for every accident scenario. Turning or crossroad accidents strongly vary in regard to the possibility of generic modelling and setting basic scenes by GIDAS parameters. The variation of turning accidents is nearly indefinite and can thus be carried out manually calling for a detailed accident modelling.

Accident scenarios from stochastic parameters

In-depth databases like GIDAS are only available for a few countries in the world. In most countries, accidents are recorded centrally in national statistics by a federal statistical office. It is not feasible to generate runnable accident scenarios out of these databases so an evaluation of safety systems based on case by case studies is not possible. For this reason the second method to generate accident scenarios, as described before, can be applied (Figure 8). This method describes the parameterisation of basic scenes by stochastic sets of values. In this way a multiplicity of various and also non-collision scenarios can be created. To assess the effectiveness of an integrated safety system, the evaluation is focused on the potential to avoid or mitigate collisions. That is why the non-collision scenarios have to be separated before this database can be used for further analysis. Weighting the stochastic accident database according to the national accident statistics enables a system evaluation for countries with non in-depth accident databases. Using this method, the correlation between weighted accident scenarios according to global statistics and in-depth accident data, the global statistic results have to be proven at first. To check this correlation, the global distribution of the GIDAS accidental parameters and the runnable GIDAS accident scenarios are used.

Open-loop- and closed-loop-simulation

An evaluation of integrated safety systems on the basis of different system modelling levels (Figure 6) demands different simulation methods. These are represented by an open-loop- and closed-loop-simulation. The selection of a specific method depends on several factors which are explained consecutively. The open-loop-method is characterised by pre-simulated driving situations in consequence of the implementation of different measures to definite time increments. The results of the pre-simulated driving situations are archived in a kind of look-up table. The simulation is based on time series of the original accident trajectory. Such a trajectory is shown in Figure 11. In the upper diagram the trajectory is represented by a velocity-time-chart und in the lower as a velocity-distance-chart. From the velocity-time-chart can be recognized that the vehicle, beginning from t=0, is moving with a constant velocity. At the point $t=t_b$ the vehicle introduces a braking manoeuvre. The collision occurs at the point $t=t_{coll}$ with a collision velocity of $v=v_{coll}$. Based on this exemplary trajectory and the charts in Figure 11, the method of the open-loop-simulation is explained. To pre-simulate driving situations, the simulation must be stopped at specified time increments, and instead of the original nominal trajectory, a measure is implemented and simulated with the current momentums. This means that a sub-simulation is carried out. This measure could be emergency braking [12]. In this special case the simulation is stopped at the point t_i and emergency braking is simulated. For this sub-simulation the current simulation parameters at the point t_i are set as the basic values for the sub-simulation. In this case, that would be the current velocity because other factors are not considered in this simple explanation. Through the implementation of the braking measure with a sharp deceleration characteristic, a new nominal trajectory is generated at the point of t_i (Figure 11). For this trajectory different parameters are archived e.g. the collision velocity, collision occurring or final positions of the objects in the simulation. At the point t_{i+1} the same braking action is implemented and simulated again and the new results are archived. The braking action is simulated through the whole chronological sequence of the scenario at definite time increments. All these steps are independent from the triggering strategy of the technical system and must be understood as pre-processing for the generation of simulation data. Whether or when emergency braking is triggered in this scenario is not relevant at this point. This method generates an accident scenario data file, which is the basis for the effectiveness of emergency braking for every simulated time t_i. This method is executed for every single accident scenario in the database and for every action that should be assessed. For the two sub-simulations at the point t_i and t_{i+1}, shown in Figure 11, the collision based on the nominal

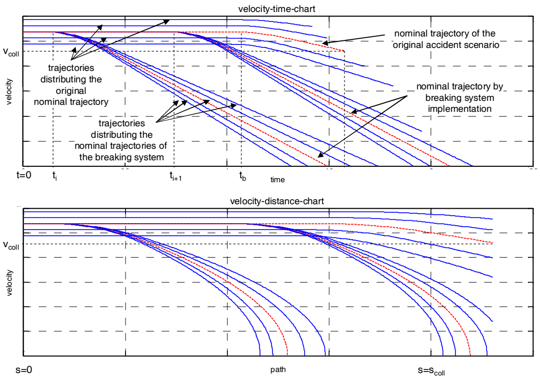

Figure 11: Time series vehicle trajectories

trajectory is prevented. This simulation method can be used for probability analysis as well. For this case not only one sub-simulation is carried out at definite time increments but several, which derive from a covering of the sharp deceleration characteristic with a parameter distribution. A band of sub-trajectories is thus generated, which disperse about the nominal sub-simulation trajectory. It can also be ascertained that not all sub-trajectories can prevent the collision compared to the nominal trajectories. As a consequence, the sub-simulations can be used to define a collision probability that is defined as the number of collisions based on the whole number of sub-simulations for a specific point t_i. The collision probability is a new parameter for a technical assessment concerning the effectiveness of an integrated safety system. To make the probability results out of the sub-simulations comparable with the nominal accident scenario, the original scenario parameters must also be distributed. The probability background can be interpreted via the technical system's own variability because of system internal or external effects. As described before, the pre-processing generates accident scenario data files as a kind of look-up table, in which the effectiveness of an emergency braking action for every simulated time t_i is disposed. To identify the effect of the simulated actions, only the scenario specific points t_i when an action is enabled, have to be detected. To assess just the actuating elements with ideal algorithm behaviour, the action always gets triggered to the specified time to collision. For every accident scenario, the action effectiveness for the point t_i, which is equal to the scenario specific time to collision, can be extracted from the look-up tables.

Another use case is to analyse the algorithm behaviour based on the nominal trajectory of the accident scenario und analyse the time of classification of a critical situation. Latency or

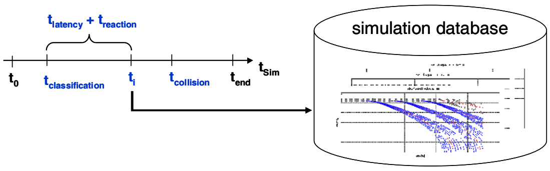

Figure 12: Evaluating action effectiveness including pre-simulated databases

reaction times can also be considered, so the triggering point t_i can be extracted as shown in Figure 12. To accomplish the system assessment in a separate post-processing step turns out to be very efficient. Through look-up tables, it is possible to replace a run-time computation with fast search operations. The savings in terms of processing time can be significant because retrieving a value from memory is often faster. Further, the simulated actions can be reused discretionally and it is possible to regard probabilistic considerations to achieve stochastic confirmed benefit statements. First of all the simulation data for the post processing step have to be created. This step requires a one time simulation effort. For more complex or interlacing actions which affect earlier measures than emergency braking regarding the chronological sequence until collision, it has to be considered that there might be feedback by driver engagement or environment behaviour. For measures triggered a short time before collision such as emergency braking, the feedback can be neglected. To assess complex measure combinations with an estimated feedback, a closed-loop-simulation is required. A closed-loop-simulation calculates the complete system behaviour for every simulation step. That means the information detected by a sensor model is conducted to the algorithm calculating the current behaviour of the safety system whether a fire or a non firer situation is existent. If there is a non-fire scene the loop is passed through again. If there is a fire scene, a warning actuating element could be triggered. The triggering of a warning actuator occurs quite a long time before collision. That means that the situation can be affected by driver engagement, the pedestrian leaving the critical area or by the sensor system. For driver modelling the closed-loop-simulation comprehends a probabilistic driver model created from studies with probands. For this purpose the distribution of driver behaviour for every single warning strategy analyzed in the studies is included. From distributions of e.g. reaction time and corresponding braking deceleration, it is possible to convey a probabilistic parameter combination and integrate stochastic driver behaviour into the simulation. This means that triggering a warning actuator leads to a simulation stop at the point of triggering and the simulation is processed several times with different sets of parameters. Further it is possible to integrate sensor models, algorithms and actuator models as described before in both simulation methods. Both simulation methods deliver technical collision parameters like collision speed or impact location. To calculate the benefit based on injuries or fatalities it is necessary to convert the technical parameters.

SYSTEM DESIGN BASED ON INJURY SEVERITY

To quantify the effectiveness of an integrated safety system in real world accidents, two kinds of parameters can be used, as described before. These are, on the one hand, the technical parameters and on the other hand, the injury severity. The injury severity can be quantified by the number of seriously injured pedestrians or fatalities. Quantifying the effectiveness by the injury severity an injury risk function can be applied. With this function it is possible to calculate the injury severity based on the technical parameters. Generally an injury risk function is defined as the probability to achieve a defined injury severity depending on quantitative influencing factors. Through injury functions different passive safety measures can be modelled having direct influence on the form of the curves [4]. Two exemplary injury risk functions are shown in Figure 13. These curves indicate the probability e.g. for a pedestrian to suffer a MAIS2+ injury at a certain collision speed. Accumulating the injury probabilities for a MAIS2+ injury of every single accident scenario in the database, the absolute number of seriously injured pedestrians can be calculated and the effectiveness of two-system configuration identified.

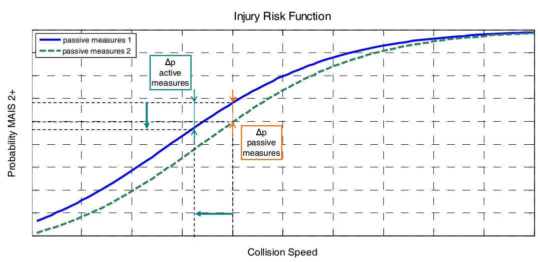

Figure 13: Exemplary injury risk functions for different passive measures

In Figure 13 the curve for passive measure 2 indicates a lower probability for a MAIS2+ injury at equal collision speed. Accordingly this curve represents more effective passive measures compared to passive measures 1. In general, the injury severity depends not just on one parameter like the collision speed but on a number of parameters influencing the grade of injury severity e.g. impact location, pedestrian age or vehicle front characteristics. To generate injury risk functions with a high modelling quality these additional parameters have to be identified. In consequence, there are more injury risk functions depending on the influencing factors. For example, injury risk functions for young and old pedestrians or frontal and lateral impacts. On the one hand, the injury risk function can be derived directly from the GIDAS database. In this case, a model for the injury severity is gained based on the vehicles' passive measures existing in the GIDAS database. To identify the influence to injury severity for defined passive measures like prospective passive measures for pedestrians, these measures have to be modelled at first because the GIDAS database contains a huge variety of vehicles and different passive measures resulting from the date of manufacturing. To model passive measures the method of injury shift can be applied [5].

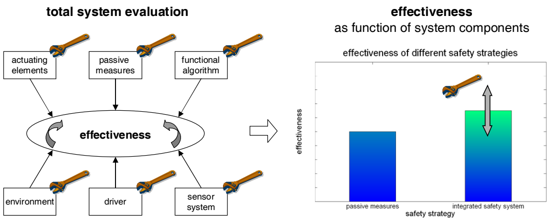

Figure 14: Effectiveness of integrated safety systems subjected to total system behaviour

With this method the expected injury reduction of a pedestrian caused by a synthetic improvement of passive measures can be modelled. Using this new distribution of injuries for every single accident in the database to generate an injury risk function, the result is a new curve with a lower probability of MAIS2+ injuries. Regarding Figure 13, the injury risk functions for passive measures 1 and 2, conveying the results of the method qualitatively. Applying injury risk curves, the effectiveness of passive measures and integrated safety systems are comparable, because a decreasing collision speed by active measures directs a decreasing injury probability for the pedestrian (Figure 13). Consequently, the described simulation method calculating the technical parameters caused by an integrated safety system on real world accident scenarios in combination with injury risk functions enables a new application spectrum designing integrated safety systems. So the effectiveness of passive and integrated system approaches can be compared during the development process (Figure 14).

CONCLUSION

Former studies indicate high potential of brake assist systems regarding the effectiveness in terms of reducing seriously injured pedestrians or fatalities in real world traffic accidents. This applies pedestrian safety in particular, because softer front end structures or measures like active bonnets illustrate limited effectiveness. Further reduction can be achieved by using integrated safety systems consisting of functional algorithms, actuating elements and sensor systems in addition to passive safety measures. To enable a requirement based system development regarding the total system effectiveness in real world traffic accidents, the effectiveness analysis has to be integrated into the function development process assuring that all results of the other development steps in terms of function definition and testing are included. An evaluation of these systems during the function development process requires new methods. A lot of information about the system's influencing factors is detected in the testing and defining process steps. This information is considered in a central simulation method including detailed models and enables a level based system evaluation. That means the influence of the system components affecting the benefit evaluation can be identified in a structured and objective way. To evaluate the system benefit on real world accident data, runnable accident scenarios from an in-depth accident database for case by case evaluations have to be created in an effective way. So a semi-automated method based on sensor equivalent accident scenes to build up the scenarios is developed. Further, it is possible to generate stochastic scenarios applied to predict the system benefit for countries with no in-depth accident information. The accident scenarios are processed in a closed- and open-loop simulation. The open-loop method is characterised by pre-simulated driving situations in consequence of the implementation of different measures to definite time increments. The system evaluation is carried out in a separate post-processing step making this method very efficient for application in the function development process. More complex combinations of different actuating elements and triggering strategies induce feedback by e.g. the driver, system components or the environment. In this case, a closed-loop simulation is required. Both open-loop and closed-loop simulation had the potential to integrate detailed models of the system components as described before. The effectiveness of a safety system can be quantified as the difference between the technical or injury based results of two system configurations. In the first step, the simulation provides technical parameters to quantify the benefit of the tested system configuration. A conversion of these to injury values requires injury risk functions. With these functions different passive measures are modelled and the effectiveness of different system strategies can be detected. Consequently, it is possible to design integrated safety systems with regard to their effectiveness in real-world accident scenarios during the development process by using the method presented in this article. The integration of the effectiveness analysis into the development process enables a requirement based system design regarding the total system effectiveness in real world accidents contributing to achieve the goal of vision zero.

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PEDESTRIAN INJURY MITIGATION BY AUTONOMOUS BRAKING

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ABSTRACT

The objective of this study was to calculate the effectiveness of a pedestrian injury mitigation system that autonomously brakes the car prior to impact at reducing fatal and severe injuries.

The database from the German In-Depth Accident Study (GIDAS) was queried for pedestrians hit by the front of cars from 1999 to 2007. Information on vehicle and pedestrian velocities and trajectories were used to estimate the field of view needed for a vehicle-based sensor to detect the pedestrians one second prior to the actual crash. The pre-impact braking system was assumed to provide a braking deceleration up to the limit of the road surface conditions, but never to exceed 0.6g. New impact speeds were calculated for pedestrians that would have been detected by the sensor. These calculations assumed that all pedestrians that were within the given field of view and not hidden by surrounding objects would be detected. The changes in fatality and severe injury risks were quantified using risk curves derived by logistic regression of the accident data. Summing the risks for all pedestrians, new casualty numbers were obtained.

The study documents that the effectiveness of reducing fatally (severely) injured pedestrians reached 40% (27%) at a field of view of 40°. Increasing the field of view further led to only marginal improvements in effectiveness.

1. INTRODUCTION

A study by Transport Research Laboratory (TRL) under contract by the European Commission (Lawrence et al., 2006) predicts that the current functionality of brake assist systems can substantially reduce pedestrian fatality rates. The effectiveness at reducing the numbers of fatally and seriously injured pedestrians was estimated to be approximately 10%. One explanation for this finding is that even slight reductions in impact speeds have a large effect on the injury outcome for pedestrian victims (Davis, 2001; Hannawald and Kauer, 2004; Rosén and Sander, 2009; Tharp and Tsongos, 1977).

There are at least two advantages of pre-impact braking: The impact energy is reduced, leading to lower risk of injury, and the secondary impact when the pedestrian hits the ground is mitigated. Injuries are often caused by the secondary impact (Gavrila et al., 2003). Pre-impact braking has been suggested as one method to reduce their severity (Meinecke et al., 2003).

However, as brake assist systems have been predicted to activate in only about 50% of all accidents (Hannawald and Kauer, 2004), a natural evolution would be to complement future systems with a suitable sensor that autonomously activates the brakes if the driver fails to take action (Lawrence et al., 2006). The current study is an attempt to analyse the effectiveness of such an enhanced brake assist system. Like the studies by Aparicio (2005) and Hannawald and Kauer (2004), this study is based on models of real-world accident data. We extend those models to predict the reduction of pedestrian injuries from an autonomously activated brake assist system. Our approach is in line with the method proposed by Lindman and Tivesten (2006).

Studying real-world accident data is a viable way to gain an increased understanding of the pre-crash movements of vehicles and pedestrians. Currently, the most detailed accident databases include vehicle travel and impact speeds, driver braking and steering manoeuvres as well as detailed sketches of the accident scenes. By combining this information it is possible to derive the pedestrian location relative to the vehicle as a function of time during the pre-crash phase. Such extended reconstructions can also serve to establish the time to collision and pedestrian location at the instant when he/she would have become detectable by a vehicle based sensor (regardless of type) and when he/she stepped out into the road. This information can guide the understanding of real-world requirements and their influence on potential system effectiveness.

The hypothetical system considered in this study contains a forward looking, vehicle-based sensor with a given field of view. The signal from the sensor is processed by a computer algorithm. If a pedestrian collision is predicted to occur, the system will autonomously activate the vehicle's brakes. The effectiveness of such a system depends on five main parameters: the field of view, detection range and accuracy of the sensor and the duration and level of the applied brake force.

Naturally, a larger field of view will detect more pedestrians. However, this also implies that the system will have to consider pedestrians further away from the road. This, in turn, will increase the sensor requirements and the complexity of activation strategies. With a greater detection range, it is possible to increase the braking duration, which will reduce the vehicle speed further before impact. However, autonomous braking implies a rather severe intervention that may or may not be welcomed by the driver. A system that activates too early may negatively affect the driver's ability to stay in control of the vehicle (ECE, 1968). Furthermore, the perceived level of system intrusion is likely larger for harder braking and longer braking durations. Earlier predictions by the system will also increase the uncertainties regarding the intent of other road users, which may lead to higher rates of false activations. In sum, there are many arguments against assuming that it is necessarily preferable for autonomous breaking systems to have a larger field of view and an earlier activation time.

2. OBJECTIVE

The main goal of this study was to estimate the potential reduction of fatally and severely injured pedestrians by an autonomous braking system as a function of the sensor field of view given a pre-impact braking activation time of one second and a maximum braking deceleration of 0.6g. These system parameters were chosen as a reasonable balance between high protection level (early brake activation and high deceleration), reduced risk of assumed negative driver reaction, and influence on ambient traffic from instances of false system activation. Although the system was likely to be beneficial both for pedestrians struck by the front and side of vehicles, our method to estimate effectiveness was more reliable for those struck by the front. The reason was that the relation between injury risk and vehicle impact speed was less clear for pedestrians struck by the side, since only some of those receive a substantial impulse, or change of momentum, in the crash. Hence, we chose to include only pedestrians struck by vehicle front ends in the detailed analysis, although some results will be presented for the full target population as well.

3. DATA AND METHODS

3.1 Data

The German In-Depth Accident Study (GIDAS) is based on accident data collected from the cities of Hanover and Dresden and their surroundings. The availability of recent, in-depth, accident reconstruction data, access, and familiarity with the database made GIDAS a natural choice for this study. A detailed account on GIDAS is provided by Otte et al. (2003). The work shifts for the GIDAS teams are specified by a statistically developed sampling plan and cover half the hours of each day and night (Otte et al., 2003; Pfeiffer and Schmidt, 2006). The GIDAS database therefore contains a fairly representative sample of German accidents with pedestrian injuries. However, a certain bias towards severe and fatal accidents is present and a method to adjust for that was used (Rosén and Sander, 2009). That study found that cases coded as "ambulant" (less than 24h medical treatment), "in-patient" (more than 24h medical treatment), and "fatal" (dead within 30 days from the accident) should be weighted with the relative factors 1.0, 0.49, and 0.36 respectively.

Injuries were coded according to the Abbreviated Injury Scale (AIS98), which is an injury classification system using standardised criteria for describing injury severity (AAAM, 2001). The system comprises six levels of injury severity, where AIS1 denotes minor injury, 2 moderate, 3 serious, 4 severe, 5 critical, and 6 fatal (currently untreatable) injury. The Maximum AIS (MAIS) gives the severity of the worst injury (of the several sustained by the victim). For example, MAIS3+ denotes cases where the severity of the worst injury was AIS3 or higher. In the following, we have denoted cases with MAIS3+ as severe and cases with less severe injuries (MAIS1 and MAIS2) as slight. Cases where the pedestrian died within 30 days were classified as fatal. All fatal cases with MAIS3+ injuries were also considered severe, which was different from the analysis of Lawrence et al. (2006) where a serious case could not be fatal.

The target population for the autonomous braking system included pedestrians struck by the front and side of motorised vehicles. However, the detailed analysis of this study was restricted to those struck by the front of a car, SUV, minibus, or van. Of all pedestrians in GIDAS struck by such vehicles, 66% were hit by the front, 29% by the side and 5% by the rear. For the fatally (severely) injured pedestrians, 90% (74%) were struck by the front, 8% (21%) by the side, and 3% (4%) by the rear. We further restricted the target population by taking into account only pedestrians who were not suspected of being intent on suicide and who were struck once by a vehicle that did not have an initial collision with another object. These restrictions excluded only a small number of cases.

From the years 1999 to 2007, 755 cases were gathered, including 38 fatally and 123 severely injured pedestrians, in which the vehicle impact speed was assessed by a GIDAS reconstruction. Of these, 243 cases contained sufficient information to estimate the pedestrian location relative to the car one second prior to impact. This final dataset contained 46 severely injured pedestrians, of which 11 were fatalities. Furthermore, 232 of the striking vehicles were passenger cars. The remaining cases included seven minibuses, one pick-up truck, one off-road vehicle, one minibus shaped, and one van. Of the fatally (severely) injured pedestrians, 10 (45) were struck by cars and 1 (1) by a minibus.

3.2 Estimating the Effect of the Autonomous Braking System

The hypothetical autonomous braking system consisted of an extension to a brake assist system that would autonomously activate the vehicle brakes when an activation signal was provided by the sensing system. As shown in Figure 1, the sensor was mounted in the centre of the vehicle front and had a given field of view. Furthermore, the sensor was assumed to operate in all light and weather conditions, but could only detect pedestrians that were within the given field of view and not obstructed by other vehicles or fixed objects such as buildings.

For each accident, information on the exact accident spot, the impact and travel speeds of the car, the exact impact location of the pedestrian on the car front, and approximate trajectories of the car and pedestrian a few seconds prior to impact were provided by the original GIDAS reconstructions. The reconstruction methods are described by Rosén and Sander (2009). Driver braking and steering manoeuvres were also given, including an estimate of the mean braking deceleration and the braking distance. Finally, pedestrian walking speeds were coded using four categories: (1) walked, (2) walked slowly, (3) walked briskly and (4) ran.

We took pedestrian age into account to generate quantitative estimates of pedestrian walking speeds in km/h (Eberhardt and Himbert, 1977). Combining this with information about the point of collision and pedestrian trajectory, it was possible to estimate the location of the pedestrian one second prior to impact. The location and travel speed of the car one second prior to impact was derived by a similar backwards calculation, beginning from the accident spot, taking impact speed, braking deceleration and vehicle trajectory into account. The locations of both the car and pedestrian enabled us to calculate the field of view needed for a sensor on the car front to detect the pedestrian. Pedestrians for which obstacles in the environment obstructed the sensor line of sight during the pre-crash phase were considered to be "not visible".

Following Danner and Halm (1994), the maximum possible braking deceleration was assessed for each case using GIDAS information on the road surface type and condition. A maximum deceleration of 0.6g was applied to all cases where the road surface type and condition allowed. In the other cases, the maximum possible deceleration was chosen. It was also assumed that the brake force had a linear ramp up time of 300 ms and then remained at a constant level. The chosen values of ramp up time and maximum braking deceleration are in line with those reported by Grover et al. (2008) for automated emergency brake systems.

The final step was to calculate new impact speeds, v', for cases were the pedestrian was visible and within the given field of view one second prior to impact, so that the autonomous braking system could have been activated. The new impact speeds followed from basic kinematics combined with the work-energy principle. In cases where the driver had braked, the original impact speed was kept if it was lower than the one provided by the autonomous braking system. In cases where the sensor would have detected the pedestrian less than one second prior to impact, the system was assumed to have no effect, even though pre-impact braking would have lowered the impact speed.

3.3 Injury Risk Functions

In order to derive injury risk functions for fatal injury and for severe (MAIS3+) injury, weighted logistic regression analysis was conducted following Rosén and Sander (2009). In order to increase statistical robustness, the larger GIDAS sample was then used, comprising 755 pedestrians of which 38 were fatally injured. To verify data quality, all fatal accidents, crashes with impact speeds exceeding 65 km/h, and 20 randomly selected cases were studied in detail. This was done by considering accident sketches, photographs, police reports, medical records, etc. As a result of these investigations, two accidents with pedestrians surviving impact speeds of 77 km/h and 108 km/h respectively were excluded from the sample due to

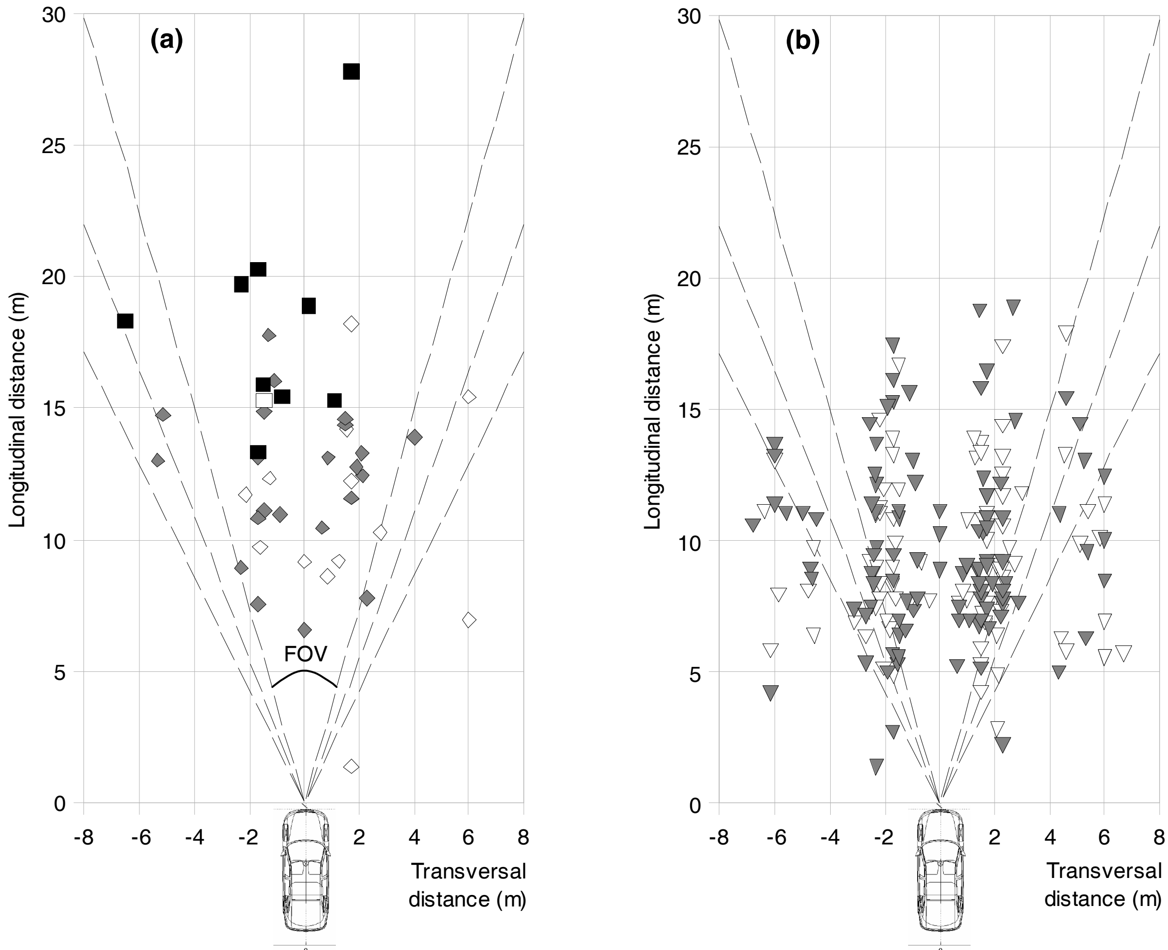

Figure 1. Pedestrian locations one second prior to impact. The dashed lines represent the field of views (FOV) 30°, 40°, and 50°. (a) Visible (not visible) fatally injured pedestrians marked with black (white) squares. Visible (not visible) severely injured survivors marked with grey (white) diamonds. (b) Visible (not visible) slightly injured pedestrians marked with grey (white) triangles.

interaction mainly with the side structure of the car. (In other words, these two pedestrians were "sideswiped" by the car and did not receive a substantial impulse in the collision.) Hence, the final sample consisted of 753 pedestrians. The fatality risk as a function of impact speed, $P_{fatal}(v)$, was then assumed to have the following form

$$P_{fatal}(v) = \frac{1}{1+\exp(-a-bv)} \qquad (1)$$

where v is the impact speed and a, b two parameters to be estimated by the method of maximum likelihood (Dobson, 2002; McCullagh and Nelder, 1989).

A similar logistic regression analysis was conducted for the risk of sustaining at least one severe injury (MAIS3+) as a function of impact speed, $P_{severe}(v)$. For this analysis, a sub-sample of 694 pedestrians was used, for which the maximum AIS was known. Of these, 123 had at least one severe injury.

3.4 Effectiveness

The new impact speeds, v', achieved with the autonomous braking system implied reduced risks of fatality and severe injuries. With the reconstruction data and risk curve, $P_{fatal}(v)$, available, it was possible to estimate the effectiveness of the autonomous braking system. The effectiveness is defined as E=1–N'/N, where N is the weighted number of fatalities in the sample and N' is the estimated weighted number of fatalities with the braking system available. The calculations can be mathematically expressed as

$$E = 1 - \sum_{i=1}^{n} P_{fatal}(v'_i)w_i \Big/ \sum_{i=1}^{n} P_{fatal}(v_i)w_i \qquad (2)$$

where n is the number of cases (243 in this study), v_i and v'_i the original and new impact speeds, and

w_i the weight factor for the i:th pedestrian. Since the new impact speeds depended on the field of view of the sensor, so did N' and, hence, the effectiveness. This made it possible to study the effectiveness as a function of field of view. We calculated the effectiveness for the following field of views: 180°, 90°, 60°, 50°, 40°, 30°, 20°, and 10°. The same analysis was then conducted for severe injury.

Let us write the number of fatalities as $N=N_{nb}+N_b$, where N_{nb} is the number of fatalities in accidents where the driver had not braked, and N_b the number of fatalities in accidents where the driver braked. Analogously, we write the estimated number of fatalities with the autonomous braking system available as $N'=N'_{nb}+N'_b$ with the same interpretation of the subscripts "nb" and "b". By restricting the sums in equation (2) to these two different subgroups, N_{nb}, N_b, N'_{nb}, and N'_b were estimated. The ratio $(N_{nb}–N'_{nb})/(N–N')$ then gave the percentage of the fatality reduction that came from cases where the driver had not braked.

The influence of braking duration was also briefly considered by calculating the effectiveness when activating the brakes at 2s, 1.5s, 1s, and 0.5s prior to impact. This analysis could not be conducted for different values of the sensor field of view, since the field of views needed to detect the pedestrians were only known at one second prior to impact. Therefore, these investigations were only conducted for a field of view of 180°.

4. RESULTS

4.1 Empirical Observations

When considering the total sample, comprising 753 cases, we found 38 fatally and 123 severely injured pedestrians. For 32 (105) of the fatally (severely) injured pedestrians, both impact speed and travel speed were known. It was then found that 41% (27%) of the fatally (severely) injured pedestrians were freely visible during the pre-crash phase, but the driver did not brake, and for another 13% (3%) the speed reduction from driver braking was less than 10% of the travel speed.

Restricting to the 243 cases chosen for extended reconstruction, there were 11 fatally and 46 severely injured pedestrians. For the fatally (severely) injured pedestrians, 60% (26%) were freely visible, but the driver did not brake or braked only marginally. These results are close to the corresponding figures for the total sample presented above, and thus provide a check of the representativeness of the sub-sample used for extended reconstructions. We may conclude that an autonomous braking system would have a potential

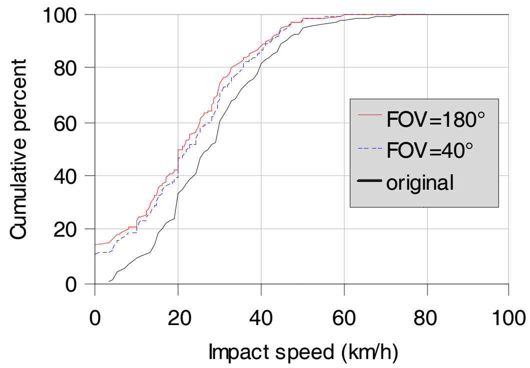

Figure 2. Cumulative impact speed distributions with and without the autonomous braking system.

to largely reduce the impact speed of the car for approximately half of the fatalities and one third of the severely injured pedestrians.

Figures 1a and 1b show the locations of the pedestrians one second prior to impact with different markers for slightly, severely, and fatally injured pedestrians. Since the vehicles typically had higher speeds than the pedestrians, pedestrian locations were more in the centreline of the sensor and farther away from the vehicles the higher the vehicle speed was. The same cases also tended to lead to higher injury severity levels. Finally, from Figure 1a, we see that a sensor with 40° field of view would have detected all but one of the visible pedestrians with fatal or severe injuries.

In total, 69% of the drivers braked, however in many cases the effect of the braking was very small. For the drivers who braked, the mean braking duration was 0.67s. Applying autonomous braking to all cases, regardless of visibility and field of view, the mean braking duration was 1.4s. (Note that activating the brakes one second prior to predicted impact will extend the actual time to impact, since vehicle speed will be decreased.)

In Figure 2, the cumulative distribution of impact speed for the sample is shown together with the corresponding distributions if the vehicles had been equipped with the autonomous braking system with 180° and 40° field of view respectively. The mean impact speed changed from 29 km/h (without the autonomous braking system) to 22 km/h (23 km/h) with a 180° (40°) field of view. Furthermore, 15% (11%) of the accidents would have been completely avoided. The mean travel speed of the cars was 39 km/h. Hence, the drivers achieved, on average, a 26% reduction of travel speed by braking (39 km/h to 29 km/h), whereas the autonomous braking system would have given a 44% (41%) speed reduction for 180° (40°) field of view.

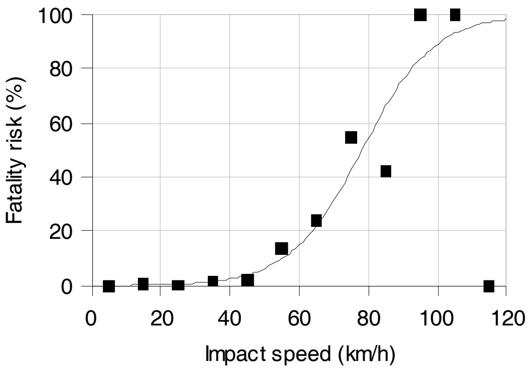

Figure 3. Fatality risk curve and empirical fatality rates (squares).

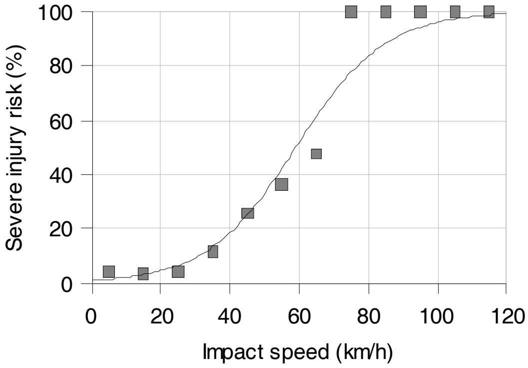

Figure 4. Severe injury risk curve and empirical severe injury rates (squares).

4.2 Injury Risk Functions

Figure 3 shows the fatality rates observed at different intervals of impact speed and the best-fit logistic regression curve. In Figure 4, similar information is given for the risk of sustaining at least one severe injury (MAIS3+). Details of the logistic regression analyses are provided in Table 1, where *a, b* are parameters to the risk function described in equation (1).

4.3 Effectiveness

Figures 5 and 6 show the estimated effectiveness of the autonomous braking system in preventing pedestrians from sustaining fatal and severe injuries for a range of sensor fields of view. For frontal impacts, the effectiveness for fatal (severe) injuries varied between 44% (33%) and 40% (27%) for field of views between 180° and 40°. The leftmost category, labelled "All", shows the predicted effectiveness when autonomous braking was applied in all cases regardless of visibility and field of view. This represents the greatest possible level of effectiveness given the unrealistic assumption of perfect information. Figures 5 and 6 also give the effectiveness for the full target population, i.e., when including pedestrians struck by the side of a vehicle. (These results were obtained by a similar analysis as for the frontal impacts.)

Table 1.
Logistic Regression Results.

	a_{fatal}	b_{fatal}	a_{severe}	b_{severe}
Estimate	–7.5	0.096	–4.6	0.078
LL	–9.0	0.067	–5.3	0.059
UL	–5.9	0.13	–3.8	0.096
P-value	<0.0001	<0.0001	<0.0001	<0.0001

Details from the logistic regression analyses. The lower limits (LL) and upper limits (UL) are for a 95% Wald confidence interval.

The effectiveness calculations can be described as follows. The weighted baseline estimates for all 243 cases were 5.07 fatally (29.9 severely) injured pedestrians, which are close to the true values of 5.36 (30.3). Applying the autonomous pre-impact braking in all 243 cases, regardless of visibility, estimated 1.63 (11.8) fatally (severely) injured pedestrians. The effectiveness therefore is $E_{\text{fatal}} = 1 - 1.63/5.07 = 68\%$ ($E_{\text{severe}} = 1 - 11.8/30.3 = 61\%$). Restricting to pedestrians who were visible, the casualties increased to an estimated 2.82 fatalities (20.1 severely injured) and an effectiveness of E_{fatal}=44% (E_{severe}=33%). The results shown in Figures 5 and 6 were generated using parallel calculations for the full range of values for the field of view.

Furthermore, it was found that 75–80% of the saved lives and 65–70% of the reduction of severely injured pedestrians came from cases where the driver had not braked.

For a sensor with 180° field of view, we studied the effectiveness as a function of the time before impact at which the autonomous braking was activated. The results are provided in Figure 7. In this analysis, it was assumed that pedestrian visibility did not change during the pre-crash phase. Naturally, in the statistical model, the effectiveness increased with activation time, since longer braking duration implies lower impact speed and, hence, injury risk. However, in real-life traffic, autonomous braking implies a rather severe intervention in the operation of a driver, which may affect the driver's ability to stay in control of his vehicle (ECE, 1968). This influence is likely larger for harder braking and longer braking durations. Earlier predictions by the system will also increase the uncertainties regarding the intents of other road users, which may lead to higher rates of false activations.

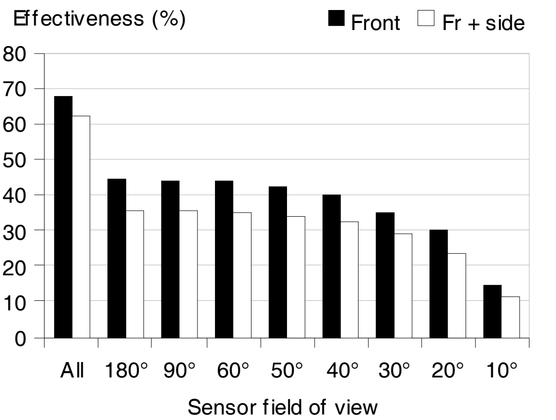

Figure 5. System effectiveness for fatality reduction. The category "All" corresponds to autonomous braking in all cases regardless of visibility and field of view.

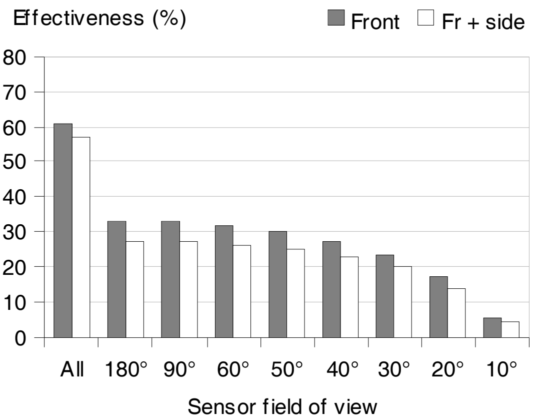

Figure 6. System effectiveness for reduction of severely injured pedestrians.

5. DISCUSSION

The effectiveness of the autonomous pre-impact braking system analysed in this study depends on how many pedestrians would be detected by the sensing system (system accuracy, field of view and detection range) as well as the duration and the level of the applied brake force. We chose to start with an analysis of the relation between sensor field of view and system effectiveness, due to the influence this parameter has on the cost and requirements on the sensing system. Figures 5 and 6 provide the results for a system that activates the brakes one second prior to predicted impact with a maximum braking deceleration of 0.6g. In some cases where the pedestrian was coded as not visible during the pre-crash phase, it is possible that he/she was only partially or temporarily obstructed from view. Even higher system effectiveness may therefore be possible if further development of detection systems and activation strategies leads to reliable detection of these pedestrians. This would decrease the gap between the effectiveness when

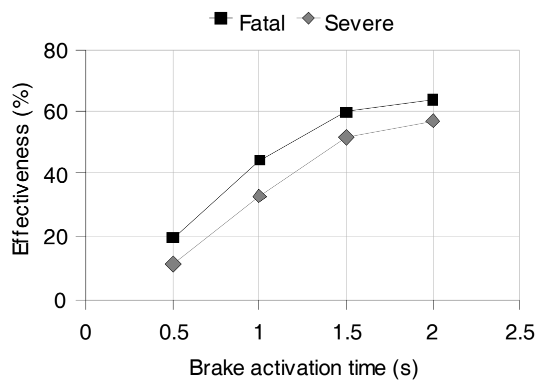

Figure 7. Effectiveness of the autonomous braking system with 180° field of view as a function of the brake activation time to impact.

braking for "All" pedestrians and when braking only for those coded as visible (see Figures 5 and 6).

A natural continuation of this study would be to analyse system effectiveness as a function of braking duration and braking level. Figure 7 provides the results of an initial investigation of this kind.

Sources of uncertainty for this study range from the inaccuracy of accident reconstructions in general to the vagary of actual and possible braking levels in particular. Predictive studies, like this one, also depend on the representativeness of the used data set. As described in subsection 3.1, we applied a weighting procedure so that GIDAS data might better resemble the total population of pedestrian accidents in Germany. However, the weighting turned out to have only a slight influence on the derived effectiveness. Like Lawrence et al. (2006), our results were found to be stable against changes in the risk curves. These findings indicate that the applied statistical methods were quite robust.

Lawrence et al. (2006) correctly pointed out that the potential effectiveness of a (non-autonomous) brake assist system is sensitive to the estimated additional deceleration that the system would generate. This is problematic since both the decelerations with and without a brake assist system are difficult to estimate accurately. This difficulty should, however, be largely avoided in this study, since the largest benefit of the autonomous braking system did not come from generating a higher deceleration in cases where the driver had already braked, but from braking when the driver failed to take action. As shown in subsection 4.3, nearly 80% of the fatality reduction came from cases where the driver had not braked. The remaining contribution came mainly from earlier activation of the brakes in cases where the driver had braked only shortly before impact. As shown in subsection 4.1, the average braking duration for drivers that braked was 0.67s, whereas the autonomous braking system had an average braking duration of 1.4s.

The detailed analyses of this study included pedestrians struck by the front of vehicles, with the main results provided in Figures 5 and 6. However, we also included the results of a similar analysis that took into account pedestrians struck by the side of vehicles. In so doing, we were assuming that the risks of fatality or severe injury as functions of impact speed could be derived for all pedestrians struck by the front and side of vehicles by simple logistic regression analysis. However, this assumption is questionable. The risk curves that we obtained (not presented here) were rather flat, since some of the pedestrians struck by the side of vehicles were merely "sideswiped" by the vehicle, or, e.g., hit only by an exterior mirror. Naturally, those pedestrians did not receive much impulse in the crash, and could therefore survive high speed crashes, which had a substantial effect on the risk curve. In other cases, the pedestrian fell over the hood and was struck badly by the A-pillar and windscreen. The flatness of the risk curve implied a lower benefit from braking. It is therefore likely that the effectiveness for pedestrians struck by the front or side of vehicles should be slightly higher than indicated in Figures 5 and 6. However, the results primarily show that the form of the effectiveness plot as a function of field of view did not change when including pedestrians struck by the side of vehicles.

In this study, the system was assumed to operate perfectly in all light and weather conditions, which might be difficult to achieve on the road. Furthermore, the system was assumed to brake for all pedestrians visible within the given field of view one second prior to impact. In real-life traffic, restrictions in system activation strategies may be necessary to gain regulatory and user acceptance.

6. CONCLUSIONS

Enhanced brake assist systems that use forward-looking sensors to predict an emergency situation are now becoming available. The approach taken in this study was to use real-world accident data to estimate the potential reduction of fatally and severely injured pedestrians from an autonomous brake assist system activated by a suitable forward looking sensor. The effectiveness was calculated as a function of sensor field of view for a system that activates the brakes one second prior to predicted impact with a maximum braking deceleration of 0.6g (see Figures 5 and 6).

For a field of view equal to 180°, the effectiveness in preventing fatal and severe injuries was 44% and 33% respectively. The effectiveness remained nearly constant when decreasing the field of view down to approximately 40°. With a field of view of 40°, the effectiveness in preventing fatal and severe injuries was 40% and 27% respectively. Taking into account all pedestrians struck by the front or side of vehicles, the exact figures changed. However, the dependence on field of view was similar.

These findings are in line with the empirical observations that approximately half of the fatally and one third of the severely injured pedestrians were visible to the driver during the pre-crash phase, but the driver did not brake or only braked marginally. Furthermore, a large majority of the visible pedestrians with fatal or severe injuries were within a 30° field of view, and nearly all were within 40°.

Various restrictions will limit the effectiveness in real-life traffic, but the results highlight the large potential in reducing fatal and severe pedestrian injuries with an autonomous braking system and that it is reasonable to limit sensor field of view to 40°.

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AUTONOMOUS BRAKING SYSTEMS AND THEIR POTENTIAL EFFECT ON WHIPLASH INJURY REDUCTION

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ABSTRACT

The paper estimates the benefits of low speed autonomous vehicle braking technologies (e.g. City Safety from Volvo) on reducing whiplash injuries, and whether driver adaptation is likely. Potential UK whiplash injury reduction and cost savings associated with autonomous braking systems are calculated. Assuming standard fleet wide fitment, predictions show autonomous braking systems (City Safety) could annually prevent 263,250 crashes, mitigate 87,750, and prevent 151,848 injuries, equalling nearly €2 billion savings in repair costs and whiplash compensation. In driver adaptation testing participants drove toward an inflatable target car at 15km/h without braking. Responses were collected from 99 driver tests, where the vehicle autonomously brakes preventing impact. 11% of drivers braked instinctively when approaching targets, and 95% of drivers stated they would not rely on City Safety for normal driving, and understood that it was for emergency braking only. Feedback was also gathered from 11 drivers experiencing the system on thousands of kilometres of normal UK roads. None reported either positive interventions or false interventions. City Safety, an example of low speed autonomous braking systems, shows huge potential for reducing crashes and whiplash injuries valued at nearly €2 billion in insurance claim savings. Other current autonomous braking systems operating at higher speeds require driver activation, and can only mitigate impact speeds. City Safety operates autonomously at low speeds and can prevent collisions occurring completely, so no risk compensation issues are expected.

INTRODUCTION

Over the last few years vehicle manufacturers have been launching a wide range of primary safety technologies. These are technologies that are designed to prevent a collision from occurring by warning the driver to intervene, or to lessen the speed and severity of the collision by autonomous vehicle braking. Some examples are Adaptive Cruise Control (ACC), Automatic Emergency Braking Systems (AEBS), and Low Speed Avoidance technologies.

ACC and AEBS

ACC uses a radar unit mounted on the front grille of the car to sense the proximity and speed of vehicles ahead. This allows the functionality of a standard cruise control system to be extended to control braking as well as acceleration. The driver can then let the ACC control acceleration and braking, and only has to provide steering input. ACC is designed to work on motorways and dual carriageways and most systems are only operational at over 30 km/h.

ACC systems also have the facility to provide a warning to the driver if the car is at risk of a collision. These warnings can take many forms including visual symbols or lights, audible beeps or 'bongs', or a haptic tug on the seat belt.

A further development of ACC is AEBS, which will automatically apply the vehicle brakes when an imminent collision is identified. AEBS aims to prevent the collision or to mitigate severity by reducing speed. AEBS functionality is known by different names by individual manufacturers, such as Collision Mitigation Braking System (CMBS) by Honda, or Collision Mitigation by Braking (CMbB) by Ford.

So both ACC and AEBS use radar sensors and show some potential for mitigating crashes, but they are not designed to prevent crashes from occurring completely. The potential effect for reducing crashes and injuries may also be limited by certain HMI (Human Machine Interface) issues. The systems are only operational when activated by the driver, and can be turned off easily if the driver chooses. The systems also issue warnings to the driver that they need to intervene to prevent a collision. Since different systems issue different types of warnings there is potential for confusion that might lead to either a lack of response from the driver, or an inappropriate response, which limits the effectiveness of the warning.

An example of a Low Speed Avoidance technology is City Safety, and that does not appear to have these associated HMI issues. This uses LIDAR

(**Li**ght **D**etection **a**nd **R**anging) sensors, which is an optical remote sensing technology that measures properties of scattered light (laser) to find range information of a distant target (vehicle in front). These LIDAR sensors are mounted behind the windscreen and scan the road ahead for approximately 6m. In a situation with a likely collision, the system will pre-charge the brakes to give a faster response if the driver does brake. Should the driver still fail to brake in an imminent collision situation, automatic braking power up to $5m/s^2$ is applied, and throttle control by the driver is disconnected. In tests at speeds up to 22 km/h undertaken by Thatcham a car fitted with the City Safety system successfully prevented contact with another car. At speeds of up to 30 km/h the system is able to mitigate collisions by 50%. The system is active for speeds up to 30 km/h. To prevent drivers from adapting their normal driving to the system the design of the system is intended to give a harsh/unpleasant braking sensation. The system is not operational against on-coming traffic, and is operational against stationery or moving traffic. The system calculates that the driver is taking evasive action if they give a large steering, throttle, or brake input, and the system is therefore overridden by the driver.

By default the system is always turned on when the vehicle starts, so it is always on and able to activate to mitigate/prevent a collision. Once the system has operated the driver is given a display notice, but there is no warning given prior to intervention of City Safety. It is not possible to give a driver warning of a potential collision since there is not enough time available once a collision risk is identified. Because City Safety is always turned on, and because it has no warnings, the HMI issues associated with ACC and AEBS are not problems for City Safety.

The City Safety system was launched as standard at the end of 2008 on the Volvo XC60, and it is expected to be fitted on other models from Volvo as well as other manufacturers. However it will still be a number of years before enough evidence can be gathered about the effectiveness of City Safety in the real world to form a conclusion as to its potential for crash and injury prevention. This paper outlines estimates of crash reduction and cost savings offered by City Safety. It also presents two preliminary studies that have aimed to investigate whether drivers are likely to adapt their driving habits to the City Safety system by relying on its crash prevention technology, with the risk that they consequently negate any advantages offered by the system by paying less attention to the road.

POTENTIAL CITY SAFETY EFFECTIVENESS ESTIMATES

Since City Safety is designed to prevent low speed collisions, it shows potential for reducing not only these crashes and the associated repair costs, but also whiplash injuries and costs. The main focus of whiplash injury reduction countermeasures has been with better seat design. Data indicates that 75% of all crashes occur below 30 Km/h [1] with the front to rear end crash at intersections being the most prevalent. British insurers report a cost in excess of €3 billion annually in the United Kingdom due to whiplash [2]. In Sweden 70% of all injuries leading to disability are due to whiplash injuries [3]. According to Watanabe [4] et al. 43.5% of all injuries from vehicle crashes were from rear impacts, and approximately 90% of these injuries were to the neck. Whiplash is an AIS 1+ injury and the vast majority of occupants who suffer initial soft tissue neck injuries typically recover fully, although around 10% of the occupants with initial neck injury symptoms continued to have symptoms after one year [5,6,7]. However collision avoidance technology offers a huge potential to avoid the sorts of collisions that typically cause whiplash injuries.

Based on dose-response models Kullgren [8] has made estimates of the effectiveness of City Safety, which indicates a 60% reduction in injured occupants. It is only possible to make estimates of the effectiveness of the system for preventing crashes at present, with only a small number of vehicles in the fleet fitted with the system. Once a greater number of vehicles can be found on the road in the real world it will be possible assess the effectiveness of the system in detail. However by identifying those typical crash scenarios where the system can be expected to have benefit, it is possible to make some estimates of the potential savings in crash reduction, both in terms of damage and injury costs.

Potential Crash Reduction

Although there are many well established crash frequency databases, such as GIDAS or CCIS, most of the criteria for inclusion relate to serious injures and typically require Police involvement or tow-aways. When comparing these to insurance statistics it is clear that the total amount of all crashes is far higher than the established databases report. The types of crash and direction of impact also tend to differ considerably. Overall there is a huge amount of under reporting is present in most published crash data sets when considering whiplash injuries or non-injury crashes handled by insurers. For example the Department for Transport reported 247,780 casualties on UK roads in 2007 [9], and yet there are around 2.7 million motor crashes resulting in an insurance claim annually in the UK [10].

Estimates of the effectiveness of City Safety for reducing all crashes (not just casualties) can be generated from the insurance claims data. These estimates assume a fleet wide fitment of City Safety. According to analysis of motor insurance claims data, around 26% of claims are for rear-end impacts where one vehicle runs into the back of another [11]. This represents 702,000 crashes from the 2.7 million motor crashes that result in an insurance claim [10]. Many of these crashes occur at intersections, junctions and traffic islands and result from poor driver attention. Most of these crashes occur at low speed (under 30km/h) in the speed range where City Safety is active. City Safety is designed to specifically operate on rear-end impacts, but it could also have a positive effect in other crash types. Effectiveness estimates for City Safety are therefore only focussed on the front-into-rear impact scenario.

Research [12] has shown that in a front-into-rear collision situation 50% of drivers will respond by applying braking. When City safety detects that the driver is braking it will disengage since the driver is in control. However for the other 351,000 crashes (50%) the driver will not brake and the system could therefore help to prevent or mitigate the crash. Previous estimates were made by the authors in [13]. These were more cautious estimates based on only 30% of drivers no applying braking [14], rather than the 50% [12] used in this paper to show the greater potential effectiveness.

Over 75% of crashes are at speeds under 30 km/h [1]. This data suggests that for the 263,250 crashes that are under 30 km/h City Safety could help to prevent the impact from occurring completely, and for the other 87,750 crashes it could help to mitigate the severity (speed) of the impact.

According to crash repair costs analysis [15] the average repair cost per vehicle is €1,868 making a total repair cost of €3,736 per crash. So for the 263,250 crashes under 30km/h that City Safety could help to prevent this equates to a saving of €983,502,000. For the 87,750 higher speed crashes it is assumed that City Safety lowers the crash speed and consequently the repair costs are brought down to the average level of €3,736 per crash, equating to a saving of €327,834,000. This gives a total saving of approximately €1.3 billion, as summarised in Table 1.

Table 1.
Summary of Estimated Crash Repair Cost Savings from City Safety

	Crash prevention	**Crash mitigation**
% of crashes over/under 30km/h	75% under 30km/h	25% over 30km/h
Number of crashes without driver braking	263,250	87,750
Average crash repair cost	€3,736	€3,736
Sub-total repair cost savings	€983,502,000	€327,834,000
Total repair cost saving	€1.3 billion	

Potential Whiplash Injury Reduction

Whiplash is a high cost burden to both the motor insurers, all those who purchase motor insurance and the wider society in general. Costs in excess of £2 billion are reported annually by British insurers due to whiplash [2]. Statistics from the Comité Européen des Assurances [16] show that four countries have a very high rate of claims for whiplash injuries, including the United Kingdom (76% of bodily injuries), Italy (66%), Norway (53%), and Germany (47%). Average claims costs linked to cervical trauma can be very high, for example Switzerland has the highest average cost per claim [16] with approximately €35,000 per claim, followed by the Netherlands (€16,500), and Norway (€6,050).

The annually UK has 432,000 whiplash injury insurance claims [17]. Analysis by Thatcham of whiplash injury claims cases [18] reveals that 70% of whiplash claims come from front impacts and rear impacts, which equates to 303,696 whiplash injuries.

Until now there have been no technologies to prevent or mitigate whiplash injuries in frontal collisions. City Safety is the first technology that offers any potential to tackle the issue of frontal whiplash, and can prevent this injury from occurring at low speeds which is an important contribution to reducing the societal burden of whiplash.

In order to calculate the possible effect on whiplash frequency the same method of estimates was used to calculate the efficacy of the City Safety system. With acceptance criteria of low speed rear end crashes where the striking car does not brake (50%

of crashes) 151,848 whiplash injuries would be saved.

The average whiplash claim cost is €4,000 [2]. This equates to an estimated cost saving of €607,392,000 for the 151,848 whiplash injuries that could be saved by City Safety. Combined with the repair cost savings of €1.3 billion, a City Safety equipped fleet could potentially reduce Insurance Claims by nearly €2 billion annually.

Driver adaptation

The potential effectiveness of any automatic braking system like the City Safety system depends upon whether a driver will adapt and rely on it, negating any crash reduction potential. There are progressively more and more automotive primary safety technologies coming onto the market from increasing numbers of manufacturers, including technologies offering similar automatic braking systems to City Safety. However there is little commonality between the different systems in terms of functionality and system operation. The introduction of these new systems raises a number of important questions. Will drivers understand the meaning of a warning when it is given, what the warning is referring to, and its criticality? More importantly will they react appropriately? Will drivers adapt to these technologies reducing any safety benefits that may have been available? In a worse situation, if one vehicle usually indicates a non-critical occurrence such as low fuel, in another vehicle a similar warning may indicate an imminent collision. Such misunderstandings could be potentially fatal.

Two test types were undertaken on the City Safety system. The first test involved creating a collision scenario that is prevented by the system. The second test type was normal driving on public roads with the system operational, followed by questionnaires used to investigate drivers' reactions and opinions of the system.

DRIVER COLLISION ASSESSMENT TEST

Method

The participants drove the test car toward an inflatable target car at 16km/h (10m.p.h.) without braking. The City Safety system autonomously braked the vehicle so preventing the impact. To avoid risk of damage to vehicles or injury to participants an inflatable target was used. The inflatable target was a life sized representation of a car to elicit the appropriate response from the driver – many people were frightened by its realistic dimensions. Prior demonstrations of the system using traffic cones revealed that whilst the system was activated correctly, driving toward the traffic cones did not alert the driver in a realistic manner because it did not resemble a real crash situation. The realistic size and shape of the inflatable car aids the drivers understanding of the situation, and so gives a more realistic response.

The collision assessment tests were carried out on a test track. The driver was asked to drive normally toward the stationery inflatable car at the required speed, but not brake (see Figure 1). The test conditions and timings varied, for example some tests were in the rain with the windscreen wiper system in operation, some in normal dry daylight conditions, and some in partial darkness.

There were 99 participant drivers. Participants were aged from 20 to 70 years, and all of them were qualified to drive in the UK. Not all participants were from the UK, with 10% from other countries internationally. Most drivers were asked to complete the survey immediately after completion of the test, and some were given chance to reflect upon their experience.

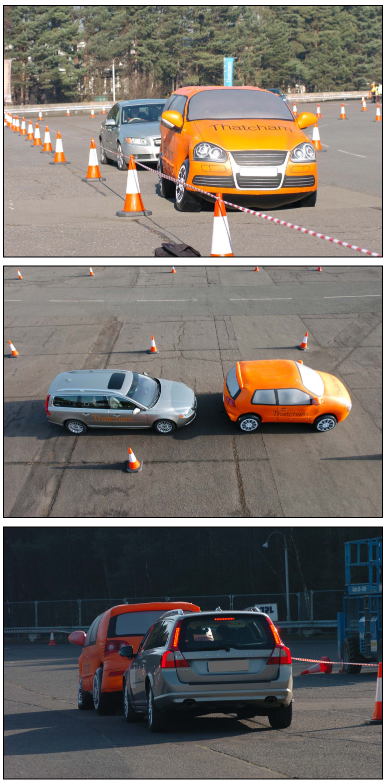

Figure 1. Driver Collision Assessment Test.

Results

Only 4% of drivers believed prior to the test that the car would not actually brake. 37% of drivers had seen the system operate for another driver so believed that the car would brake automatically. 59% of drivers believed prior to the test that the car would brake without having seen it operate previously.

67% of drivers felt the urge to apply the brakes as they approached the target balloon car and did not act upon it. 11% of drivers felt the urge to brake and actually applied braking by pressing the brake pedal. Some of these drivers actually had to repeat the test several times in order to overcome their instinctive fear of a collision and their consequent urge to apply braking. 22% of drivers did not feel any urge to brake as they approached the target.

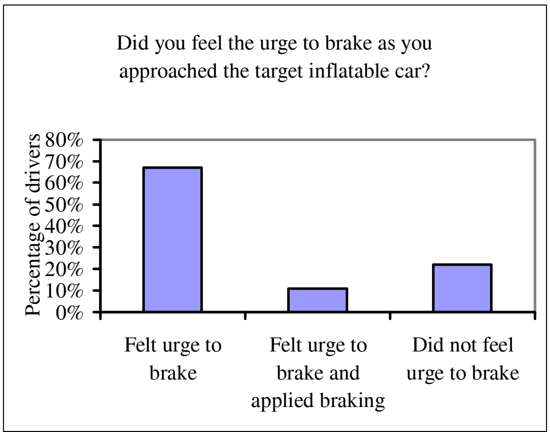

Figure 2. Drivers urge to brake in response to collision situation.

Assuming that they could afford it, 93% of drivers said that they would choose to have City Safety fitted on a car that they were purchasing.

Drivers were asked if they would rely on the City Safety system to brake for them during normal driving conditions i.e. that they would adapt their driving style to incorporate the functionality of the system. Only 5% of drivers stated that they would rely on City Safety during normal driving. 95% of drivers stated that they would not rely on City Safety during normal driving, and that it was only for automatic braking in emergency situations if the driver was distracted.

Discussion

The collision assessment survey results from drivers reveal a strong trend indicating that they are unlikely to adapt their driving style to a City Safety type system, and allow the system to brake for them. 78% of drivers felt the urge to brake when approaching the target and 95% of drivers stated that they would not rely on the system during normal driving. Driver adaptation to the City Safety system therefore seems highly unlikely.

There was also a group of non-participants i.e. those drivers who refused to participate. They were so afraid of relinquishing control of the vehicle braking to the vehicle that they would not participate in the collision assessment test. This also confirms the trend that drivers are unlikely to adapt their driving style to rely on the system to brake for them in normal driving. These 5 drivers' responses are not counted in the analysis of the 99 drivers who did participate in the tests.

2 drivers commented on their perceived increased risk of a rear-end impact in additional comments on the survey. Their concern was that the car behind would be more likely to run into the rear of their car when City Safety braked suddenly. These drivers were informed that City Safety cannot apply more braking force than the driver so cars autonomous braking is merely replacing that of the driver. If the car does not have City Safety fitted and the driver does not brake there would inevitably be a crash, consequently leaving the person travelling behind little time to respond either since no brake lights would show. The autonomous braking of City Safety activating the brake lights could indeed help to warn any following drivers earlier, hence adding to the potential benefit of the system.

ROAD DRIVING TEST

Method

Participants were loaned the test vehicle shown in Figure 3 for a period of up to one week to allow familiarisation with the controls. The test car was an S80 loaned by Volvo that was retro-fitted with the City Safety system for purposes of the research. The system is only fitted to new cars, and was launched on the XC60 in November 2008.

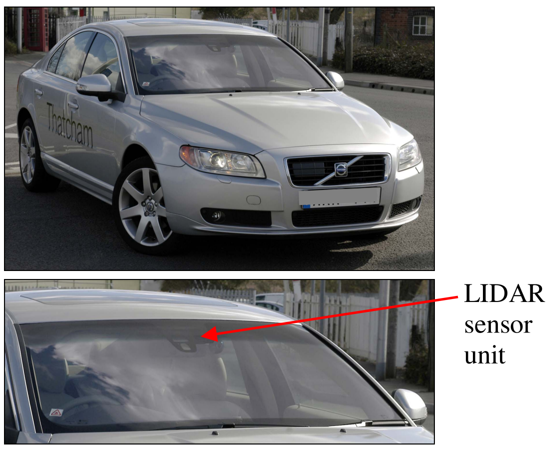

Figure 3. Road driving test vehicle fitted with City Safety.

The drivers used the car for normal road driving within the UK on varying urban and inter-urban journeys. Feedback was gathered from 11 drivers who regularly travel high mileages. The mileage travelled included an equal split between motorways as well as urban and rural roads, all of which were normal UK roads, for a combined distance of over 20,000 kilometres. Participants were aged between 25 and 55 years old, and all held full driving licences.

Results

During the road driving trials all the 11 drivers had the City Safety system operational, since it could not be de-activated on the test vehicle. For all drivers, no positive interventions of the City Safety system were reported, and no false interventions either.

50% of drivers reported that they felt safer than usual knowing that they were driving the car fitted with City Safety that had the capability of preventing a low speed collision. 30% felt no different driving the test vehicle compared to their usual driving. 10% of drivers felt more confident driving the car fitted with City Safety, and the remaining 10% felt more nervous.

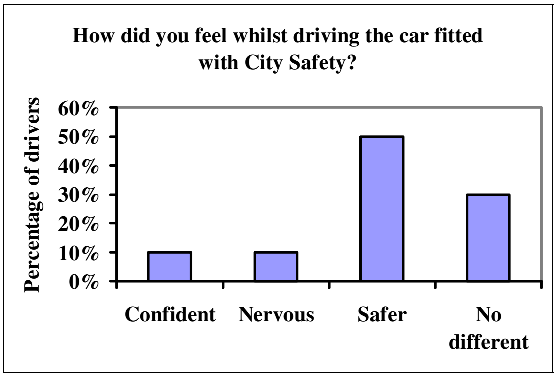

Figure 4. How drivers felt whilst driving car fitted with City Safety on normal UK roads.

Only 2 of the drivers were aware of the system whilst driving. These drivers were conscious that they could see the components of the system or they were monitoring whether the system was operating. The majority of drivers (82%) were not aware of the system during normal driving, so it was in the background and did not distract them.

Discussion

None of the drivers encountered an emergency situation where the system would activate, so the City Safety system did not actually intervene for any drivers during their road trials. None of the drivers encountered a situation where City Safety was required to prevent a collision. Furthermore there were no false interventions. False interventions could annoy drivers and lead them to mistrust such technologies preventing their widespread adoption in the vehicle fleet, so the lack of false interventions in this study is an important finding.

The majority of the participant drivers reported that they felt safer, or no different to normal, driving when using the system. This indicates that most drivers were content with City Safety on their car. The 2 road drivers who were aware of the system during normal driving noticed it because of the prototypical nature of the equipment fitted onto the loan vehicle's windscreen with visible components and wiring. Production vehicles have the system sensors cosmetically encased and will consequently be less noticeable.

CONCLUSIONS

In order to identify an impending low speed impact the City Safety system uses a LIDAR sensor mounted in the front windscreen. The car brakes are automatically applied when an imminent collision is identified. The automatic braking can prevent an impact under 15 km/h and can mitigate an impact between 15 and 30 km/h. The City Safety system prevents common low speed crashes where whiplash typically occurs. It shows potential for reducing the burden on the wider society as well as insurers. The UK estimates presented indicate the system could affect 351,000 crashes annually by preventing or mitigating the crash. The estimates show that City Safety could also save over 150,000 crashes involving whiplash injuries. This equates to an estimated cost saving of nearly €2 billion.

Studies of driver responses in normal road driving showed no interventions of the system, including no false activations. Collision prevention testing involved drivers driving toward an inflatable target car resulting in automatic application of the brakes to prevent an impact. In these collision assessment tests the majority of drivers felt the instinctive urge to brake in response to the collision situation that was created. Drivers also stated that they understood that the system is designed for emergency situations only and they would not rely upon the system in normal driving. This driver study indicates that driver adaptation to the City Safety system seems unlikely.

The City Safety system appears to offer significant benefits to all drivers in preventing the most common sort of impacts. The system is low cost and can be readily made available across a new car fleet. Estimates presented in this paper indicate that significant reductions in injuries and repair costs are possible. Due to the late activation of the system in the collision process and the harsh and unpleasant emergency braking applied, an activation of City Safety is expected to discourage drivers from adapting to the technology.

ACKNOWLEDGEMENTS

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eVALUE – A Test Programme for Active Safety Systems

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ABSTRACT

Active safety systems are massively implemented into new vehicle generations and offer a high potential in decreasing road accidents. While testing and rating of the passive safety of vehicles are based on established and accepted methods and programmes, no such are available for active safety of cars or trucks today. Thus it is difficult to assess the performance of those systems for industry, legislation and further stakeholders. In particular, the customer cannot judge about the active safety of different vehicles based on easy-to-understand ratings as they are offered by different NCAP programmes. This leads to a relatively low awareness of active safety systems and hinders a high market penetration.

The main focus of the European research project "Testing and Evaluation Methods for ICT-based Safety Systems (eVALUE)" is to define objective methods for the assessment of active safety systems. The methods are based on relevant traffic scenarios that, according to investigated statistics and databases, represent the majority of accidents, where active safety systems can come into effect. The considered systems are chosen based on market availability and penetration, e.g. ACC, Lane Keeping Assistant or ESC. Both the systems as well as the scenarios are clustered into four different domains, each being addressed with distinctive test procedures.

In the end, this new and highly needed test programme will allow the assessment of the overall safety performance of a vehicle with respect to active safety systems. However, the eVALUE consortium will only define the test methods while the thresholds for the specific values are not specified. This remains the competence of every institution adopting the test methods and actually applying them in order to assess different vehicles. The later results of the programme will increase the public awareness for active safety systems and foster the development within the industry.

INTRODUCTION

Modern society strongly depends on mobility, and the need for transport of both people and goods is expected to grow further in the future. Cleaner, safer and more efficient transport systems are needed. Mobility and especially road transport cause major societal problems: accidents, pollution and congestions. More than 40,000 lives are lost every year due to road accidents in the European Union only, and the costs are estimated to be about 2 % of its GDP [1].

The European Commission and its member states have made major efforts to improve traffic safety, and the results can be seen in a decreasing number of fatalities in many European countries [2]. Nowadays new ways must be found to reduce the number of fatalities and in-juries even further. The public awareness of the enormous impact that active safety systems would have on road safety must be raised. It must be easy for the customer to understand the benefits of safety systems based on Information and Communication Technologies (ICT).

The average car buyer cannot assess the performance of active safety systems in vehicles, nor their impact on traffic safety. Today, there are no publicly accepted test methods and no established ways to communicate the test results. The situation is quite different for passive safety systems, where test programs such as Euro NCAP have established impact test methods and ways to explain the test results in different levels of detail. While the car buyers may compare star ratings for passive safety between different cars, the professional safety engineer may compare measurement data from the tests.

Going forward to this goal of accident free traffic, evaluation and standardised testing methods for active safety systems are essential. This is the main focus of the European research project "Testing and Evaluation Methods for ICT-based Safety Systems (eVALUE)" which is funded under the

7th Framework Programme of the European Commission. It has a duration of 36 months. The consortium consists of eight partners from four European countries and is led by the Institut für Kraftfahrzeuge (ika) of RWTH Aachen University.

Partners come from both research organisations and industry, including vehicle OEMs. In particular, Centro Ricerche FIAT (Italy) and Volvo Technology Corporation (Sweden) contribute as OEMs while Germany's Ibeo Automobile Sensor is a supplier of laser scanners. SP Technical Research Institute of Sweden and Statens Väg- och Transportforskningsinstitut (VTI) are research organisations from Sweden with Fundación Robotiker and IDIADA Automotive Technology from Spain being well-known as research and testing suppliers.

OBJECTIVES

Performance test results presented to the public will help to promote the use of active systems. This has also been underlined by the eSafetyForum working group on Research and Technological Development in their "Recommendations on forthcoming research and development" [3].

By this means, also the research and development of new safety systems is encouraged. The long-term goal is to provide a basis for de-facto standards that will be used by all involved stakeholders. This has already proven to be an effective way in terms of promoting passive safety [4].

In the first phase, the eVALUE project is focusing on safety systems available for today's vehicles. Active systems currently under development or close to market entrance may be included in the project at a later stage. The aim is to identify evaluation and testing methods, especially for primary safety systems, with respect to the user needs, the environment and economic aspects.

An intensive communication with key stakeholders has been started and will accompany the project throughout its duration. The partners are aware of the fact that additional testing methods will not easily be accepted and adopted especially by involved industry. In addition, most manufacturers or suppliers already perform in-house testing of their systems and vehicles. Thus, a harmonisation of those methods is sought wherever possible. Besides industry, other stakeholders like national authorities, customer organisations or standardisation working groups active in this field are also contacted.

However, the project will not perform any activities which lead to a direct standardisation of the methods developed. Furthermore, there will not be any pass or fail criteria defined for the different performance values. The focus will be set on objective and repeatable methods while rating will be up to the users of these methods.

METHODOLOGY

Today, a number of passive and active safety systems as well as intelligent driver support systems are already in the market. A trend towards more pro-active and increasingly integrated safety systems is apparent. The performance of all these systems is affected substantially by the properties of the vehicle itself. For instance, such vehicle properties include tire characteristics, vehicle dynamics behaviour and friction potential in road/tire contact. Also the control strategy and algorithm quality of the active safety systems can improve the performance towards accident free traffic.

The Approach in Defining Test Methods

In 2007, the ASTE study [5] has investigated the feasibility of performance testing for active safety systems. In addition, it aimed at needed methods and principles for verification and validation of those systems. Therefore, different approaches were considered. The system approach is based on the capabilities of specific systems and mapped to traffic scenarios. Performance of the different systems with similar functions is then assessed.

The scenario approach is directly based on traffic scenarios. The vehicle is tested as a black-box and its overall performance in those scenarios is determined. As a third option, a document-based approach was discussed. This could complement physical testing and might be particularly valuable for HMI testing.

According to the conclusions of the study, vehicle active safety shall be tested following the scenario-based approach. It was further stated that performance testing of active safety systems is technically and economically feasible and that a consensus between different stakeholders will be possible. The importance of communicating test results in a very simple way was underlined.

The eVALUE project is a direct follow-up of this study. Most partners are now part of the eVALUE consortium. Together, objective methods will be developed, enabling the estimation of the safety impact the regarded active safety systems have.

Figure 1 gives an overview of a scientific approach for the development of the testing and evaluation methods. Based on accident statistics, relevant scenarios will be derived that represent the majority of accidents in which active safety systems could possibly mitigate the outcome. A vehicle will be assessed by applying the procedures. Those shall be recognisable also by the end customer as critical situations that can happen at any time. One example could be approaching suddenly congesting traffic or a similar, non-moving obstacle. The benefit of active safety systems (e.g. by automatic braking in this case) will thus be even more clear.

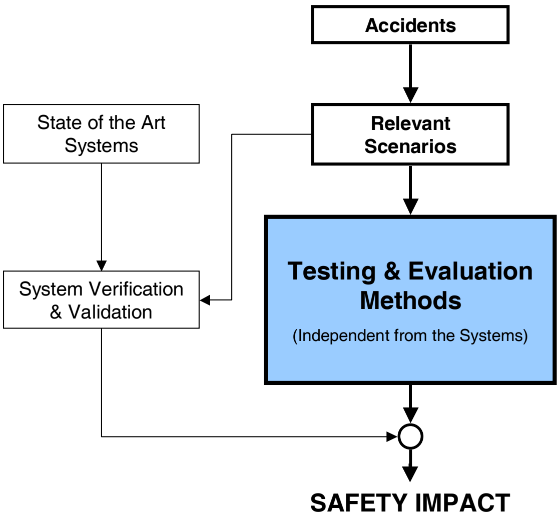

Figure 1. Scientific Approach for Assessment Development

Unlike the assessment of vehicle passive safety, the systems contributing to active safety will be regarded in detail. From verification and validation, e.g. fault rates are be analysed and their influence on the overall safety impact is taken into account.

Validation of the systems includes the interaction with the environment/infrastructure and driver actions. For both testing the vehicle as a whole and the systems in detail, relevant scenarios have to be found and/or defined.

Systems to be Regarded

The road-map of active safety systems with their time horizon is given in Figure 2. They are clustered into four domains. These are the longitudinal domain, the lateral domain, the domain for yaw/stability assistance and an additional domain. This additional domain is yet to be defined. Scenarios are defined for the same domains thus taking into account the interaction of different systems which might come into effect in the same situation.

Out of those domains, the following eight systems have been chosen. This decision is mainly based on the availability on the market with a penetration rate of more than 50,000 vehicles:

- System Cluster 1 (longitudinal assistance)
  - ACC
  - Forward Collision Warning
  - Collision Mitigation, by braking
- System Cluster 2 (lateral assistance)
  - Blind Spot Detection
  - Lane Departure Warning
  - Lane Keeping Assistant
- System Cluster 3 (yaw/stability assistance)
  - ABS
  - ESC
- System Cluster 4 (additional assistance)
  - Not defined at this stage

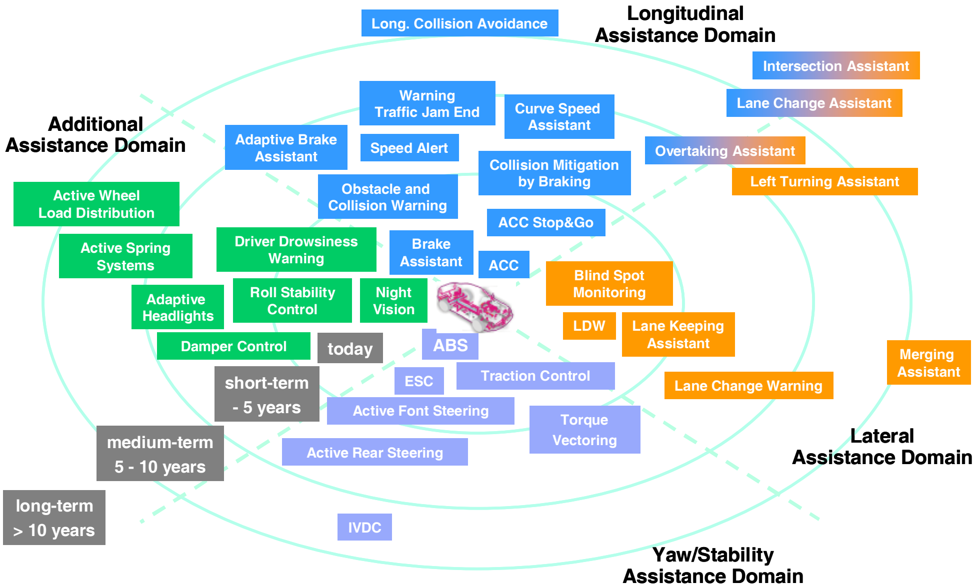

Figure 2. Clustered Road-map of Active Safety Systems

Considered Scenarios

The derivation of relevant scenarios from accident statistics directly has already turned out to be a challenge. No reliable accident databases are available that are capable of delivering a comprehensive analysis of accident circumstances for the whole of Europe. While some European projects such as TRACE [6] have been working on ideas for the harmonisation of accident statistics, waiting for them being available is not acceptable. Thus the partners have defined relevant scenarios based on information that is available today. This includes standards for testing of certain systems, results from other projects and the expertise of the involved institutions.

For System Cluster 1, three different scenarios have been chosen. They represent a straight road, a curved road and a target, which is transversally moving in the way of the subject vehicle.

Regarding the straight road, the objective of the chosen scenario is to validate that the subject vehicle can detect and handle (warn, support, and/or intervene) a target vehicle in the same lane, Figure 3.

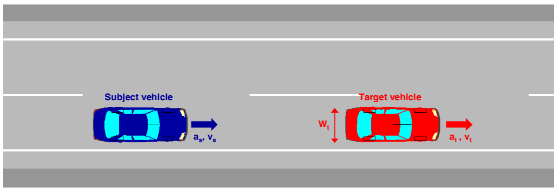

Figure 3. Straight Road Scenario (Cluster 1)

The same objective applies for the scenario, however for a curved road, Figure 4.

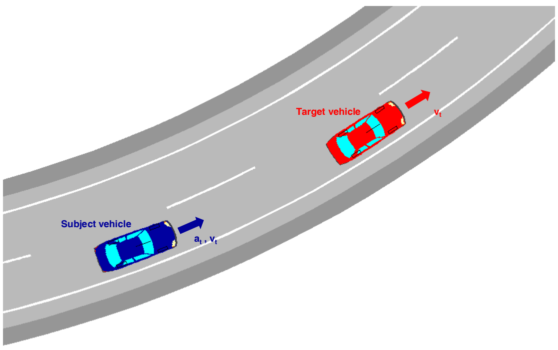

Figure 4. Curved Road Scenario (Cluster 1)

The objective of the third scenario is to validate that the subject vehicle can detect and handle (warn, support, and/or intervene) a target (e.g., other vehicle, pedestrian,…) which moves lateral to the subject vehicle, Figure 5.

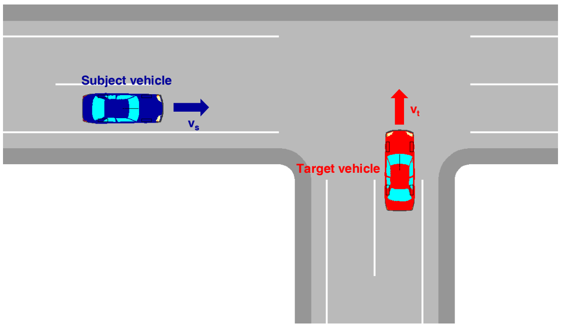

Figure 5. Transversally Moving Target Scenario (Cluster 1)

The System Cluster 2 is addressing systems which are providing lateral assistance. For straight as well as curved roads, a differentiation is made regarding lane and road departure. Accordingly, four different scenarios are considered.

The first scenario is meant to validate the subject vehicle capability to avoid involuntary (left/right) lane departure driving on a straight road, Figure 6.

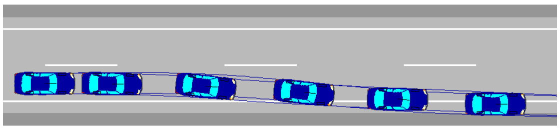

Figure 6. Lane Departure on a Straight Road Scenario (Cluster 2)

As a form of extension of the first scenario, the second is meant to validate the subject vehicle capability to avoid involuntary road departure driving on a straight road, Figure 7.

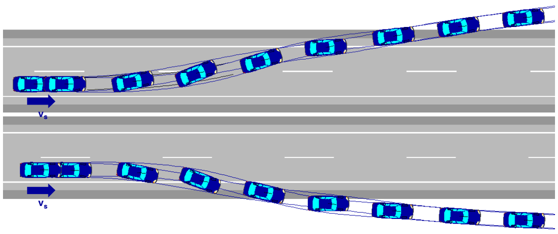

Figure 7. Road Departure on a Straight Road Scenario (Cluster 2)

Comparable to the first two, the second and third scenario of Cluster 2 regard lane or road departure while the subject vehicle is driving in a curve. Again, the capability to avoid the involuntary lane or road departure is the objective here, Figure 8.

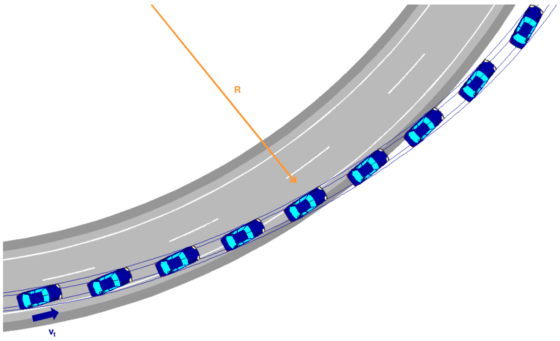

Figure 8. Lane or Road Departure in a Curved Road Scenario (Cluster 2)

A modification to the aforementioned is given by scneario five and six, namely to validate the subject vehicle capability to avoid involuntary lane departure driving on a straight road just before entering an upcoming curve, Figure 9.

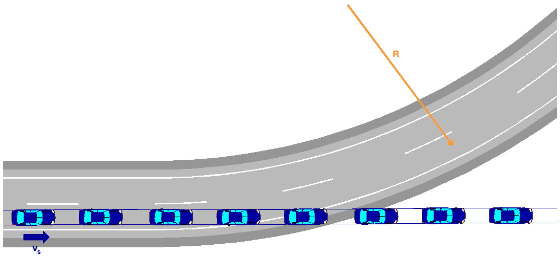

Figure 9. Lane or Road Departure on a Straight Road Just Before a Curve Scenario (Cluster 2)

While these scenarios do not consider interaction with a second (called target) vehicle, the seventh scenario does so. It addresses lane change collisions which are well-known in multi-lane traffic both at low and high speeds, Figure 10.

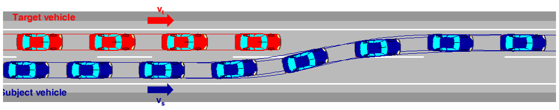

Figure 10. Lane Change Collision Avoidance on a Straight Road Scenario (Cluster 2)

Yaw and stability assistance is given by systems which have been collected under System Cluster 3. Here, some manoeuvres are already established in testing. One example is braking on μ-split, i.e. surfaces with different friction coefficients, Figure 11.

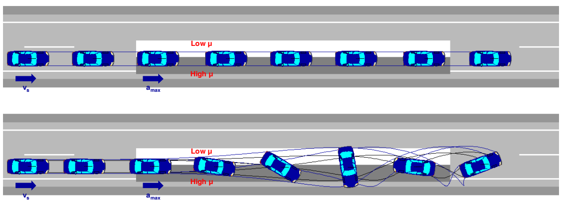

Figure 11. Emergency Breaking on μ-Split Scenario (Cluster 3)

The capability of the vehicle to avoid loss of control in a sudden obstacle avoidance manoeuvre is regarded with the second scenario in Cluster 3, Figure 12.

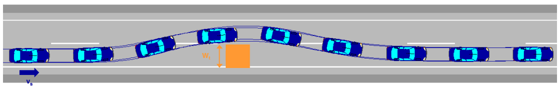

Figure 12. Driver Collision Avoidance Scenario (Cluster 3)

Finally, critical situations linked to curved roads are represented by the third and fourth scenario of Cluster 3, Figure 13-14.

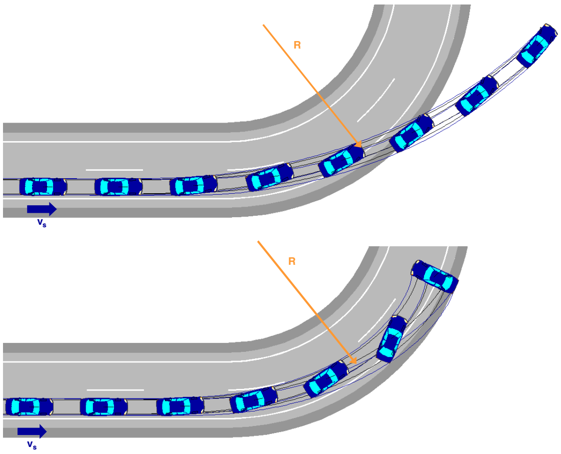

Figure 13. Fast Driving into a Curve Scenario (Cluster 3)

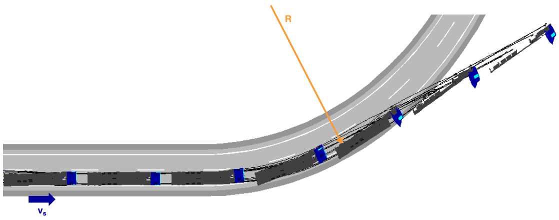

Figure 14. Roll Stability Scenario (Cluster 3)

All scenarios do not only consider passenger cars but generally also apply for trucks and busses. However, it has not been decided yet to what extent the project can regard the special requirements by commercial vehicles concerning active safety test methods.

Current Development and Next Steps

Having defined the scenarios, the development of the methods themselves has been started. The main focus will be on physical testing with a certain support from simulation where this seems appropriate. Verification and validation of the systems will mainly be done by lab testing. In general, the most suitable methods and procedures will be taken to reveal the active safety performance in the best way.

CONCLUSIONS

In the development of automotive active safety systems, no generally accepted standards are available today. Manufacturers of systems, components or vehicles all need to develop their own testing procedures in order to provide both development goals and means to evaluate the system performance. Large R&D efforts are undertaken in parallel by various companies in order to provide the technological background for the development of testing procedures.

Due to this situation of inhomogeneous testing practice throughout the industry, test results acquired in different manufacturer-specific tests cannot be compared by customers and authorities. Furthermore, manufacturers have no means to assess their systems in a generally accepted way.

The outcome of the eVALUE project will be explicit testing procedures/protocols for active safety systems that can found the basis for a de-facto standard whilst and after the duration of this project. In addition, communication with stakeholders that might be involved in a later standardisation process has been established to get a broad picture of currently on-going standardisation efforts towards those systems.

The project started in January 2008 and will continuously generate results. Due to the production deadline, the latest findings cannot be covered by this paper but are available on the project's website under www.evalue-project.eu.

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NOTE

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NEW TEST AND EVALUATION METHODS FOR FUTURE CAR2X COMMUNICATION BASED DRIVER ASSISTANCE

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ABSTRACT

Wireless communication technologies between cars and infrastructure (Car2X communication) will play a major role for future driver assistance. Many new applications and services in the fields of vehicle safety, comfort and infotainment will be possible. New test and evaluation procedures are required to cover future cooperative traffic scenarios with many cars and infrastructure equipment involved. An enrichment of real test situations with simulated environment scenarios ("Extended Reality") is proposed as an approach to develop and test such systems. An integrated development and test environment provides a flexible and configurable combination of both, real and simulated units including OnBoardUnits, RoadSideUnits, MonitoringDevices and on-board displays with modules e. g. for wireless communication (WAVE, DSRC, WLAN, UMTS), positioning (GPS), vehicle and infrastructure interfaces (CAN-Bus), which can be combined in any manner. Based on the integrated architecture a real Car2X testing scenario consisting of a car communicating with RoadSideUnit(s) providing traffic sign and traffic light information was first developed and tested in full simulation mode in the lab. Then the same scenario was validated in a real test car on the real test track of the Connected Vehicle Proving Center in USA still with a simulated infrastructure environment. Based on that received information warning messages appeared on the on-board display. Active driver assistance functions can be triggered as well. The novel approach allows evaluation of the technology benefits and effectiveness with significantly reduced efforts as compared to traditional operational testing methods. This paper will cover the technology employed; the assistance and safety scenarios evaluated and give an outlook on the future use of the technology in combination with field operational tests.

INTRODUCTION

Future Driver Assistance Systems in vehicles will also be based on advanced technologies like Car2X communication techniques. Adding wireless communication to cars enables multiple new opportunities for enhancing safety, mobility, energy efficiency and driving experience in vehicles, which never existed before. But this also has implications on the requirements for test and evaluation procedures.

When considered in a very simplified fashion Car2X communication maybe mistakenly viewed as just another type sensor which is simple and well known in the art testing and evaluation methods. However, when considered from a more detailed point of view, it becomes apparent that a significantly more complicated scope of testing and evaluating is required: Now a car exchanges information with other cars (C2C) or roadside (C2R) or the infrastructure (C2I). For example it might get the information regarding an accident or glazed frost hundreds of meters ahead. These sample use-cases illustrate that the sources of relevant quantities for test and evaluation of those Driver Assistance Systems are not anymore a physical or a controlled part of the vehicle. Hence the vehicle with its assistance systems can no longer be tested stand-alone. This kind of vehicle has to be tested in a complete environment consisting at any times of many other cars and Road-Side-Equipment (RSE) such as traffic lights, equipped with communication technology. In terms of cooperative systems it has to be considered that the environment of the vehicle operates within is not static. The behavior of the vehicle itself influences its environment. It may cause traffic lights to change the current and programmed phase or it may cause other cars and their driver assistance systems to react on the current situation. The new requirements illustrated above have to be considered and evaluated during all development-stages: from the research and development of applications to their final test and evaluation it is highly desired to use the cost effective simulated environment on a development PC at early stages and introducing progressive levels of reality with real vehicles and a real environment. Thus simulation tools are indispensable for the development of future Driver Assistance Systems under complex and dynamic traffic scenarios that include many communication units. Common simulation tools are commonly used for simulating the communication network (e.g. ns-2 [1]) or the traffic flow (e.g. VISSIM [2]). But these tools usually run in simulation-time and not in real-time. They cover only parts of a whole Car2X scenario and are not designed for the combination of communication networks, traffic and individual Car2X scenarios. Optimized vehicle communication technologies are still a part of research and standardization processes both in Europe [3][4] and the United States [5][6]. Nevertheless, even at an early stage, verification and validation capabilities help research scientists, communication engineers and developers of driver assistance systems (which are basically the users of those communication technologies), because they provide possibility of immediate feedback.

DEVELOPMENT ENVIRONMENT VIILAB

The software package viilab (vehicle infrastructure integration laboratory) [7] has been especially designed for the requirements of Car2X application developers. viilab is an integrated development and test environment designed to support the whole development process of Car2X-based driver assistance systems from the initial idea up to pilot-series.

Basic Architecture

The development environment viilab is based on a modular software-architecture (see figure 1).

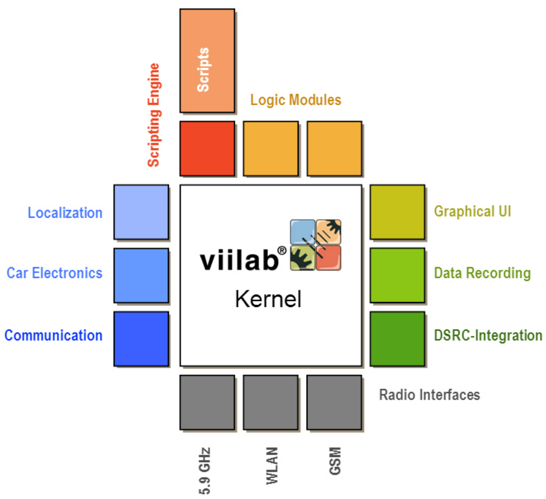

Figure 1. viilab architecture.

There are basically two types of modules: (1) Modules to connect the environment such as communication modules (DSRC, WLAN, etc.), vehicle modules (CAN-Bus, GPS, Display/HMI, etc.) and infrastructure modules (traffic light adaptor, traffic control adaptor, traffic monitoring camera, etc.). (2) Logic modules (a.k.a. decision modules) which implement the driver assistance functionality and handle all information from the other modules. The viilab kernel manages the lifetime (startup and shutdown) and scheduling of all software modules and functions as their runtime environment.

Unit Set-up

The different types of units and their specific behaviors are achieved by assembling the necessary environmental modules with the related logic module. For instance a typical OBU has a communication module, a CAN-Bus module, a GPS module, a display/HMI module and a logic module. The logic module contains the driving assistance application(s). The logic module deals with all the OBU modules, processes the received data, calculates the results/outputs and overall defines the behavior of this specific OBU. A typical RSU for an intersection for example, consists of a communication module, a traffic light and traffic control module and the appropriate logic module to handle these information-sources. Figure 2 illustrates a sample configuration for an OBU and a RSU.

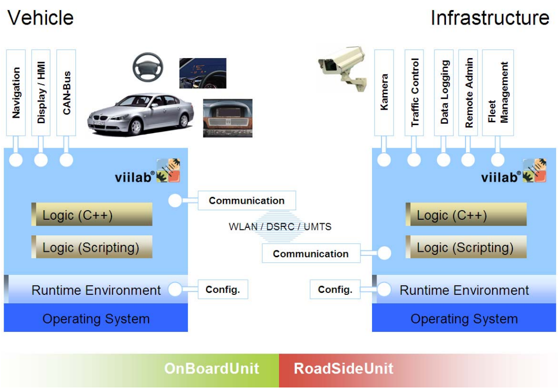

Figure 2. viilab sample configurations for OBU and RSU.

Scenario Set-up

A typical Car2X-scenario consists of many elements. Since a running viilab-unit is only a single process, a scenario is simply a combination of units each represented by a process. Depending on the needs and the stage the development process, the combination of all those units can easily run on only one computer or, if so desired, on many different computers (see chapter simulation enhancements).

Rapid development support

Viilab incorporates two parallel concepts: It supports the rapid development and prototyping of Car2X applications and at the same time enables the low-level coding and thus highly efficient development of algorithms and/or for integration of new hardware. The first concept – rapid development – is realized by a scripting language which has been specifically adapted to the needs and requirements of communication based driver assistance systems. It is often used to realize parts of the unit-logic, e. g. to for the combination of vehicle communications events with vehicle electronics. The scripting option is mostly attractive for actuating elements in each part of the Car2X-application that are under development where it is highly desirable and efficient to easily implement changes without any compiling effort. The second concept – highly efficient low-level code development – is realized by the fact, that viilab offers a C/C++ API which is designed to further be used for effective implementation of hardware modules.

viilab user interface

To complete a working Car2X system a user interface must be provided. In-car displays can be rapidly developed and customized with a specific viilab GUI development environment called viilab user interface (vui). vui uses SOAP/TCP based information transfer which enables remote display access. This also enables a distributed installation, where the GUI may run on a different device to avoid high processor loads on critical communication events due to display updates. vui is based on the Gecko Rendering Engine and XUL technology. This approach allows a highly flexible development process and a strict separation between design, layout and user interaction. Just as viilab it supports different operating systems, e. g. Linux and Windows (XP, Vista). To simplify handling of states, vui provides a configurable storyboard concept. A control file specifies states and their transitions, significantly exceeding the possibilities provided by a classic state machine. Therefore changes in order of display states can be immediately applied without a requirement to modify any source code.

SIMULATION ENHANCEMENTS

The architecture of viilab which was discussed in the previous chapter also leads to transparency of the module implementation and operating mode. As the software-interfaces for each module like a positioning module for example stay the same, regardless of the specific implementation of the module there is no possibility for the other modules to realize weather the positioning data provided through the interface is real or simulated.

Simulation of Position Data

Most Car2X-Applications are location based. Therefore position data is very commonly essential. In reality the position of a vehicle can be detected by receiving the signals of the Global Positioning System (GPS) by using of a GPS-receiver device. For simulation on a computer other sources of real GPS data have been developed. At the moment there are four possible ways for GPS data input as figure 3 illustrates.

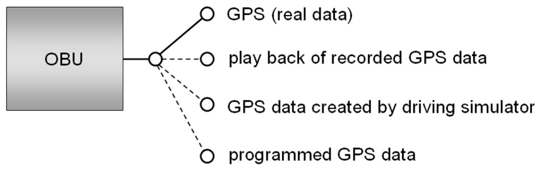

Figure 3. Options for the vehicle position data source.

One option is to play back GPS data that was recorded in a vehicle during real and actual test drive. Except for simulation purpose recording and playback of position data is necessary for reproducibility. In terms of continues changing of GPS signal there is no possibility to accomplish exactly the same test-drive twice. The position data of the vehicle can also be fully simulated by a driving simulator with the car driving on a virtual test track. For simple investigations the creation of programmed virtual GPS data is sufficient, for example when a car is driving only straight forward.

Simulation of Communication Range

Similar to this inter-module-transparency feature, viilab supports also transparency between units. Because the connection between units is via communication interface, a unit is not able to realize if the received messages are generated by a real or a simulated unit. To prepare the simulation modes (see next chapter) where many units are running on one machine a "Virtual-Air"-functionality has been introduced: All units, running on one workstation, could always exchange Car2X-messages because they are connected via the communication device. This is unrealistic because in full reality, communication between vehicles (OBUs) and infrastructure (RSUs) are effected by the actual environment they operate within. For example, an OBU and a RSU might be outside of the wireless communication range depending on the wireless technology, the communication protocol and the environment. Therefore the "Virtual-Air" calculates with the mentioned parameters the possible connection distance and decides depending on the current unit distances if units are within connection range. Only when communicating units are within that range messages are exchanged between them.

Monitoring

A simulation of a Car2X scenario with all the different modules and across various OBUs and RSUs can become complicated to follow and trace actual sequences of events. A mechanism to visualize the complete set of this important information is needed. A viilab Monitoring application (MON) has been developed which displays the current position of the units and hence (a defined clipping of) the scenario. Following the principles of the viilab architecture the MON is also a specific assembling of modules with the viilab kernel: A communication module used for receiving the positions of the other units, a display module that functions as connector to the display-application, and a logic module that refines the positions for the display-application.

SIMULATION MODES

With all the previously explained design-decisions and tools the integrated development environment viilab allows a variety of different simulation modes. They differ on the level of "virtuality". Scenarios and all Car2X components involved may be simulated, components may be simulated, real or partially real and some components maybe simulated and others real, etc. Two simulation modes and their domain will be explained below using the example of an intersection scenario which is illustrated in figure 4.

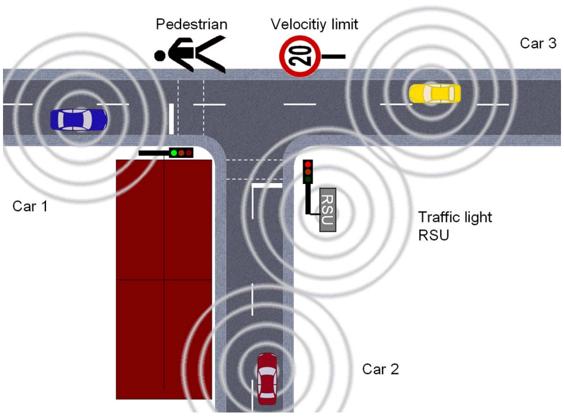

Figure 4. viilab intersection scenario.

Full Simulation Mode

In the full simulation mode all viilab processes (units) are fully simulated and are all running on one computer in the laboratory. In the example three cars with OBUs and one RSU are simulated. The positioning is simulated as well as the connection-range due to the fact, that it is a full simulation, without real positioning hardware and any wireless-connections. A MON unit is used to monitor the scenario. In this mode basic algorithms and driver assistance systems can be developed and tested without any financial or safety risk.
The intersection-scenario in the full simulation mode is illustrated in figure 5.

Figure 5. viilab intersection scenario.

The OBUs of the three cars amongst others have the following functionalities: Displaying of traffic signs, pedestrians and current traffic light Signal, Phase and Timing (SPT). Additionally there is a RSU running, sending out traffic sign information, SPT messages, and a virtual pedestrian. These messages sent by the RSU are received by the OBUs. Beside the 3 OBUs and 1 RSU there is a fifth viilab-process running – the MON process. Finally there are three vui running, each of them connected to one OBU. The vui as in-car-display / HMI visualize the driver assistance function. Other possible "outputs" like a vibrating-steering-wheel for warning purposes, usually activated via CAN-Bus are not part of this full simulation mode.

Extended Reality Mode

The novel test and evaluation method for future Car2X Communication based Driver Assistance is the "Extended Reality" method. It means the enrichment of real test situations with simulated environment scenarios. Since as was explained and demonstrated so far simulated units are transparent to their environment a real unit can not distinguish between real and simulated units within its communication-range. This offers a large variety of "virtuality"-grades or in other words a large variety of "Extended Reality"-situations.
Using the same given intersection scenario example (see figure 4) one of the three OBUs now is used in a real car. It uses now a real positioning hardware and it is connected to the vehicle (e.g. via CAN-Bus). The other two OBUs, the RSU and the MON can either run similar to the full simulation mode on the same machine or run on different machines. For example, these modules may be executed on an additional Notebook inside the car and be connected to the real OBU via communication

technology. Now one real test-car is part of the scenario. The functionality of the driver assistance system that is under development can be tested and evaluated. Now in-car equipment, e.g. a Head-Up-Display, a vibration-steering-wheel, or other actuators can be integrated and tested.

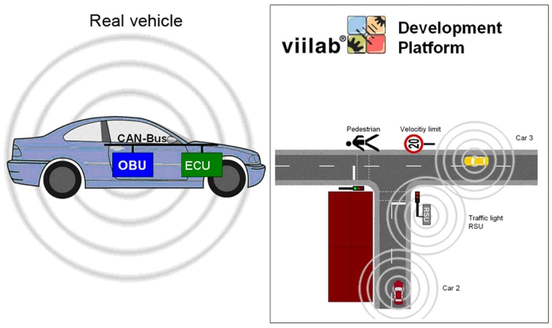

Figure 6. viilab "Extended Reality" simulation: A real vehicle with a simulated Car2X environment.

The level of "Extended Reality" is adjustable. For safety purposes testing in the real test-car may initially start with a simulated positioning. Hence the car can remain stationary but the actuators inside the car for example as well as the vui can be set to react in reality. The modular and scalable viilab architecture allows a smooth transition from a fully simulated scenario to a complete real scenario through a step by step replacement of simulated components or units by real ones. It must be pointed out, that the Car2X-application - the driver assistance system – stays completely the same: There are no changes needed to algorithms or other developed modules from a full simulation, through the "Extended Reality" method, to a completely real test drive. Thus using the viilab development environment the testing and evaluating of any Car2X communication application can be performed without a disruption to the development process in a short time and at low risk for driver and hardware. This "Extended Reality" method and approach enables best in calls Design for Testability (DFT) practices and a Test Based Development (TBD) processes. It shortens or even eliminates expensive, time consuming and generally not efficient and ineffective testing phases (pre-alpha, alpha, beta, etc.) that are normally executed after an application was already fully developed. With the "Extended Reality" method, the Car2X application under development is tested, evaluated, verified and validated in parallel to the development processes.
Development process will start in the full simulated mode to evaluate and verify the base design requirements and will end with in the full "Extended Reality" mode. Verification and quality feedback is provided to application developers and product managers in real time, leading to a higher quality and better accepted Car2X application the first time. Less time is spent on quality assurance testing and Alpha/Beta tests and the number of iterations and expensive version releases is dramatically reduced.

EXEMPLARY DEVELOPMENT PROCESS

A typical development process will be described next based on real projects at the Connected Vehicle Proving Center (CVPC) [8] in Michigan, USA.
In addition to a sophisticated Connected Vehicle laboratory that includes vehicle electronics laboratory, access to an Anechoic Chamber, a Cray Computer laboratory, a Network Operations Center, a Vehicle 3D simulator, large garage and a Test Operations Center, the CVPC is engaged in building Connected Vehicle proving grounds on the Michigan International Speedway (home of the NASCAR races) private grounds and is operating a several test and evaluation sites on public roads in South East Michigan (Greater Detroit Area). Based on real data of infrastructure components of the test and evaluation site which the CVPC operates at the intersection of 9 mile road and Hwy 10 ("the Lodge"), the existing actual testbed was mapped as a fully simulated scenario for viilab. The testbed route was transferred as a track for a driving simulator, which generates realistic driving behaviour of the simulated car. With this simulation environment new functionalities, specific to the actual and real test area, have been developed: For Example new traffic signs have been implemented such as a US-bridge-height (going under the Southfield freeway), two traffic light RSUs adopted to USA-compliant SPT messages (without a red-orange-phase), a stop sign, a parking lot sign and more. All displaying units were configured and adapted to the USA language, standards and preferences. Figures 7, 8 and 9 are showing screenshots of the MON and the vui connected to the simulated OBU of one car (the car is monitored as a green dot).

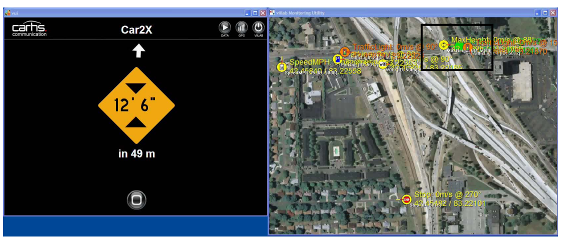

Figure 7. Displaying of max bridge height going under Southfield freeway.

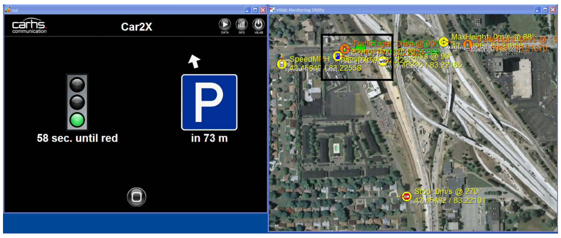

Figure 8. Displaying of current SPT and parking lot information.

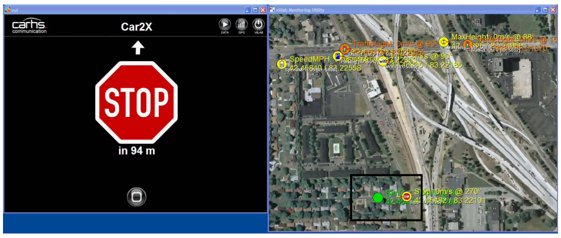

Figure 9. Displaying of stop sign.

The simulated car uses simulated positioning data out of a driving simulator.
After developing the driver assistance system in the full simulation mode for the 9-mile testbed an "Extended Reality" test was performed. In particular the test was not performed on 9-mile testbed were the roads and traffic patterns are known and well documented but on open public roads that are not a part of any testbed setup. The test took place at Traverse City, Michigan as part of the 2008 Management Briefing Seminars [9] which is a conference dedicated to Auto Industry Executives. Traffic signs and a traffic light RSU providing the SPT messages were realized as "Extended Reality". This generated the simulated environment to an actual car as if there were real RSUs along the public roads, sending out information messages.

Figure 10. A real car running vui on two in-car-displays, displaying the parking lot information received from "Extended Reality".

As is illustrated in figure 10 there is little difference, from point of view of a driver testing and evaluating the driver assistance system, between testing the Car2X application in complete reality or a with "Extended Reality" enhanced actual road.

OUTLOOK

Car2X applications are built upon existing technologies and no new invention of technology. Still Car2X systems are complex. They introduce a challenging integration of multiple enabling technologies like Vehicle Electrical Control Units, Vehicular communication networks, driver assistance computing hardware, aftermarket equipment, inter-car communication systems, mobile communications systems, intelligent transportations systems and roads. The enabling infrastructure requires cooperation across industries. Many of the required technologies are still a subject to research and required interfaces are still being defined and standardized. New test and evaluation methods like "Extended Reality" are proposed to ease the development process of these multi-discipline, complicated, driving assistance systems. The continuous improvement of simulation capabilities to support a Car2X development environment is vital. To help mitigate the complexity real test-beds were and are constructed around the world. In Germany a test-bed is currently under development within the SIM-TD Project [10]. In the US a large test-bed was created as part of the US Department of Transportation Prove of Concept (POC) project which was concluded, in Michigan, last year. The Connected Vehicle Proving Center operates multiple physical test-beds as part of its Car2X testing and evaluation capabilities, some on public roads and some on private roads. However, physical, full reality test-beds are not a replacement to simulation. While test beds are excellent for overall solution evaluation and final operational testing, they are less suitable and more cumbersome for functional testing through the development process. The role of simulation and its advantages in an application development process are well documented and today are basic capability in any field. The use of simulation at certain stages of the development process is by far more productive, enhanced further by the "Extended Reality" method that allows taking advantage simultaneously of both: the simulation and the testbed. The mapping of these testbeds into a simulation environment like viilab is necessary to support developers of Car2X applications. Enhancement of simulation tools is a key and required. Like the rest of Car2X applications development aspects, simulation tools dedicated for Car2X applications need to continue evolving. As

soon as new expertise becomes available or an interface is standardized it has to be introduced into the simulation system.
The mutual progress and development of simulation tools and physical test-beds are crucial to provide an effective development environment. The combination of both into a common development process, using a method like the "Extended Reality", yields best development process as was already proven in many other fields of application development, some less complex than Car2X.

SUMMARY

The development of future Car2X communication based Driver Assistance poses a complex problem with regard to testing and evaluation. New test and evaluation methods help to meet those new demands and support a more efficient, simplified development-process. The viilab "Extended Reality" simulation is a powerful tool to rapidly develop and test Car2X communication applications and services for traffic scenarios at low risk for driver, hardware and budgets. It is possible to develop and test the applications and algorithms in detail highly efficient. In particular, a smooth transition from complete virtual simulation on one computer to a complete testing-scenario on many units can be accomplished without disruption to the development process. Application developers can better engage in Test Based Development methods where they can test and evaluate their efforts as they progress. Finally the discussed simulation methods pave the way for testing of future driver assistance systems with regard to the currently proposed testbeds.

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