

# **A TEST PROGRAMME FOR ACTIVE VEHICLE SAFETY – DETAILED DISCUSSION OF THE EVALUE TESTING PROTOCOLS FOR LONGITUDINAL AND STABILITY FUNCTIONALITY**

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## **ABSTRACT**

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

From January 2008 until December 2010, the European research project eVALUE has been working on objective testing and evaluation methods for active safety functions. According to investigated statistics and databases, critical and accident-prone driving situations have been identified that represent the majority of accidents, where active safety functions can come into effect. The methods are mainly based on physical testing of the full vehicle and do not take into account the influence of a single function, but rather the response of the vehicle as such. Intensive physical testing and application of the test protocols was performed in order to validate and improve the methods proposed by the consortium.

Another important topic concerns indicators, which show potential to assess the safety benefit by different active safety functions. Here, a major challenge was given by the lack of required input data, i.e. detailed accident statistics. A first set of indica-

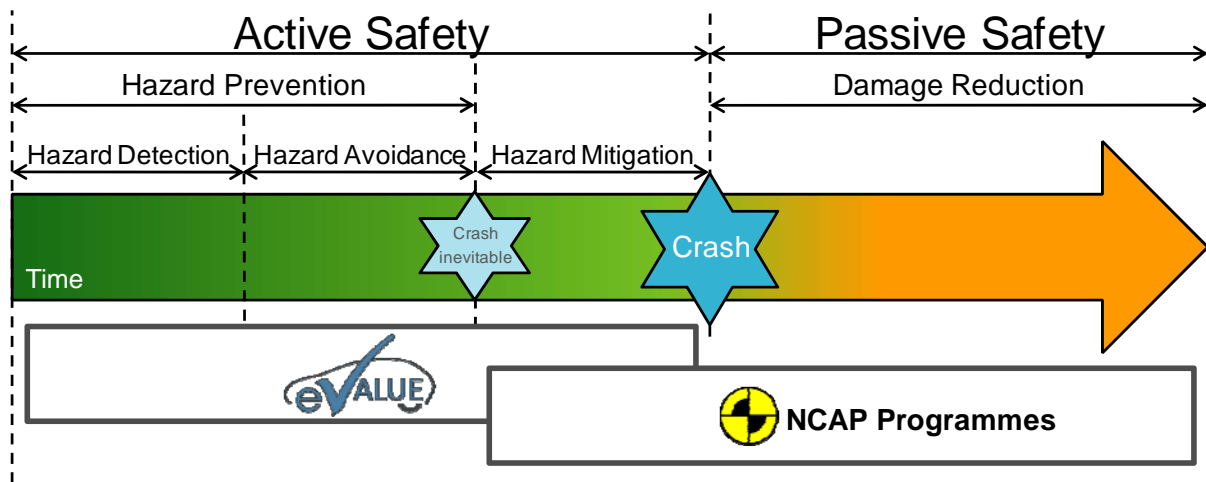
tors has been identified and proposed by the project consortium for further investigation.

The proposed new and highly needed test programme allows a first assessment of the overall safety performance potential of a vehicle with respect to active safety. However, the eVALUE consortium only defined the test methods while thresholds for specific indicator values and the derivation of final quantitative overall test results are not specified. This is left to the competence of every institution adopting the test methods and actually applying them in order to assess different vehicles. We believe that results gained from our programme will increase the public awareness for active safety functions and foster the development within the industry. However, the project partners also identified and expressed additional research need beyond the scope of the project, e.g. regarding accident statistics and driver behaviour models.

## **INTRODUCTION**

Modern society strongly depends on mobility, and the need for transport of both people and goods is expected to grow 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 34,000 lives were lost in 2009 due to road accidents in the European Union only [1], and the costs are estimated to be about 2 % of its GDP.

The development of road vehicles during the past decade has led to vehicles with improved passive safety. Systems of airbags, seat belts and protective structures have increased safety for the drivers, passengers and lately also pedestrians. Testing programmes for assessment of these passive safety measures have been established.



**Figure 1. Timeline of Active and Passive Safety**

Over the last years, active safety functions have been massively implemented into new vehicle generations, offering 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 such functions for industry, legislation and further stakeholders. In particular, the customer cannot compare the active safety provided by different vehicles based on easy-to-understand ratings as they are offered by different new car assessment programmes (NCAPs), see Figure 1.

The main focus of the European research project "Testing and Evaluation Methods for ICT-based Safety Systems (eVALUE)" was to define objective methods for the assessment of vehicle active safety. Since the start of the project, several other initiatives have identified this need for standardised testing and assessment methods. Although some of these projects are on-going, similar methods have been presented recently and a worldwide harmonisation process is required.

The eVALUE consortium consisted of eight partners from four European countries and was led by the Institut für Kraftfahrzeuge (ika) of RWTH Aachen University. Partners were Centro Ricerche FIAT (Italy) and Volvo Technology Corporation (Sweden), contributing as OEMs, SICK AG (Germany) as a sensor supplier, SP Technical Research Institute of Sweden and Statens Väg- och Transportforskningsinstitut (VTI) as research organisations from Sweden and Tecnalía Transport and IDIADA Automotive Technology from Spain as research and testing suppliers.

The test methods investigated and defined by the eVALUE project are compiled in protocols for both inspection of the subject vehicle as well as physical

testing of it. They give a baseline for the assessment of the active safety performance of a vehicle. However, thresholds for specific values have not been specified by the consortium.

While some procedures are soon ready for implementation, some others require additional work that was out of scope for the project. These open research needs are summarised in the end.

### OBJECTIVES

Performance test results presented to the public will help to understand the benefit of active safety functions. This has e.g. also been underlined by the European eSafetyForum working group on Research and Technological Development in their "Recommendations on Forthcoming Research and Development" [2].

By this means, also the research and development of new safety functions is encouraged. Accordingly, the long-term goal was and must be to agree on testing protocols that will be used by all involved stakeholders. This has already proven to be an effective way in terms of promoting passive safety [3].

However, the eVALUE project did not perform any activities which would have led to a direct standardisation of the methods developed. Furthermore, there were no pass or fail criteria defined for the different performance values. The clear focus was on objective and repeatable methods while rating remains to the potential users of these methods or methods based on the ones developed by the eVALUE project.

It must also be underlined that certain limitations apply to the scope of the project given by the limited time and resources that were available. Figure 2 highlights this scope in the context of safety

performance analysis, which is based on real life accidents. The derivation of scenarios that represent dangerous traffic situations and the development of test methods based on those scenarios were part of the eVALUE project, while performance rating and subsequently an estimation of the safety impact could not be covered. This safety impact would in the end have an effect on the accidents, thus closing the circle.

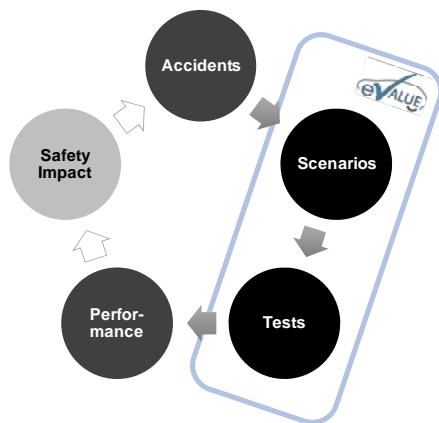
## METHODOLOGY

In 2007, the ASTE study [4] investigated the feasibility of performance testing for active safety functions. In addition, required methods and principles for verification and validation of those functions were investigated. Therefore, three 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 e.g. basic HMI evaluation.



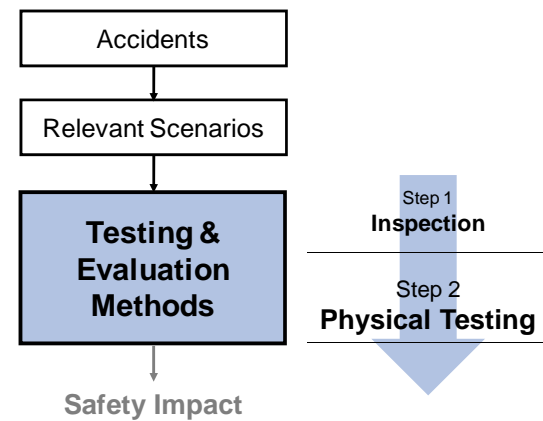
**Figure 2. Safety Performance Analysis and eVALUE Project Scope**

According to the conclusions of the study, vehicle active safety shall be tested following the scenario-based approach. The eVALUE project, a direct follow-up of this study, had most of the ASTE partners as members of its consortium.

Figure 3 gives an overview of the eVALUE approach for the development of the testing and evaluation methods. Based on accident statistics,

relevant scenarios have been derived that represent the majority of accidents in which active safety functions could possibly mitigate the outcome.

A vehicle will be assessed by applying these novel methods and evaluating it in the identified accident-prone scenarios under controlled testing conditions. The scenarios shall be recognisable by the end customer as critical situations that can happen during normal driving. One example is approaching suddenly congesting traffic. The benefit of active safety functions like automatic braking will then become apparent.



**Figure 3. Scientific Approach for Active Safety Assessment Development**

The technical development of the project was executed in a serial way. After the definition of the concept to be followed, the different testing strategies with respect to laboratory testing, physical testing and simulation as well as reviews by means of inspections were analysed. In the following step, the actual transition of the different test procedures into testing and inspection protocols was carried out. This was strongly linked to extensive physical testing. Since the application of the protocols led to valuable experiences this iterative approach of developing the testing protocols allowed a continuous improvement to their final form over the whole project period.

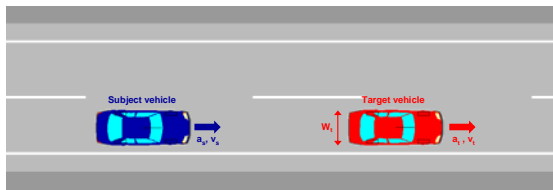
## DEVELOPMENT

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. While for instance some European projects such as TRACE [5] have been working on ideas for the harmonisation of accident statistics, waiting for them being available was not acceptable. Thus the eVALUE partners have defined relevant scenarios based on information that was available at the time being. This

included standards for testing of certain systems, results from other projects and the expertise of the involved partners.

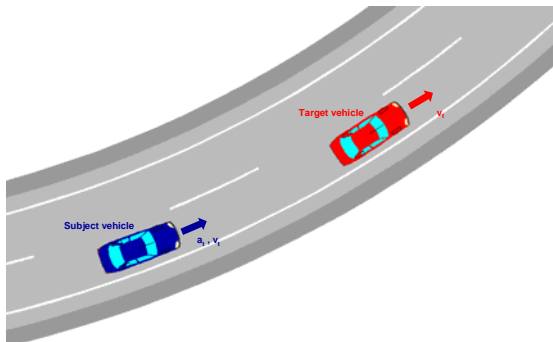
For the longitudinal direction, three different scenarios have been chosen. They represent a straight road, a curved road and a target, which is transversally moving in the way of the subject vehicle.

Regarding the straight road, the objective of the chosen scenario is to validate that the subject vehicle can detect and handle a target vehicle in the same lane, Figure 4. To handle the target vehicle means, that the subject vehicle warns or supports its driver and/or intervenes autonomously.



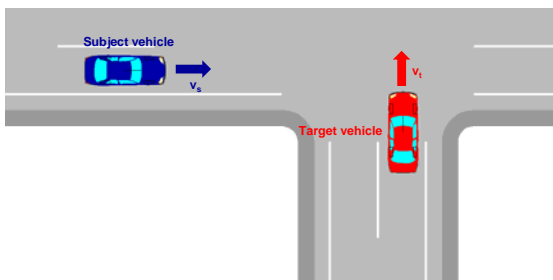
**Figure 4. Rear End Collision on a Straight Road**

The same objective applies for the second scenario, however for a curved road, Figure 5.



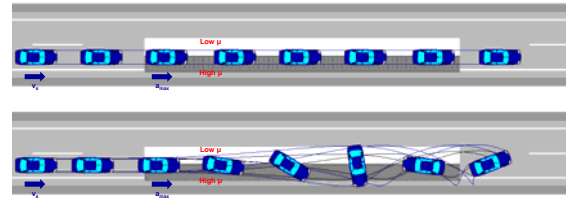
**Figure 5. Rear End Collision on a Curved Road**

The objective of the third scenario is to validate that the subject vehicle can detect and handle a target (e.g. other vehicle or pedestrian etc.) which moves lateral to the subject vehicle, Figure 6.



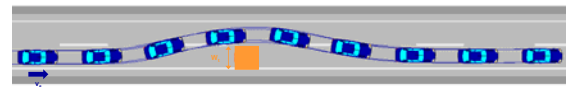
**Figure 6. Transversally Moving Target**

Regarding the assessment of yaw and stability assistance, four manoeuvres are already established in testing or as standards. One example is braking on  $\mu$ -split, i.e. surfaces with different friction coefficients, Figure 7.



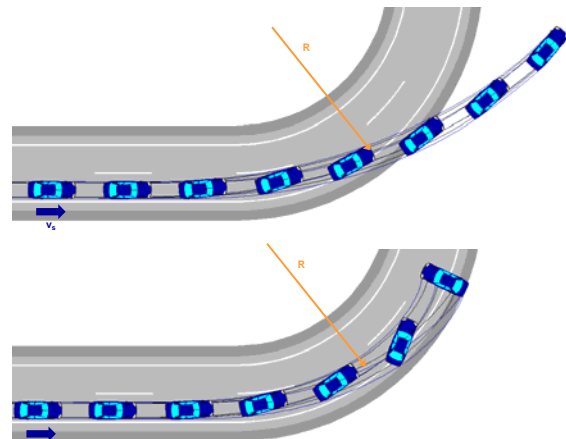
**Figure 7. Emergency Braking on  $\mu$ -Split**

The capability of the vehicle to avoid loss of control in a sudden obstacle avoidance manoeuvre is chosen as the second scenario, Figure 8.



**Figure 8. Obstacle Avoidance**

Finally, critical situations linked to curved roads are represented by the third scenario, Figure 9.

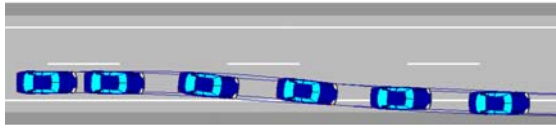


**Figure 9. Highway Exit**

All scenarios do not only consider passenger cars but generally also apply for trucks and busses. However, special requirements by commercial vehicles concerning active safety test methods have not been analysed due to time constraints.

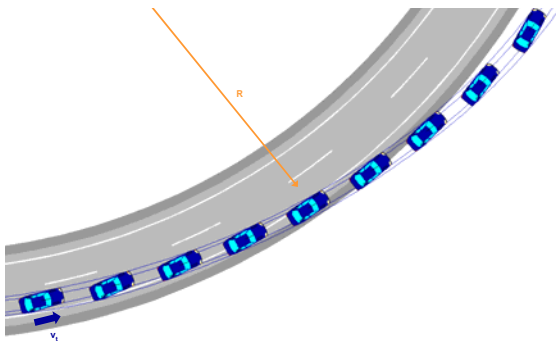
Assistance and safety functions in the lateral direction of travel have also been analysed by the project. The development showed that these functions, as their implementation has started only recently, require significant additional efforts in order to develop comprehensive testing and evaluation methods. They are thus not in the focus of this paper. However, critical scenarios have also been identified and shall be mentioned.

The first scenario is meant to validate the subject vehicle capability to avoid involuntary (left/right) lane departure driving on a straight road, Figure 10.



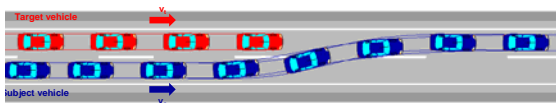
**Figure 10. Lane Departure on a Straight Road**

Comparable to the first, the second scenario regards a 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 11. A similar scenario is given in case of a lane departure on a straight road just before a curve, but may require a different set of testing parameters.



**Figure 11. Lane Departure in a Curve**

While the first two scenarios do not consider interaction with a second (called target) vehicle, the third scenario does so. It addresses lane change collisions which are well-known in multi-lane traffic both at low and high speeds, Figure 12.



**Figure 12. Lane Change Collision Avoidance**

Based on the described scenarios, the eVALUE test programme consists of inspection and physical testing protocols. In the following, a brief overview is given. A complete description can be found in the publicly available “Final Testing Protocols” [6]. Figure 13 describes the proposed performance testing process in general.

### Inspection Protocols

By inspection of the subject vehicle, important aspects such as the functionality of the different safety functions on board including any limitations as described in the documentation, the HMI used

for warning and information of the driver, environmental conditions applying for the test. It further includes efforts made by the manufacturer in terms of functional safety are investigated and documented.

The inspection protocols define a systematic and comprehensive analysis. The objective is to identify and determine the capability of the vehicle. Most parts of the inspection are done studying the documentation and interviewing the manufacturer, but other parts of the work might be done investigating the vehicle.

### Physical Testing Protocols

The core of performance testing is the physical testing of the subject vehicle. The purpose of this type of test is to assess the overall performance of the vehicle rather than testing one particular safety function under different scenarios, i.e. specific real driving situations, which are relevant regarding the functionality of the considered safety systems.

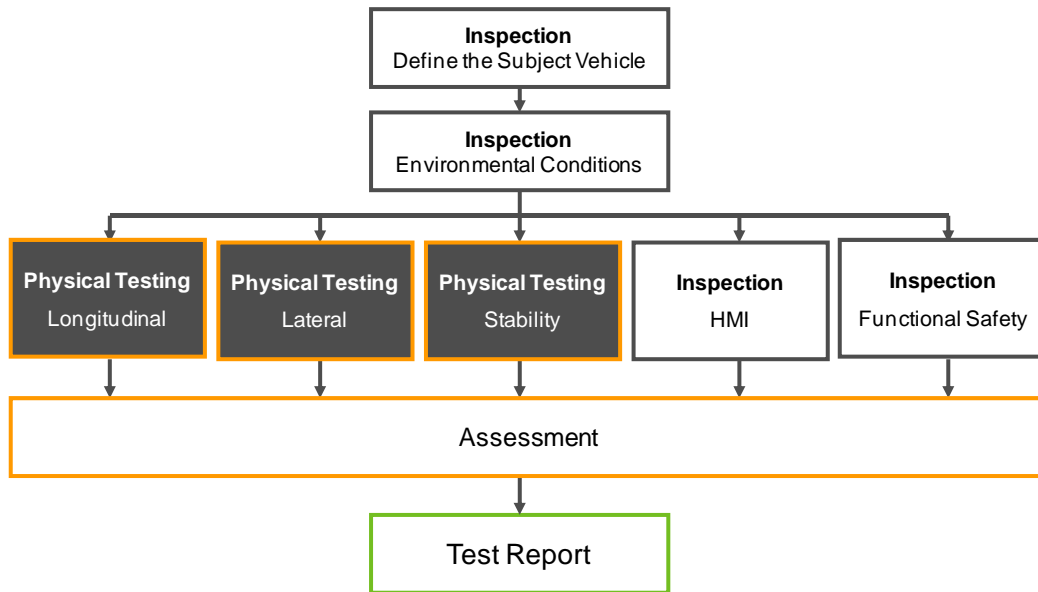
In order to do so, a differentiation between longitudinal, lateral and stability-related functionality was followed. This differentiation reflects the different levels of driver support as well as it supports the development within different expert groups. It is imaginable that a similar differentiation can be made in a later implemented test programme since it seems understandable for the customer. This, however, depends on the organisation to implement the procedures.

Each physical testing protocol contains all relevant information which is necessary to perform the related tests. This includes the general scope, references and definitions, test conditions regarding track, weather and visibility, data collection and measurement, and configuration of the vehicle under test. It is followed by the principles of the specific test, the objectives, requirements on the target and driver used, and finally the test procedure and data processing.

### Safety Indicators

Adequate safety performance indicators are essential to characterise the behaviour of the tested vehicle according to the concept adopted in eVALUE. The number of selected indicators of safety performance should be limited in order to reduce the complexity of the assessment.

A safety performance indicator shall reflect a real impact on road safety and should not be confused with test conditions or measured values. Test conditions are prerequisites for the test procedure e.g. the speed of the target vehicle. Measured values are



**Figure 13. The eVALUE performance testing process**

logged during the test e.g. the global position of the subject vehicle. The concept is to select the most important safety performance indicators where a real impact on road safety can be expected.

An assessment of the most representative safety performance indicators was made to quantify the overall safety performance of the vehicles. They have been chosen to a) characterize the safety performance associated to the sequence of events that take place in the current test, b) provide information about the tested vehicle to the developer and c) quantify the test results for comparison with a threshold value. In this regard, also the issue of open or closed loop testing is important, i.e. taking driver reactions into account or not when evaluating the performance of the vehicle. To be as realistic as possible, it is desirable to perform close loop tests. However, the lack of comprehensive driver behaviour models prevents this in many cases.

Based on some investigations, the eVALUE partners propose to use the following safety performance indicators for the longitudinal-related active safety performance:

- Collision speed
- Time-to-collision (TTC) at warning

For the stability-related performance, the following indicators are proposed:

- Mean longitudinal deceleration
- Equivalent deceleration
- Equivalent deceleration on different tracks
- Use of adherence
- Stability
- Yaw rate ratio
- Lateral displacement

- Driver intention following
- First steering wheel torque peak
- Wheel lift
- Relative radius
- Slip angle

These indicators and the formulas for their calculation are described in detail in the report “Final Testing Protocols” [6]. They must also be subject to further investigation and harmonisation between different initiatives.

## RESULTS

In the following, the protocols for physical testing of longitudinal and stability-related functions are presented in detail.

### Longitudinal Physical Testing Protocols

As described above, the physical testing protocols for the longitudinal direction are based on the identified critical driving scenarios. The first tests described aim to represent a scenario where a vehicle is approaching another vehicle which is moving slower in the same direction, decelerating, or being stationary on a straight or curved road.

The test is based on the observation of the subject vehicle behaviour when executing the manoeuvres specified in the respective test. The open loop tests are focusing on the vehicle's technical performance.

The objective of the open loop test is to evaluate the technical performance of the vehicle, without considering natural response and feedback from an arbitrary driver. A professional driver or a driving robot is used for triggering an action from the vehi-

cle. There are three open loop tests depending on the type of action from the professional driver or driving robot (no action, mild brake after warning, and strong brake after warning). The outcome of the tests will depend on the level of assistance from the subject vehicle (warning, support, and/or intervention).

To facilitate a possible collision, the target vehicle is simulated by a vehicle dummy similar to ordinary vehicles with regard to physical dimensions and detection characteristics. For each of the three tests there are a number of test cases. The test cases represent different combinations of subject vehicle speed as well as target vehicle speed and deceleration. Additionally, the test cases consider: straight road, left curve, or right curve.

The following measurements need to be recorded while testing:

- Local time reference
- Local position of both vehicles
- Speed of both vehicles
- Longitudinal deceleration of both vehicles
- Longitudinal distance between both vehicles
- Lateral distance between vehicles
- Warning instant
- Collision instant (if there is any)
- Brake pedal actuation force

After the pre-stabilisation period,  $t_1$ , the initial speeds (and clearance) has been established by the use of professional drivers in the subject and target vehicles. Depending on the test case, the target vehicle may initiate a robot-controlled braking at  $t_2$ .

Subsequently, typical driver action is simulated by doing nothing (passive driver) when the warning is issued or by a robot-controlled braking after a typical reaction time has elapsed. The tests progress until a collision occurs or when the speed of the subject vehicle is equal or lower than that of the target vehicle, i.e. no collision.

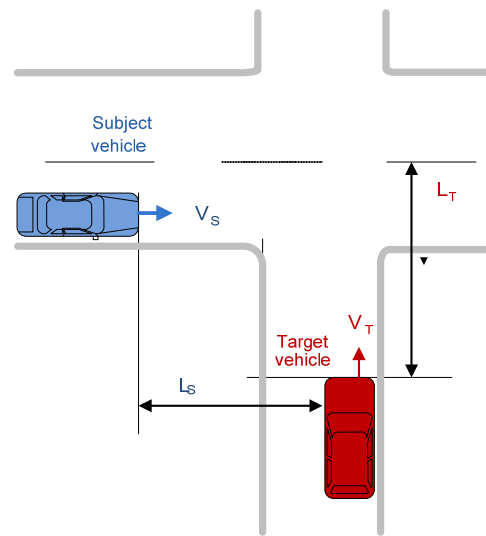
For each of the three tests (no, mild or strong braking), a number of test cases have been specified, characterised by different speed combinations of the subject and target vehicle, initial clearance between them, different target vehicle decelerations as well as the road's topology (straight or curved). Full details can be obtained directly from the protocols, which are publicly available.

The test procedure for the transversally moving target scenario is similar, also open loop. The moving target can in this case be a passenger vehicle, a motorcycle or a pedestrian. Again, three different levels of reaction are utilised: no, mild or strong

braking by the driver or driving robot. The initial conditions are described by Figure 14.

The different test cases are related to different initial speeds of the subject and target vehicle as well as different subject and target vehicle distances.

For the longitudinal-related performance of the vehicle, the indicators collision speed and time-to-collision (TTC) at warning are proposed to be utilised. Their derivation based on the results of the described tests is described in the protocols [6].



**Figure 14. Initial Conditions for Transversally Moving Target Test (Vehicle Target)**

Since dedicated initiatives are focussing on the development of testing protocols for this domain, development beyond the eVALUE proposals is already underway, and even harmonisation processes between the initiatives are under first discussions.

### Stability-related Physical Testing Protocols

In the stability-related testing protocols, open and closed loop manoeuvres are proposed. This is due to the fact that it either seems reasonable to integrate a driver reaction or that the test procedure itself requires a steering input. The protocols for the stability domain refer to the same references, definitions etc. as the longitudinal protocols.

The first protocol based on the  $\mu$ -split scenario describes the test procedure for testing the safety performance of the subject vehicle during a braking manoeuvre on dissimilar surfaces so that the left wheels of the vehicle are exposed to a significantly different coefficient of friction ( $\mu$ ) than the right wheels.

The open loop test is to evaluate the technical performance of the vehicle while either a professional driver or a driving robot is used to trigger an actuation from the vehicle. The closed loop test is to evaluate the overall performance of the vehicle when considering natural response and feedback from the driver. A driver is used to trigger an actuation from the vehicle.

In the open loop test, the braking manoeuvre consists of braking from a speed of 50 km/h to 0 with the steering wheel kept at 0° during the manoeuvre. In the closed loop test, the braking manoeuvre consists of braking from a speed of 100 km/h to 0 with the driver acting on the steering wheel to try to make the vehicle run in a straight line.

The following measurements need to be recorded while testing:

- Distance
- Speed
- Position
- Longitudinal acceleration
- Lateral acceleration
- Steering wheel angle
- Yaw rate
- Brake force trigger
- Brake friction material temperature

For the open loop test, three test cases are proposed, which are differentiated by initial speeds (50 or 100 km/h) and friction (high, low or split with the first two required in order to determine braking distances on non-split surfaces). For the closed loop test, a constant initial speed of 100 km/h is proposed.

Out of the measurements, it is proposed to generate the following three safety performance indicators for the open loop test:

- Mean longitudinal deceleration
- Equivalent deceleration
- Equivalent deceleration on different tracks

For the closed loop, it is proposed to generate as indicators:

- Use of adherence
- Stability

The required formulas are defined in the protocol document [6].

Representing the obstacle avoidance scenario, the corresponding testing protocol requires extra safety performance indicators to be evaluated during the well-established sine-with-dwell manoeuvre. However, the manoeuvre itself is performed exactly as described in the ECE R13-H regulation or in the NHTSA FMVSS126 conformation test. Besides the

measures specified in the ECE R13-H regulation, the steering wheel torque shall be recorded.

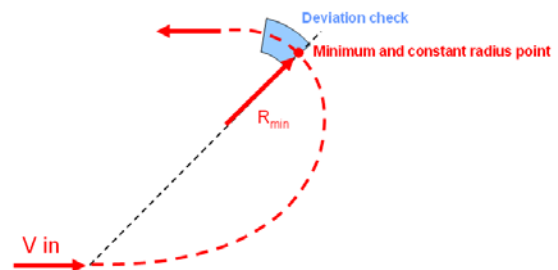
Again, this is an open loop test, and a steering robot is used to trigger an actuation from the vehicle.

Out of the measurements, it is proposed to determine the following safety performance criteria:

- Yaw rate ratio
- Lateral displacement
- Driver intention following
- First steering wheel torque peak
- Wheel lift

Yaw rate ratio and lateral displacement are measurement according to ECE R13-H regulation, while steering wheel torque is measured to describe the effort of the driver to perform the manoeuvre. Driver intention following means how closely the vehicle responds (in terms of yaw motion) to driver's intention (commanded by the steering wheel). Wheel lift is used to describe roll-over stability with the tip-up criteria directly carried over from NHTSA fishhook test.

The third protocol describes the test procedure for testing the safety performance of the subject vehicle e.g. when exiting a highway at too high speed. The vehicle has to follow a closing radius trajectory, Figure 15. It is defined as an open loop test utilizing however a steering robot to follow the trajectory with high accuracy.



**Figure 15. Highway Exit Trajectory**

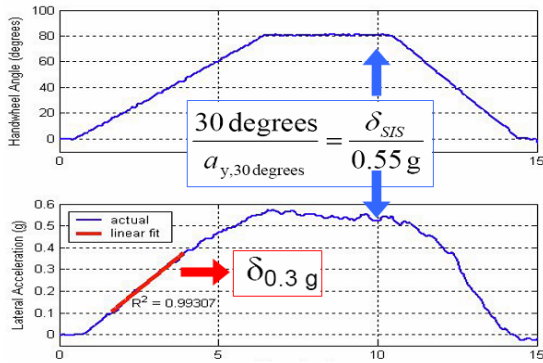
For these tests, the following measurements are recorded:

- Distance
- Speed
- Position
- Lateral acceleration
- Steering wheel angle
- Steering wheel torque
- Yaw rate
- Centre of gravity sideslip angle

At first, the Slowly Increasing Steer (SIS) manoeuvre is used to characterize the lateral dynamics of the subject vehicle. The manoeuvre is used to pro-



vide the data necessary for determining the steering wheel angle ( $\delta_{0.3g}$ ) capable of producing a lateral acceleration of 0.3 g. This steering wheel angle is then used to determine the magnitude of steering required during the manoeuvre. A speed of 80 km/h and a ramp steer of 13.5 °/s are used, Figure 16.



**Figure 16. Vehicle Steer Characterisation**

This is followed by a curve manoeuvre, which is performed without throttle (coasting) using a steering rate of 0.3 g/s and a steering angle of 0 to 6.5 • ( $\delta_{0.3g}$ ).

Afterwards, successive runs are performed at increasing vehicle speed and steering wheel rate. The speed is increased in 5 km/h steps from 80 km/h until a final speed of 110 km/h. Each test case should be performed once. In the end, another curve manoeuvre is performed without throttle (coasting). The steering rate is increased proportionally to the vehicle speed increase (compared to initial run) again using a steering angle of 0 to 6.5 • ( $\delta_{0.3g}$ ).

These tests aim at determining the safety performance indicators relative radius, slip and wheel lift for the subject vehicle. The relative radius ( $R_{rel}$ ) is the difference between the trajectory radius in the test run ( $R_i$ ) and the trajectory radius in the initial test run ( $R_1$ ):  $R_{rel} = R_i - R_1$ .

In all cases, measurement of radius is made at the end of the steering wheel ramp. The slip angle at the centre of gravity of the vehicle is used as an oversteer indicator. The wheel lift is used to assess roll stability.

The maturity of the stability-related protocols is regarded as rather high, which is underlined by the fact that very similar protocols are under discussion for implementation e.g. within the Euro NCAP organisation.

## DISCUSSION

Preliminary and final results of the technical development have been discussed with interested and renowned experts from inside and outside of the consortium at several occasions. This was in line with the very open approach the project partners have decided to follow right from the beginning of the project in order to allow an unhindered exchange with organisations and experts not directly involved in the project.

Assessment of active safety in the longitudinal direction is currently within the scope of several projects and initiatives. The corresponding protocols developed by the eVALUE partners are rather mature, but cannot go in as much detail as dedicated projects can. Reviewing experts however acknowledged the pioneering work that was done by eVALUE and was taken over in the meantime by consortia such as ASSESS [7] and vFSS, which are also striving for a worldwide harmonisation.

The protocols for evaluation and assessment of lateral safety are probably the least mature and major efforts need to be invested in the future to enhance them.

### Weaknesses and Open Issues

The eVALUE project followed the objective to develop testing and evaluation methods for active safety functions. However, during the early phase of the project, this objective was shifted towards testing methods that take the full vehicle rather than a specific function or system into account. Being one of the first projects active in this regard and with this intention, experiences were made that disclosed issues of high relevance for the development of vehicle active safety assessment methods but could not be covered by the project. The partners then decided to follow a straight forward approach based on data which was available at the time. However, good science requires pointing out those open issues, allowing them to be addressed at a later stage by different initiatives and, thus, allowing the improvement of the presented results.

In accordance with the above given weaknesses, future research is needed in order to finalise the testing protocols and allow an application for real assessment purposes. This includes a fully comprehensive accident database that is freely available for both the development of new and enhanced safety functions on the road towards the vision of halving the number of road fatalities until 2020 [8] as well as for the derivation of the most relevant traffic scenarios with respect to active safety functions and the impact they have on real life safety on our roads.

Furthermore, standardised driver reactions need to be investigated and later-on implemented into driving robots. This would then allow taking the driver reaction into account and thus fully assess the safety performance of a vehicle. An investigation of statistical effects on performance results and, related to this, an open discussion within the research community whether only one trial per test can be acceptable need to take place as well. This would re-quire a large number of tests at different locations as a test programme cannot only be performed at the same location (cf. the different certified test laboratories for passive safety testing) and under the exact same conditions (e.g. weather due to the required space and testing outdoors).

These research topics are of common interest for all involved stakeholders and can thus be addressed in joint consortia in order to avoid duplication of work and waste of resources.

## CONCLUSIONS

For the performance assessment of automotive active safety functions, still no generally accepted standards are available today. Manufacturers of systems, components or vehicles all developed and use their own testing procedures in order to provide both development goals and means to evaluate the system performance.

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 still have no means to assess their systems in a generally accepted way.

The eVALUE project now offers testing protocols for vehicle active safety that can found the basis for either implementation or more detailed specification, depending on the level of definition. The scenario-based approach taking the full vehicle rather than a specific system into account is today generally supported. While the methods for stability-related testing are regarded as mature, testing of longitudinal and lateral safety function requires more research.

This is also necessary in order to reach accepted methods and protocols among all stakeholders fostering the perception and understanding of the active safety performance of a specific vehicle.

Communication with and amongst stakeholders that might be involved in a later standardisation process has been established and will remain in the future, e.g. in the future workshops to be organised by the support action ActiveTest [9].

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## NOTE

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# RCS-TUG STUDY: BENEFIT POTENTIAL INVESTIGATION OF TRAFFIC SAFETY SYSTEMS WITH RESPECT TO DIFFERENT VEHICLE CATEGORIES

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## ABSTRACT

The multiplicity of accident causation has led to development of various traffic safety systems for collision avoidance or reduction. Since the customer will not purchase all these systems, a question of prioritization of these systems for the manufacturers as well as authorities arises.

In previous papers a method was described which investigated the benefit potential of 43 different systems. The in-depth accident database ZEDATU which includes fatal accidents in Austria was used to select a sub-sample of accidents. For those, the pre-collision phase was reconstructed in detail with numerical accident reconstruction using PC-Crash. The efficiency of safety systems was calculated either by integration of intervening systems in the simulation (ESC, ABS, Brake Assist and Evasive Maneuver Assistant) or by subjective evaluation of the pre-collision situation. This study, called RCS-TUG study (Retrospective Case Study of the Graz University of Technology), exhibited the advantage that many different systems were analyzed in detail using the same sample with a comparatively high case number. This led to improved comparableness.

In another previous paper, the selected sample (n=217) of the database was weighted to achieve statistical representativeness, since single vehicle accidents were underrepresented. For each of the selected 43 systems, the potential for collision avoidance or reduction of severity was analyzed. The results were compared to findings in literature and the authors proposed a prioritization for traffic safety systems. The results indicated that especially systems effective in lateral vehicle dynamics (Evasive Maneuver Assistant, Lane Keeping Assist, ESC) offer significant potential to avoid fatal injuries, as well as autonomous Brake Assist, Collision Warning Systems and Driver Vigilance Monitoring.

The present study continues the analysis of the RCS-TUG study. The new analysis differentiates between the vehicle categories such as motorized two-wheelers, light trucks, passenger cars, trucks and busses with respect to the ego-vehicle. Additionally, the database was checked for errors.

The limitations of the study are the restriction to fatal accidents in the area of Austria. Additionally some systems are evaluated by subjective judgment of the authors.

## INTRODUCTION

The variety of causations of traffic accidents [1, 2] has led and will lead to development of many different countermeasures for traffic accidents, [3, 4]. Countermeasures for traffic accidents can operate on the primary/active (collision avoidance and collision severity mitigation), secondary/passive (reduction of injury risk) or tertiary (post-crash treatment) safety level of the involved traffic element: human, vehicle or environment. In [3] a brief overview of 161 different systems is provided; detailed descriptions of these traffic safety systems can be found in the literature, e.g. [5-7]. Many different studies [7-20] have been conducted to evaluate the safety potential of traffic safety systems. In the author's opinion, many of these studies face one or more of the following problems, [21]:

- Level of detail in statistical accident databases;
- Number and representativeness of in-depth accident databases;
- Comparability of potentials on different systems;

Therefore, the present study investigates many different traffic safety systems with the same methodology and the same database. As described above, methodology and the accident database are described in detail in [4, 22-24].

## METHODOLOGY

The RCS-TUG study is an ‘a priori’ benefit investigation method of the ‘case-by-case analysis within database’ type, see [25, 26]. It uses the ZEDATU database [27] which is an in-depth accident database with more than 950 cases and 763 database arrays per accident. It covers fatal traffic accidents of Austria. For the previous and the present evaluations 217 cases as a subsample of the year of 2003 were used. For these cases the pre-collision phase starting at the conflict point could be reconstructed in detail using numerical accident reconstruction software [28]. It was found that this subsample is statistically biased since single-vehicle accidents are underrepresented. The reason is that the examination of the accident scene was sometimes not sufficient for reconstruction of the pre-collision phase since the question of guilt was not always a primary target of the court. Therefore the subsample was weighted by comparing the proportion of the accident type of the subsample with all fatal accident of that year, [21]. With this corrected database, several conclusions for the benefit effectiveness could be drawn. The present paper extends these analyses.

## RESULTS

Figure 1 recapitulates previous findings of the RCS-TUG study, [21]. The safety potential is ranked according to the ‘avoidance’  $A_s$  of system  $S$ . Symbol  $A_s$  is the percentage of cases where the accident is prevented automatically by the system, thereby preventing the fatalities and reads

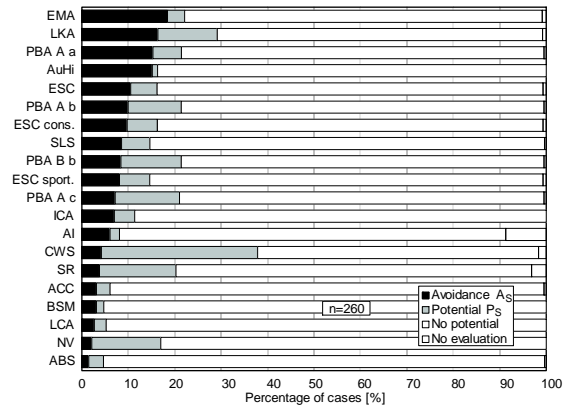
$$A_s = \frac{n_{A,S}}{n_S} \cdot 100 [\%] \quad , \quad (1).$$

with  $n_{A,S}$  the number of avoided accidents by safety system  $S$  and  $n_S$  the number of evaluated cases of safety system  $S$ .

Additionally the ‘potential’  $P_s$  was assessed, where a prevention of the fatality is possible but either the accident was not fully avoided or the potential depends on additional parameters such as a correct driver reaction upon warnings of the system. Potential  $P_s$  reads

$$P_s = \frac{n_{P,S}}{n_S} \cdot 100 [\%] \quad , \quad (2).$$

with  $n_{P,S}$  representing the number of collisions with possibly prevented fatalities by safety system  $S$  and  $n_S$  the number of evaluated cases of safety system  $S$ .



**Figure 1. Safety potentials of safety systems in weighted RCS-TUG, [21]**

For the meaning of the abbreviations in Figure 1 refer to Table 3 in the appendix. It can be seen that an Evasive Maneuver Assistant (EMA) provides the highest potential for system controlled accident avoidance, but the highest overall potential have Collision Warning Systems (CWS), when the driver reacts accordingly. The results of the first evaluation of the RCS-TUG study are explained in detail in [4, 21]. Especially the results are compared with other studies from literature. For the present evaluation, the database was reanalyzed.

### Influence of the Vehicle Category

The database was prepared to define the vehicle category of the ego-vehicle, which was typically the accident causer.

Accordingly, the analysis separated the Vehicle group ID 1: motorized two-wheelers; 3: cars; 4: light trucks; 5 and 10: trucks and busses see Table 1., [29, 30].

The related number of cases for each vehicle category  $n_V$  can be seen in Table 2. Obviously, the quality of the analysis is highest for passenger cars ( $n_V=164$ ), followed by the trucks/busses category ( $n_V=34$ ) and motorized two-wheelers ( $n_V=30$ ). For light trucks the number of cases is low ( $n_V=12$ ). Although the case number is high only in passenger cars, trends are analyzed and discussed in the following.

**Table 1.**  
**Vehicle categories in the ZEDATU database**

Body Style Code	Vehicle Group ID	BodyStyle
0	0	not applicable
1	1	Moped or Mofa under 50cc
2	1	Motorcycle under 125cc
3	1	Motorcycle over 125cc
4	1	Motorcycle with sidecar
5	1	Scooter
6	3	Hatchback
7	3	Saloon
8	3	Estate
9	3	Convertible
10	3	Sports car
11	3	Off-road
12	3	SUV
13	3	Derivative
14	3	Van - Multi-Purpose-Vehicle
15	4	Caravanette
16	4	Minibus
17	4	Microvan based pick-up
18	4	Dropside - large pick-up
19	4	Micro Van
20	4	Box Van
21	4	Crew cab
22	4	Dedicated
23	5	Rigid box
24	5	Rigid flat
25	5	Rigid tipper
26	5	Rigid curtain side
27	5	Rigid liquid - powder
28	5	Demountable
29	5	Dedicated truck
30	5	Articulated
31	5	Semitrailer
32	2	Trike
33	2	Three wheeled vehicle
34	6	Bicycle
35	11	Train
36	11	Tram
37	7	Tractor
38	10	Bus
88	8	other
99	99	Unknown

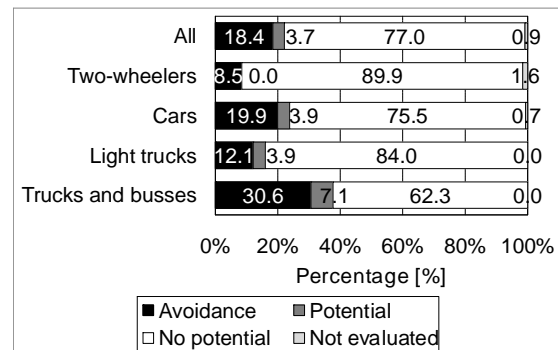
**Table 2.**  
**Number of cases  $n_V$  for each vehicle category**

Vehicle type	Number of cases $n_V$
All	260
Two-wheelers	30
Cars	164
Light trucks	12
Trucks and busses	34
Others	54

Not surprisingly, the highest benefit of all safety systems system is ‘Autonomous Driving’. Because of the difficult realization, the results are not presented and discussed. The following presentation of the results is in the same order than presented in [21].

### **Evasive Maneuver Assistant (EMA)**

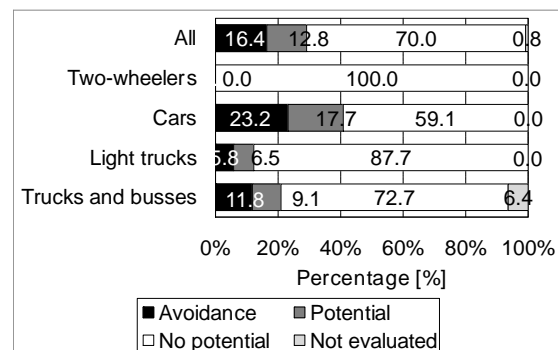
EMA systems have not been introduced into the market for technological and legal reasons. Yet research dealing with this topic is ongoing and previous benefit analyses have showed significant potentials [21].



**Figure 2. Influence of vehicle type on EMA**

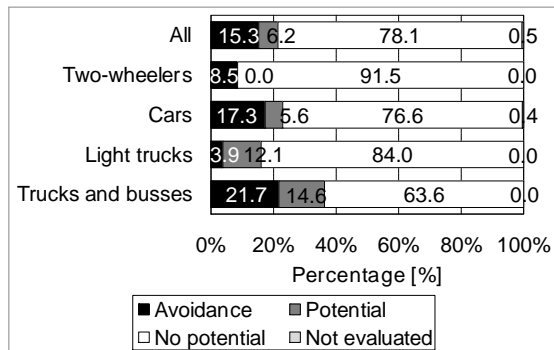
Figure 2 shows the influence of the vehicle category on the benefit of EMA. For trucks and busses, EMA tends to provide more potential than the other vehicle categories. The benefit for motorized two-wheelers is low. The same methodology as for doubled-tracked vehicles was applied [22], yet for two-wheelers such a system would be even more complicated than for double-tracked vehicles.

**Lane Keeping Assist (LKA)** Figure 3 shows the influence of the vehicle category on the safety benefit of Lane Keeping Assist. The benefit is significantly higher in cars than in trucks/busses, indicating the higher occurrence of lane departure of that vehicle category. Due to the system’s definition it is not feasible for two-wheelers.



**Figure 3. Influence of vehicle type on LKA**

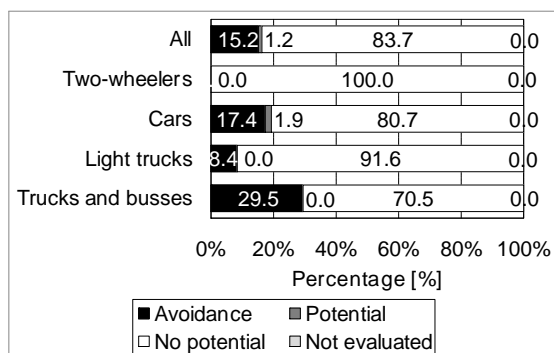
**Predictive Brake Assist (PBA)** Figure 4 shows the influence of the vehicle category on the safety benefit of PBA. For the analysis in the present paper the most efficient PBA system of the RCS-TUG analysis was chosen. This is a full braking action of the driver following a collision warning of the human-machine-interface with 0.8s reaction time; this equals an automated emergency braking 1.8s before an anticipated forward collision. In the RCS-Study this was system 'A' and driver behavior 'a', [4].



**Figure 4. Influence of vehicle type on PBA (System 'A' and driver reaction 'a')**

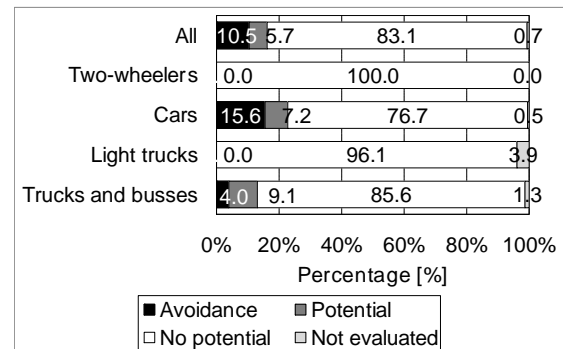
The potential of this considered PBA system is higher in trucks and busses than in the other categories. Note that even for two-wheelers some potential was found.

**Automated Driving on Highways (AuHi)** Figure 5 shows the influence of the vehicle category on the safety benefit of automated driving on highways. For trucks and busses this is significantly higher than in all other types of vehicles.



**Figure 5. Influence of vehicle type on AuHi**

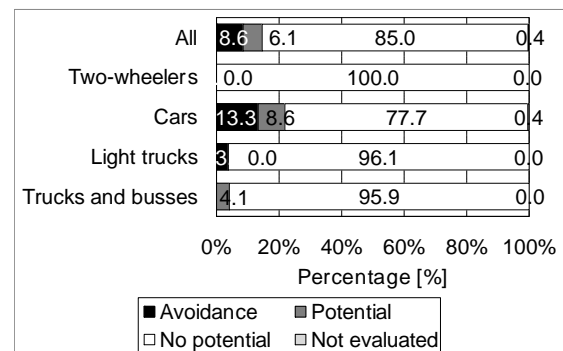
**Electronic Stability Control (ESC)** Figure 6 shows the influence of the vehicle category on the safety benefit of ESC. In this evaluation only a standard set-up of the ESC was analyzed. The influence of different intervention strategies (sportive, standard, conservative) as analyzed in [21] was not evaluated.



**Figure 6. Influence of vehicle type on ESC**

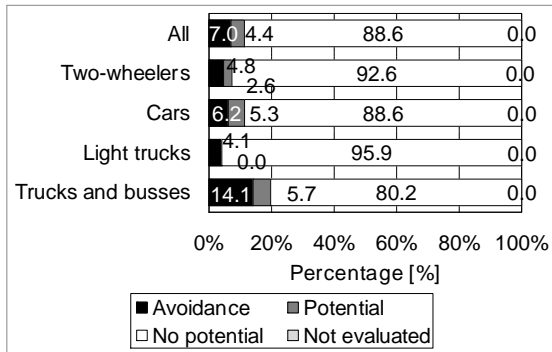
The benefit potential is significantly higher in passenger cars compared to trucks and busses, for two-wheelers this system is not feasible.

**Speed Limiting System (SLS)** Figure 7 shows the influence of the vehicle category on the safety benefit of speed limiting systems as analyzed in the RCS-TUG. Whereas for two-wheelers the system was not defined, a real benefit was only found in passenger cars.



**Figure 7. Influence of vehicle type on SLS**

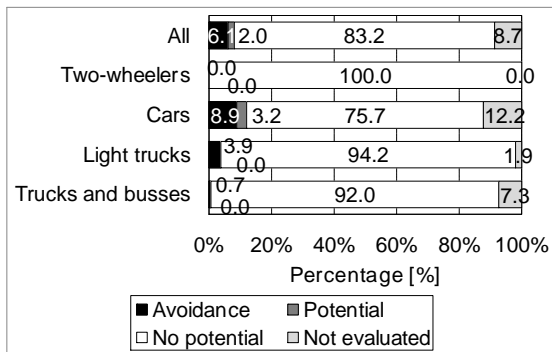
**Intersection Collision Assistant (ICA)** Figure 8 shows the influence of the vehicle category on the safety benefit of ICA systems.



**Figure 8. Influence of vehicle type on ICA**

The potential is more evenly distributed among the different types of vehicles, where the highest potential is in trucks and busses.

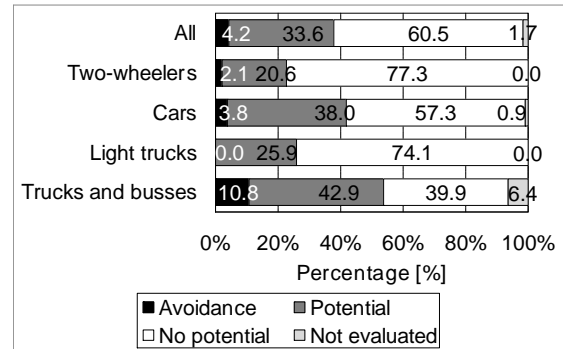
**Alcohol Interlock (AI)** Figure 9 shows the influence of the vehicle category on the safety benefit of alcohol interlock systems.



**Figure 9. Influence of vehicle type on AI**

The analysis reveals that in the used ZEDATU database drunk driving is mainly an issue of car drivers, whereas it could not be found in two wheelers and hardly in trucks and busses. For professional truck and bus drivers, the blood alcohol limit in Austria is zero, whereas for the others it is 0.5 %. However, note the comparably high number of not evaluated cases, where an expert statement on alcohol impairment of the driver was missing.

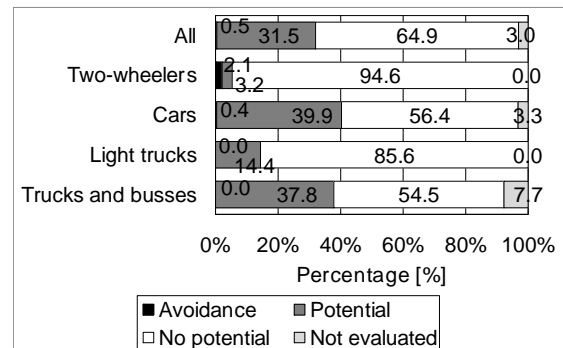
**Collision Warning Systems (CWS)** Figure 10 shows the influence of the vehicle category on the safety benefit of CWS systems.



**Figure 10. Influence of vehicle type on CWS**

Here the distribution is a bit more evenly, with a slight trend for higher potential in trucks and busses. Note that the majority of the cases are rated 'potential' since the driver has to react in a proper way to the warning of the human-machine-interface. In PBA systems a partially automated braking of the systems reverses these results of CWS systems.

**Driver Vigilance Monitoring (DVM)** Figure 11 shows the influence of the vehicle category on the safety benefit of DVM systems.



**Figure 11. Influence of vehicle type on DVM**

According to this study, vigilance is an issue which is same common for car and truck/bus drivers, while only small numbers in two-wheeler category were found.

**Further systems** Further systems with less potential can be found in the appendix where all investigated systems are presented, see Table 4.

### Prioritization

Table 4 in the appendix shows the proposal of a system ranking with respect to benefit potential. To overcome the issue of separate rating of avoided  $A_{S,V}$  and potentially  $P_{S,V}$  prevented fatalities a

weighting method was applied. For this purpose the weighting method given in (3) was applied:

$$W_{S,V} = \frac{A_{S,V} \cdot W_A + P_{S,V} \cdot W_P}{n_{S,V}} \cdot 100 [\%] \quad , \quad (3).$$

where  $W_{S,V}$  is the weighted benefit potential of system  $S$  in vehicle category  $V$ ;  $A_{S,V}$  the number of avoided collisions by system  $S$  in vehicle category  $V$ ;  $P_{S,V}$  the number of possibly avoided fatalities by system  $S$  in vehicle category  $V$ ;  $n_{S,V}$  the number of all cases of vehicle category  $V$  investigated for system  $S$ ;  $W_A=1.0$  and  $W_P=0.5$  weighting factors. Thereby the importance of definitely avoided collisions was rated double than compared to the possibly avoided fatalities. The choice of the weighting factor was done by judgment of the authors.

## DISCUSSION

Although the number of cases for the motorized two-wheelers and truck/bus drivers are significantly lower than for passenger car drivers some observations and trends can be discussed for these categories. For drivers of light trucks the numbers are too small. For the following discussion it has to be emphasized that systems that require driver interaction had been analyzed by subjective evaluation of the pre-collision phase which is a possible source of error. Automated driving is not discussed because of the difficult technological implementation.

### Two-wheelers

The beneficial potential of Advanced Driver Assistance Systems (ADAS) in two-wheelers is rather small compared to other vehicle categories. The most effective systems according to the present analysis are Collision Warning Systems, Evasive Maneuver Assistant, Predictive Brake Assist, Lane Change Assistant, Blind Spot Monitoring (see Table 4.) and Intersection Collision Assistant. The weighted potential  $W_{S,V}$  drops below 5% for further systems. Since a 100% fleet penetration and a 100% working system without failures was anticipated, the potential of these further systems is considered small.

### Cars

The most effective systems ranked by the weighted potential  $W_{S,V}$  and with  $W_{S,V}>10\%$  are: Lane Keeping Assist, Collision Warning Systems, Evasive Maneuver Assistant, Driver Vigilance Monitoring, Predictive Brake Assist, Electronic Stability Control, Automated Driving on Highways, Speed Limiting Systems, Seat Belt Reminder, Night Vision, Speed Recommendation and Alerts and Alcohol Interlock. The most effective systems

are rather lateral vehicle control related, compared to trucks and busses.

### Trucks and busses

For trucks a little bit different rating was observed. Ranked by the weighted potential  $W_{S,V}$  and with  $W_{S,V}>10\%$  they are: Evasive Maneuver Assistant, Collision Warning Systems, Automated Driving on Highways, Predictive Brake Assist, Driver Vigilance Monitoring, Automatic Cruise Control, Intersection Collision Assistant, Lane Keeping Assist and Blind Spot Monitoring. A more pronounced potential of longitudinal assistance compared to lateral assistance was observed, ESC is not present at the top ten systems for trucks.

### Light trucks

For light trucks the small number of cases does not allow discussions for reasons of statistical significance.

## SUMMARY

Previous researches on the benefit of traffic safety systems for prevention of fatalities in road accidents were continued using the RCS-TUG analysis approach. These studies are based on the ZEDATU database which covers fatal accidents in Austria. A total of 260 cases in the year of 2003 were analyzed for benefit of 43 different systems for prevention of fatalities. The special characteristics of the RCS-TUG study are the in-depth investigations of the pre-collision phase using a database with a comparatively high case number. The present investigation focused on differences on the benefit of traffic safety systems within the vehicle categories motorized two-wheelers, light trucks, passenger cars, trucks and busses. The investigation showed that a comparatively low benefit for two-wheelers is to be expected. For light trucks the number of cases was too small to draw conclusions. For cars, the analysis showed that a trend exists that Advanced Driver Assistance Systems for lateral vehicle control is more beneficial compared to trucks and busses where the benefit of systems of longitudinal vehicle control support is higher.

The authors emphasize that it is not intended to remove well established systems such as ABS from the vehicle because of less observed benefit, since this could increase cases that have been already prevented by penetration into the vehicle fleet. The study is intended to support decisions for introduction of systems especially in all vehicle segments and to prioritize systems in terms of introduction to the market.



## OUTLOOK

Further investigations will deal with combinations of traffic safety systems, reflecting vehicles which are equipped with more than one system. Also the fatality risk will be investigated in more detail by application of injury risk functions to the cases where the ADAS have decreased collision severity but not prevented the fatality.

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APPENDIX

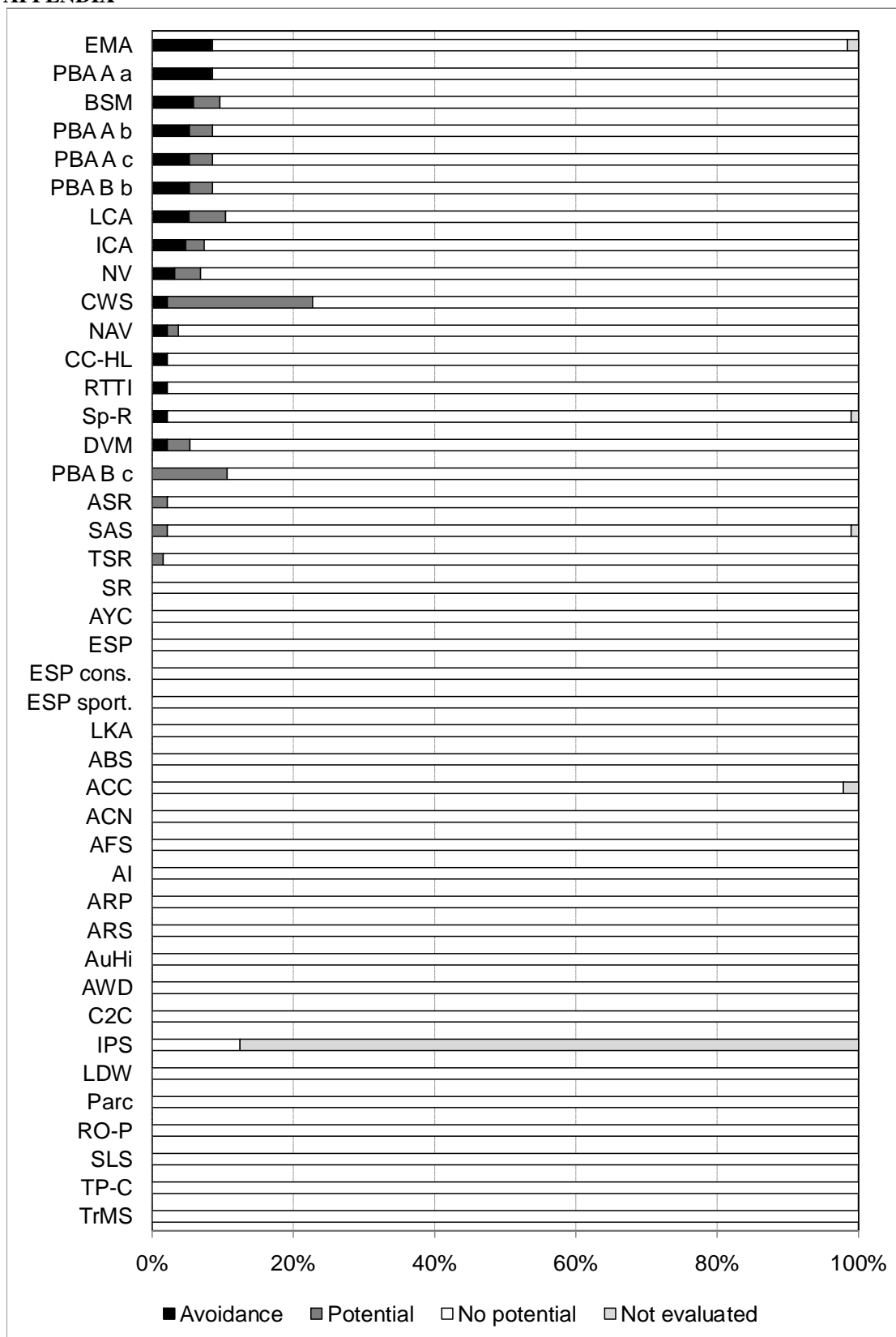


Figure 12: Percentage of Avoidance  $A_{S,V}$  and Potential  $P_{S,V}$  for vehicle category ‘two-wheelers’

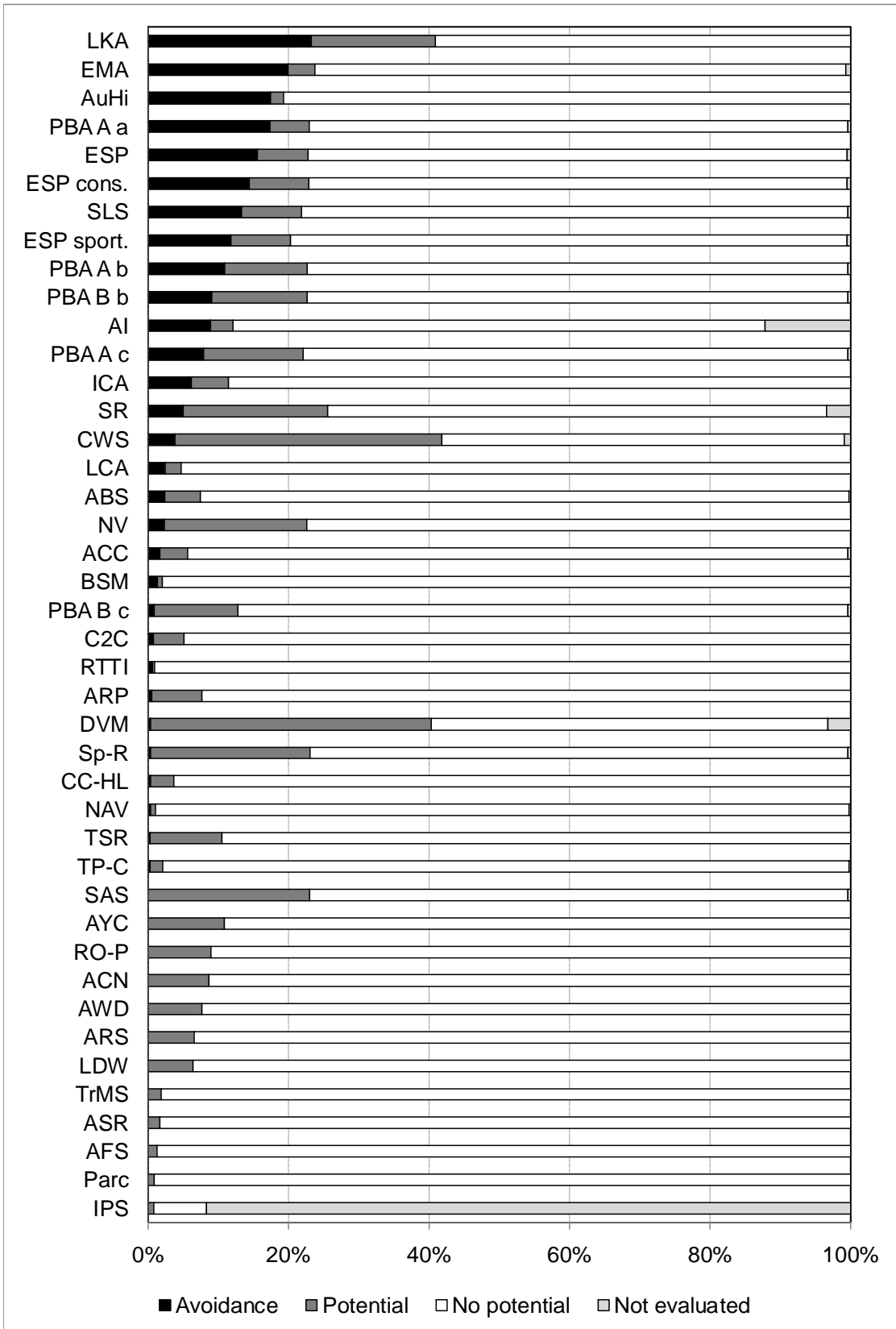


Figure 13: Percentage of Avoidance  $A_{s,v}$  and Potential  $P_{s,v}$  for vehicle category 'cars'

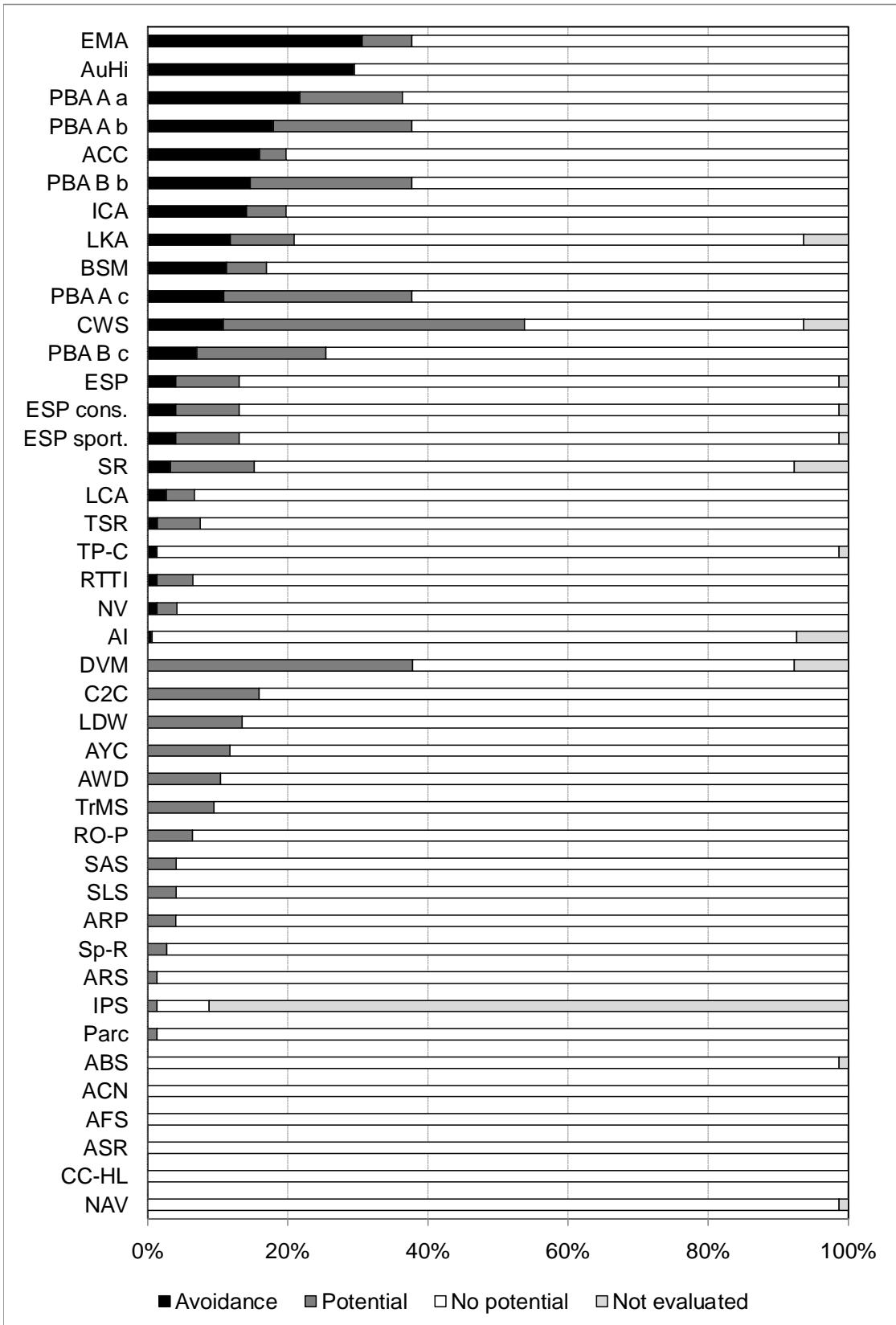


Figure 14: Percentage of Avoidance  $A_{s,v}$  and Potential  $P_{s,v}$  for vehicle category ‘trucks and busses’

**Table 3.**  
**Investigated traffic safety systems in RCS-TUG**

Abbr.	Description
ABS	Anti-Lock Braking System
ACC	Adaptive Cruise Control
ACN	Automatic Crash Notification
AFS	Active Front Steering
AI	Alcohol Detection and Interlock
ARP	Active Rollover Protection
ARS	Active Rear Steering
ASR	Anti-Slip Regulation
AuDr	Autonomous Driving
AuHi	Automated Highway
AWD	All Wheel Drive
AYC	Active Yaw Control
BSM	Blind Spot Monitoring
C2C	Inter-Vehicle Communication Systems
CC-HL	Cornering/Axis Controlled Headlights
CWS	Collision Warning
DVM	Driver Vigilance Monitoring
EMA	Evasive Maneuver Assistant
ESP	Electronic Stability Program
ESP cons.	ESP conservative
ESP sport.	ESP sportive
ICA	Intersection Collision Avoidance
IPS	Intelligent Crash Protection
LCA	Lane Changing Assistant
LDW	Local Danger Warning
LKA	Lane Keeping Assist
NAV	Navigation Systems
NV	Night Vision
Parc	Parctronic
PBA A a	Predictive Brake Assist, intervention strategy A, driver reaction a
PBA A b	Predictive Brake Assist, intervention strategy A, driver reaction b
PBA A c	Predictive Brake Assist, intervention strategy A, driver reaction c
PBA B b	Predictive Brake Assist, intervention strategy B, driver reaction b
PBA B c	Predictive Brake Assist, intervention strategy B, driver reaction c
RO-P	Rollover Protection
RTTI	Real Time Traffic Information
SAS	Speed Alerting System
SLS	Speed Limiting System
Sp-R	Speed Recommendation
SR	Seatbelt Reminder and Buckle Sensor
TP-C	Tire Pressure Control
TrMS	Traffic Management System
TSR	Traffic Sign Recognition and Alert

**Table 4.**  
**Weighted Potential  $W_{s,v}$  for different vehicle categories**

Ranking	All vehicles	Weighted potential [%]	Two-wheelers	Weighted potential [%]	Cars	Weighted potential [%]	Trucks and busses	Weighted potential [%]
1	LKA	23	CWS	12	LKA	32	EMA	34
2	CWS	21	EMA	9	CWS	23	CWS	32
3	EMA	20	PBA A a	9	EMA	22	AuHi	29
4	PBA A a	18	LCA	8	DVM	20	PBA A a	29
5	DVM	16	BSM	8	PBA A a	20	PBA A b	28
6	AuHi	16	PBA A b	7	ESP	19	PBA B b	26
7	PBA A b	16	PBA A c	7	ESP cons.	19	PBA A c	24
8	PBA B b	15	PBA B b	7	AuHi	18	DVM	19
9	PBA A c	14	ICA	6	SLS	18	ACC	18
10	ESP	13	PBA B c	5	PBA A b	17	ICA	17
11	ESP cons.	13	NV	5	ESP sport.	16	LKA	16
12	SR	12	DVM	4	PBA B b	16	PBA B c	16
13	SLS	12	NAV	3	SR	15	BSM	14
14	ESP sport.	11	CC-HL	2	PBA A c	15	SR	9
15	NV	10	RTTI	2	NV	12	ESP	9
16	ICA	9	Sp-R	2	Sp-R	12	ESP cons.	9
17	Sp-R	8	SR	2	SAS	12	ESP sport.	9
18	SAS	8	ESP	2	AI	10	C2C	8
19	PBA B c	7	ESP cons.	2	ICA	9	LDW	7
20	AI	7	ESP sport.	2	PBA B c	7	AYC	6
21	ACC	5	ASR	1	AYC	5	AWD	5
22	TSR	4	SAS	1	TSR	5	TrMS	5
23	AYC	4	TSR	1	ABS	5	LCA	5
24	LCA	4	AYC	1	RO-P	4	TSR	4
25	BSM	4	LKA	1	ACN	4	RTTI	4
26	RO-P	3	ABS	0	ARP	4	RO-P	3
27	C2C	3	ACC	0	AWD	4	NV	3
28	ABS	3	ACN	0	ACC	4	SAS	2
29	AWD	3	AFS	0	LCA	4	SLS	2
30	LDW	3	AI	0	ARS	3	ARP	2
31	ARP	3	ARP	0	LDW	3	Sp-R	1
32	ACN	3	ARS	0	C2C	3	TP-C	1
33	ARS	2	AuHi	0	CC-HL	2	AI	1
34	CC-HL	2	AWD	0	BSM	2	ARS	1
35	TrMS	1	C2C	0	TP-C	1	IPS	1
36	RTTI	1	IPS	0	TrMS	1	Parc	1
37	TP-C	1	LDW	0	ASR	1	ABS	0
38	NAV	1	Parc	0	RTTI	1	ACN	0
39	ASR	1	RO-P	0	NAV	1	AFS	0
40	AFS	0	SLS	0	AFS	1	ASR	0
41	Parc	0	TP-C	0	Parc	0	CC-HL	0
42	IPS	0	TrMS	0	IPS	0	NAV	0

# Safety Impact of an Integrated Crash Warning System Based on Field Test Data

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## ABSTRACT

This paper provides the results of an analysis conducted to assess the safety impact of an integrated vehicle-based crash warning system based on naturalistic driving data collected from a field operational test. The system incorporates four functions that warn the driver of an imminent rear-end crash, excessive speed to an upcoming curve, lane-change crash, or unintentional lane departure. The safety impact is assessed in terms of observed changes in driving behavior, exposure to driving conflicts, near-crash experience, and projected potential reductions in the number of annual target crashes. Unintended consequences are examined by analyzing driver engagement in secondary tasks and eyes-off-the-forward-scene behavior. A total of 108 subjects, split by gender and three age groups, participated in the field test by driving in an unrestricted manner for a period of six weeks each. In the first two weeks, designated as the baseline period, the subjects performed their naturalistic driving with the system turned off while the data acquisition system collected their performance data. In the last four weeks, designated as the treatment period, the system was turned on and provided the subjects with visual, auditory, and haptic crash warning signals. This paper discusses the safety impact of the system for individual subject groups based on gender and age. The integrated system has the potential to reduce the number of rear-end, opposite-direction, lane-change, and road-departure crashes involving at least one passenger car. Moreover, the system did not influence drivers to engage in more secondary tasks.

## INTRODUCTION

An integrated vehicle-based crash warning system was developed and tested under the Integrated Vehicle-Based Safety System (IVBSS) initiative of the United States Department of Transportation's (U.S. DOT) Intelligent Transportation System program [1]. The system was designed to address

rear-end, curve-speed, lane-change, and roadway departure crashes for light vehicles that encompass passenger cars, vans and minivans, sport utility vehicles, and light pickup trucks with gross vehicle weight ratings less than or equal to 4,536 kg. The IVBSS initiative was launched in November 2005 as a two-phase, multi-year cooperative research effort between the U.S. DOT and an industry team led by the University of Michigan Transportation Research Institute and supported by Visteon, Takata, and Honda. In the first phase, the team designed, built, and verified through a series of track and public road tests that the integrated safety system prototype met the performance requirements and was safe for use by unescorted volunteer drivers during a planned field operational test. In the second phase, the team devised the field test concept, built a vehicle fleet of 16 passenger cars, and conducted the field test using 108 participants who drove the IVBSS-equipped cars as their own personal vehicle for 6 weeks each.

The Volpe National Transportation Systems Center of the U.S. DOT's Research and Innovative Technology Administration performed an independent evaluation to assess the safety impact, gauge driver acceptance, and characterize the capability of the integrated crash warning system. This paper focuses on the safety impact assessment of this independent evaluation.

## System Description

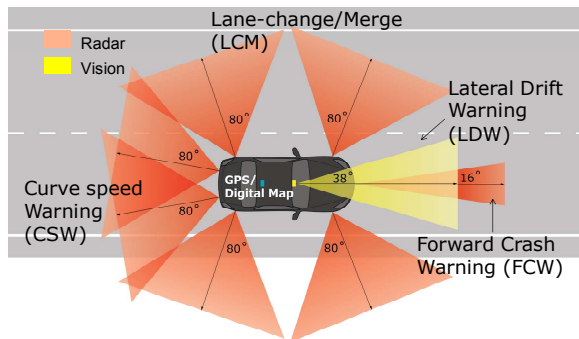
The integrated safety system assists drivers in avoiding or reducing the severity of crashes by providing the following four crash warning functions [2]:

- Forward crash warning (FCW)
- Curve-speed warning (CSW)
- Lane-change/merge (LCM) warning
- Lane-departure warning (LDW)
  - LDW cautionary (LDW-C): refers to alerts issued when the vehicle drifts out



- of its lane into a clear area (unoccupied lane or clear shoulder).
- LDW imminent (LDW-I): refers to alerts issued when the vehicle drifts into an occupied lane or towards a roadside object, causing potential for a collision.

Using radar and vision-based sensors, the integrated system addresses crashes in which an equipped vehicle strikes the rear end of another vehicle (FCW), approaches a curve at excessive speed (CSW), changes lanes or merges into traffic and collides with another same-direction vehicle (LCM), and unintentionally drifts off the road edge or crosses a lane boundary (LDW). Figure 1 illustrates the field of view for the various sensors of the integrated system.



**Figure 1. Integrated system sensor coverage**

System alerts are communicated to the driver through a combination of auditory, haptic, and visual warnings. Figure 2 shows the visual elements of the driver interface and system controls. The visual elements include a center display and blind spot monitoring lights in the side rear-view mirrors. System controls consist of a three-position volume switch and a mute button that temporarily silences the alerts for a two-minute period. Auditory alerts are issued through speakers in the dashboard (FCW and CSW) and each side of the driver's headrest (LCM and LDW-I). Haptic alerts are transmitted through vibrations on each side of the driver's seat (LDW-C) and a brake pedal pulse (FCW).

### Description of Field Operational Test

The field operational test employed 108 subjects from southeast Michigan who drove 16 IVBSS-equipped 2006 and 2007 Honda Accords. While an Accord was used as the prototype test vehicle, the research conducted in this field test applies to all light vehicles. Subjects were balanced for gender and age, including younger (20-30 years old), middle-aged (40-50 years old), and older (60-70 years old) groups.



**Figure 2. Driver-vehicle interface of the integrated system**

Throughout their participation in the field test, the subjects drove the instrumented vehicle in an unrestricted manner.

The field test started in April 2009 and ended in early May 2010. A within-subject experimental design was implemented where each subject experienced two test conditions over a period of 40 days. During the first condition, called the baseline period, subjects drove the instrumented vehicle for about 12 days with the integrated safety system turned off. In the second condition, treatment period, subjects drove the vehicle for about 28 days with the integrated safety system enabled. Even though the system alerts were disabled during the baseline period, the on-board data acquisition system recorded all data and alerts. All analyses were conducted within subjects.

Throughout the course of the field test, drivers accumulated over 213,000 miles (343,000 km) of driving – 32% during the baseline period and 68% during the treatment period. The number of alerts issued per 100 miles (161 km) in the baseline period ranged from 1.5 to 53.6, with an average of 14.0 alerts per 100 miles. Alert rates decreased during the treatment period. The driver with the lowest alert rate during the treatment period received 1.7 alerts per 100 miles and the driver with the highest alert rate received 28.8 alerts per 100 miles. The average alert rate across drivers during the treatment period was 8.3 per 100 miles. About 84% of all alerts issued during the field test were cautionary drift alerts.

## TARGET CRASHES

The integrated safety system was designed to address the pre-crash scenarios listed in Table 1. Pre-crash scenarios identify vehicle movements and the critical event immediately prior to a crash [3]. Based on crash statistics from the 2004-2008 National Automotive Sampling System General Estimates System (GES) crash databases, light vehicles were involved in crashes preceded by these 9 pre-crash scenarios at an average annual frequency of about 2,674,000 police-reported crashes in the United States.

**Table 1. Annual frequency of target crashes by pre-crash scenario**

Pre-Crash Scenario	Crashes	% Crashes
Rear-end/lead vehicle stopped	907,000	33.9%
Rear-end/lead vehicle decelerating	378,000	14.1%
Road edge departure/no maneuver	371,000	13.9%
Changing lanes/same direction	311,000	11.6%
Turning/same direction	195,000	7.3%
Negotiating a curve/lost control	181,000	6.8%
Rear-end/lead vehicle moving	177,000	6.6%
Opposite direction/no maneuver	103,000	3.9%
Drifting/same direction	51,000	1.9%
Total	2,674,000	100.0%

Each pre-crash scenario listed in Table 1 is described below:

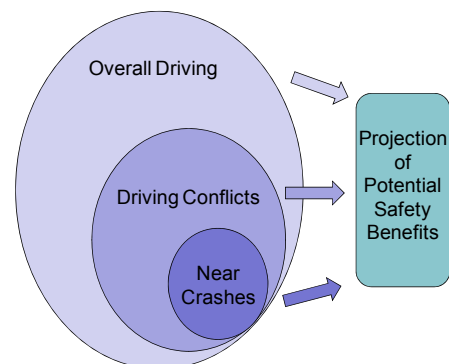
- Rear-end/lead vehicle stopped: driver is going straight and then closes in on a stopped lead vehicle. In some of these crashes, the lead vehicle first decelerates to a stop and is then struck by the following vehicle, which typically happens in the presence of a traffic-control device or when the lead vehicle is slowing down to turn.
- Rear-end/lead vehicle decelerating: driver is going straight while following another lead vehicle and then the lead vehicle suddenly decelerates.
- Road-edge departure/no maneuver: vehicle is going straight or negotiating a curve and then departs the edge of the road at a non-junction area. Vehicle was not making any maneuver such as passing, parking, turning, changing lanes, merging, or a prior corrective action in response to a previous critical event.
- Changing lanes/same direction: driver is changing lanes, passing, or merging and then

encroaches into another vehicle traveling in the same direction.

- Turning/same direction: driver is turning left or right at a junction and then cuts across the path of another vehicle initially going straight in the same direction.
- Negotiating a curve/lost control: driver is negotiating a curve and loses control of the vehicle.
- Rear-end/lead vehicle moving: driver is going straight or decelerating and then closes in on a lead vehicle moving at a slower constant speed.
- Opposite direction/no maneuver: vehicle is going straight or negotiating a curve and then drifts and encroaches into the lane of another vehicle traveling in the opposite direction.
- Drifting/same direction: driver is going straight or negotiating a curve and then drifts into an adjacent vehicle traveling in the same direction.

## SAFETY IMPACT ASSESSMENT METHODOLOGY

Safety impact is assessed in terms of changes in drivers' behavior when the system was enabled, and the potential of the system to reduce the number of target crashes. Figure 3 illustrates the analysis framework used to assess the safety impact. This framework divides the driving experience of test subjects into three areas: overall experience, driving conflicts, and near crashes. Overall driving data include all field test exposure. Driving conflict data are comprised of high-risk driving scenarios in which a crash would occur if the driver did not intervene. Near crashes constitute a small subset of longitudinal and lateral driving conflicts in which an intense driver response was observed.



**Figure 3. Safety benefits framework**

## Overall Driving

To determine changes in overall driving, both driver performance and driver attention were analyzed. Driver performance was assessed by comparing overall driving data from the baseline and treatment periods. The following measures were used to define driver performance:

- Travel speed
- Time headway
- Number of lane changes per 100 miles driven
- Proportion of signaled lane changes
- Number of lane excursions per 100 miles driven
- Duration of lane excursions
- Speed at curve entry

Driver attention to the driving task was analyzed through video analysis of driver behavior during the 10 seconds leading up to about 17,000 system alerts. Driver behavior leading up to alerts that occurred during the baseline period (muted to the driver but recorded by the system) was compared to behavior leading up to alerts during the treatment period. The following measures were used to define driver attention:

- Frequency of secondary tasks
- Frequency of eyes off forward scene

## Driving Conflicts

The analysis of driving conflicts focused on driver encounter and response to various dynamically distinct driving situations that correspond to the pre-crash scenarios listed in Table 1. These driving scenarios were extracted from the field test data through the application of data mining algorithms that took into account the location and vehicle dynamics of the IVBSS-equipped vehicle, the relative location and dynamics of surrounding vehicles and objects, and the geometry of the roadway. The algorithms differentiated between four different types of conflicts:

- Rear-end: host vehicle approaches a lead vehicle that is stopped, decelerating, or moving a slower, constant speed.
- Lane-change: host vehicle makes a lane change or drifts into an adjacent lane and encounters another vehicle.
- Road-departure: host vehicle departs the roadway.

- Curve-speed: host vehicle approaches a curve with excessive speed.

The data mining algorithms extracted 20,839 driving conflicts or 10.2 conflicts per 100 miles from the field test data.

## Near Crashes

The analysis of near crashes addressed driving conflicts of each type that resulted in a driver response above a certain intensity level. Thus, near crashes constitute a subset of longitudinal and lateral driving conflicts in which an intense driver response was observed during the field test data based on various kinematic measures. Near-crash thresholds were determined using distributions of intensity measures recorded in the field test [4]. By applying the near-crash criteria shown in Appendix A, the query of the processed numerical database extracted 1,946 potential near crashes from the field test data. A video analysis was conducted for each near crash to determine whether a valid threat was actually present in the driving scenario. As a result, a total of 1,810 near crashes or about 93% contained a valid threat. The analysis compared the experience with valid near crashes between the baseline and treatment periods.

Two-tail paired *t*-tests were performed for all safety impact analyses that compared data between the baseline and treatment periods. A paired *t*-test is used to determine if there is a statistically significant difference between the means of the same subjects under different circumstances. A two-tailed test is used when the mean under the treatment condition could be either greater than or less than the mean during baseline. For all these *t*-tests, a *p* value of 0.05 or 95% confidence level was used to claim statistical significance in observed differences.

## Projection of Potential Safety Benefits

The system's potential to reduce the number of target crashes is ideally measured from actual crash data. However, only three crashes occurred during the field test. Thus, this analysis estimates potential safety benefits of the integrated system using driver experience with near crashes observed during the field operational test. The exposure to near crashes in the baseline and treatment periods provides a suitable, surrogate measure to estimate the potential safety benefits because it captures the frequency and severity of driving conflicts encountered during the field test. Equation (1) estimates the effectiveness of

each system function for each driver based on driver exposure to near crashes with and without the assistance of the integrated system [5]:

$$E(S_i) = 1 - \text{PNC}_w(S_i)/\text{PNC}_{wo}(S_i) \quad (1)$$

$\text{PNC}_w(S_i) \equiv$  Near crash rate of type  $S_i$  in treatment  
 $\text{PNC}_{wo}(S_i) \equiv$  Near crash rate of type  $S_i$  in baseline

To project the annual reduction in the number of target crashes, effectiveness estimates of system functions were applied to the corresponding number of annual crashes for each pre-crash scenario listed in Table 1 [6].

## RESULTS

This section presents results related to overall driving, driving conflicts, near crashes, and the projection of potential safety benefits.

### Overall Driving

When driving with the integrated system, drivers showed changes in time headway, turn signal usage, frequency of lane departures, and duration of lane departures. Drivers did not show significant differences in travel speed, frequency of lane changes, speed at curve entry, or attention to the driving task.

Drivers showed a small decrease in time headway when driving over 25 mph (40 km/h) on non-freeway roads with the system enabled. Drivers did not show a significant change when driving on freeways. Table 2 shows the results of the paired  $t$ -test, where  $n$  represents the number of drivers in the test and a bold  $p$  value indicates significant results.

**Table 2. Paired  $t$ -test results of mean headway in second**

	Road Type	
	Freeway	Non-Freeway
Baseline	1.41	2.05
Treatment	1.37	1.98
$p$	0.16	<b>0.00</b>
$n$	108	108

Drivers showed a significant increase in the proportion of lane changes in which they used their turn signal overall, and for each age and gender group. Overall, drivers used their turn signal during

62% of lane changes in the baseline and 75% of lane changes during the treatment, indicating that driving with the integrated system encourages drivers to use their turn signal. These results are shown in Table 3. Drivers increased turn signal use on both freeway and non-freeway roads.

**Table 3. Paired  $t$ -test results of percent of signaled lane changes**

	Overall	Gender		Age (years)		
		Male	Female	20-30	40-50	60-70
Baseline	62%	56%	69%	67%	60%	61%
Treatment	75%	72%	78%	78%	76%	72%
$p$	<b>0.00</b>	<b>0.00</b>	<b>0.00</b>	<b>0.00</b>	<b>0.00</b>	<b>0.00</b>
$n$	108	54	54	36	36	36

Drivers showed an overall 21% decrease in the rate of lane excursions when driving with the integrated system. As shown in Table 4, results were significant for each age and gender group, indicating that drivers maintained better lane positioning when driving with the integrated system. While the rate of lane excursions was much higher during freeway driving than non-freeway driving (55.9 per 100 miles compared to 20.6 per 100 miles), drivers showed a larger reduction in the rate of lane excursions on non-freeway roads (25% compared to 20%).

**Table 4. Paired  $t$ -test results of lane excursions per 100 miles**

	Overall	Gender		Age (years)		
		Male	Female	20-30	40-50	60-70
Baseline	38.7	37.1	40.3	41.1	40.4	34.5
Treatment	30.6	29.2	32.0	33.2	29.6	29.0
$p$	<b>0.00</b>	<b>0.00</b>	<b>0.00</b>	<b>0.00</b>	<b>0.00</b>	<b>0.01</b>
$n$	108	54	54	36	36	36

In addition to experiencing fewer lane excursions with the system enabled, the duration of the lane excursions that occurred were an average of 3% shorter with the system enabled, suggesting that drivers were returning to their travel lane more quickly. Results were significant overall, and for males and middle-aged drivers, as shown in Table 5.

**Table 5. Paired *t*-test results of lane excursion duration in seconds**

	Overall	Gender		Age (years)		
		Male	Female	20-30	40-50	60-70
Baseline	2.72	2.70	2.74	2.72	2.72	2.72
Treatment	2.64	2.59	2.69	2.70	2.56	2.65
<i>p</i>	<b>0.03</b>	<b>0.02</b>	0.38	0.61	<b>0.01</b>	0.44
<i>n</i>	108	54	54	36	36	36

In the video analysis of alert scenarios, two measures pertaining to driver attention were recorded: presence of secondary tasks within 10 seconds before a system alert was issued, and whether or not drivers had their eyes off the forward scene for over 1.5 continuous seconds within the 5 seconds before an alert. Secondary tasks include behaviors exhibited by the driver that do not support the driving task and could be potentially distracting. These measures describe how attentive drivers are to the driving task with and without the integrated system.

The most frequent secondary tasks engaged in by the drivers in alert scenarios included talking to or looking at passengers (19% of all alerts), grooming (8% of alerts), talking on cellular phones (7% of alerts), and looking outside the car (6% of alerts). Secondary task engagement ranged from 17% of alerts for a middle-aged female driver to 87% of alerts for a younger female driver.

Table 6 shows the percent of alerts in which drivers were engaged in secondary tasks overall, and by age group and gender. Overall, drivers were engaged in secondary tasks during 52% of the alerts issued during the baseline period and 54% of the alerts issued during the treatment period. Younger drivers were engaged in secondary tasks more frequently than older and middle-aged drivers. The change in secondary task engagement was not significant overall, or for any of the age or gender groups.

**Table 6. Paired *t*-test results of percent of analyzed alerts with secondary tasks**

	Overall	Gender		Age (years)		
		Male	Female	20-30	40-50	60-70
Baseline	52%	54%	51%	60%	50%	46%
Treatment	54%	54%	53%	60%	52%	49%
<i>p</i>	0.28	0.83	0.20	0.89	0.41	0.27
<i>n</i>	107	54	53	36	35	36

Similar to the results of secondary task engagement,

there were no significant differences in driver's eyes-off-forward-scene behavior leading up to an alert between the baseline and treatment periods. Drivers had their eyes off the forward scene during 7% of the alerts during the baseline period, and during 6% of alerts in the treatment period. Table 7 shows the results broken down by age group and gender.

**Table 7. Paired *t*-test results of percent of analyzed alerts with eyes off forward scene**

	Overall	Gender		Age (years)		
		Male	Female	20-30	40-50	60-70
Baseline	7%	8%	6%	8%	7%	6%
Treatment	6%	7%	5%	8%	6%	5%
<i>p</i>	0.34	0.51	0.48	1.00	0.36	0.28
<i>n</i>	107	54	53	36	35	36

The results for driver attention indicate that drivers are no more likely to engage in secondary tasks or take their eyes off the road leading up to scenarios that trigger system alerts when the system is enabled. These findings suggest that the system does not impose unintended negative consequences on driver attention.

### Driving Conflicts

While there were no significant differences between the baseline and treatment periods in the overall rate of conflicts, results showed an overall decrease in the rate of conflicts at speeds over 55 mph (88.5 km/h). When broken down by conflict type, the data revealed a decrease in the rate of lane-change and road-departure conflicts on curved roads. Additionally, results showed a reduction in the duration of road-departure conflicts on straight roads. These results indicate that drivers got into fewer lateral potential crash situations when driving with the integrated system.

### Near Crashes

Driver involvement in valid near crashes was analyzed using the exposure measure of the number of near-crash encounters per 1,000 miles traveled. This analysis included only the drivers who were exposed to near crashes in both the baseline and treatment periods. Data were broken down by near-crash type, gender, age group, and road type.

Table 8 shows the results of the paired *t*-tests comparing the rate of all near crashes between the baseline and treatment periods. For all near-crash

types combined, only younger drivers showed a significant change in the rate of near crashes (a 19% reduction).

**Table 8. Paired *t*-test results of average number of near crashes per 1,000 miles**

	Overall	Gender		Age (years)		
		Male	Female	20-30	40-50	60-70
Baseline	9.64	10.64	8.31	12.20	9.24	7.06
Treatment	9.19	10.00	8.10	9.84	9.82	7.74
<i>p</i>	0.45	0.42	0.82	<b>0.05</b>	0.57	0.44
<i>n</i>	91	52	39	33	30	28

When broken down by near-crash type, results showed an overall decrease in the rate of lane-change and road-departure near crashes. No significant changes were observed in the rate of rear-end or curve-speed near crashes.

Tables 9 and 10 show the results for lane-change and road-departure near crashes, respectively. Drivers experienced an overall 33% reduction in the rate of lane-change near crashes and an overall 19% reduction in road-departure near crashes. Males experienced a significant reduction in lane-change near crashes, females experienced a significant reduction in road-departure near crashes, and younger drivers experienced a significant reduction in both types of near crashes.

**Table 9. Paired *t*-test results of average number of lane-change near crashes per 1,000 miles**

	Overall	Gender		Age (years)		
		Male	Female	20-30	40-50	60-70
Baseline	2.12	1.72	2.73	2.63	1.92	1.55
Treatment	1.43	1.08	1.93	1.48	0.95	1.79
<i>p</i>	<b>0.02</b>	<b>0.03</b>	0.20	<b>0.02</b>	0.06	0.58
<i>n</i>	37	22	15	16	10	11

**Table 10. Paired *t*-test results of average number of road-departure near crashes per 1,000 miles**

	Overall	Gender		Age (years)		
		Male	Female	20-30	40-50	60-70
Baseline	5.40	5.45	5.34	6.19	5.12	4.77
Treatment	4.38	4.62	4.05	3.99	5.02	4.19
<i>p</i>	<b>0.00</b>	0.08	<b>0.03</b>	<b>0.00</b>	0.87	0.33
<i>n</i>	74	43	31	27	24	23

Table 11 shows the results of the road-departure near

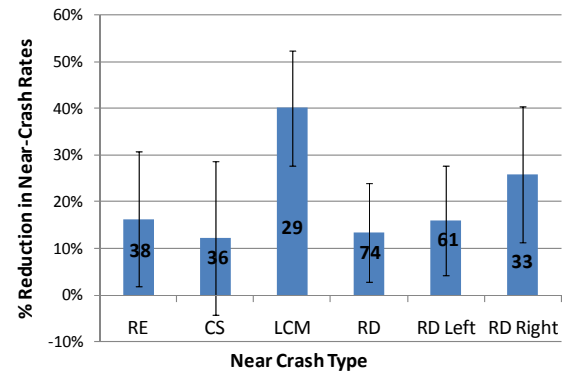
crashes broken down by departure direction. While there is a trend towards a reduction in road-departure near crashes to the left ( $p = 0.06$ ), most of the improvement was in the reduction in near crashes to the right.

**Table 11. Paired *t*-test results of road-departure near crash rates by departure direction**

	Left	Right
Baseline	4.58	2.75
Treatment	3.69	1.68
<i>p</i>	0.06	<b>0.00</b>
<i>n</i>	62	35

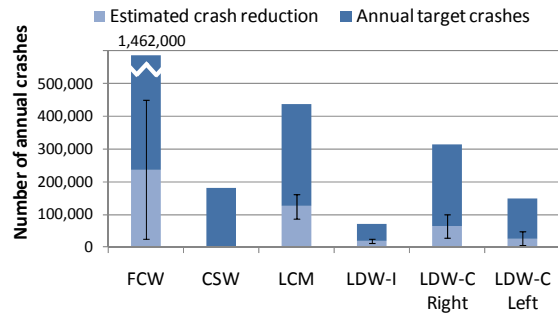
### Projection of Potential Safety Benefits

Figure 4 illustrates the mean effectiveness,  $E(S_i)$ , of the system for each near-crash type (error bars represent 95% confidence interval and values shown in each bar represent the number of drivers included in each analysis) calculated using Equation (1). Based on the mean and 95% confidence interval, the system showed a reduction in rear-end, lane-change/merge, all road-departure, left road-departure, and right road-departure near crashes.



**Figure 4. Average system effectiveness values by near-crash type**

Potential safety benefits from 100% deployment of the integrated safety system were projected using the effectiveness values shown in Figure 4 and annual crash frequencies listed in Table 1. These projections are supported by the analysis of driver exposure to driving conflicts and near crashes discussed in the previous section. Figure 5 shows the annual target crashes, the mean estimated crash reduction, and the 95% confidence bounds for each system function.



**Figure 5. Annual target crashes and estimated crash reductions with full deployment of the integrated system, by system function**

With an overall system effectiveness range between 6 and 29%, approximately 162,000 to 788,000 police-reported crashes could be prevented annually if all light vehicles in the United States were equipped with the integrated safety system. The following list ranks the system functions in terms of their maximum annual crash reduction potential:

1. FCW: 450,000 police-reported rear-end crashes
2. LCM: 163,000 police-reported lane-change crashes
3. LDW-C right: 101,000 police-reported road-departure crashes
4. LDW-C left: 47,000 police-reported road-departure and opposite-direction crashes
5. LDW-I: 27,000 police-reported lane-change crashes

Safety benefits could not be estimated for the CSW function due to the lack of statistically-significant differences between baseline and treatment periods in the analysis of near-crash exposure and the analysis of system effectiveness. Moreover, safety benefits could not be estimated for the LCM function in turning scenarios due to insufficient exposure to these scenarios during the field test.

## CONCLUSIONS

Drivers experienced positive changes in their driving behavior when driving with the integrated system, including an increase in turn signal usage and a decrease in the rate of lane excursions. These results indicate that the integrated safety system reinforces good driving habits and helps drivers maintain better lane positioning. Additionally, drivers did not experience an increase in either the frequency of secondary tasks or instances of having their eyes off the forward scene when driving with the system

enabled, indicating that the integrated system does not promote a degradation in driver attention.

One result that suggests a potential unintended consequence of the integrated system is the decrease in headway when drivers follow a lead vehicle on non-freeway roads. Although the 3% reduction is statistically significant, it is unlikely to have a negative impact on safety as the average treatment time headway of 1.98 s is still considered to be safe [5]. In addition, this shorter time headway in the treatment period did not lead to more rear-end driving conflicts or near crashes in the field test.

During the field test, drivers experienced significant reductions in both lane-change and road-departure near crashes when the system was enabled. Additionally, drivers showed significant positive effectiveness for three of the four crash warning functions. Based on the reduction of near crashes that drivers experienced, the integrated system could help prevent approximately 161,000 to 787,000 police reported crashes annually (between 7 and 29% of target crashes).

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**APPENDIX A: NEAR-CRASH THRESHOLDS**

Conflict Type		Variable	Value
Rear-end		POV is moving	
		Min TTC	< 3 s
		Max deceleration	> 4.0 m/s
		Brake duration	> 0.5 s
Curve speed		Max lateral acceleration	> 3.5 m/s <sup>2</sup>
		Speed reduction at tightest point of curve	≥ 3 m/s
		OR	
		Max lateral acceleration	> 4.5 m/s <sup>2</sup>
		Speed reduction at tightest point of curve	< 3 m/s
Lane change	Straight road	No lane excursion	
		Max lateral acceleration	≥ 1.0 m/s <sup>2</sup>
		OR	
		Maximum lane excursion	0.1 m - 0.3 m
		Max lateral acceleration	≥ 0.75 m/s <sup>2</sup>
		OR	
	Depart to outside of curve	Maximum lane excursion	0.3 m - 0.9 m
		Max lateral acceleration	≥ 0.0 m/s <sup>2</sup>
		No lane excursion	
		Max lateral acceleration	≥ 0.5 m/s <sup>2</sup>
		Normalized relative acceleration	> 0.25
		OR	
	Depart to inside of curve	Maximum lane excursion	0.1 m - 0.9 m
		Max lateral acceleration	≥ 0.0 m/s <sup>2</sup>
		Normalized relative acceleration	> 0.75
		OR	
		No lane excursion	
		Max lateral acceleration	≥ 0.0 m/s <sup>2</sup>
Road Departure	Straight road	Maximum lane excursion	0.1 m - 0.3 m
		Max lateral acceleration	≥ 1.5 m/s <sup>2</sup>
		OR	
		Maximum lane excursion	0.3 m - 0.9 m
	Depart to outside of curve	Max lateral acceleration	≥ 1.0 m/s <sup>2</sup>
		Maximum lane excursion	0.1 m - 0.9 m
		Max lateral acceleration	≥ 1.0 m/s <sup>2</sup>
	Depart to inside of curve	Normalized relative acceleration	> 0.25
		Maximum lane excursion	0.1 m - 0.9 m
		Max lateral acceleration	≥ 2.5 m/s <sup>2</sup>
		Normalized relative acceleration	> 2.25



# DRIVER ACCEPTANCE AND BEHAVIORAL CHANGES WITH AN INTEGRATED WARNING SYSTEM: KEY FINDINGS FROM THE IVBSS FOT

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## ABSTRACT

The Integrated Vehicle-Based Safety System Field Operational Test (IVBSS FOT) was conducted to develop and evaluate an integrated system of crash warning technologies. A field operational test was conducted with prototype integrated crash warning systems onboard both passenger vehicles and heavy trucks. The evaluation reported here focused on driver acceptance of the integrated system, as well as identifying changes in driver behavior associated with the system. The integrated system was designed to address rear-end, lateral drift, and lane-change/merge crashes. The light vehicle system also addressed curve speed crashes.

One hundred and eight light vehicle drivers and 18 professional heavy truck drivers were recruited for the field operational test. The passenger car drivers used a prototype vehicle as their own personal vehicle. The commercial drivers used the heavy truck as part of their daily work. A data acquisition system captured onboard data, and analyses were conducted on driver performance and secondary task behaviors. Subjective feedback from questionnaires, debrief interviews, and focus groups were also analyzed.

Drivers on both vehicle platforms were largely accepting of these systems. Several behaviors were observed to be influenced by the presence of these systems; other behaviors were unaffected.

## INTRODUCTION

Analyses by the US Department of Transportation (US DOT) indicate that 61.6 percent (3,541,000) of police-reported, light-vehicle crashes and 58.7 percent (424,000) of police-reported, heavy-truck crashes could potentially be addressed through the widespread deployment of integrated crash warning systems that address rear-end, roadway departure, and lane-change/merge collisions [1].

Furthermore, integration can be expected to significantly improve overall warning system performance relative to the non-integrated subsystems. This would result from each warning functionality being able to leverage additional sensors, i.e. sensors required for the other warning functionalities, creating a better awareness of the driving context. This may improve the reliability of threat detection, allowing more timely warnings, and also reduce invalid or nuisance warnings which may help driver acceptance.

The IVBSS project was launched to develop and evaluate a state-of-the-art integration of multiple crash warning technologies, and field operational test the systems with drivers recruited from the general public and from a commercial trucking fleet. Three crash-warning subsystems were integrated into both light vehicles and heavy trucks in the IVBSS program. The systems were:

- Forward crash warning (FCW), intended to warn drivers of the potential for a rear-end crash with another vehicle,

- Lateral drift warning (LDW), intended to alert drivers that they are drifting outside their travel lane,
- Lane-change/merge warning (LCM), designed to warn drivers who are initiating lane changes that adjacent same-direction vehicles are present (accompanied by full-time side-object-presence indicators), and
- Curve speed warning (CSW) (light vehicles only), which warns drivers if they may be traveling too fast to travel comfortably through an upcoming curve.

The IVBSS FOT was conducted under a cooperative agreement between the US DOT and the University of Michigan Transportation Research Institute (UMTRI). UMTRI team partners included Visteon Corporation, Eaton Corporation, Honda R&D America, TK Holdings, and Con-way Freight. A separate analysis of the data in the FOT was conducted by the US DOT Volpe National Transportation Systems Center, including estimation of the integrated system’s potential safety benefits.

This paper is arranged in sections, including: a description of the integrated systems; a methodology section; a report on the travel made during the tests as well as the frequency of warning events; a description of the results addressing driver acceptance; a separate section on driver behavioral changes related to the integrated system; and a conclusions section.

## INTEGRATED SYSTEM DESCRIPTIONS

The integrated systems were prototypes that were designed to address specific crash scenarios that were identified by the US DOT [1]. The design process included using these scenarios to establish functional requirements [2], [3], then determining technical specifications for the systems [4], [5]. A program of human factors research was also pursued within the project, providing guidance for both the driver-vehicle interface (DVI) requirements as well as rules for handling situations in which two or more warnings were requested within a few seconds.

Prototypes of the two platforms were then validated using a set of objective test procedures. Throughout this process, the methodology for the two vehicle platforms was similar, but given the differences in vehicle types and use, the system designs and driver interfaces were different in implementation.

### Light vehicle platform

The light vehicle platform development was led by Visteon and TK Holdings, with support from UMTRI on systems engineering and human factors, and technical support from Honda R&D America for installing the system on a set of MY 2006 and 2007 Accord SE sedans. (The warning systems are not related to Honda OEM products.) The system included seven radars: one long-distance 77 GHz forward-looking sensor and six 24 GHz radars to cover the adjacent lanes as well as a distance of 10 to 15 m behind the vehicle for overtaking traffic (see Figure 1). A vision system was used to identify lane boundaries and provide lane position and lateral drift warning functions. Automotive-grade, non-differential global positioning system (GPS) was used with an onboard digital map to predict upcoming curvature for the curve-speed warning, as well as providing information about the roadway for other warning functions. A fleet of 16 such vehicles was built.

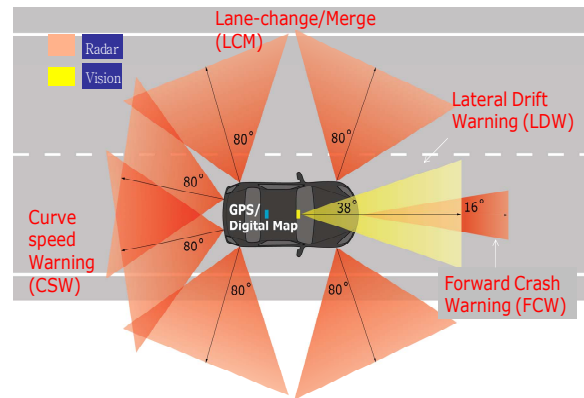


Figure 1. Light vehicle sensors (not to scale).



**Figure 2. Light vehicle fleet of 16 vehicles.**

The FCW function responded to moving and stationary targets, employing assumptions about an inattentive driver’s response time and likely deceleration levels, as well as other considerations. The warning for the FCW was a combination of an auditory cue (a series of short beeps), plus a brief brake pulse. The CSW function warned the driver during approaches to a curve, using thresholds for a comfortable lateral speed. Since the purpose of the warning for CSW is similar to that for FCW – to ensure the driver looks forward to assess the situation – the CSW shared the same auditory cue with the FCW. The CSW did not include a brake pulse, given that the time criticality of driver response is a bit less for CSW.

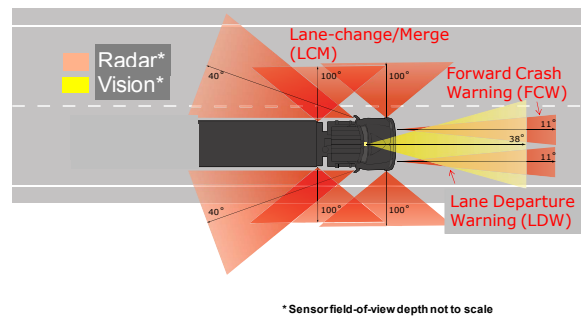
The set of warnings for lateral motions of the vehicle employed two different driver cues. If the vehicle was moving across a lane boundary (with no turn signal applied), and the adjacent space was unoccupied, then a set of pulsing motors in the seat pan provided the driver with a simulated rumble strip (and no auditory cue). If there was either a potential threat in the adjacent space, such as same-direction traffic or a nearby roadside barrier, then the driver would receive an auditory alert with directionality (left side warning for left-going motion). This was true whether the turn signal was applied or not.

Several seconds after a warning, a message in text was shown to the driver on the center console, including “Hazard ahead”, “Sharp Curve”, “Left Drift,” or “Left Hazard.” This was not used as a stimulus, but to allow the driver to better understand the system. Note that the driver could not disable the alerts in either FOT, and could not alter the timing of the alerts. There was a volume adjustment, but the minimum level was chosen to provide enough signal to noise ratio that driver would hear even the quietest setting. The vehicle sound system volume was lowered briefly in situations where an alert was

presented while the sound system volume was very high.

### Heavy truck platform

The heavy truck integrated system was installed on ten MY2008 International TransStar 8600s (two-axle units) which were purchased by Con-way Freight for use in their commercial line-haul and pickup and delivery operations in the Detroit area. The integrated system was developed and installed by Eaton Corporation, with the lane tracking and lateral drift warning system provided by TK Holdings. Navistar (parent company of the International brand) provided technical assistance in the integration. Pickup & delivery was typically conducted with one trailer (28 to 32 foot, or a 45 to 53 foot trailer). Almost all line-haul driving was done in a double trailer configuration. The sensor set is shown for the heavy truck in Figure 3, and a photo of a FOT tractor is in Figure 4.



**Figure 3. Heavy truck tractor and sensor coverage (not to scale).**



**Figure 4. An IVBSS tractor.**

The driver-vehicle interface (DVI) for the heavy truck FCW included auditory and visual information. A set of short tones was given as time headway decreases to 3 sec, 2 sec, or 1 sec. A crash warning tone is also given when crossing a threshold that is based on the distance and closing kinematics relative to the forward target. A small screen mounted on the dash provided yellow indicators for the headway alerts and a red icon for the crash warning. Moving across a lane boundary triggered a directional auditory tone, with an accompanying graphic on the visual screen. If a lane change was initiated when traffic occupied the adjacent space, a directional auditory signal was provided. Anytime there was adjacent-lane traffic, color light emitting diodes (LEDs) installed on the forward A-pillars was illuminated so a driver consulting the side mirrors would see them.

## **METHODOLOGY**

### **Light vehicle**

The light vehicle field operational test involved the recruitment of 108 drivers, each of whom used a prototype vehicle for their own personal use over six weeks. During the first 12 days, the integrated system did not issue warnings to the driver, but was taking sensor readings and performing all calculations. The system then automatically enabled itself, and the driver is exposed to the warnings for another four weeks. Thus the individual driver's behavior and performance was compared to their own baseline. The light vehicle FOT took 12.5 months to complete.

Drivers were recruited within the southeast portion of Michigan, an area that is approximately 10,000 sq mi (260,000 sq km). This area includes metropolitan Detroit, its suburbs, a few smaller cities, and rural areas. Drivers were contacted randomly using a driver's license database from the state of Michigan. The final sample included 18 drivers in each of six age/gender cells, with age groups 20 to 30 yrs, 40 to 50 yrs, and 60 to 70 yrs. Gender was evenly split.

Each driver received an hour of training with the system, including a short test drive, and then they had full freedom to use the vehicle as they chose. They

were only contacted during the six week period if the remote health-monitoring system indicated to researchers that the vehicle may need attention. Upon the completion of their driving, the driver returned the vehicle to UMTRI, completed a questionnaire, and was interviewed about specific alerts they received (using a video review). Twenty eight of the driver also participated in one of three focus groups. Each driver was paid \$250 for his or her time spent traveling to UMTRI and for completing the subjective data protocols. The questionnaires covered the individual and the integrated warning functions, usability, comprehension, perceptions of safety benefit, system performance, and acceptance issues.

The prototype vehicle fleet included an UMTRI data acquisition system that collected all data from the radars, GPS, five video streams, and the prototype subsystem data bus traffic, as well as vehicle data bus information. This totaled up to 700 different signals at rates of 10 to 100 Hz, continuously collected. Remote monitoring of the fleet was done using cellular modems, with automatic diagnostics tools in place to maintain progress of the experiment. The bulk of the data was uploaded upon the driver's return, verified, and loaded into a set of relational databases for analysis.

### **Heavy truck**

The Con-way fleet purchased the ten tractors, and agreed to have those retrofitted with the integrated system before the tractors entered normal operations at a terminal in the Detroit area. Twenty drivers were recruited from the existing drivers at that terminal, with the reward of a minimal amount of employee "points," plus the use of a newer tractor during their shift. The tractors were used for two shifts per day, so that each of the drivers essentially drove an equipped tractor all the time during the ten-month FOT period. Half the drivers drove a daytime pickup & delivery operation, operating in the Detroit metro area. The other half drove line-haul routes at night, transferring freight to terminals a few hundred miles away, returning home during the same shift.

This FOT also employed a within-subject design. Each driver had approximately two months in the baseline condition, and eight months with the system

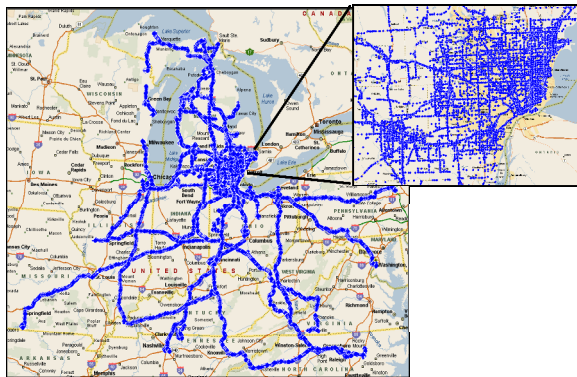
providing alerts. There were no structured interactions with the drivers during this period of time. At the end of the test, the drivers did complete a questionnaire addressing usability, comprehension of the functions and interfaces, system performance, perceptions of safety benefit, and acceptance. The tractors were also equipped with a data acquisition system that was similarly integrated to produce a very rich data set. Both the cellular modem-enabled monitoring operation and the direct download of data were similar to that described for the light vehicle platform.

## EXPOSURE & SYSTEM EVENTS

Table 1 summarizes the distance traveled, trips (ignition cycles), and driving time associated with the onboard data gathered in the FOTs. Figures 5, 6, and 7 show the travel for the light vehicles and heavy trucks, respectively.

**Table 1.**  
**Travel during the FOTs**

	Light vehicle	Heavy truck
Distance	213,309 mi 343,214 km	601,944 mi 968,528 km
Trips	22,657	22,724
Hours	6,164	13,678

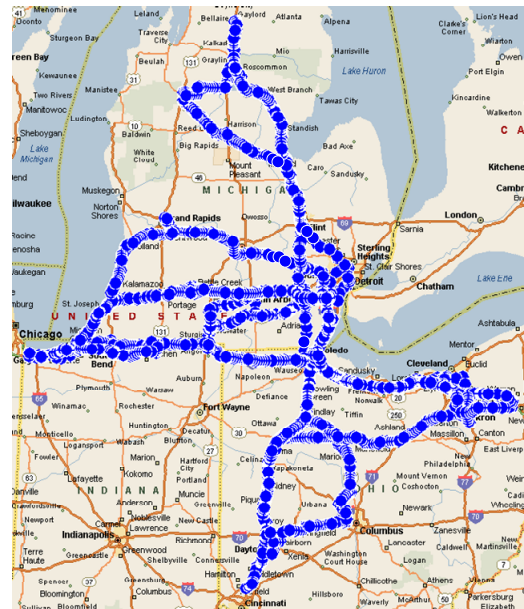


**Figure 5. Light vehicle platform travel.**

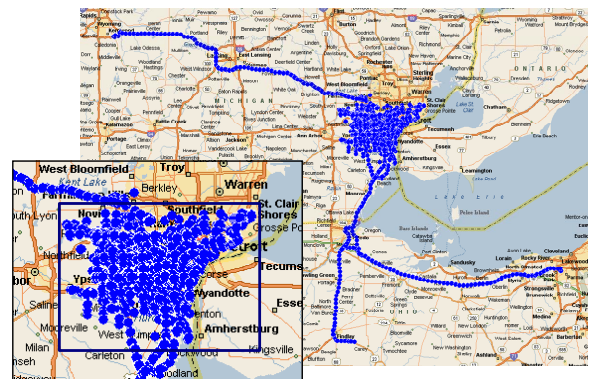
The mean alert rates (across drivers) when the system was enabled was 7.9 and 18.3 per 100 mi (161 km) for the light vehicle and heavy truck, respectively. Individual's alert rates varied substantially. For example, the individual with the highest light vehicle

alert rate has more than 15 times the alerts, per unit distance, as the driver with the lowest rate.

Figure 8 shows the relative frequencies of the different warnings in the FOTs (averaging across the different driver experiences, and using data from the period in which the system was enabled to present alerts). Most warnings were lane drift warnings, which often reflected the common occurrence of drivers allowing their vehicle to cross a lane edge in situations where they may have felt little crash risk.



**Figure 6. Heavy truck platform line-haul travel.**



**Figure 7. Heavy truck platform pickup & delivery travel in the Detroit area.**

Another common cause of these particular warnings is unsignaled lane changes. Notice for the light vehicle population, the occurrence of FCW and CSW alerts is relatively rare, with a combined mean alert rate of 0.8 warnings per 100 mi (161 km). For the heavy truck drivers, lane-change/merge alerts were the second most common, although many of these were invalid alerts associated with false targets from reflections and ‘ghosting’ effects from radars looking backwards besides the large surface of box trailers. The truck FCW also had a fairly pronounced set of false positives for stationary objects, especially bridges and roadside objects. Given the repetitive nature of some of the routes, a geo-location feature to suppress false positives based on past history could have been an effective feature.

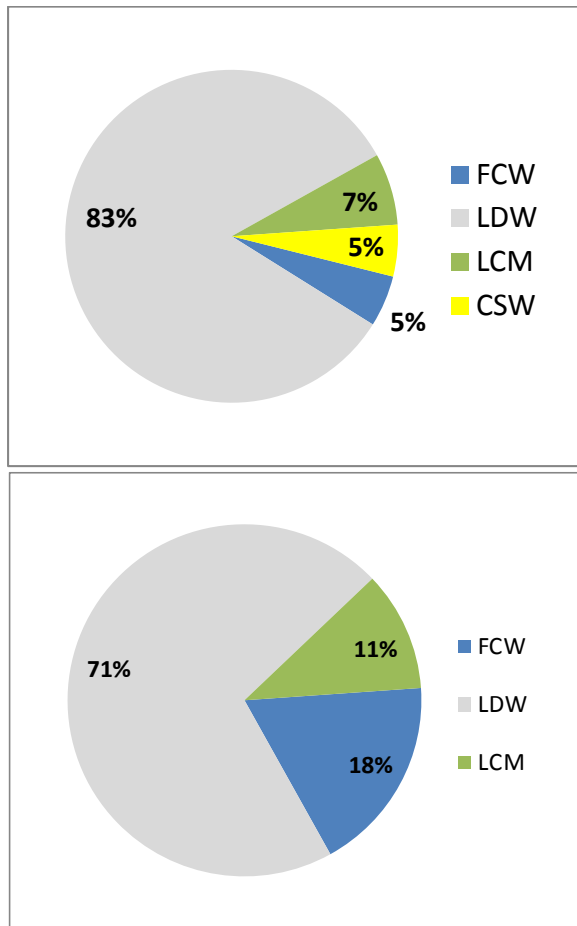
## RESULTS: DRIVER ACCEPTANCE

Light vehicle drivers were accepting of the integrated system and rated it well in terms of both usefulness and satisfaction, with 72 percent of all light vehicle drivers reporting they would like the integrated system in their personal vehicle. The majority of light vehicle drivers reported that they were willing to purchase the integrated system. However, most drivers were not willing to spend more than \$750.

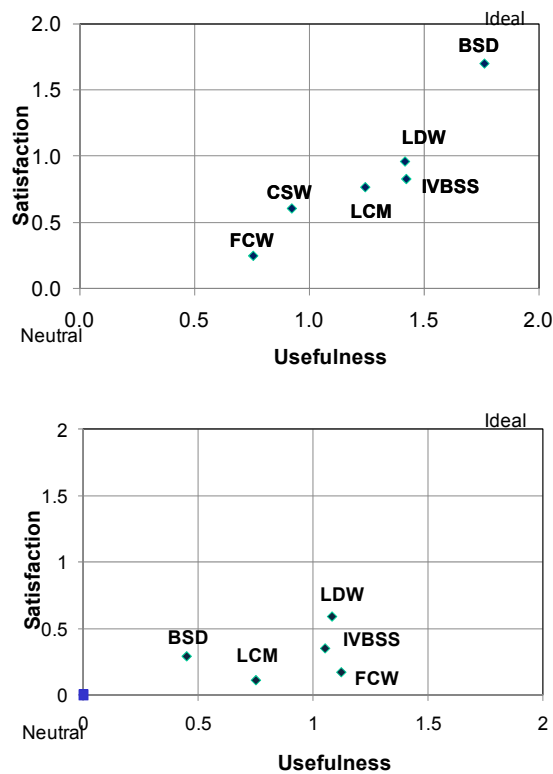
Fifteen of 18 heavy truck drivers stated that they would prefer driving with an integrated crash warning system, and they would recommend purchasing trucks with an integrated system.

Most light vehicle drivers self-reported that their driving behavior changed as a result of driving with the integrated system. The most frequently mentioned change in behavior was an increase in turn-signal use, which was the result of receiving LDW warnings provoked by failing to use turn signals when changing lanes (which is confirmed by the objective data). Heavy truck drivers reported that the integrated system made them more aware of the traffic environment, particularly their position in the lane, and eight heavy truck drivers stated that the integrated system potentially helped them avoid a crash. Thus there was evidence that both light vehicle and heavy truck drivers will be accepting of such systems. Furthermore, in responding to the questionnaire, both sets of drivers reported believing such systems will increase their driver safety.

Subjective feedback was used to compute ratings of the individual system features on the Van der Laan scale [6]. The Van der Laan scale shows “usefulness” and “satisfaction,” each on a scale from -2 to 2, where positive ratings are for positive responses. The values are computed from a set of questions specifically designed for this purpose. The mean ratings for each subsystem as well as the integrated system are shown in Figure 9. All warning features score in the positive quadrants for both usefulness and satisfaction.



**Figure 8. Fraction of warnings by warning type for light vehicle (upper chart) and heavy truck (lower chart).**



**Figure 9. Van der Laan scale: usefulness and satisfaction as reported by light vehicle drivers (upper ) and heavy truck drivers (lower).**

Light vehicle drivers rated the lateral subsystems (LCM with BSD and LDW) more favorably than the longitudinal subsystems (FCW and CSW), and reported getting the most satisfaction out of the BSD component of the LCM subsystem. Light vehicle drivers found the integrated system to be useful in particular when changing lanes and merging into traffic. Light vehicle drivers reported FCW to be the least usefulness and least satisfying of the subsystems. Numerous light vehicle drivers commented that they did not like the brake pulse that accompanied warnings.

Heavy truck drivers stated that the system was convenient and easy to use, despite a relatively high ratio of invalid warnings to valid warnings when responding to stopped objects ahead or lane change/merge scenarios. Heavy truck drivers clearly preferred the LDW system the most, rating it the most satisfying of the three subsystems, with FCW being rated the most useful. LDW was a particular

favorite for the line-haul heavy truck drivers, given the long hours and great distances covered on limited access roadways. However, both P&D and line-haul heavy truck drivers mentioned the headway time element of the FCW subsystem as being particularly helpful.

Light vehicle drivers did report in the questionnaires, debrief interviews, and in focus groups that there were alerts that they did not consider necessary. Older drivers were more forgiving than middle-aged or younger drivers in this regard, even though the rate of invalid alerts was relatively constant across age groups.

## RESULTS: BEHAVIORAL CHANGES

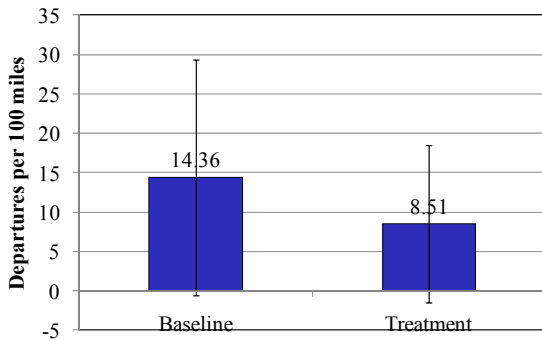
Specific research hypotheses were posed a priori, and then addressed with onboard data or subjective data. Several statistical techniques were used, with the two most common techniques being general linear model and linear mixed model techniques. Findings that are based on results of a mixed linear model are derived from a model, not directly from raw data *per se*. However, model-predicted means and probabilities were checked against queries of the raw data set to validate the models. In all uses of linear mixed models, drivers were treated as a random effect. Significant factors in the linear mixed model approach were determined using a backwards step-wise method. Additional information regarding the statistical techniques used in analyzing the heavy truck field test data can be found in the data analysis plans for the project.

The independent variables varied slightly between analyses, but often the variables included whether the integrated system was enabled, the road class, wiper state (surrogate for precipitation), truck route type, and sometimes speed and trailer weight, as well as several others. References for details are cited in the following discussions.

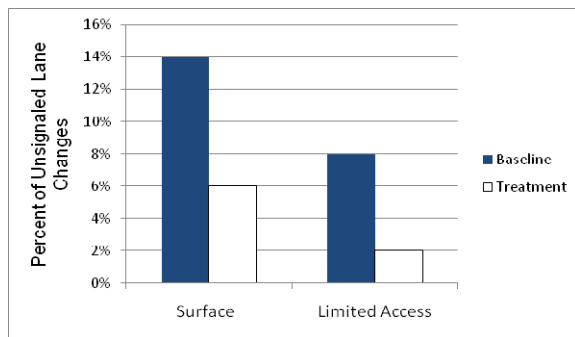
### Light vehicles

Analysis of onboard data showed statistically significant support for the following, at  $p < 0.05$  (see [7] for detailed discussion of each of these):

- A 41% lower rate of lane departures with the integrated system (see Figure 10)
- A reduction of more than 50% in the fraction of lane changes in which a turn signal was not used, both on limited access and surface roads (see Figure 11)
- A 16% decrease in the time spent outside the lane on lane departures after which the driver returned the vehicle to the original lane (from a mean of 1.98 to 1.66 sec)
- A 13% increase in the number of lane changes per mile (even when accounting for several independent variables).
- Increase from 21% to 24% in the fraction of following time at headways of less than 1 second.



**Figure 10. Frequency of light vehicle lane departures with and without the integrated system.**



**Figure 11. Frequency of unsigned lane changes in the light vehicle test.**

Two of these are unexpected outcomes: the increase in lane change frequency and the decrease of headway time. The cause behind each is not clear,

but may be a reflection of increased driver confidence due to the integrated system; if so, it does not extend to other measures of related driving behavior. Specifically, here was no statistically significant effect of the integrated system on the following:

- No increase in secondary tasks while driving with the system.
- Mean position in the lane did not depend on whether the integrated system was enabled.
- No change in the general locations of adjacent vehicles when an LCM warning occurred (i.e., there was no clear trend suggesting drivers were filling gaps differently with the system).
- No change in conflict levels, as measured by the peak deceleration needed in any event to avoid striking the rear end of another vehicle.
- No change in frequency of hard-braking events or brake response time in FCW situations.
- No effect on lateral accelerations in curves, or on braking levels when approaching curves.

### Heavy trucks

Analyses were performed that were similar to those done for the light vehicles. Analysis of onboard data showed statistically significant support for the following, at  $p < 0.05$  (see [10] for detailed discussion of each of these):

- Drivers move closer to the lane center when the integrated system is active, from 10.8 cm right of center with a disabled system to 9.1 cm right of center with the system.
- Slightly longer time headways, from 2.84 sec to 2.97 sec [9].
- Drivers had shorter brake response times (from 1.56 sec to 1.35 sec) [9].

There was no statistically significant effect of the integrated system on the following:

- No increase in secondary tasks while driving
- No decrease in lane departure frequency, although 13 of 18 drivers had fewer departures.
- No change in how long the vehicle is outside its lane (unlike the effect seen in light vehicles).
- No change in turn signal use during lane changes (unlike light vehicles).



- No change in the general locations of adjacent vehicles when an LCM warning occurred (i.e., there was no clear trend suggesting drivers were filling gaps differently with the system).
- No change in the rate of lane changes (unlike light vehicles).
- No change in forward gap distances during lane changes.
- No change in the frequency of hard-braking events.

As reported earlier, drivers did feel positive about these systems and there was no evidence of negative, unanticipated risks for the heavy truck system.

## CONCLUSIONS

The IVBSS FOT studied driver acceptance and behavioral changes of 108 light vehicle drivers and 18 heavy truck drivers while they were operating vehicles equipped with prototype integrated warning systems. The systems addressed forward crashes, lane drift crashes, and lane change/merge crashes. The light vehicle system also addressed curve-overspeed crashes.

Drivers were generally accepting of both systems, with functions addressing lane drifts and blind spot indications being the most popular. A number of analyses were reported in this paper which addressed behavioral changes including driver performance and secondary task behavior. For light vehicle drivers, the most striking changes in behavior were a 41% decrease in the frequency of lane departures, and a large increase in the usage of turn signals during lane changes. The time spent at shorter headways did increase, however. For the heavy truck drivers, there were slightly longer headways with the system and faster brake response times.

The outcome of these tests suggests it is possible to develop and successfully deploy a system with multiple functions without overwhelming or confusing the driver with warnings. In fact, drivers as a whole were positive about the system and 72% of the light vehicle drivers would like to have a similar system on their own vehicle, and 15 of the 18 commercial heavy truck drivers felt the same way.

## ACKNOWLEDGMENTS

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All reports generated by the UMTRI team for the IVBSS program can be found at: <http://www.umtri.umich.edu/ivbss.php>

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## ECALL SYSTEM: FRENCH A POSTERIORI EFFICIENCY EVALUATION

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### ABSTRACT

An automatic emergency call system appeared on Peugeot and Citroën vehicles in France since 2003, which has been rewarded by Euro NCAP in 2010 as an advanced innovative solution. The LAB in close cooperation with the CEESAR has set up a study aiming at evaluating the effectiveness of this system. The eCall efficiency evaluation will be based on real accidents where eCall was automatically triggered. It will aim to confirm or not the assumptions given by the European Commission: 2 500 lives saved in Europe if 100% of the fleet is equipped with such a system.

Several studies using "a priori" methods were already led on eCall benefit evaluation (Trace, eImpact and LAB results). In this study, we suggest a benefit evaluation with "a posteriori" method, based on real accident cases involving vehicles equipped with eCall. For each studied case, an expert judgment is realized to qualify or not eCall vital contribution. All these judgments allow estimating system global efficiency.

Created in 2004, the specific "eCall" database contains about 3 100 automatic emergency call notifications. More than 150 variables summarize accident circumstances, involved eCall vehicle information's, feelings of people cared for by this means as well as rescue teams feedback. Four eCall efficiency can be applied for each person involved in the accident: eCall considered as not necessary, eCall considered as useful, eCall considered as urgent and eCall considered as vital. ECall is considered as useful when involved occupants were not able to prevent the rescue team and/or did not know how to be located. The system is considered as urgent when eCall is judged as useful and when the victim has severe injuries that could be degraded. ECall is considered as vital when the victim has severe injuries that could be made this victim to die.

The "eCall" database is rather new and limited in number of coded cases. It is not representative of accidents in France. Indeed, accidents are selected with regard to their interest (new vehicles, accident typologies). However, it is regularly filled with

accident cases whose number increases due to the presence of more and more PSA eCall system in Europe. Thanks to this, the "a posteriori" benefit evaluation is unique and is based, for the first time in Europe, on real life accident cases where automatic triggered eCall occurred.

This new study allows to refine the eCall system effectiveness with a 2.8 % benefit regarding fatalities. This result based on real world accidentologic data is lower than the figure initially estimated in the 2000s, which was about 5 to 6 %. Besides, this evaluation only focused on passenger cars with an assumption of 100% of equipment rate. All these surveys allow us to define a realistic effectiveness interval of this device between 3% and 10%. It represents a real additional system against road deaths and injuries, in particular for accidents occurring at night, in rural areas and involving a single vehicle. The outcome of this paper can be used for the current discussion taking place in Europe for the foreseen regulation on 112.

### INTRODUCTION

For many years now, car manufacturers have devoted enormous efforts in order to improve the safety level of their vehicles. The first action line was primary safety, which purpose is to prevent the accident from happening. The second line of action, secondary safety, addresses the vehicle's occupant protection during a crash. These two action lines are still the ones receiving the most attention for safety reasons, but recently, solutions regarding the post-accident period are emerging: the eCall is at the forefront of tertiary safety. From the beginning of 2011, the emergency call service is now operational in 11 countries of Europe on both PSA Peugeot and Citroën passenger cars (except Peugeot 107, 4007 and Citroën C1, C-crosser) fitted with a telematic unit either as a standard or as an option. More than 765 000 vehicles fitted with this device, have been sold in these countries.

### HOW DOES ECALL WORK?

The procedure of the telematic device can be triggered manually or automatically. In an emergency situation, the occupant of the vehicle

presses the SOS button on the telematic terminal for at least two seconds. In a severe impact, if the vehicle's pyrotechnic equipment has been triggered (airbag or seat belt pretensioner), the vehicle itself sends out the SMS message containing the basic information mentioned previously and the request for voice contact. As soon as the button is pressed or an automatic trigger happened, the telematic terminal sends an SMS message to the call centre assigned to cover the area in which the vehicle is located. This SMS message contains vital information for dealing with the emergency. As soon as the call is intercepted, these details appear immediately on the call centre operator's control screen, in the form of a customer sheet, location on a digital map, etc. In this way, the call centre operator has useful data available even before establishing direct telephone voice contact with the occupant of the vehicle.

Once voice communication has been established with the driver, the call centre operator analyses the situation more closely. Then he analyses the situation, he checks the location on various types of map, and if necessary informs the emergency services responsible for the area in which the vehicle is currently located, giving them all the information about the situation.

Depending on the situation, but only in France, the call centre operator can also call on one of the emergency doctors permanently stationed at the call centre, using a three-way conferencing system with a view to assess the situation more accurately or to give advice while waiting for help to arrive. The three-way conferencing system can also be used to take care of people travelling outside their own country. Communication can be in their own language from the call centre in the relevant country, while the local public services will, if necessary, be informed in their own language by the national centre, which covers the accident's location. At that stage, the procedure continues "on field" with the intervention of the emergency services at the scene of the accident until the people involved are taken care of face-to-face.

In all cases, if there is no response from the accident victim, the established protocol requires the call centre operator to try to make contact with the vehicle within a limited time: when the set time has elapsed, the operator has to transmit the alert to the emergency services on the basis of the information contained in the SMS message: type of vehicle, GPS coordinates of the vehicle, type of energy of the vehicle.

The advantage of this telematic architecture is the Third Party Service (TPS), which can sort out the accident and then send the emergency services only

if it is necessary. Some other eCall systems are based on this way of working (On Star-General Motors; OnCall-Volvo; BMW Assist-BMW; ...)

## DATA COLLECTION

### Victim interview

In this new context of an automatic emergency call system deployment, the LAB/CEESAR has set up a study to obtain experimental results about the system's operation and effectiveness and the feelings of people cared for by this means. This makes possible to compute the time saved in getting the emergency services to the scene and check the operation of the telecommunications systems and systems for locating the accident. A special questionnaire has been created for this study. It contains a score of very specific questions. The questions are listed in 4 sections:

- an accident analysis section to give details of the circumstances of the accident, place, time, number of occupants, injuries, how long the emergency services took to arrive, etc.
- a technical section to give information about how the system operated at the time of the accident, the communication between the people involved and the emergency centre, the telephone company used, etc.
- a section for the user/person involved to provide feedback.
- a section for the fire brigade to provide feedback from the accident

Even if, the eCall system is deployed in 11 European countries, this safety benefit study concerns only "French accidents".

When we are informed about accidents involving a vehicle equipped with the eCall system, we select cases whose are the most interesting (accidents with injuries, accidents at night, accidents with only one vehicle...). We try to contact the car driver. It is important to note that interviews with victims are not always easy to get (less than one victim over two answers to our appeals). Consequently, we loose many data. When we reach the driver, we follow the steps of the questionnaire mentioned above.

When the crash is severe and the damaged vehicle available, we also make an in depth study of their vehicle. Indeed, we record the deformation of the vehicle's structure to assess the energy dissipate during the crash; as well as the parts of the passenger compartment which could have injured the occupants. In addition, we make a manual test on the eCall system to verify following the vehicle structure deformation, that eCall is still triggered.

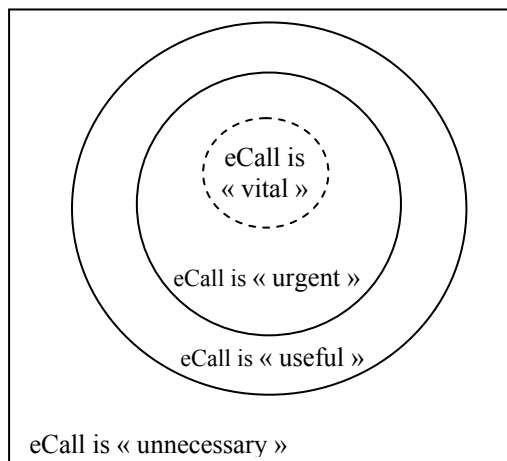
When the call centre contact the fire brigades (in France), a questionnaire is sent to them, to get information about their intervention. The aim is to get their point of view about this eCall system. All these information are saved in an anonymous Access database (this database is described in the next chapter).

### Expert judgment

Following the interview realised with the accident victim, we can put forward a judgment on the different levels of usefulness of the eCall system.

Four categories have been defined. The road accidents in which, eCall is “unnecessary” for the victims. The ones where eCall is “useful” for the victims. The other ones where eCall is “urgent” for the victims. Finally the road accidents in which eCall has been judged as “vital” for the victims. Hereafter, the graph shows the sharing out of accidents according to the four specific judgments. It means that an accident where eCall has been judged as “vital” is also considered as “urgent” and “useful”. As it will see after, to judge cases as “urgent”, we include a notion of seriousness added to hypotheses, which allow us to judge an eCall “useful”.

The cases judged as “vital” are those for which, if there had not been the eCall system, the victim would have been died because of their injuries.



**Figure 1. The sharing out of accidents according to eCall judgment.**

**“Unnecessary” cases** The eCall system is judged unnecessary when:

- there are direct witnesses on the accident scene;
- victims are not or slightly injured and can call emergency services, ...

For example: the driver of a Peugeot 3008 follows a road with right of way in urban area, during the day. He is going to cross an intersection where the traffic lights are off. But a Renault Laguna coming from his right does not respect the road sign. The collision is unavoidable. The Renault Laguna hits with its front left side, the right side of the Peugeot 3008 (at the wheel level).

In this case, the eCall system is triggered but is considered as “unnecessary”. In fact, there are witnesses who can alert emergency services. There are two lightly injured persons (contusions) and one who is not injured. Nevertheless, the eCall system allows a quick intervention of services associated as the tow truck or the police to regulate the traffic... (non exhaustive list).



**“Useful” cases** To judge the eCall usefulness, some hypotheses have been expressed.

Various criteria of accidents can make the eCall useful for the victims (non exhaustive list):

- road accident with a single vehicle, by night and in a rural area;
- the car’s occupant are stuck in their car;
- nobody gets a GSM;
- car occupants don’t know the accident localization;
- the vehicle is not visible from the road;
- there is no direct or indirect witness who can call emergency services and locate himself; ...

For example: an accident occurs in a slope on a remote road in a rural area, at night. A Peugeot 407 slips on ice and crashes into a tree.

The driver is isolated and stuck in his car. He is slightly injured. He has been only shocked by the impact and a little bit hurt at neck and left shoulder.



A few minutes later, a Volvo car leaves the road too and realizes a glide (about ten meters) above the Peugeot 307. The Volvo lands 3 meters down below. There is one injured person in the Volvo (vertebra compression).

In this accident, the eCall system has been considered urgent, because these French tourists travelling in Austria did not know the accident place and because this eCall has permitted to help quickly the injured person involved in the Volvo car. We can see on the picture below the vehicles' final position after the accident.

**“Vital” cases** A case is judged as « vital » when the serious injuries of the victims could take them to death:

- internal bleeding;
- amputation;
- all the injuries which concern the vital organs...

For example: on a minor road, in a rural area, the Peugeot 407 goes out of control at a roundabout, crosses the opposite lane, hits the kerb, then the bank, and rolls for a distance of about twenty meters. While the two passengers in the vehicle are unconscious due to the impact, the voice of the emergency call centre operator wakes the driver from his blackout. The driver answers and confirms to the emergency call centre the need of assistance

**“Urgent” cases** We consider the eCall system as urgent when, with one or more criteria from the eCall useful, we add a seriously injured person in the accident:

- loss of consciousness;
- to feel faint;
- bad weather can also make the situation worse ...

For example: in a snowstorm, a Peugeot 307 slips on a slope mountain road between, Garnish and Fusen (Austria) and falls in a ditch. It rolls over and finishes on its roof, stopped by a rock (on driver door side). The driver estimates his speed at 10 km/h. In the Peugeot 307, there are three passenger's car and only one slightly injured (broken clavicle).



The impact was extremely violent and resulted in the partial ejection of the passenger's head through the right-hand side window, causing serious injuries to his skull. It is certain that the rapid arrival of the emergency services saved the passenger's head injuries from getting worse. The driver suffers from minor head injuries. This road accident with only one car, by night in a rural area makes the eCall “vital”. There is no witness and the passenger's car was seriously injured. We can see on the picture before, the important Peugeot 407's roof deformation.

## EVALUATION METHODOLOGY

In 2010, the LAB/CEESAR carried out another study to assess the eCall efficiency; this one was called "a priori" study [1]. The data used in this evaluation were previous to the setting up of the system assessed. We used an other database coming from fatal accidents reports (called PVM2000) in France for years 2002 and 2003.

In this study, we assess the PSA Peugeot Citroën eCall system efficiency by the experience feedback of this system. This evaluation called "a posteriori" deals with events whose occur in the past. It is based on experience, on real events (here, accidents with automatic eCall triggered). This evaluation consists in study the results, the consequences of the eCall setting up. To achieve this goal, we will use the database described below (next sub-heading).

### Database introduction

Created in 2004, the specific "eCall" database contains about 3100 automatic emergency call notifications, taking all countries together where eCall is deployed. As explained above, this study includes 150 variables which not only detail information about the circumstances of the accident, but also accurate assessments of occupants' injuries, expert reports on the vehicles involved and feedback on the eCall system from the fire rescue teams.

The Access database is divided into 5 tables described below.

- Accident circumstances

This table is filled in predominantly every week with the call centre accident feedback.

- Vehicle equipped with the eCall system

This table groups together the information on the PSA Peugeot Citroën vehicle equipped with the eCall (brand, model, eCall system type ...), and feedbacks coming from the manual test on the eCall system realized on the damaged vehicle.

- Car occupants

It takes into account all the information concerning occupants: age, height, weight, injuries ...

- Questionnaire to the victims

This table contains the driver answers about the questions asked during the phone call interview. This questionnaire is divided into 4 sub-parts:

*Technique of eCall system* (does the driver know the eCall, what was the SIM card used in the system, how long between the crash and the call ...)

*Accidentology* (is there some witnesses, how long between the call and the emergency services intervention ...)

*Fire brigade (answered by the victim)* (has the vehicle been cut by the firemen to leave an injured person, how long it takes ...)

*Victim* (what was the driver's feeling with regard to the eCall system)

- Emergency services + questionnaire to the fire brigade

This last table has been created in 2007, following the setting up of a questionnaire sent to the fire brigades (in France) when the call centre called them during an accident.

In France between January 2004 and mid 2011, 2 032 automatic emergency calls were recorded (originating from Peugeot and Citroën cars). 202 calls from vehicles fitted with it have been studied in depth. Our study is based on these 202 accident cases to evaluate the eCall effectiveness, and more particularly the 418 people involved.

### Representativeness of the eCall accident database

The "eCall" database is rather new and limited in number of coded cases. Accidents are selected with regard to their relevance (new vehicles, accident typologies). However, it is regularly filled with accident cases whose number increases due to the presence of more and more PSA eCall system in Europe

To evaluate the representativeness of the eCall accident database, we take into account the French national accident statistics. It is representative for accidents involving at least one passenger car without neither pedestrians nor two wheelers. In 2009, there were 67 104 persons involved in an injured accident involving at least one passenger car without neither pedestrians nor two wheelers.

The eCall database is in some ways representative for French accidents. Indeed, we select cases we want to study according to some criteria (single accident, at night, in rural area, with injuries...).

Regarding this comparison, the eCall database is fully representative for the day/night criteria. It is also representative for fatal accidents involving at least one passenger car without neither pedestrians nor two wheelers.

On the contrary, accidents involving only one passengers' car (36.8% compare to 18% for France) or accidents in rural area (59.2% compare to 36.4% for France) are over represented in relation to accidents occurred in France. The eCall database is also over represented for accidents with minor

injuries (56.2% compare to 35.7% for France) and under represented for accidents with serious injuries and with uninjured people. Regarding roads network, the eCall database is largely over represented for the following categories: freeways, state highways and others minors roads (roads predominantly in rural area). Accidents in urban areas are on the contrary, under represented in the eCall database (35% compare to 63.6% for France).

### Methodology description

- 1) Carry out accident case samples based on the eCall database with filters like: single vehicle accident, or rural accident, or accident at night or either a combination of 2 or 3 of the previous criteria. We obtain 8 accident typologies (figure 2).

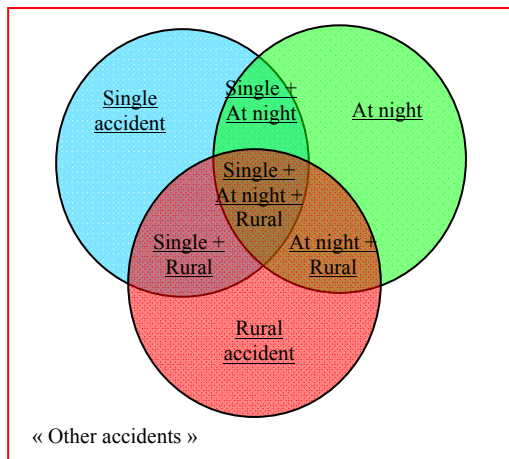


Figure 2. Accident typology distribution

- 2) Study individually each accident cases previously selected.
- 3) Build a template with all accidents typologies defined previously and classify the accident cases according to these criteria. Then make an expert judgment regarding the eCall effectiveness for each accident situations.
- 4) For each previous typology of accidents, calculate the percentage of accident cases where the emergency call is relevant as unnecessary or as useful or as urgent or as vital.
- 5) Calculate the real effectiveness of the emergency call, by multiplying the percentage of injured people with the percentage of cases where the emergency call is considered as relevant (unnecessary, useful, urgent or vital).
- 6) Calculate the number of injured people that eCall can help or save per year in France if 100% of the fleet is equipped with this system.

### RESULTS

### Sample description

The figure below (figure 3) shows the distribution of the 418 people, according to the 4 specific judgments.

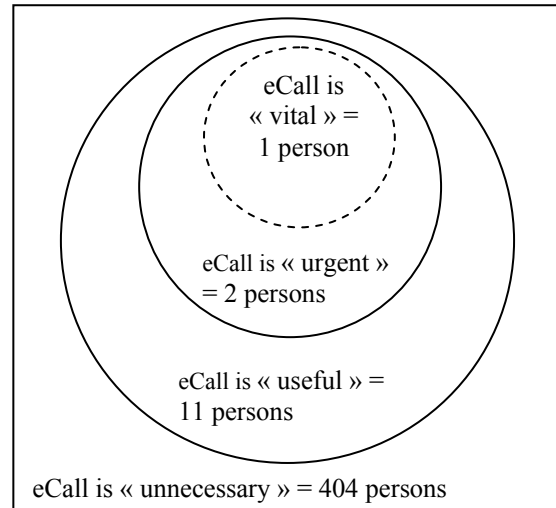


Figure 3. The sharing out of the 418 people according to eCall judgment.

The initial sample is of 418 people is split:

- 103 people are involved in accidents with a single passenger car
- 131 people are involved in accidents with at least one passenger car at night
- 253 people involved in accidents with at least one passenger car in a rural area.

The figure below (figure 4) shows the people distribution according to their accident typologies (single, at night and in rural area) and according to their associated combinations.

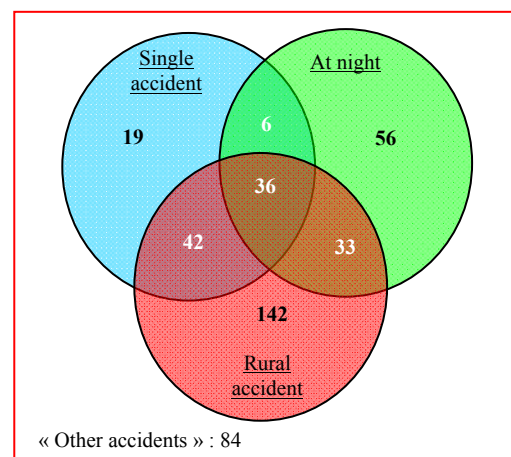
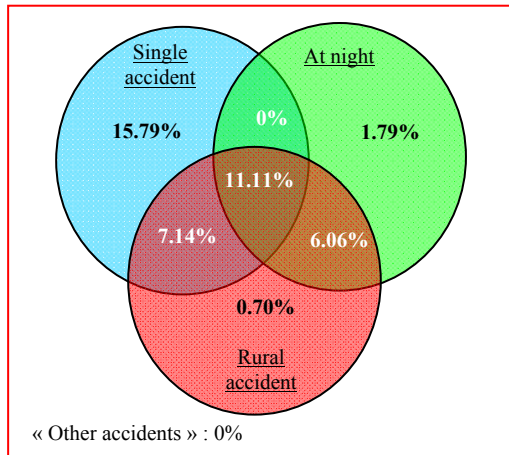


Figure 4. Distribution of people involved in accidents according to their accident typology. Safety benefit calculation when eCall has been judged as “useful”



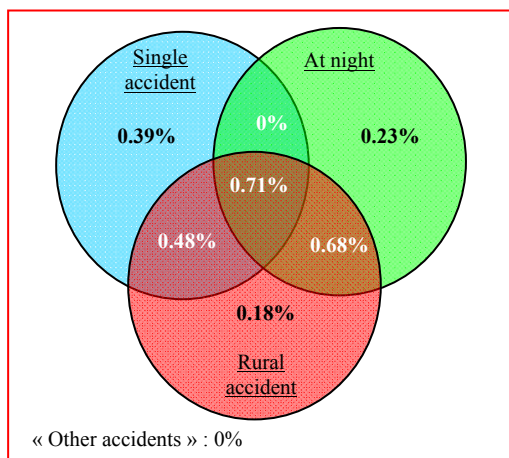
We need to remind ourselves that the people for whom eCall has been judged as “useful” include people for whom eCall has been judged as “urgent”. And the people for whom eCall has been judged as “urgent” include people for whom eCall has been judged as “vital” (see figure 1). The next figure shows us the percentage of people for whom eCall has been judged as “useful”.



**Figure 5. Percentage of people for whom eCall has been judged as “useful”.**

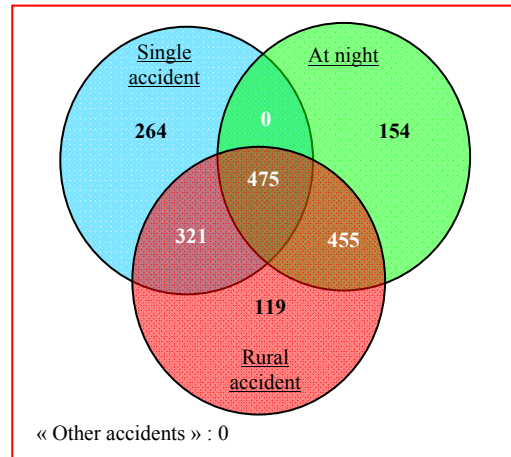
Regarding this distribution, eCall appears as more “useful”, with 15.8% efficiency, for accident involving only a single vehicle.

The results of the real efficiency calculation based on the total of person involved in injured accidents are in the figure 5. The global real efficiency is 2.67% based on 67 104 persons involved in injured accidents involving at least one passenger car, without neither pedestrians nor two wheelers (in France in 2009).



**Figure 6. Real “useful” efficiency calculation: 2.67%**

The next step is to calculate the number of people the eCall system would have been able to help.



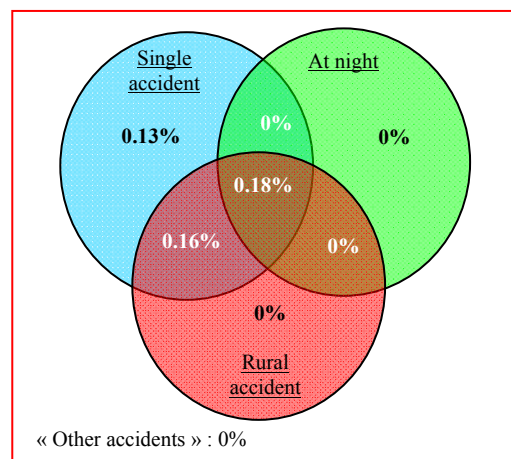
**Figure 7. Number of people “helped”: 1 788**

Taking into account people for whom the eCall system has been judged “useful”. The figure before (figure 7) shows that 1 788 people would have been helped in 2009 in accidents involving at least one passenger car, without neither pedestrians nor two wheelers.

**Safety benefit calculation when eCall has been judged as “urgent” or as “vital”**

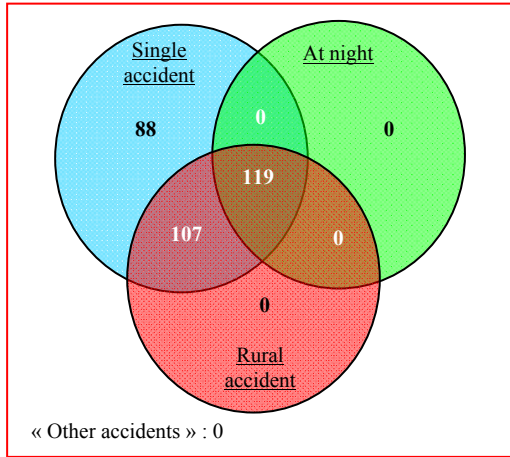
**“Urgent”** We apply the same methodology for people for whom eCall has been judged as “urgent”. The results are shown hereafter in figures 8 and 9.

This global real “urgent” efficiency is 0.47% based on 67 104 persons involved in injured accidents involving at least one passenger car, without neither pedestrians nor two wheelers (French national data 2009).



**Figure 8. Real “urgent” efficiency calculation: 0.47%**

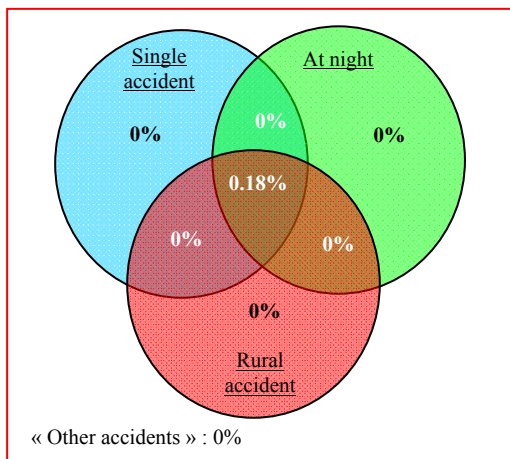
It means that eCall has avoided the injuries worsening for 314 persons.



**Figure 9.**  
**Number of people judged as “urgent”: 314**

**“Vital”** We apply one more time the same methodology for people for whom eCall has been judged as “vital”. The results are shown hereafter in figures 10 and 11.

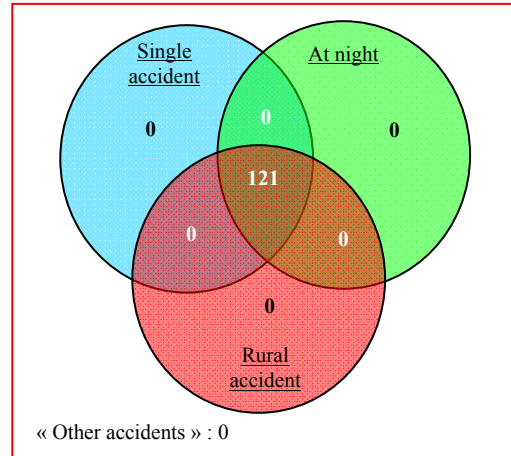
In that case, the global real “vital” efficiency is 0.18% based on 67 104 persons involved in injured accidents involving at least one passenger car, without neither pedestrians nor two wheelers (French national data 2009).



**Figure 10.**  
**Real “vital” efficiency calculation: 0.18%**

It means that if there were no eCall, 119 persons would have been died because of their injuries.

If we related this last number to the total number of death occurred in France in 2009 (4 273 deaths), the benefit regarding fatalities would be 2.8% for passenger cars with an equipment rate at 100 %.



**Figure 11.**  
**Number of people judged as “vital”: 119**

**ECALL EFFECTIVENESS ACCORDING TO OTHER STUDIES**

**Table 4.**  
**eCall effectiveness according to other studies**

Study referencies	Effectiveness (number of death reduced)	Countries studied
E-Merge [3] [13]	5 – 10%	European Union 15
AINO Study [4] [13]	4 – 8%	Finland
eImpact [5] [13]	3.6% < 5.8% < 7.3%	European Union 25
SEISS [6] [13]	5 – 15%	European Union 25
TRACE [7] [13]	10.80%	Australia
SBD [8] [13]	3%	UK
Erie County ACN field test [9] [13]	20%	USA – New York
Czech eCall study [10] [13]	3 – 9%	Czech Republic
Swedish eCall study [11] [13]	2 – 4%	Sweden
Dutch eCall study [12] [13]	1 – 2%	Netherlands
CEESAR-LAB (“a priori” methodology) [1]	5.1%	France
CEESAR-LAB (“a posteriori” methodology)	2%	France

These studies (table 4) are based on different countries with population, road safety politics and emergency services organisation whose are different one country to another.

The range between the minimum and the maximum of eCall effectiveness calculated is quite large and reaches 19%. Our two studies “*a priori*” and “*a posteriori*” are in the 1<sup>st</sup> quarter of this range.

## CONCLUSIONS

The paper presents an “*a posteriori*” benefit evaluation of an eCall device. This evaluation is unique and for the first time in Europe based on real life case accidents with automatic triggered eCall device. However, we have to take care of the eCall efficiency calculation because our study is based on only 202 accident cases, which means 418 people involved. Whereas the previous study, “*a priori* method”, was based on more than 1 500 fatal accidents reports. Nevertheless, regarding these two studies, we can say that the eCall efficiency is included in an interval between 2.8% and 5%.

This new study allows refining the eCall system effectiveness with a 2.8% benefit. This result based on real world accidentologic data is in the lower range of numerous other international studies done in the past. Besides, this evaluation only concerns passenger cars with an equipment rate at 100 %. All these surveys allow us to define a realistic effectiveness interval of this device between 3% and 10%. It represents a real additional system against road deaths and injuries, in particular for accidents at night in rural areas involving a single vehicle.

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# BENEFIT ASSESSMENT OF FORWARD-LOOKING SAFETY SYSTEMS

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## ABSTRACT

Forward collisions are still the most relevant scenarios in the German accident situation with personal damage. Therefore forward-looking safety systems have a high potential to reduce the number of casualties or to mitigate their injury severity.

To assess the benefit of these forward-looking safety systems, a new benefit assessment method will be presented in this paper. The method uses real accidents out of the GIDAS. Additionally to the collision speed of the vehicle and other impact parameters, all accidents in GIDAS are reconstructed regarding the movement of all participants in the last seconds prior to the impact. This movement is used to simulate the accident initiation phase with and without the influences of forward-looking safety systems. Subsequent to this simulations the differences with and without safety system could be compared case by case. The results could be converted into different absolute measures like reduction of fatalities or severely injured pedestrians, using injury severity functions.

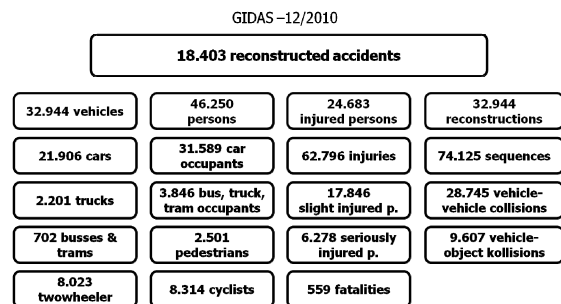
The results of this study are different correlations, depending on the system functionality, between the reduced impact speed due to braking prior to the crash and the assessed mitigation on injury severity. The results of the single case simulation could be summarized to access the overall benefit of these systems in the whole accident scenario.

With this method it is possible to assess the expected benefit of future safety systems or equally suitable to evidence the benefit of current safety systems on the market.

The papers show the detailed procedure of the method and some examples of usage the results.

## GIDAS

For this paper accident data from GIDAS (German In-Depth Accident Study) was used. GIDAS is the largest in-depth accident study in Germany. The data collected in the GIDAS project is very extensive, and serves as a basis of knowledge for different groups of interest. Due to a well defined sampling plan, representativeness with respect to the federal statistics is also guaranteed. Since mid 1999, the GIDAS project has collected on-scene accident data in the areas of Hanover and Dresden. GIDAS collects data from accidents of all kinds and, due to the on-scene investigation and the full reconstruction of each accident, gives a comprehensive view on the individual accident sequences and its causation.



**Figure 1 – extent of GIDAS real accident database**

As described in Figure 1 more than 18.000 complete reconstructed accidents are available in GIDAS.

The project is funded by the Federal Highway Research Institute (BASt) and the German Research Association for Automotive Technology (FAT), a department of the VDA (German Association of the Automotive Industry). Further information can be found at <http://www.gidas.org>.

## POTENTIAL OF FORWARD-LOOKING SAFETY SYSTEMS

Especially for the potential of forward-looking safety systems not only front to rear accidents are of interest.

Depending on the critical situation of each accidents, forward-looking safety systems could have potential for accidents that causes during

- turning off scenario
- turning into scenario
- crossing of pedestrians
- resting traffic situations
- longitudinal traffic scenarios.

The aspect of guilty or not could be in- or excluded in the analysis. For the used method in this study the question of guilt was not separated. So it is assumed for instance, that a system operates even when a critical situation occurs, independently of the question, who have had the right of way in the situation.

Following this aspects out of GIDAS nearly 56% of all first impacts of cars are frontal impacts, which could be defined as principally addressed by forward-looking safety systems. These principally addressed cases certainly include accidents where forward-looking safety systems will have partly, marginal or sometimes also no effect, but nevertheless this ratio shows the high priority of forward-looking vehicle safety systems to further reduce accident and injury severity.

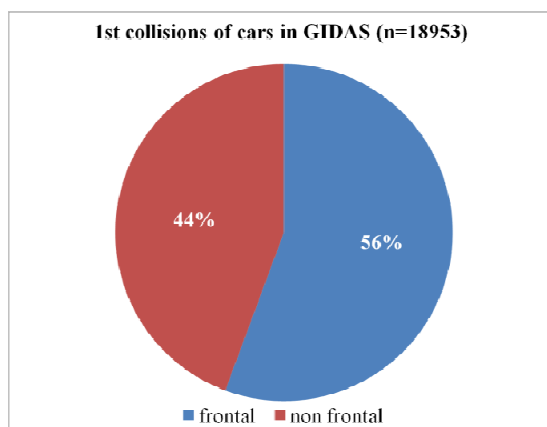


Figure 2 – First impacts of cars

Figure 3 shows the number of pedestrian which impact frontal to the car. This ratio of 71% is much higher than the average of all collision partners of

cars. It shows therefore the very high priority of forward-looking safety systems in car to pedestrian accidents.

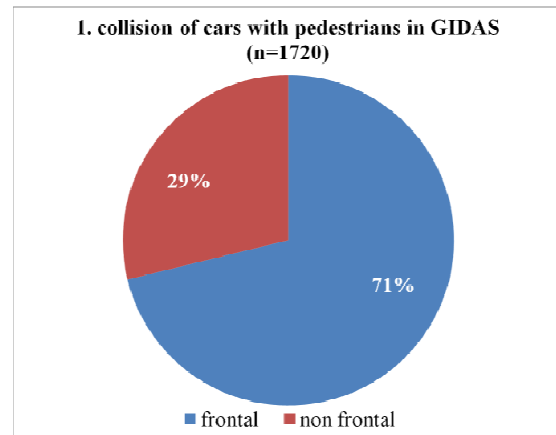


Figure 3 – First impact of cars with pedestrians

For a better description of the benefit assessment method in this paper, all further analysis and results are referred only to car to pedestrian accidents.

## METHOD TO ESTIMATE THE SYSTEM EFFECTIVENESS

In the past different methods were used to estimate the benefit of safety systems. Especially for forward looking safety systems, methods using simulation are coming more and more important. These mainly prospective analyses have the advantage, that already system in a status of an idea could be assessed regarding the benefit in real world accidents.

### Prospective case by case analysis

Prospective case by case analyses mostly using real world accident data. For this study the data from GIDAS effective 12/2010 was used. In Figure 4 the principle methodology of a prospective case by case analysis is shown.

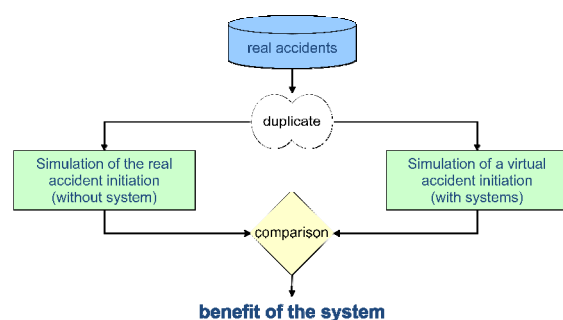


Figure 4 - Prospective case by case analysis

Every accident initiation phase will be simulated in detail to gain knowledge about the circumstance which leads to this accident. After that, the complete functionality of the system or system idea will be implemented in the simulation process. In this step a virtual accident initiation will be simulated, which includes all changes due to the system influence. Afterwards the differences between the real and the virtual accident simulation will be compared. These differences show directly the benefit of the system in the single case.

## SIMULATION OF ACCIDENT INITIATION SEQUENCES

To simulate the accident initiation sequences some information are necessary. In the following chapters the real as well as the virtual simulation of accident initiations will be explained.

### Information from accident site

The method uses detailed informations out of the accident sketch, which is available for all accidents in GIDAS. Figure 5 show an example of such an accident sketch.

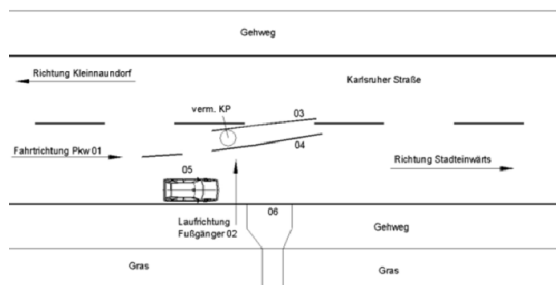


Figure 5 - Detailed accident sketch

Not all information of these accident sketches are important for the simulation process. Therefore only the necessary information as shown in Figure 6 are derived from the accident sketch.

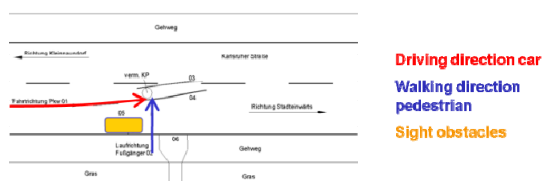


Figure 6 - Derived information from accident sketch

Additionally to these mainly static data of the accident site, the movement of all participants are necessary. These information are included in the accident reconstruction records of GIDAS. The initial movement as well as all sequences up to the first impact, the impact parameter and all post impact movements are recorded in detail in several records. This information is used to reconstruct and simulate the real accident initiation.

Figure 7 shows initial situation of the reconstruction.

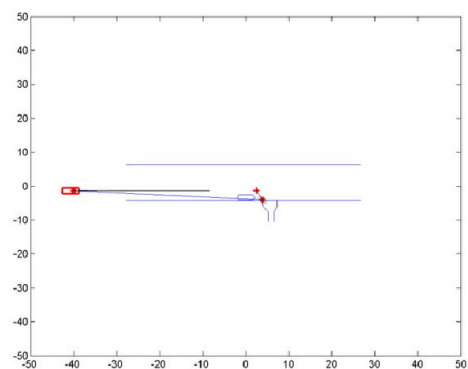


Figure 7 – Initial situation of reconstruction

### Simulation of the real accident initiation

Subsequent to the reconstruction of the accident, the complete initiation phase will be simulated using a dynamic computer simulation environment MATLAB, Carmaker or the like. In Figure 8 the result of such a computer simulation is shown.



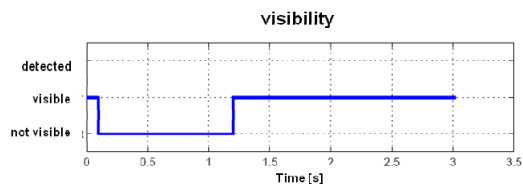
Figure 8 - Simulation of the real accident initiation (side view)

As shown in Figure 9 it is possible to vary the perspective on every static or dynamic point in the scenario.



**Figure 9 - Simulation of the real accident initiation (drivers view)**

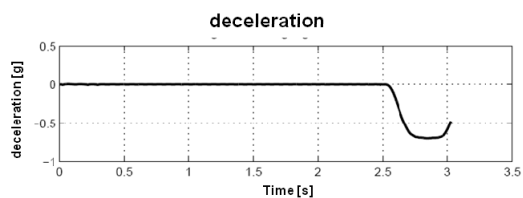
Parallel to the simulation it is possible to analyse different parameters chronologically. In Figure 10 the chronological visibility of the pedestrian due to view obstacle “parked car” is shown.



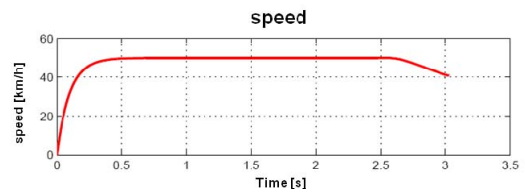
**Figure 10 - Visibility of the pedestrian in the real accident initiation**

The consideration of view obstacles is very important, cause of the known high influence in car to pedestrian accidents.

In addition to that the deceleration and consequent to that the driven speed are shown in Figure 11 and Figure 12.



**Figure 11 - Deceleration of the car in the real accident initiation**



**Figure 12 - Speed of the car in the real accident initiation**

With this detailed simulation of the real accident scenario it is possible to get a better understanding of the single accident and to define possible avoidance strategies.

### Definition of the forward looking safety system

To simulate a virtual accident initiation with the influence of a safety system, the system operating mode has to be defined previously. The more accurate the system is described, the better and the more robust results could be estimated.

Especially the following parameters, exemplary for a forward-looking sensor based safety system, have a high influence of the system benefit itself:

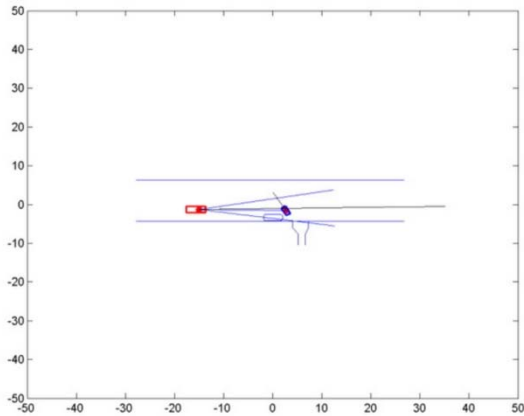
- Triggering algorithms
- Sensor characteristics
- Sensor position at car

The triggering algorithm is responsible for an early detection of the pedestrian and has therefore a direct influence on the benefit of the system. Nevertheless the system has to be considering that the rate of false positive is as low as possible.

The sensor characteristic itself describes the sensor range and angle. These parameters have also a direct influence on an early detection of the pedestrian. At last, the position of the sensor in the car (e.g. on the front or at the windscreen) has an influence on the detection of the pedestrian and therefore a direct influence on the system benefit.

In Figure 13 the definition of a forward-looking sensor based safety system is shown.





**Figure 13 - Definition of the forward-looking safety system**

With the detailed definition of the forward-looking safety system it is now possible to simulate the accident initiation again.

### Simulation of the virtual accident initiation with system

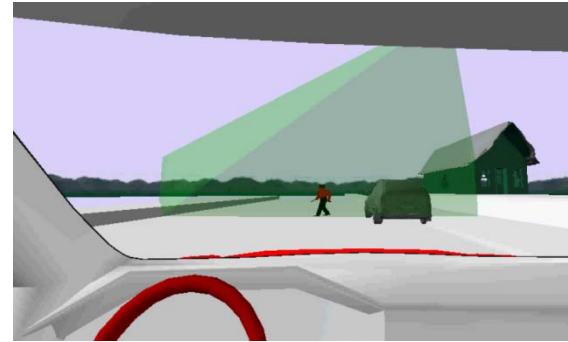
The simulation of the virtual accident initiation with safety system starts at the same initial situation as in the real accident situation.

Additionally the complete system operating mode was implemented in the car. Therewith the system interacts with the accident initiation situation and could reduce for instance the speed automatically if the pedestrian was detected.

In Figure 14 and Figure 15 the virtual accident initiation for the example case is shown.

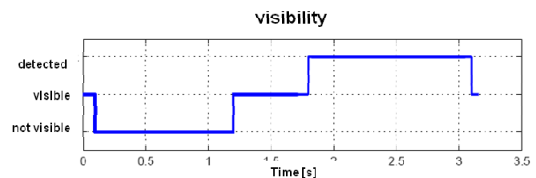


**Figure 14 - Simulation of the virtual accident initiation (side view)**



**Figure 15 - Simulation of the virtual accident initiation (drivers view)**

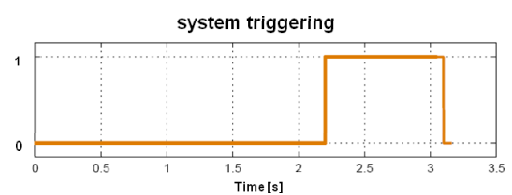
In Figure 16 the visibility and the detection of the pedestrian is shown in a chronological order prior to the crash.



**Figure 16 - Visibility of the pedestrian in the virtual accident initiation**

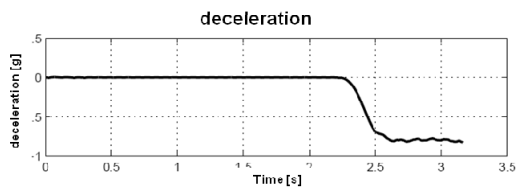
It could be seen, that nearly half a second after the pedestrian was visible (not behind a view obstacle), the system could detect the pedestrian.

In Figure 17 - System triggering in the virtual accident initiation Figure 17 the system activation is shown. This activation mainly considers to the system triggering algorithm.



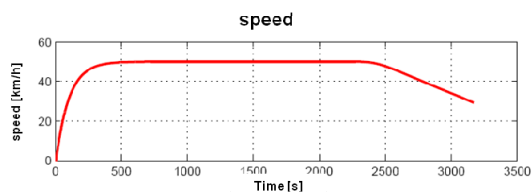
**Figure 17 - System triggering in the virtual accident initiation**

The system activation leads to an autonomous emergency braking of the car. This results in a deceleration as shown in the Figure 18.



**Figure 18 - Deceleration of the car in the virtual accident initiation**

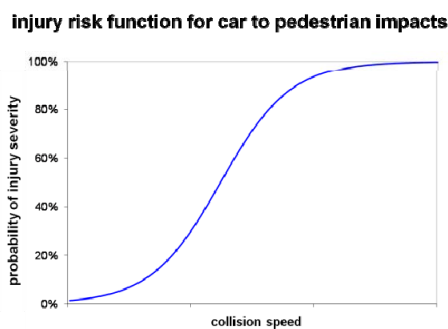
In Figure 19 the corresponding speed curve is shown.



**Figure 19 - Speed of the car in the virtual accident initiation**

In comparison to the real accident situation it could be seen, that the collision speed in the virtual crash scenario is reduced from nearly 40 km/h (see Figure 12) to less than 30km/h due to the activation of the forward-looking safety system and the autonomous emergency braking. The effect is limited due to the fact that the driver has also reacted in the real crash. (see Figure 11)

The reduced collision is now used to calculate the expected benefit in mitigation of injury severity. Therefore the injury risk function as shown Figure 20 was used.



**Figure 20- injury risk function for car to pedestrian impacts**

This described procedure for the single accident was further done for all car to pedestrian accident in GIDAS. With this method it is possible to estimate the overall real world benefit of this forward-looking safety system.

This overall benefit only depends on the system operating mode and the detailed defined and described triggering algorithm, sensor characteristics and position at the car.

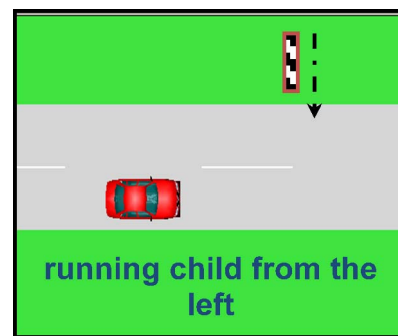
Due to those very specific properties of the single system, the results could not be generalized to other comparable forward-looking safety systems.

## CORRELATION BETWEEN TESTRESULTS AND REAL WORLD BENEFIT

To compare the system effectiveness between different forward looking safety systems a lot of test procedures were developed in the past. But the developed test procedures could only verify limited number of scenarios. Additionally that it could be only assumed that the test results of the scenario are correlating with the real world benefit of the system.

### Test scenario for forward-looking safety systems

In Figure 21 a typical test scenario for forward-looking safety systems is shown. The car often has an initial speed of about 40 km/h and the walking speed of the pedestrian is mostly near to 5 km/h.

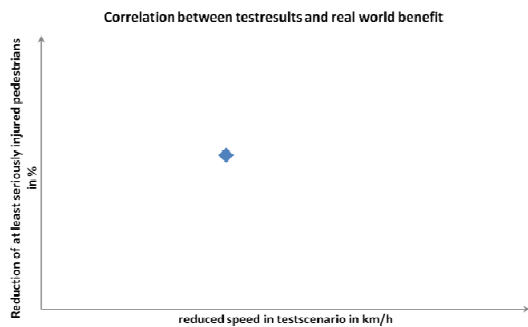


**Figure 21 – Test scenario for forward-looking safety systems**

Each system could be tested with this scenario. But depending on the system specification and operating mode, every system will have a specific test result.

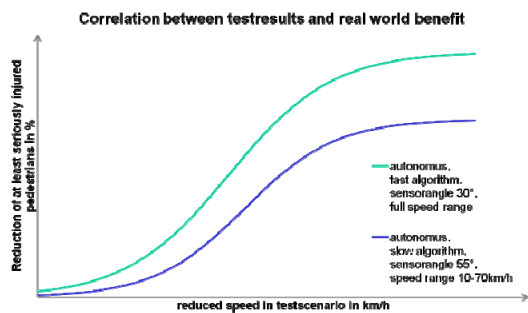
### Correlation to real world benefit

In Figure 22 a specific real world benefit in correlation to the result of this system in the test scenario is shown.



**Figure 22 - Correlation between testresults and real world benefit (single system)**

In a further step in this study correlation between comparable system configurations and the expected real world benefit regarding to the result of the test were developed.



**Figure 23 - Correlation between testresults and real world benefit (system groups)**

Like shown in Figure 23 it is possible, to correlate the result of the test scenario of a specific forward looking safety system to the real world benefit of this system.

Therewith it is possible to assess the benefit of forward-looking safety systems much more in detail. Especially properties of the system like system operating mode in darkness or speed ranges which do not have an effect in the testscenario could be considered due to the real world benefit of the system

This method is suitable to any test procedure so that rating methods could consider these system properties too. It is therefore qualified to include these system properties, which could not be directly tested. The test effort could be reduced and simultaneous the benefit of non testable properties could be implemented in the rating procedure.

## SUMMARY

The complexity of forward-looking safety systems will further increase in the future. Not all system specifications and properties could be tested with fungible expence. The paper describes a method to simulate all system specifications in detail using case by case simulations.

In addition to that system groups with comparable specifications could be assessed regarding the real world benefit. The correlation to different test scenarios and results gives the possibilities to include these properties into the real world benefit estimation.

Therewith the test effort could be reduced significantly and the accuracy of the benefit assessment could be further optimized.

# THE VICTORIAN INTELLIGENT SPEED ASSIST AND HEAVY VEHICLES TRIAL: ANALYSIS OF DEVICE ACCEPTABILITY AND INFLUENCE ON SPEED CHOICE

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Paper Number 11-0244

## **ABSTRACT**

The road safety benefits of Intelligent Speed Assist (ISA) have been demonstrated in passenger car trials. These benefits, however, have yet to be replicated in the heavy vehicle (trucking) industry. This small-scale trial conducted by the Transport Accident Commission (TAC) in collaboration with the Victorian Transport Association (VTA) with the cooperation of several heavy vehicle transport companies sought to assess the relative merits of ISA in terms of driver acceptability, speed choice, and fuel consumption.

The study was a pre-post design. Prior to the installation of the ISA device, a GPS device was fitted to six heavy vehicles and vehicle speed and trip characteristics were continuously recorded. An advisory ISA device was then installed for a period of four to six weeks. Seven drivers participated in the trial and completed a survey before and after the trial.

Prior to the study, six of the seven drivers stated they would find a device that would assist their speed choice to be useful, while four believed a device that would prevent them speeding would also be valuable. Following the trial, six drivers reported finding the system helpful in preventing

them from speeding, rating it as 5 or above on the 10 point scale. Opinions were more divided in terms of the accuracy of the speed limit map, with two drivers rating it as very poor.

Analysis of speed data indicated mixed benefits of ISA with a reduction of up to 21% in the odds of travelling over the posted speed limit; however reductions were speed zone dependent. ISA was most effective in improving compliance at the higher speed zones ( $\geq 80$ km/h) and not at all for the mid-level speed zones. Analysis of the speed data indicated an increase in the mean speed in the mid-level speed zones but a reduction in the lower and higher speed zones.

Device acceptability appears to play some role in the effectiveness of advisory ISA systems, however the relationship is complex. Further work that explores the relationship between acceptability of ISA and compliance with the assigned speed limit is required.

## **INTRODUCTION**

Speeding is recognised to be a leading contributor to the occurrence of crashes and their associated level of injury severity.[1-4] There is a considerable body of work that examines the factors associated with exceeding the speed limit,

and these include personal characteristics (e.g., age, gender), trip purpose, perceived level of detection by police, as well as the perceived credibility of the assigned limits themselves.[5-9]

Compliance with posted speed limits is a critical facet of a safe transport system.[10] As noted by Jiménez and colleagues, and supported by a large number of research studies, the setting of speed limits – and associated compliance, leads to more appropriate driving speeds and less variability in travelling speeds, leading to a safer road environment. [11] Speed has been identified as a major factor in heavy vehicle crashes and there has been a push both in Australia and globally to address speeding behaviour – as well as a range of other behavioural, organisational and vehicle safety concerns as a means of improving heavy vehicle safety.

### **Heavy vehicle safety and crashes in Australia**

In Australia, for the 12-month period ending June 2010, 258 people died as a result of 212 crashes that involved heavy trucks or buses. One-quarter of those killed were occupants of the truck/bus itself (60% single vehicle crash).[12] Truck-involved fatalities account for approximately one-fifth of those killed on Australian roads, despite representing approximately only 4% of registered vehicles in Australia.

This over-representation can be explained by increased vehicle mass and exposure. It has been reported that heavy vehicles account for 8% of the total kilometres travelled in Australia and on a per distance rate travel twice that of passenger vehicles.[13]

Given their high rates of exposure, transport drivers are unsurprisingly the most frequently involved group in work-related crashes in Australia. This was shown in a study of 13,124 drivers involved in crashes during the period 1997-2002 in New South Wales, Australia. In this study, nearly half of all fatalities resulting from work-related crashes were drivers of heavy vehicles and speeding was associated with 15% of crashes. [14]

An analysis of the Australian National Coronial Information System (NCIS) of heavy vehicle deaths in Victoria in the period 1997 to 2007 reported that speeding was associated with 36% of crashes where the driver of a heavy vehicle was killed. In this study all of the truck drivers that were killed were male, one-third involved the vehicle leaving the roadway and 17% of drivers were detected with an illicit drug in their system; seatbelts were worn by only 40% of the 61 drivers killed.[15]

The importance of the heavy vehicle industry to the economy – whether it be in the movement of goods

or people, cannot be underestimated. This will increasingly be the case in the future given that road freight is predicted to double by 2020. With fuel costs expected to rise [16, 17], the role of speed management in assisting drivers and helping companies reduce crashes, contain costs and remain competitive is thus likely to play an increasingly important role in the operational plans of many transport operators. It is within this context that government regulation and road safety management plans are likely to be crucial.

### **Regulations and road safety management systems focussed on heavy vehicles**

In recognition of the importance of the transport sector to the economy, governments have increasingly relied upon regulations that focus on improving safety in the sector. Bodies such as the USA Federal Motor Carrier Safety Administration (<http://www.fmcsa.dot.gov/>)[18], the National Transport Commission in Australia (<http://www.ntc.gov.au/>)[19] and the European Commission (<http://ec.europa.eu/transport>)[20] have regulations focussed on professional drivers that cover driver licensing, alcohol and fatigue control, the transportation of dangerous goods as well as vehicle dynamics. The explicit link between scheduling and the adherence to speed limits has been recognised through the introduction of regulations designed to control the expectations of transport operators and their clients with respect to delivery times.

In addition to regulations, road safety management plans are becoming increasingly common in the private sector. This has stemmed from a recognition of the significant loss of productivity associated with crashes and the resultant injuries.[10] Indeed, the Michelin Challenge Bibendum Road Safety Taskforce notes that much can be achieved in the reduction of work-related crashes though the ‘*collective mobilization of private companies*’ though the adoption of innovative policies.[21]

The proposed ISO Standard for *Road-traffic Safety Management Systems – Requirements and Guidance for use (ISO 39001)*[22], currently under development (<http://www.iso.org>), falls under the ambit of occupational health and safety in the transport sector domain and is designed to promote effective road safety management. A key component of effective road safety management in the fleet context is speed control. In Australia this has been recognised by the Australian Transport Council who set a target of a 30% reduction in heavy vehicle associated crashes due to improved speed management.[13] New active safety system technologies, such as Intelligent Speed Assist devices (ISA), offer a potential way to assist the

driver – and the fleet operator, in ensuring speed limit compliance.

**A role for Intelligent Speed Assist (ISA) Systems in heavy vehicles**

Advisory ISA systems are a driver support system that uses knowledge of the road network and GPS technology to improve compliance with the posted speed limit by delivering visual and / or auditory warnings to the driver. More interactive ISA systems actively discourage (via haptic feedback) or prevent the driver from exceeding the speed limit (i.e., intervening, over-rideable or not over-rideable). [23-26]

A number of studies have documented the benefits of ISA technology in ‘reducing speed, speed variability and speed violations’.[23, 25, 27, 28] Devices that exercise a greater control over the driver are seen to be most beneficial, as opposed to simple advisory systems, however these controlling systems are less likely to be acceptable to drivers.[23, 26] Reductions in mean speed, the 85<sup>th</sup> percentile speed and percentage of distance travelled over the speed limit have all been documented with the use of ISA.[25, 28] Using these observed reductions in speed, substantial reductions in the number of crashes and of individuals injured have been estimated.[29]

Despite these benefits, a number of negative effects have been observed with ISA. Two key issues are the acceptability of the system warnings [11] and driver adaptation or system over-reliance. [23, 25, 26, 30] System over-reliance is of concern as faster speeds on bends and in approaching intersections have been observed. In addition, young drivers and males appear to be less accepting of the ISA device and it is precisely this group that could benefit most from ISA given their heightened crash risk.[28]

While the beneficial effects of ISA have been demonstrated in passenger cars, no study had demonstrated the value of ISA in heavy vehicles at the time this study was planned. This was despite the findings of a comprehensive review undertaken in 2003 by Regan, Young and Haworth that concluded that ISA systems have the potential to deliver a range of benefits for the heavy vehicle industry, including improved speed control and improved fuel efficiency.[31]

This study set out to examine whether the potential benefits of ISA observed in passenger cars would translate to heavy vehicles.

**The current study: a real-world trial of ISA in heavy vehicles in Victoria**

The Transport Accident Commission (TAC) in collaboration with the Victorian Transport Association (VTA) and with the cooperation of

three heavy vehicle transport companies conducted a small scale trial in an attempt to assess the relative merits of ISA in terms of speed choice, driver acceptability and fuel consumption.

A preliminary paper published elsewhere examined in detail the pre-and post-survey (qualitative) responses for all drivers in the trial and used on-road data for two drivers to examine the on-road effect of ISA. The preliminary analysis reported mixed findings with the level of benefit being speed zone dependent.[32]

This paper presents an examination of the effect ISA has on the change between the number of recorded occasions the driver exceeded the assigned speed limit in the baseline (pre-ISA period) period compared to the ISA trial period, overall and for each speed zone. Also of interest was the association between the perceived usefulness of the device and compliance with the speed limit.

**METHOD**

**Participants**

Seven drivers from three transport companies agreed to participate in the trial. The drivers provided informed consent to participate and each completed a questionnaire before and after the completion of the study.

Participating companies/vehicles were selected on the basis of the following criteria:

- they had significant Victorian-based long distance travel undertaken by a number of company vehicles;
- trucks in the study were of similar makes and models and operate repeat trips within Victoria, and
- the company is committed to providing data for evaluation purposes and to allow access to drivers for a briefing session and to complete pre-/post-questionnaires

**Design of the trial**

The trial was designed as a pre-post study of ISA. (Figure 1). Phase 1 collected baseline data using a GPS logger while Phase 2 was the ISA trial period. Hence the trial was a simple baseline vs. ISA trial of the effect of ISA in improving speed limit compliance.

Phase 1	Phase 2
Baseline speed assessment (‘baseline’)	ISA trial period (‘trial’)

**Figure 1. Design of the ISA trial**

Each Phase differed slightly in duration for each company and driver for operational reasons. In general, Phase 1 was approximately four weeks in

length while Phase 2 was approximately 8 weeks duration.

### **The ISA device for use in the trial**

The ISA technology deployed was advisory; that is, it did not limit the speed of the vehicle but simply provided the driver with auditory and visual warnings when the speed limit was exceeded. No data was collected by the advisory ISA device but rather it served purely to advise the driver of the speed limit at each particular moment in time. The ISA device was programmed to alarm when the driver exceeded the assigned speed limit by two km/h for a period of two seconds or more. The driver could override and switch the ISA device off if needed. No data was collected from the vehicle speedometer though the ISA device was calibrated to the speedometer.

### **Data sources**

Data collected in the trial included a pre-post participation questionnaire, the logged trip data referred to as the GPS-Enhanced data and the Transport Operator Trip logs. Each is discussed below.

**Survey data** - A *pre-trial survey* was completed by each participating driver with the aim of capturing a range of attitudes to speeding and the likely benefits of 'smart' technology in aiding the driving process. Attitudinal data was collected using either a 5-point Likert scale (1: strongly disagree to 5: strongly agree) or via free text responses. Demographic information was also collected.

A *post-trial survey* was completed to obtain feedback concerning the usability and acceptability of the ISA device, as well as attitudes relating to road safety more generally. A number of attitudinal questions were repeated from the pre-trial survey, permitting a pre-post analysis to be undertaken.

**GPS-Enhanced data** – In Phase 1, the baseline period, a GPS data logger was installed into the truck to collect speed and associated trip data. Drivers were aware of the data logging capability of the GPS device however they could neither see nor interfere with the device.

The GPS device continually collected detailed information in 15 second cycles. For each cycle, speed (km/h) was captured as were GPS co-ordinates, time and date, distance covered (metres) and bearing / heading.

The GPS logged data was enhanced via linkage with the Victorian road network using Geographic Information System (GIS) software. Vehicle position was established using the longitude and latitude of each cycle. Of particular relevance was

the assignment of the speed limit of the road for each recorded cycle. Allowance was given for school day periods associated school speed zones and shopping zones with variable speed signs. The linkage was conducted by the Roads Corporation, Victoria (VicRoads).

**Transport Operator Trip Logs** – At the conclusion of the trial, companies provided extensive trip logs for each of the trucks involved in the trial. This included the drivers of each trip, the date of vehicle use, destination, odometer readings, load mass, and fuel consumption or fuel refill amount and date. The time of day that the trip was undertaken and completed was not reported in the trip logs.

The trip logs were critical in determining which data cycles to analyse. While two drivers were the sole drivers of their vehicles for the duration of the trial, one truck was driven by five drivers, two of whom were in the study; one truck was driven by 10 drivers (one in trial) 1 truck was driven by 11 drivers (one in trial), while another truck was driven by 19 drivers. It was then necessary to link the driver log data to the GPS enhanced dataset to ensure that only those drivers that were enrolled in the trial (i.e., drivers of interest) were included in the analysis. Where multiple drivers drove the truck on a single day, data pertaining to that day was excluded from the analysis.

### **Data Analysis**

A single database was constructed that linked the pre-/post-survey data, the trip log data and the GPS Enhanced dataset. This dataset formed the basis of the analysis reported here.

For the survey data, median values and the associated range among respondents were presented due to the ordinal nature of most of the items and the small sample size. Non-parametric statistics were used to examine pre-post survey responses where appropriate.[33]

The principal outcome of interest was the change in the number of cycles that the vehicle travelled over the posted speed limit following the installation of the ISA device compared to the baseline period. Analysis of the effect of ISA included time cycles 'where the vehicle was in motion and the speed limit of the road was known'. Hence, this excluded cycles: i.) where the vehicle was not in motion (including when stationary at lights or off-road), and / or ii.) where the assigned speed of the vehicle was unknown.

To examine the change, if any, in the number of timed cycles the vehicle exceeded the assigned speed limit, calculation of the percentage point difference in cycles over the speed limit was determined overall and for each speed zone.

A General Estimating Equation (GEE) logit model was used to assess the effectiveness of the ISA device [34-36]. The GEE logit model was considered the most appropriate model given the repeated measures nature of the data with speed captured in 15-second cycles and the fact that each subsequent 15-second cycle would be correlated with that immediately prior, with this correlation likely diminishing with every cycle; that is, for repeated observations taken through time, those observations taken more closely to one another in time are likely to be more highly correlated than those taken further apart - this is known as an *autocorrelation*. It is critical to specify the nature of the working correlation matrix in order to account for the within-subject correlations. Ideally we would specify an unstructured matrix as this states that the correlation between any two cycles is unknown and thus needs to be estimated. An alternative model uses an autoregressive matrix of the first order (AR(1)) which would be acceptable as the interval length is constant between any two observations although this is not always true. Due to computational limitations (i.e., processing power, number of observations), an exchangeable within-subject correlation matrix was used. The autocorrelation matrix used assumes that the correlation between any two responses on any one driver is the same

The base main effects model of the effect of ISA on vehicles travelling in excess of the posted speed limit was: speed zone (note: 80km/h + was used in the model due to the GEE failing to converge when all speed zones were included), day of week, and the post-ISA device rating of the usefulness of the device. The repeated measures term was the driver variable. The dependent variable was the vehicle travelling over the posted limit, expressed as a dichotomous outcome.

Analysis was performed in SAS V9.2 of the SAS System for Windows.[37] Statistical significance was set at  $p \leq 0.05$ .

### Ethics approval

The trial was conducted by the Transport Accident Commission with the data analysis conducted with the approval of the Monash University Human Research Ethics Committee.

## RESULTS

### Driver characteristics

The characteristics of the drivers are presented in Table 1 below. All of the drivers were male, 4 were aged under 50 years of age, and driving experience ranged from 10 – 19 years (median: 19 years). None of the drivers had heard about ISA prior to the commencement of the trial.

**Table 1. Characteristics of the drivers involved in the trial**

Characteristics	Number	Percent
Male (%)	7	100
Age category		
30 – 39	2	28.5
40 – 49	2	28.5
50 – 59	2	28.5
60+	1	14.25
Fined for speeding prior 5 years	2	28.5
Heard of ISA before trial	None	None
Driving experience	10 – 45 years, median: 19	

### Pre-trial views of speed assist devices and speed behaviour

Drivers were asked a series of questions as to whether they would find a ‘smart’ speed warning device useful and their awareness of the speed limit when driving (Table 2).

Despite none of the drivers having heard of ISA prior to the trial, 6 of the 7 agreed that they would find a device that told them whenever they exceeded the speed limit useful. These same 6 drivers agreed that they sometimes exceeded the speed limit without realising it, and of these four agreed that they would find a device that stopped them going over the speed limit useful; the other two drivers who agreed that a simple advisory device would be useful altered their view to neutral on the usefulness of a more controlling device after the trial had concluded.

Three of the seven drivers stated they were neutral to *always being aware of the speed limit*, two agreed, and one disagreed. In combination, these findings suggest these drivers might find value in an ISA device. On the other hand, one driver disagreed that any device – advisory or controlling, would be useful, was neutral to ‘sometimes going over the limit without realising’ and strongly agreed that he was always aware of the speed limit. These divergent views are important to consider in the subsequent findings presented below.



**Table 2. Pre-trial views of the perceived usefulness of ISA and speeding behaviour**

Rating item	Median †rating	Range‡
A device that told me whenever I went over the limit would be useful	4 (agree)	2 - 5
A smart device that stopped me from going over the speed limit would be useful	4 (agree)	2-5
I go over the speed limit sometimes without realising it	4 (agree)	3-4
I am always aware of the speed limit	3 (neutral)	2-5

† Rating scale: 1 – strongly disagree; 2 – disagree; 3 – neither; 4 – agree; 5 – strongly agree

**Post trial driver views of ISA captured by the survey**

At the conclusion of the trial drivers were asked to rate ISA according to how useful it was, its road safety benefits, how helpful it was, and how accurate it was, using a 10 point scale (with 10 as the highest most positive rating). The responses were as follows:

- Five drivers reported finding the system useful and to have road safety benefits, rating it as 5 or above on a 10 point scale;
- Six drivers reported finding the system helpful in preventing them from speeding, rating it as 5 or above on the 10 point scale
- Four drivers rated the accuracy of the speed limit map as 6 or higher, while one driver gave a rating of 4 while two drivers gave the lowest possible rating of very poor (1)
- Four of the seven stated they needed to over-ride the system or turn it off at some point;
- Six of the seven stated that the default volume for the auditory warnings was acceptable, while one stated it was too loud, although six stated the volume should be controllable, and
- To the question of whether drivers looked at the speedometer less due to the presence of the ISA device, three agreed, two were neutral and two strongly disagreed; of the latter two, one rated the digital speed map as very poor while the other suggested a device to show the speed prior to exceeding the limit –

notably, this driver also pointed to the issue of calibration of the device and the difference in reading against the truck speedometer.

Finally, the pre- and post surveys indicated that the drivers held very conservative views of speeding, universally disagreeing to questions such as, *I think it is ok to drive a little bit faster if you are a good driver* and *It is easy to avoid being caught speeding*.

**Summary of recorded 15-second cycles**

The GPS recorded vehicle movement and associated information every 15-seconds. Only cycles where the where the truck was moving were used in the analysis, and those periods where the truck was off-road and stationary or stopped in traffic were excluded. There were somewhat fewer cycles recorded in the baseline period than during the ISA trial period, with the total recorded moving time translating to 934.4 hours and 1082.7 hours of continuous driving respectively; in total, 2017 driving (moving) hours were recorded. The crude odds ratio for an ISA benefit was 0.82 (95<sup>th</sup>% CI: 0.81-0.83), which means that the crude (unadjusted) odds of travelling over the speed limit when ISA was active were 18% lower than during the baseline period.

**Table 3. Overall data collected, including consideration of under/at vs. over limit (vehicle moving)**

	Baseline	ISA
<b>Time cycles captured</b>	224,269	259,870
Under or at limit	192,999 (86.1%)	229,386 (88.3%)
Over limit	31,270 (13.9%)	30,484 (11.7%)

**Effect of ISA on the speed profile**

ISA has been shown previously to influence speed distributions differentially according to speed zone. Table 4 presents evidence for an increases in the overall mean speed and notable increases in the mean speed and median in the 50km/h zone, the 60 km/h and the 70 km/h speed zones.

In contrast, reductions in the mean speed can be observed in the 80 km/h, 100 km/h and 110 km/h speed zones. There was little difference in the median and the 85<sup>th</sup> percentile speeds travelled.

**Table 4. Speed profile before and during ISA installation**

Speed zone(s)	Baseline Mean speed; Median; 85 <sup>th</sup> %	ISA Mean speed; Median; 85 <sup>th</sup> %
Omnibus† (all)	77.7; 92; 100	78.5; 92; 100
40 km/h	28.9; 29; 44	29.2; 29; 44
50 km/h†	27.9; 18; 53	31.9; 26; 55
60 km/h†	41.2; 45; 59	42.5; 47; 60
70 km/h†	46.9; 51; 68	48.7; 53; 70
80 km/h‡	65.1; 70; 82	63.8; 69; 81
90 km/h	78.4; 81; 99	79.4; 85; 99
100 km/h‡	92.3; 98; 101	91.9; 98; 100
110 km/h‡	97.4; 100; 101	95.1; 100; 100

† P ≤ 0.05, Higher ‡ P ≤ 0.05, Lower

#### Regression modelling of the effect of ISA

Using the recorded speed and the assigned speed limit to the road, we determined the number of cycles where the vehicle exceeded the posted speed limit. We can see an overall 2.23 percentage point reduction in the total number of 15-second cycles over-limit in the ISA trial period relative to the baseline period; this is derived by simple subtraction of the percent cycles over the limit in the ISA trial period (11.74%) from the baseline period (13.98%).

The GEE logit regression model was used to assess the influence of the ISA device on episodes of exceeding the speed limit. In short, after adjusting for correlated outcome data and controlling for speed zone, day of week and the post-ISA trial rated ‘usefulness’ of the device, the odds of the drivers exceeding the speed limit were reduced by 21% compared to the pre-trial period. This difference was statistically significant (OR: 0.79, 95<sup>th</sup>% CI: 0.70 – 0.91, p=0.001).

As evident in Table 5, this positive benefit of ISA was not uniform across speed zones, with benefit observed in the 50km/h (OR: 0.86, 95<sup>th</sup>% CI: 0.79 – 0.94, p=0.002) and the 80km/h and faster speed zones (OR: 0.73, 95<sup>th</sup>% CI: 0.63 – 0.88, p=0.001). The 50km/h result appears anomalous given the higher percentage point increase in being over-limit and the negative OR that indicates a benefit; the OR result is a consequence of effect of the covariates and / or the effect of one driver being over-represented in this speed zone (as an aside, this is known as Simpsons Paradox). It remains the

case that the adjusted OR is the appropriate value to interpret and is indicative of a significant benefit of the ISA system.

**Table 5. Effect of ISA device overall and by speed zone on the number of recorded violations of the speed limit**

Effect of ISA device	% point diff. in over-limit	Association with over-limit cycles		
		OR	CI	P
Omnibus (all speed zones)	-2.23	0.79	0.70-0.91	0.001
40 km/h	-1.30	0.91	0.48-1.73	0.7
50 km/h	+4.74	0.86	0.79-0.94	0.002
60 km/h	+1.39	0.99	0.74-1.31	0.9
70 km/h	+3.87	1.01	0.74-1.37	0.9
80 km/h plus	-3.33	0.73	0.63-0.88	0.001

#### Post-trial attitudes to the usefulness of the ISA device

Of interest was the association between attitudinal responses to the acceptability and usefulness of the ISA device and travelling over the posted speed limit. This was modelled in the same GEE model as presented in Table 5. Table 6 shows that for driver responses as to the usefulness of the ISA device (rated on a 1, not at all to 10, extremely useful), there was little association overall. However it can be seen that for every 1-point increase in perceived usefulness of ISA there was a 17% lower odds of exceeding the speed limit in the 60 km/h and 70km/h zones. This finding could be a manifestation of drivers relying on the ISA system and hence there is no change in the vehicle over-limit episodes. This is supported by a higher mean speed in these zones in the ISA trial compared to baseline. It is possible the truck drivers take more immediate preventative action in these road contexts when the device alarms given the increased complexity of the environment. As the ISA device was calibrated to the speedometer and drivers rely on the device to monitor their speed, and consequently there was no difference in vehicle over-limit episodes between the two periods; this explains nicely why there is a relationship between perceived usefulness of ISA in these speed zones with respect to a reduced likelihood of exceeding the assigned limit.

**Table 6. Association between rated ISA device usefulness and over-limit episodes**

Effect of ISA device (pre-post), overall and by speed zone	Association with over-limit cycles		
	OR	CI	P
Omnibus (all speed zones)	0.96	0.41-1.29	0.3
40 km/h	1.20	0.93-1.54	0.2
50 km/h	1.12	0.84-1.50	0.8
60 km/h	0.83	0.75-0.92	≤0.001
70 km/h	0.83	0.75-0.92	≤0.001
80 km/h plus	0.73	0.41-1.29	0.3

## DISCUSSION

Despite the small scale nature of this trial, which involved seven drivers from three trucking companies, the richness and volume of the data lead us to report four key findings with respect to the implementation of ISA.

First, the drivers who had previously not heard of ISA prior to the introduction of the trial and who reported uniformly conservative attitudes to speeding reported differential levels of acceptability and usefulness of the ISA device. This was despite the finding that most of the drivers agreed or strongly agreed prior to the trial that a device that informed them they were exceeding the speed limit would be useful, as would a device that prevented them from speeding.

Second, there was an increase in the mean travel speeds in the lower range speed zones and a reduction in the higher speed zones with the introduction of the ISA system. There have been previous reports of drivers 'driving to the ISA device' and our results appear to reaffirm this at least in the case of the lower speed zones.

Third, there was a statistically significant 21% reduction in the odds of exceeding the posted speed limits overall, though this effect was not uniform and was present in the lower end and was particularly pronounced in the high-end speed zones. ISA had little influence on the odds of exceeding the speed limit in the 60 km/h and 70km/h zones, though importantly the mean speed in these zones did increase significantly.

Fourth and finally, we explored the survey responses with respect the perceived usefulness of the ISA device. It was interesting that the relationship emerged in the 60km/h and 70km/h

speed zone in the absence of an ISA effect and in the context of higher mean speeds. This provides further support for the notion that in these speed zones, which tend to have much greater complexity in the environment, that drivers rely on the ISA device, which when it alarms they react accordingly and slow down; hence there was no observable statistical benefit of the ISA device since the ISA device was calibrated to the speedometer. This could give drivers an opportunity to place greater emphasis on recognizing and responding to road hazards, and hence these results also explain the finding that the perceived usefulness of ISA was associated with the likelihood of exceeding the assigned speed limit.

That a beneficial effect of the ISA device was present in the higher speed zones is reassuring, particularly as it is these zones that there is more opportunity for 'free speed' driving uninfluenced by the presence of other drivers.

Analysis of the post-trial survey data reported previously bear relevance to the new findings report here. [32] The survey results reported previously found that despite most drivers regarding ISA as helpful in preventing them from speeding, the majority were not interested in being involved in future ISA trials. This pointed lack of enthusiasm might be a consequence of some of the practical issues and perceived limitations of the ISA device that became evident in the rollout of the trial. Three of the seven drivers reported needing to override the system during the trial while two drivers needed to turn the system off, principally due to inaccuracies in the speed limit map; one also expressed a profound dislike for the auditory warnings. Once the inaccuracies in the speed limit map became evident in the early phase of the trial, considerable effort – both financially and in person hours, was put into upgrading the speed map which was of benefit to the drivers who entered the trial at a later date. In addition to ensuring a 'perfect' speed zone map to the extent possible, modifications to the devices such as the inclusion of a volume control button and the redesign and customisation of auditory warnings could help build greater acceptance of the technology among heavy vehicle drivers.

## Limitations and Lessons

In the analysis of the trial two key technical matters came to light, the first relating to the matching of the GPS co-ordinates to the exact location and hence speed zone, and the second concerns the statistical analysis methods utilised for this type of data.

The first issue is a technical concern that relates to the imperfect matching of the longitude and

latitude co-ordinates of the road on which the vehicle was travelling with respect to assignment of the speed limit. This appears to be due to a lack of precision and ability to differentiate the speed zones at certain locations, for instances on bridges and service/slip roads. Our investigations do however indicate that i.) the error rate is low, and ii.) the error would be systematic and hence unbiased with respect the pre-post installation period of the ISA device. We are further benefited in this trial by the truck drivers in the study driving consistent routes, commencing each day at largely the same point of origin and driving a consistent pattern of destinations. Consequently we consider that our percentage difference of cycles and Odds Ratio values comparing baseline to the ISA trial period would not be biased by this problem.

The repeated measures nature of the data collected and the dichotomous outcome (i.e., vehicle over-limit) presented a considerable analytical challenge, particularly as the relatively new GEE logit model was used in this analysis. Despite having over 500,000 records, admittedly for only seven drivers, we were limited in the number of covariates that we could model, while the modelling of interactions proved extremely difficult. The inclusion of covariates in addition to the day of week and a single attitudinal measure of acceptability such as time of day, weather conditions, and additional demographic, route and vehicle characteristics would be ideal, however vast number of observations would be required and the associated computing power required would be immense.

Finally and as already noted, we report the difference in the percentage of cycles over the assigned speed limit. This is an important methodological consideration as the 15 second interval, while used to capture cycles over the assigned speed limit, is unlikely to represent a singular speed violation episode, particularly given the mass, and hence momentum of the truck. That is, it is most probable that a number of sequential 15-second cycles represent a singular speed violation episode. Future analysis will need to determine an appropriate algorithm in order to discriminate 'speeding' behaviour associated with throttle control from braking and gliding as a means of slowing down once an ISA speed alert has activated.

## CONCLUSIONS

In summary, the TAC in collaboration with the Victorian Transport Association (VTA) and with the cooperation of several heavy vehicle companies conducted a small scale trial to assess the relative merits of ISA in terms of driver acceptability and speed choice. By the conclusion of the trial, there was a divergence of opinion with respect to driver

acceptability of the device with some key issues emerging that require further investigation. In particular, further work is required on this dataset before a complete understanding of the relationship between acceptability and the effectiveness of ISA in mitigating speed among this group of drivers can be gained.

Overall, there was a significant 21% reduction in the likelihood of drivers exceeding the speed limit in the ISA trial period compared to the baseline period, and this effect was particularly strong in the higher speed zones. Despite a number of significant challenges both in the conduct of this research and the analysis of the collected data, the positive results encourage the initiation of larger-scale trials of active safety technology in the heavy vehicle industry. Further analysis is required to determine whether the differences in speed compliance result in fuel consumption benefits.

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## NOTE

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# The Efficiency of PRE-SAFE® Systems in Pre-braked Frontal Collision Situations

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## ABSTRACT

Vehicle safety today is evaluated on the basis of standardized crash tests. The goal is to classify the level of safety using tests which can be reproduced and repeated at any time. In laboratory tests, the evaluation of safety systems and their assessment for effectiveness commonly begins after the time of collision.

In a real accident situation, conditions could, however, be different. In accident situations, passenger car occupants are already exposed to lateral or longitudinal acceleration forces resulting from emergency braking or skidding. These accelerations lead to occupant displacements and thus to situations in which occupants are no longer in their initial positions when the collision occurs. This naturally affects the protective efficiency of the restraint systems. The development of modern systems to prevent accidents or reduce their severity will cause such situations to occur much more frequently in the future. Autonomous emergency braking systems accordingly reduce the impact energy on the one hand, but have a considerable influence on the occupants' interaction with the vehicle on the other hand.

There are currently no tools available for determining the impact of a dynamic driving situation and of the resulting change in a restraint system's protective efficiency. Nor are there any comparisons available on the behavior of human beings, as opposed to crash test dummies, in the low g-phase immediately before a collision.

The objective of this paper is to find and evaluate a method for approximating the crash test for exemplary dynamic driving responses in the case of longitudinal traffic escalation. This paper thus begins by identifying, by means of selected examples, the

problems faced when comparing real accidents and crash methodology.

In studies on the behavior of real vehicle occupants and crash test dummies in dynamic driving situations, movements are analyzed and differences described. The behavior of the dummies tested in such dynamic driving situations is analyzed with regard to shortcomings and potential points of action. To assess points of action for their efficiency, specifically performed crash tests including previous dynamic driving brake responses are discussed and evaluated. A concluding assessment of the behavior of both the occupant and the dummy aims to determine the suitability of crash measurement data for evaluating the overall situation.

## INTRODUCTION AND MOTIVATION

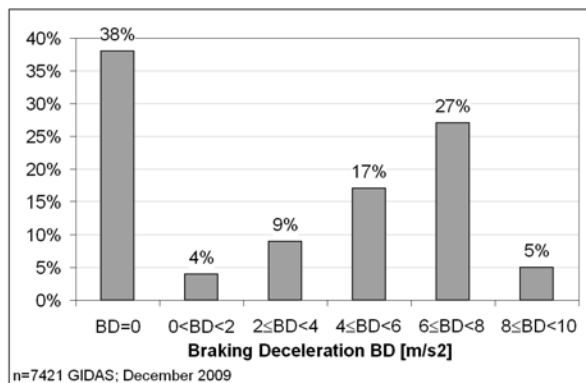
Automotive safety has made significant strides in the last 30 years. Today, vehicles are equipped with effective restraint systems such as airbags, seat belts with belt tensioners and force limiters, integrated deformation zones and deformation-resistant passenger cells, as well as coordinated structural and restraint measures. All of these features have resulted in an optimization of the effectiveness of the safety systems. In addition to these passive safety features, today's vehicles feature a very high level of safety thanks to supplementary active safety systems such as antilock systems ABS, electronic stability program ESP and brake assist system BAS. These systems are already, to a very large extent, available as standard and are supplemented by optional support systems. Vehicles may be equipped with active safety systems for distance warning and control, including the emergency braking function, as well as systems for lane holding. In the transition area between active and passive safety, new functions (e.g. PRE-SAFE®) can help create advantageous occupant positions in critical situations. Reversible measures are implemented if these systems detect situations, via

sensors for monitoring the vehicle environment, which are critical and could result in an accident. These reversible measures, such as belt tensioning or the correction of unfavorable seat settings, help to improve the situation for the occupants. To accomplish this, the systems use sensors such as wheel speed, yaw, roll, pitch and deceleration sensors for early accident detection and to determine the accident severity by means of algorithms which have been specifically formulated for interpreting the vehicle environment. The automated response of the vehicle is comparable to how a person responds, in terms of their reflexes, in a critical situation. The vehicle responds and thus protects the occupants. Sensors and actuators are heavily interlinked for this purpose.

Current crash test methodologies do not include the influence of dynamic driving variables on the occupant/vehicle position prior to a crash test. However, this is required in order to conduct a thorough assessment of the entire accident situation in a holistic manner. No simulation or experimental tools currently exist for evaluating the effects of pre-crash dynamics. This paper is intended to highlight a pragmatic method for this purpose.

### PROBLEM IDENTIFICATION

The German In-Depth Accident Study database (GIDAS) was analyzed to evaluate frontal collisions in which the braking deceleration was documented. A deceleration greater than/equal to  $4 \text{ m/s}^2$  was documented in 49% of the resulting 7421 cases. Approximately one third of all cases documented severe braking deceleration levels greater than  $6 \text{ m/s}^2$  (Figure 1).



**Figure 1: Distribution of the braking deceleration in the case of a frontal impact**

This high proportion of accidents preceded by severe braking deceleration justifies an investigation of the effects of deceleration on the position of the

occupants at the start of the accident and the effects of these positions on occupant loads. If emergency braking is initiated by the driver or an autonomous braking system before a potential collision, then this results in a forward displacement of the occupants with a correspondingly high deceleration. Passengers are, in particular, often surprised by the accident prevention response and cannot, therefore, counteract the displacement with an appropriate body response.

PRE-SAFE® can reduce the forward displacement during emergency braking by means of a reversible belt tensioner as shown in Figure 2. Two restraint scenarios are compared in this figure. In one situation, the occupant has been restrained in an emergency braking situation by means of reversible belt tensioning, while the occupant is restrained by means of the vehicle-sensitive belt lock in the other depicted situation. The resultant forward displacement path depends on the vehicle deceleration, the size and weight of the occupant, the leverage ratios between the hip and clavicle as well as the seating position and the resulting geometry of the three-point seat belt. These diverse parameters and how precisely they affect an average occupant displacement thus had to be ascertained in a road test study involving human test subjects.

### ROAD TEST STUDY, INVOLVING HUMAN TEST SUBJECTS, ON OCCUPANT BEHAVIOR IN BRAKING SITUATIONS

A road test study, involving human test subjects, was carried out prior to the crash tests in order to determine occupant behavior in emergency braking situations.



**Figure 2: Longitudinal displacement of the occupant in the case of a braking maneuver with/without PRE-SAFE®**



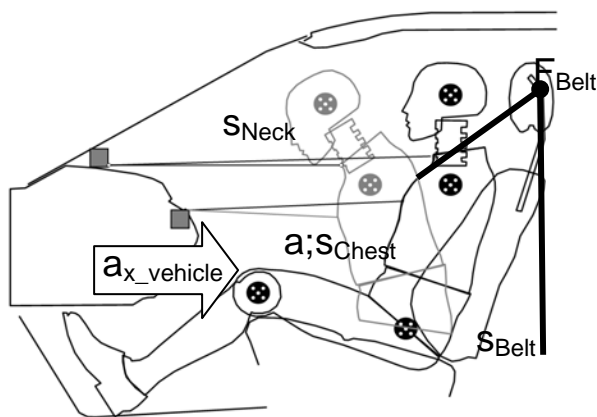
Braking tests were initially carried out with human test subjects representative of 50th percentile characteristics. Their behavior was analyzed by means of the following measured values:

- Forward displacement of the chest and neck
- Belt force on shoulder and pelvis
- Belt extension
- Chest acceleration
- Vehicle longitudinal deceleration
- CAN signals for BAS, ABS and trigger status
- Occupant behavior recorded via camera

Reference tests were also carried out on the vehicle in order to determine the deceleration performance (Figure 3).

The occupant sizes and seating positions were standardized in accordance with the European New Car Assessment Program test protocol. The size and weight of the human test subjects corresponded to the 50th percentile classification. A 50% H III dummy was used for comparison purposes.

The occupant behavior under the influence of braking deceleration was tested on the front passenger seat of a current Mercedes-Benz E-Class model.



**Figure 3: Use of cable and point measurements for the forward displacement of the dummy and real person**

The tests were carried out on a straight test route. The initial velocity before the start of deceleration was a constant 65 kph. The brake application was carried out automatically in order to be able to generate reproducible deceleration curves.

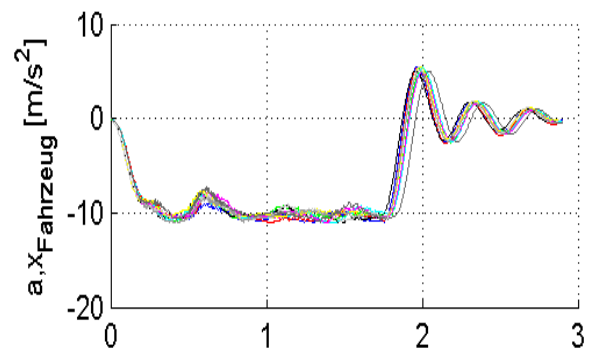
An automated braking device was installed in the vehicle for this purpose, in which a pneumatic ram, with a defined pedal operation curve, applied the pedal force after a specified start condition.



**Figure 4: Automated braking device**

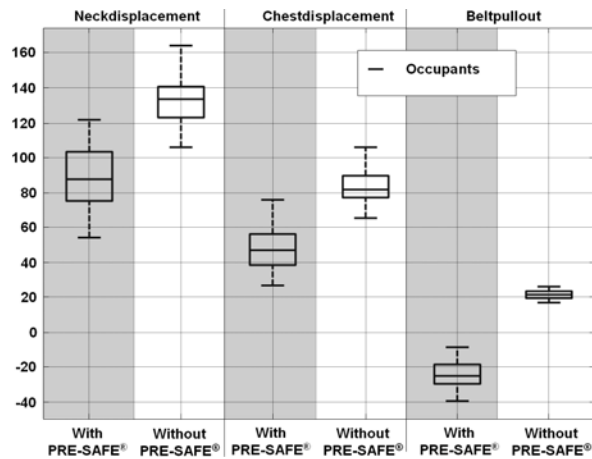
In view of use in the subsequent crash tests as well, the device is not allowed to influence the dummy behavior. This is accomplished by means of the device shown in Figure 4.

With this device, the dummy feet can be positioned without being negatively influenced by the automated braking device.



**Figure 5: Five examples of longitudinal deceleration measurements, actuated by the pneumatic ram**

The pedal curve was selected so that the vehicle is able to control itself at its slip limit by means of its own brake assist system (BAS) and antilock brake system (ABS). This curve was determined during a prior assessment of the test subjects. A reproducible pedal force and deceleration curve are possible thanks to the mechanically supported brake application (Figure 5). Five braking tests were carried out, with and without PRE-SAFE<sup>®</sup>, for each human test subject; the maximum displacement values are shown by means of box plots (Figure 6).



**Figure 6: Occupant behavior measured via neck and chest forward displacements, as well as belt unwinding with and without PRE-SAFE®**

The median forward neck displacement of the occupants with the PRE-SAFE® belt tensioner could be reduced for all human test subjects from 134 mm to 88 mm (i.e. by 34%) in comparison with tests conducted without PRE-SAFE®.

The median forward chest displacement of the occupants with PRE-SAFE® could be reduced for all human test subjects from 82 mm to 47 mm (i.e. by 42%).

The described tests were repeated with the H III 50% frontal impact dummy in order to compare dummy behavior under the same conditions. The same measured values were recorded during these tests. The results indicate that dummy motion during braking is significantly different from that of the human test subjects. Although the reversible belt tensioning via PRE-SAFE® minimized the forward displacement of the test dummy, the absolute forward displacement of the dummy was less than that of the median human test subject as described below.

The median forward neck displacement of the dummy with PRE-SAFE® could be reduced from 90 mm to 49 mm (i.e. by 46%). The median forward displacement for the dummy chest was reduced from 59 mm to 32 mm (i.e. also by 46%). However, as noted above, the dummy behavior at both measuring points (neck and chest) did not correspond to the behavior of the human test subjects in terms of forward displacement.

In terms of interaction with the seat belt, the dummy behaves in a much more rigid manner during the braking phase and accordingly with less forward displacement than the average value for a human test subject. The data clearly indicate that the scatter

range of the measured values for the occupants is greater than that for the dummy.

The analysis of the difference between the human test subjects and the dummy, in terms of the forward displacement, was further supported by means of video analysis.

The human occupant behaves differently than the dummy as deceleration increases once the brakes have been applied. This is particularly noticeable when the vehicle deceleration reaches approximately  $3 \text{ m/s}^2$ , as the seat belt retractor then locks to prevent further seat belt unwinding, while the occupant continues to move forward. This added motion was not observed with the test dummy. This additional displacement is nearly equivalent to the difference in the forward displacement between the human occupant and the dummy. The cause of this difference is the unique elasticity of the human occupant and dummy bodies. Unlike human subjects, the dummy has no elastic "tissue-like" padding or bulky clothing which would permit the dummy to continue moving forward despite a locked seat belt.



**Figure 7: Foam layer on dummy for optimizing the occupant kinematics in the braking phase**

The body elasticity parameters were examined in greater detail in a third series of tests, which were developed based on these findings. For this purpose, different rigid foams were positioned between the

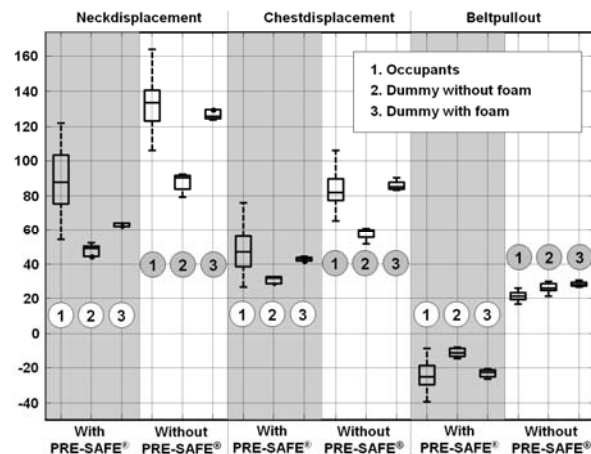
dummy and seat belt in an attempt to reproduce the displacement variation observed with human subjects.

Figure 7 shows the optimized 2-piece foam configuration (material PUR-E; density 35 kg/m<sup>3</sup>; dimensions 160 x 100 x 40 mm and 80 x 100 x 40 mm) between the belt and dummy. This simulation of adipose tissue within the overall occupant/belt system resulted in the following kinematic values in comparison to the respective median occupant value (Figure 8):

In the case of the tests without PRE-SAFE<sup>®</sup>, the forward neck displacement of the dummy falls between the lower quartile and median value. The maximum forward displacement was thus ideally reproduced at this measuring point.

When these tests were reproduced with PRE-SAFE<sup>®</sup>, the measured dummy neck displacement was consistent with the values obtained with human test subjects; however, it tended to lie at the lower end of the value range.

The forward chest displacement of the dummy -- both with and without PRE-SAFE<sup>®</sup> -- fell within the interquartile range and thus ideally in the human test subject scatter band.



**Figure 8: Occupant and dummy behavior measured by means of neck and chest forward displacements as well as belt unwinding with/without PRE-SAFE<sup>®</sup>**

In the case of the tests with PRE-SAFE<sup>®</sup>, all measured values for the belt unwinding fall within the upper quartile; in the case of the tests without PRE-SAFE<sup>®</sup>, the measured values fall within the top scatter band of the human test subjects.

It can therefore be said that the interaction between the dummy with foam was comparable to that of the human test subjects. A preliminary comparison of the kinematics of the human test subjects and dummy without foam modifications showed no similarity during the preliminary braking phase. Because the kinematics and position of the dummy relative to the airbag immediately before the impact are key factors with regard to performance during the accident, a precise simulation of this kinematics was required in order to conduct an additional test in the vehicle crash.

The documented values show that the occupant kinematics of a human test subject can be approximated by an H III frontal impact dummy fitted with foam insert. What is important with regard to the modification using the foam insert is that the behavior is only influenced during braking. However, this modification must not influence the dummy behavior during the crash.

To confirm this, an analysis of crash tests with and without foam inserts was carried out. The results have shown that the same force is applied at the shoulder belt; the dummy / vehicle interaction can thus take place with a uniform belt force and the crash response is not affected by the foam insert.

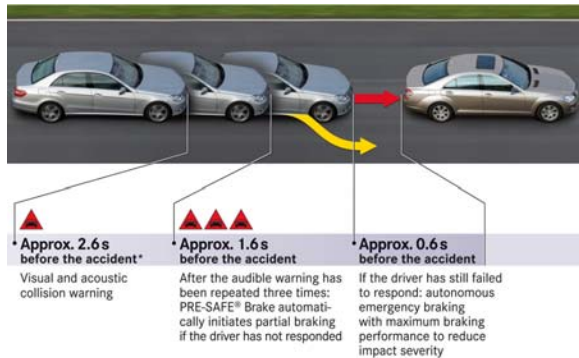
### DETERMINATION OF THE DECELERATION PERFORMANCE OF THE PRE-SAFE<sup>®</sup> BRAKE

The PRE-SAFE<sup>®</sup> brake for autonomous deceleration in longitudinal traffic has been part of the optional DISTRONIC PLUS since model year 2009 in the E- and S-Class Models. The system detects if the vehicle is approaching stationary objects or objects that are driving in the same direction via one short-range sensor and two long-range sensors (Figure 9).



**Figure 9: Area covered by short- and long-range radar**

If the vehicle is approaching a stationary obstacle or an obstacle that is driving in the same direction, the system emits both a visual and acoustic warning to the driver approx. 2.6 s before the calculated point in time of the crash. If the driver does not respond, the vehicle starts, approx. 1.6 s before the crash, with partial brake application and restraint of the occupants by means of the reversible belt tensioners. At this point in time, the driver still has approx. 1 second in which to prevent the accident. This is no longer possible from approx. 0.6 s before the calculated point in time of the crash (Figure 10).



**Figure 10: Escalation in longitudinal traffic**

A test collision obstacle was used in the controlled test environment for determining the potential of the PRE-SAFE® brake (Figure 11).



**Figure 11: Collision with test obstacle**

This obstacle represents a vehicle with regard to the reflected intensity for the sensor system. 50 kph was selected as the starting velocity. Several tests were carried out with the obstacle and the velocity reduction was documented by means of deceleration and velocity measurements. The average velocity reduction determined for all the tests was 25 kph. The test velocity was thus specified as 25 kph for a starting velocity of 50 kph.

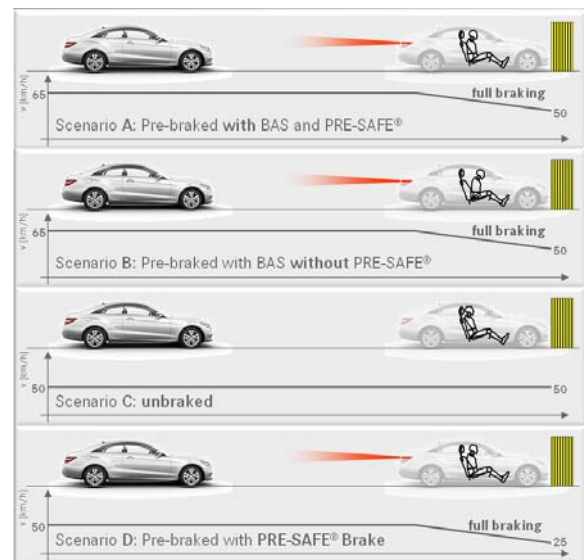
### SETUP FOR DETERMINING THE POTENTIAL OF PRE-SAFE® AND THE PRE-SAFE® BRAKE

Three crash tests were initially carried out (Figure 12) in order to determine the potential offered by reversible protective systems in frontal collisions.

Braking was initiated around 500 ms before the start of the collision in scenario A. The pneumatic ram described earlier was activated by means of a light barrier for this purpose. This decelerated the vehicle with the support of the brake assist system and at the same time simulated emergency braking initiated by the driver followed by a collision.

The deceleration, which was regulated in each case by the antilock system ABS, took place at the slip limit. The activation of the brake assist system BAS and with it the PRE-SAFE® actuators, in particular the reversible belt tensioners, was ensured due to the selected actuation parameters of the pneumatic ram. The braking distance was selected so that the velocity was reduced from 65 kph to 50 kph. A maximum deceleration of around  $10 \text{ m/s}^2$  was achieved similar to the preliminary tests at a high friction coefficient.

The same test configuration was repeated in scenario B, but without activation of the PRE-SAFE® system, in contrast to scenario A. The forward displacements determined in the braking tests were carried out in both configurations with the foam insert in order to enable the required forward displacements by the dummy. Scenario C corresponded to a conventional crash test, that is, without pre-braking. The same impact velocity of 50 kph was selected in the first three tests so that the crash energy could be factored out as an influencing factor. In each case, braking initiated by the driver was simulated. Scenario D corresponded to a situation in which the vehicle is automatically decelerated to the measured collision velocity of 25 kph via the PRE-SAFE® brake system without driver intervention.

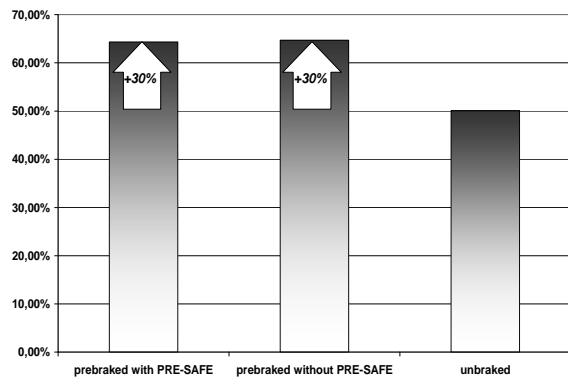


**Figure 12: Crash scenarios**

The comparison of the results from tests A and B reveals the full extent of the effect that occupant restraint - via the reversible belt tensioners - has on the occupant loads. The comparison of the results from tests A, B and C allows us to draw conclusions on how occupant contact is influenced during braking deceleration. The comparison of the results from tests C and D, in turn, shows how the reduction in the collision velocity by the vehicle itself, i.e. without driver intervention, can influence the occupant loads.

### DISCUSSION OF RESULTS

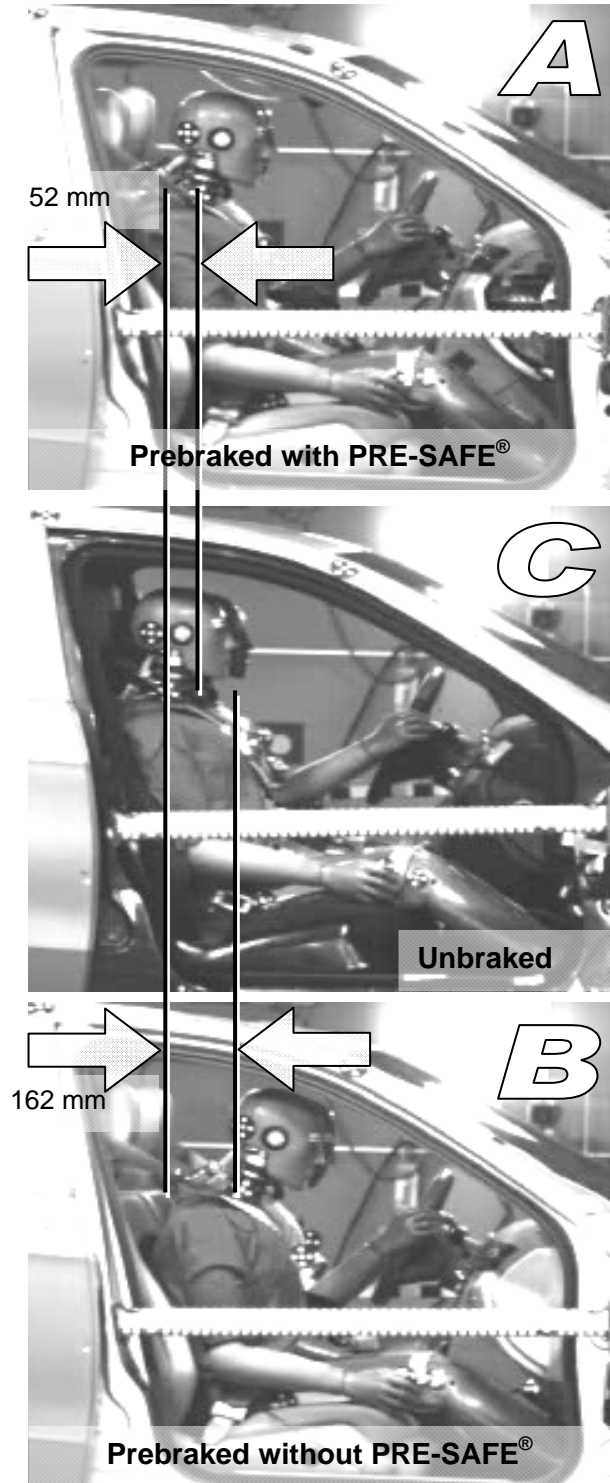
The ride-down effect (RDE) was initially calculated in order to determine the extent of the front passenger contact in both tests with pre-braked collision in comparison to scenario C. For this purpose, a best-fit straight line was drawn through the 25% and 75% values of the first maximum in the initial increase of the resulting chest acceleration for the first three tests with the same collision energy, and the intersection of these lines was determined via the time axis. The vehicle has already covered a certain deformation path by the time the first noticeable energy transmission is transferred to the occupant via the blocked belt due to the vehicle deceleration. The RDE was determined by calculating the extent of the front end deformation at this point in time in relation to the maximum deformation length.



**Figure 13: Ride-down effect**

An improvement of around 30% can be determined for the ride-down effect (RDE), in relation to the unbraked test C (Figure 10), when the two braked tests (A and B) are compared. This value shows that the vehicle deceleration and pitch initially have a positive effect on occupant contact when the same restraint system is used and with the same collision energy (Figure 13).

This is merely a required condition and not a sufficient condition for low occupant load values.



**Figure 14: Forward displacement comparison**

Another condition involves optimizing the restraint systems and occupant position at the time of collision.

The occupant's position relative to the airbag can affect the loads to which the occupant is subjected, in particular the head, neck and chest loads.

The vehicle movements and the resulting occupant movements were similar to those observed in the preliminary tests with human test subjects due to the use of the vehicle's own systems. These were calculated by means of a visual measuring method at the very moment the collision began (Figure 14).

The effects of the forward displacement and of the ride-down effect shall now be analyzed in greater detail. Ordinates scaled as percentages are used for this purpose, whereby the basic test from scenario C represents the 100% value, with the X-axis representing the chronological sequence in seconds.

Figure 15 shows airbag inflation contact at 36 ms during the resulting head acceleration of both braked tests. This does not have a negative effect on the maximum load. Instead, the load values have fallen by approx. 30% relative to the standard load case due to the improved contact via the seat belt system as well as due to the quicker pressure increase in the airbag system due, in turn, to the lower inflation volume.

The occupant position in scenario A is an optimum compromise between forward displacement and contact, with a 40% reduction in the head acceleration.

Due to the lower crash energy in scenario D, the maximum load of the resulting head acceleration can be further reduced to just 30% of the initial load.

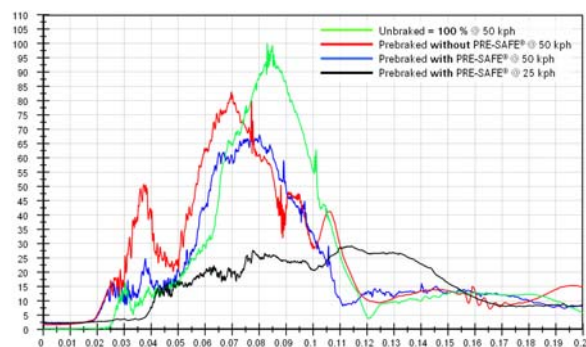


Figure 15: Resulting head acceleration  $a_x$ .

Due to the early load applied to the head, an increase in the neck shearing force in scenario B can also be observed, although this does not have a negative effect on the maximum load.

In Figure 16, a significant deterioration in the neck moment (extension) around Y can be observed. The cause for the significant increase, by approx. 120%, in scenario B (braked load case without PRE-SAFE®) is the forward displacement of the head position together with the rapid pressure increase in the pre-compressed airbag. This stops the head from being "plunged" any deeper into the airbag; the thorax, however, moves further forwards due to the kinematics determined by the belt force limiter. The load due to the severe extension of the neck thus increases. In load case D, the moment loading in the extension movement could again be significantly reduced, due to the lower collision energy in connection with the early occupant contact, which in turn is due to the occupants being appropriately restrained with PRE-SAFE®. The slight increase in the flexion load direction is to be classified as uncritical with regard to the absolute flexion load value.

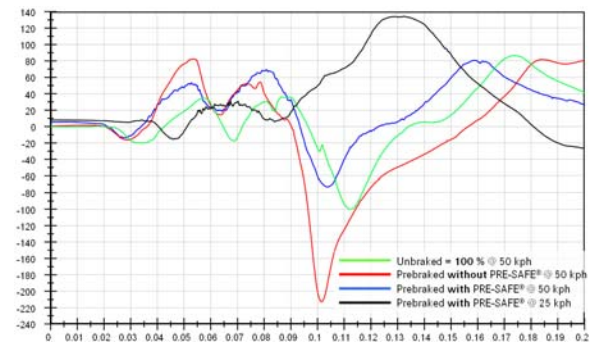


Figure 16: Neck moment  $M_y$ .

An improvement can also be seen in both chest acceleration and chest deflexion, due to the improved dummy contact via the belt. Early occupant contact due to the braking deceleration can be identified on the one hand; this effect can be further improved via a prior belt tensioning with PRE-SAFE® (Figure 17).

This advantage of the contact can, on the other hand, also be seen in the maximum load. When the brakes are applied, the chest deflexion value decreases by 23% due to the early and homogeneous force effects acting on the dummy. This decrease can be as much as 33% where the PRE-SAFE® belt tensioner is used for contact. Reduced collision energy in connection with PRE-SAFE® occupant restraint also represents the optimum here from among all four tested load cases. The load can be reduced to 45% of the original load.

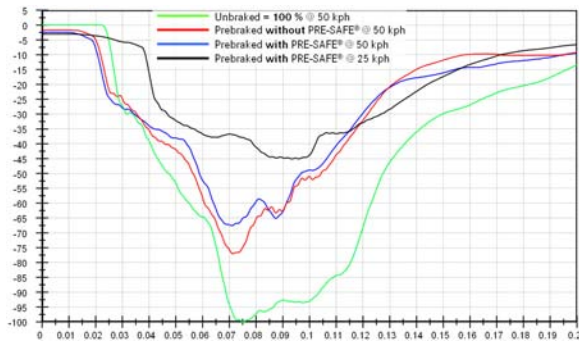


Figure 17: Chest compression  $D_s$

Although the effects of braking deceleration can be observed in the resulting pelvis acceleration, no difference can be ascertained between the tests with and without PRE-SAFE<sup>®</sup>. This is because the reversible belt tensioner and occupant restraint acts mainly on the upper body (Figure 18). The reduction in the collision energy becomes apparent, however, in the maximum load in test D: The load recorded here was 67% lower than the original load.

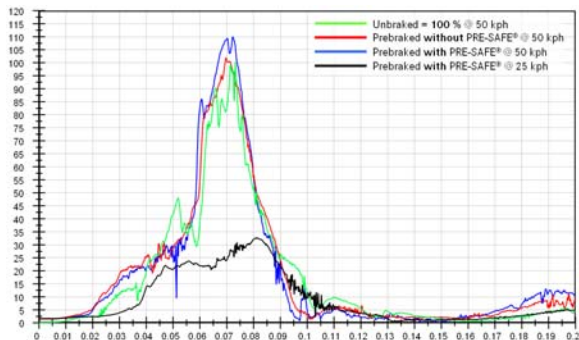


Figure 18: Pelvis acceleration  $a_r$

A 75% decrease in collision energy meant that vehicle intrusion was 50% lower (Figure 19).

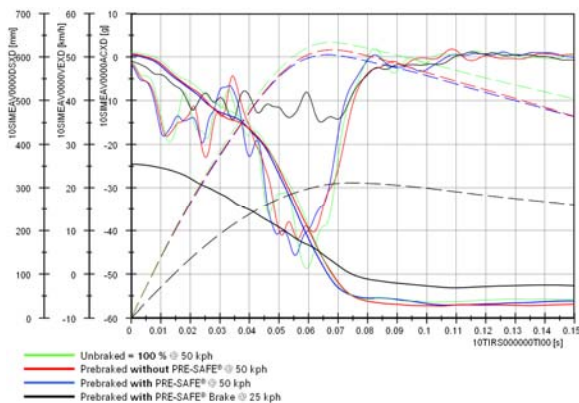


Figure 19: Decelerations and deformations

## SUMMARY

The study has shown the effect that pre-braking has on occupant movement and subsequent occupant loading. This use case represents a relevant constellation worth investigating, as braking with a deceleration of  $> 4 \text{ m/s}^2$  was initiated in almost 50% of the documented frontal collisions, while braking with a deceleration of  $> 6 \text{ m/s}^2$  was initiated in a third of the documented cases.

The study began by comparing and assessing the initially inadequate forward displacement values of the H III dummy by means of tests with volunteers. The dummy behavior during the braking phase could be adapted via measures in the belt/dummy system so that the movement was within the range for volunteers. The preliminary test showed that the measures did not have any effect on the crash results.

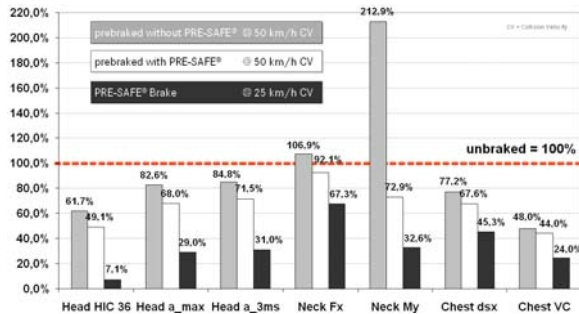
This simple model of the test before and after  $t_0$  initially only applies for the front passenger. Tests on volunteers have shown that braking initiated by the driver results in supporting forces at the interfaces to the vehicle that reduce forward displacement. The driver can, however, also be taken by surprise by the braking situation and no longer have the opportunity to counteract the introduced braking force in the case of maneuvers initiated by automatic emergency braking systems.

The braking deceleration itself has a positive effect on the contact and restraint of the occupants. Some variables have been improved solely via the ride-down effect, acceleration curves tend to be more homogeneous, and the energy is reduced over a longer period due to the improved contact.

It is important that the head-to-torso interaction in particular is controlled in a positive manner by the PRE-SAFE<sup>®</sup> belt tensioner. The kinematics can be positively influenced through preventive restraint in braked crash situations. The neck load is significantly less than in the unbraked test. All head, neck and upper torso values are also, once again, below the loads that can be achieved by occupant contact alone.

However, besides any occupant protection measures, the most efficient way to reduce the occupant load when a hazard has been detected is to initiate emergency braking that reduces the accident severity. The protection of occupants as well as of other road users can again be significantly increased in this way.

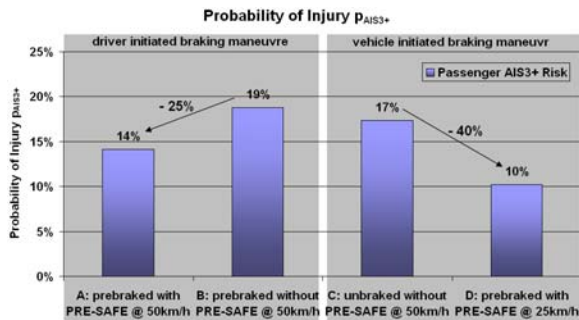
Figure 20 shows the load distribution of all four tests relative to the standardized unbraked crash (scenario C). For individual load criteria, the reduction in the collision energy by 75% can be directly passed on to the occupants. What is important though is that the dynamic driving situations prior to a collision are supported by reversible occupant protection measures.



**Figure 20: Comparison of the maximum loads**

The risk of the front passenger experiencing serious injuries (AIS3+) in one of the constellations was determined for all four tests (Figure 22). The risk curves for the head, neck, chest and femur were calculated using the NHTSA injury risk criteria for the 50th percentile dummy, in order to be able to classify a serious injury as being AIS3+.

$$p_{\text{JointAIS3+}} = 1 - (1 - p_{\text{Head}}) \times (1 - p_{\text{Neck}}) \times (1 - p_{\text{Chest}}) \times (1 - p_{\text{Femur}})$$



**Figure 21: Probability of injury  $p_{\text{JointAIS3+}}$**

Looking at the two scenarios on the left in Figure 21, the risk of sustaining a serious injury (AIS3+) is reduced from 19% to 14%, if, as simulated, braking is initiated by the driver before the collision occurs and the occupant is restrained via a reversible belt tensioner.

This corresponds to a risk reduction of 25%.

The diagram on the right in Figure 21 shows the case where the vehicle is decelerated in advance via the PRE-SAFE® brake, without driver intervention, when a risk of collision has been detected.

If the collision is detected in advance by the vehicle and the speed is automatically reduced, as measured, via the PRE-SAFE® brake, the risk of a serious injury (AIS3+) can be reduced from 17% to 10% due to the reduction in speed together with the occupant contact. This corresponds to a risk reduction of approx. 40%.

The results confirm the findings of an initial study on the topic, which was carried out by the largest German automobile club ADAC in 2006. The refinement of the method employed at that time means that we can now see the potential benefits that can be attributed to the PRE-SAFE® reversible belt tensioning system and the contact through braking deceleration. The test methodology employed means that a systematic statement about the actual potential can be made thanks to the validated interaction between the dummy and vehicle during braking deceleration. The occupant and dummy behavior must initially be examined before testing involving severe longitudinal decelerations, as the initial position of the dummy immediately before the collision is crucial for the arising load values.

A significant reduction in the vehicle repair costs, including for possible accident partners, is another benefit besides the reduction in the accident severity. A 52% reduction in the repair costs has been calculated for a reduction in the collision velocity from 50 kph to 25 kph as a result of the PRE-SAFE® brake.

## OUTLOOK

The growing number of reversible protective systems and driver assistance systems means that an integral analysis of occupant safety is becoming ever more important. It is not enough merely to examine the reduction in speed prior to the start of collision – the occupants also need to be analyzed in terms of how they interact with the vehicle immediately prior to the collision. This applies to all types of collisions, not just frontal impacts.

Modeling under test conditions has, of course, its limits, as it only enables us to simulate specific, simple and one-dimensional processes.



The virtual simulation of integral constellations, however, has great potential. Validated occupant or human models will, in the future, provide us with an insight into the benefits of pre-triggering systems.

The aim here will be not just to restrain occupants so that they stay in the required position, but to show that proactive, moving systems require state-of-the-art tools for calculating the efficiency of these proactive safety systems.

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# Design and Evaluation of an Integrated Vehicle Safety System for Longitudinal Safety and Lateral Stability

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## ABSTRACT

This paper describes the design and evaluation of an integrated control strategy for longitudinal safety and lateral stability. The objective of the integrated control strategy is to optimally coordinate independent brake inputs for longitudinal collision-safety and lateral stability in various driving situations such as lane change with braking and circular turning with braking, etc. The proposed integrated vehicle safety system is applied to the vehicle equipped with Smart Cruise Control (SCC)/Collision Avoidance (CA) and Vehicle Stability Control (VSC). The proposed control system consists of a supervisor, control algorithms, and a coordinator. The proposed system has three control modes which are normal driving, integrated safety I, and integrated safety II. According to the corresponding control mode, the longitudinal and lateral control algorithms calculate the desired motion of the subject vehicle. Based on the desired longitudinal force and the desired yaw moment, the coordinator determines the throttle angle and the brake pressures by using optimal distribution. Closed-loop simulations with the driver-vehicle-controller system are conducted to investigate the performance of the proposed integrated vehicle safety system. Finally, the proposed control system was also implemented in a sport utility vehicle and tested in

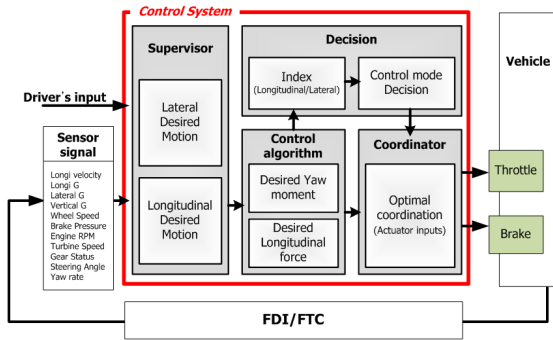
several driving situations.

## INTRODUCTION

To improve handling performance and active safety of vehicles, a considerable number of active control systems for vehicle lateral dynamics and longitudinal collision-safety have been developed and utilized commercially over the last two decades. For example, Vehicle Stability Control (VSC), Adaptive Cruise Control (ACC), Stop-and-Go (SG), Lane Keeping Support (LKS), Collision Warning and Collision Avoidance (CW/CA), assisted lane change and automated parking assist have been extensively researched and there has been many development since the 1990's [1-6]. These systems are believed to reduce the risk of accidents, improve safety, and enhance comfort and performance for drivers. These advanced driver assistance and active safety systems open new possibilities in accident prevention [7-9]. With the introduction of these systems, there is the possibility for creating synergies, but also a risk of introducing conflicts. For example, since the ACC/Collision Mitigation Brake (CMB)/CA and VSC systems share the brake, an independent integration of the ACC/CMB/CA and VSC system may result in unexpected behavior of the controlled vehicle and even worse dynamic behavior compared to an uncontrolled vehicle case. Moreover, to obtain

both lateral stability and safe clearance to avoid rear-end collisions in severe driving situations, coordinated control of the actuators is necessary.

To solve this problem, this study presents the integrated control strategy with obtaining the ACC/CMB/CA and VSC functions in severe driving situation such as lane change with braking, circular turning with braking. The integrated control algorithm consists of four steps, i.e., a supervisor, control algorithms, decision, and a coordinator. The supervisor determines desired vehicle motions such as a desired yaw rate to improve vehicle lateral stability and a desired longitudinal acceleration to avoid rear-end collisions. The control algorithm calculated a desired yaw moment and longitudinal force to track the desired yaw rate and the longitudinal acceleration, respectively. The decision determines control modes which are normal driving, integrated safety I, and integrated safety II based on a longitudinal and lateral index to illustrate the danger of collision and lateral sliding in the current driving situation. From the control algorithm and the decision, the coordinator distributes brake inputs of each wheel optimally based on the current status of the subject vehicle. Fig. 1 shows the integrated vehicle safety control system scheme.



**Fig. 1 Integrated vehicle safety system scheme.**

The performance of the proposed control system has been evaluated via both simulations and vehicle test. The vehicle tests for a driver-vehicle-controller system have been conducted to prove the improved performance of the proposed control system over individual control systems such as ESC and SCC/CA.

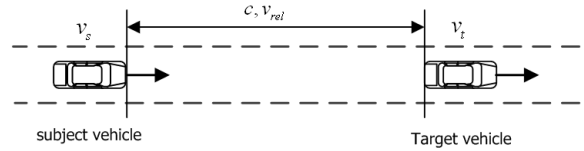
## SUPERVISOR

A task of the supervisor is to determine desired vehicle motions such as a desired yaw rate and a desired longitudinal acceleration.

The desired longitudinal acceleration is determined based on the SCC system with a severe braking system. It calculates the desired longitudinal acceleration to improve drivers' comfort during normal, safe-driving situations and to completely avoid rear-end collision in vehicle following situations. As shown in Fig. 2, a relationship between a subject vehicle and the target vehicle can be expressed as following state equation:

$$\begin{aligned} \dot{x} &= Ax + Bu + Gw \\ &= \begin{bmatrix} 0 & -1 \\ 0 & 0 \end{bmatrix} x + \begin{bmatrix} 0 \\ -1 \end{bmatrix} u + \begin{bmatrix} \tau \\ 1 \end{bmatrix} w \end{aligned} \quad (1)$$

where,  $\tau$  is the linear coefficient, i.e., time gap. The states are  $x^T = [x_1, x_2] = [3c_d - c, v_t - v_s]$ , the input,  $u$ , is the desired longitudinal acceleration and the disturbance,  $w$ , is the target vehicle acceleration.  $c_d$  and  $c$  are the desired range clearance and actual clearance between the target and subject vehicles and  $v$  indicates velocity.



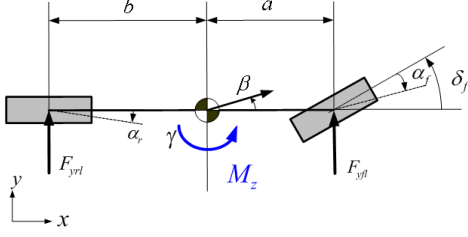
**Fig. 2 Relationship between the subject vehicle and the target vehicle.**

From (1), the desired longitudinal acceleration considering a ride quality, a driving characteristic of the driver and collision avoidance is determined using a linear quadratic optimal problem.

$$\begin{aligned} a_* &= -k_1(v_s) \cdot (c_d - c) - k_2(v_s) \cdot (v_t - v_s) \\ a_{des} &= \begin{cases} a_{upper}(v_s) & \text{if } a_* > a_{upper}(v_s) \\ a_* & \text{if } a_{min}(v_s) \leq a_* \leq a_{max}(v_s) \\ a_{lower}(v_s) & \text{if } a_* < a_{lower}(v_s) \end{cases} \end{aligned} \quad (2)$$

A detailed description about the desired longitudinal acceleration is provided in the previous research [10].

The desired yaw rate to improve vehicle lateral stability is determined to satisfy maneuverability for steering intention of a driver and lateral stability for a side slip angle. From this goal, the desired yaw rate can be theoretically determined by using the 2-D bicycle model with a linear tire model. Fig. 3 shows the 2-D bicycle model including direct yaw moment:



**Fig. 3 Bicycle model including direct yaw moment.**

From Fig. 3, the dynamic equation can be presented as follows:

$$\begin{bmatrix} \dot{\beta} \\ \dot{\gamma} \end{bmatrix} = \begin{bmatrix} \frac{-2(C_f + C_r)}{mV_x} & \frac{2(-l_f C_f + l_r C_r) - 1}{mV_x^2} \\ \frac{2(-l_f C_f + l_r C_r)}{I_z} & \frac{-2(l_f^2 C_f + l_r^2 C_r)}{I_z V_x} \end{bmatrix} \begin{bmatrix} \beta \\ \gamma \end{bmatrix} + \begin{bmatrix} \frac{2C_f}{mV_x} \\ \frac{2l_f C_f}{I_z} \end{bmatrix} \delta_f + \begin{bmatrix} 0 \\ \frac{1}{I_z} \end{bmatrix} M_z \quad (3)$$

where,  $C_f$  and  $C_r$  represent the cornering stiffness at front and rear side, respectively.  $l_f$  and  $l_r$  are the distance between the CG and front/rear axle.  $I_z$  is a moment of inertia about z-axis. The steady state yaw rate of the bicycle model is introduced and the maneuverability of a vehicle is considered to reflect the driver's intention, which is expressed as a function of the vehicle longitudinal velocity and driver's steering input as follows [11]:

$$\gamma_{ref\_yaw} = \frac{1}{1 - \frac{m(l_f C_f - l_r C_r)v_x^2}{2C_f C_r (l_f + l_r)^2}} \frac{v_x}{l_f + l_r} \delta \quad (4)$$

Moreover, excessive body sideslip of a vehicle makes the yaw motion of a vehicle insensitive to driver's steer input and threatens the lateral stability. As the sideslip angle of a vehicle increases, the stabilizing yaw moment due to the steer input decreases, and thus, the lateral behavior of a vehicle becomes unstable. Therefore, the other desired yaw rate to maintain body sideslip angle in reasonably small range is required. In this case, the desired yaw rate is determined as follows [7]:

$$\gamma_{ref\_lateral} = K_2 \beta + \frac{2F_{yf} \cos \delta + 2F_{yr}}{mv_x} \quad (5)$$

Two different reference yaw rates are combined into a single desired yaw rate properly depending on the driving situations as follows:

$$r_d = \sigma_1 r_{ref\_yaw} + \sigma_2 r_{ref\_lateral} \quad (6)$$

A detailed description about the desired yaw rate is provided in the previous research [7].

## CONTROL ALGORITHM

Control algorithm calculates a desired longitudinal force and a desired yaw moment to track the desired longitudinal acceleration and desired yaw rate, respectively. Based on the desired longitudinal acceleration from (2), the desired longitudinal force is obtained as follows:

$$F_{x,des} = m \cdot (a_{des} + K_p e_a + K_i \int e_a dt) \quad (7)$$

$$\text{where, } e_a = a_{des} - a$$

The main goal of the desired yaw moment is to make the actual yaw rate to follow the target yaw rate which is defined from (6). To determine the desired yaw moment, a 2-D bicycle model described in Fig. 3 was used. From (3), the dynamic equation about the yaw rate including the direct yaw moment is presented as follows:

$$\dot{\gamma} = \frac{2(-l_f C_f + l_r C_r)}{I_z} \beta + \frac{-2(l_f^2 C_f + l_r^2 C_r)}{I_z v_x} \gamma + \frac{2l_f C_f}{I_z} \delta_f + \frac{1}{I_z} M_z \quad (8)$$

The sliding mode control method is also used to determine the desired yaw moment. The sliding surface and the sliding condition are defined as follows:

$$s_2 = \gamma - \gamma_{des}, \quad \frac{1}{2} \frac{d}{dt} s_2^2 = s_2 \dot{s}_2 \leq -\eta_2 |s_2| \quad (9)$$

where,  $\eta_2$  is a positive constant, The equivalent control input that would achieve  $\dot{s}_2 = 0$  is calculated as follows:

$$M_{z,eq} = -I_z \left( \frac{2(-l_f \hat{C}_f + l_r \hat{C}_r)}{I_z} \beta - \frac{2(l_f^2 \hat{C}_f + l_r^2 \hat{C}_r)}{I_z v_x} \gamma + \frac{2l_f \hat{C}_f}{I_z} \delta_f \right) \quad (10)$$

Finally, the desired yaw moment for satisfying the sliding condition regardless of the model uncertainty is determined as follows:

$$M_{z,des} = M_{z,eq} - K_2 \cdot \text{sat} \left( \frac{\gamma - \gamma_{des}}{\Phi_2} \right) \quad (11)$$

where, the  $K_2$  is a sliding gain which satisfies the sliding condition.

The automatic driving and collision safety are achieved by the longitudinal force and the lateral stability is ensured by the yaw moment control.

## DECISION

A task of the decision is to determine the control mode based on the index-plane using longitudinal and lateral indexes. The index-plane consists of a normal driving mode, an integrated safety mode I, and an integrated safety mode II. In order to determine the control mode, it is necessary to monitor the reference indexes related with a lateral stability and the collision danger between the subject vehicle and the target vehicle. Fig. 4 shows the index-plane proposed in this paper. If the longitudinal index (lateral index) exceeds unit, the danger of collision (unstable lateral motion) is high. The object of proposed control system is to satisfy both longitudinal safety and lateral stability. However, since both the desired longitudinal force and the desired yaw moment always cannot be satisfied, one of the two control systems should be given off by the control mode. As shown in the Fig. 4, in the case of the integrated safety I mode, the longitudinal safety control to avoid rear end collision has control priority. In contrast, in the case of the integrated safety II mode, the lateral stability control to improve vehicle lateral motion has control priority.

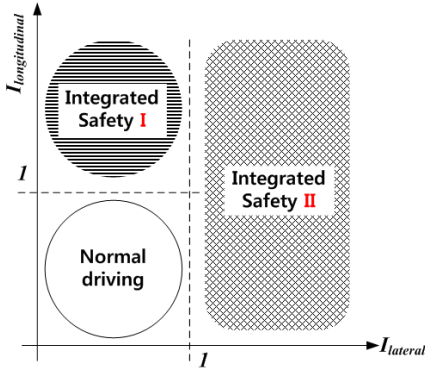


Fig. 4 Control modes in the index-plane.

The longitudinal index to monitor the vehicle-to-vehicle collision can be determined by using a warning index and an inverse TTC which are developed in previous research [2, 3]. The warning index represents the danger of physical collision in the current driving situation. The inverse TTC ( $TTC^{-1}$ ) which is visual effect for the collision is a well-known parameter in CW/CA systems. The functional equation for the warning index and the inverse TTC is provided in the previous research [1]. In the case of the warning index beyond a threshold value and the inverse TTC below a threshold value, it indicates that

the current driving situation is in a safety region. Otherwise, the current driving situation can be dangerous. Therefore, the longitudinal index is determined using manual driving data for vehicle following. As shown in Fig. 5, the inputs are the warning index and the inverse TTC, and the output is the longitudinal index.

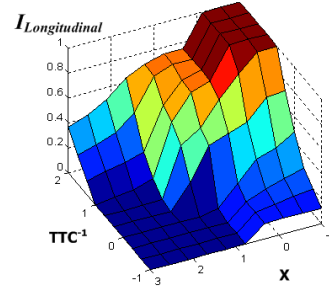


Fig. 5 Longitudinal index of a collision-danger.

The lateral index can be determined by using the desired yaw moment from (11).

$$I_{lateral} = \frac{|M_{z,des}|}{M_{z,th}} \quad (12)$$

Where,  $M_{z,th}$  is threshold value.

## COORDINATOR

Based on the desired longitudinal force and the desired yaw moment, the coordinator manipulates a throttle and brake. There are three coordination methods by the control mode. Fig. 6 shows the coordination scheme.

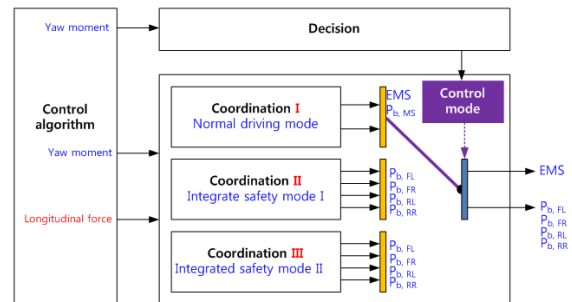


Fig. 6 Coordination scheme

As shown in the Fig. 6, the coordinator calculates the throttle and brake pressures of each wheel based on the coordination methods. In the case of the normal driving mode, since the current driving situation is neither rear-end collision nor unstable vehicle lateral motion, both throttle and brake inputs are determined by coordination I. However in the

case of the integrated safety mode I and II, since the current driving situation is rear-end collision or unstable vehicle lateral motion, only brake inputs of each wheel are determined by coordination II or III.

### Coordination I

In the case of the normal driving mode, the throttle and brake inputs are determined by the coordination I method. The control principle of the throttle actuator is based on reverse dynamics. Depending on the desired longitudinal force, the coordination I applies throttle or not. If the desired engine torque is larger than a minimum engine torque generated with the closed throttle, the throttle control is necessary. Switching logic with a boundary layer is necessary to avoid frequent switching between throttle control or not. The throttle angle is computed from the desired engine torque using an engine map and a torque-converter map [10].

$$\alpha = EM^{-1}(\omega_e, T_{net,des}) \quad (13)$$

$$\text{where, } T_{net,des} = T_p(\omega_e, \omega_t) + K_e(\omega_{e,des} - \omega_e)$$

where  $T_p$  and  $T_{net,des}$  are the pump torque and the desired net engine torque.  $\omega_e$ ,  $\omega_{e,des}$  and  $\omega_t$  are the engine speed, the desired engine speed and the turbine speed, respectively.  $EM$  indicates the engine map. From (13), the throttle angle which is suitable for the acceleration situation from the control algorithm is determined.

The brake pressure is applied when the desired longitudinal force by the control algorithm is negative value. Since the brake torque is proportional to the brake pressure, the desired brake pressure can be obtained by the equation:

$$P_{b,i} = \frac{r}{K_b} F_{x,des}, \quad i = FL, FR, RL, RR \quad (14)$$

where,  $K_b$  and  $r$  are the lumped gain for the entire brake system and radius of wheel, respectively. Since the brake value in the normal driving mode is small, the differential distribution effect for the given braking force is very insignificant in the vehicle lateral motion. Therefore the coordination I do not consider the differential braking.

### Coordination II

If the longitudinal index exceeds unit and the lateral index below unit, only brake inputs of each wheel to avoid the rear-end collision are determined by the

coordination II. Since the lateral index below unit, the differential braking for vehicle lateral stability is not need. However if the differential distribution for the given brake force is available, the maneuverability of the vehicle will be improved. Therefore, the coordination II determines the brake pressures of each wheel using an optimal algorithm to improve the maneuverability of the vehicle. Due to the danger of rear-end collision, the longitudinal control should have control priority, i.e. the sum of the brake forces of each wheel should be same the desired longitudinal force. For this purpose, in the case of the positive desired yaw moment, the optimal problem for the brake forces of each wheel can be stated as follows:

Minimize:

$$J = \left( \begin{array}{c} -\frac{t}{2}(F_{x,Pb\_FL} - F_{x,Pb\_FR}) \\ -\frac{t}{2}(F_{x,Pb\_RL} - F_{x,Pb\_RR}) - M_{z,des} \end{array} \right)^2 \quad (15-a)$$

Subject to:

$$\begin{aligned} f(x) &= \sum_{i=FL}^{RR} F_{x,Pb\_i} - F_{x,des} = 0 \\ g_1(x) &= F_{x,Pb\_FR} \leq 0 \\ g_2(x) &= F_{x,Pb\_RR} \leq 0 \end{aligned} \quad (15-b)$$

where,  $F_{x,Pb\_FL}$ ,  $F_{x,Pb\_FR}$ ,  $F_{x,Pb\_RL}$ , and  $F_{x,Pb\_RR}$  are the brake control inputs of the front-left, front-right, rear-left, and rear-right wheels, respectively.

The cost function of the proposed optimal coordination is the difference between the desired yaw moment and the sum of the generated yaw moment by tire longitudinal forces. This cost function means that since both the desired longitudinal force and the desired yaw moment always cannot be satisfied, the longitudinal control should have a control priority. The tires forces have to satisfy the following constraints: i) the sum of the generated longitudinal forces of each wheel should be equal to the desired longitudinal force, ii) the braking forces as the control input should have a negative value.

### Coordination III

If the lateral index exceeds unit regardless of the longitudinal index, only differential brake inputs of each wheel to improve vehicle lateral stability are determined by the coordination III. However, if there is a danger of the rear-end collision, the differential brake inputs considering the collision should be

determined by the coordination III. Therefore, in the case of the positive desired yaw moment, the optimal problem for the brake forces of each wheel can be stated as follows:

Minimize:

$$J = \left( \sum_{i=FL}^{RR} F_{x,Pb\_i} - F_{x,des} \right)^2 \quad (16-a)$$

Subject to:

$$f(x) = -\frac{t}{2} (F_{x,Pb\_FL} - F_{x,Pb\_FR}) - \frac{t}{2} (F_{x,Pb\_RL} - F_{x,Pb\_RR}) - M_{Z,des} = 0 \quad (16-b)$$

$$g_1(x) = F_{x,Pb\_FR} \leq 0$$

$$g_2(x) = F_{x,Pb\_RR} \leq 0$$

To calculate the control inputs which satisfy the proposed optimal process in (15) and (16), Hamiltonian is defined. Based on first order necessary conditions for the Hamiltonian, six equations with six unknown values can be derived.

## EVALUATION

The response of the vehicle with the integrated vehicle safety system was evaluated in simulation. To prove the improved performance of the proposed integrated vehicle safety system, a conventional safety system consisting of ESC and SCC/CA systems was used. In the conventional system, the lateral stability control has a control priority than the longitudinal safety control, i.e., if there are both rear-end collision danger and unstable lateral motion of the vehicle in the current driving situation, only the lateral stability control system without the longitudinal safety control system should be operated by the conventional system.

Computer simulations were conducted using vehicle simulation software, CarSim, and Matlab/Simulink. Simulations for a lanechange maneuver and a circular turning maneuver have been conducted.

### Lanechange Maneuver

In this test, while following a target vehicle which is driving on a dry road, a single lane change maneuver has been conducted by a sudden deceleration of the target vehicle. Because of the lane change maneuver, the target vehicle is changed to another vehicle which is driving with low speed. This situation needs

longitudinal safety control by the changing target vehicle and the lateral stability control by the sudden lane change maneuver simultaneously. Fig. 7 shows the test scenario.

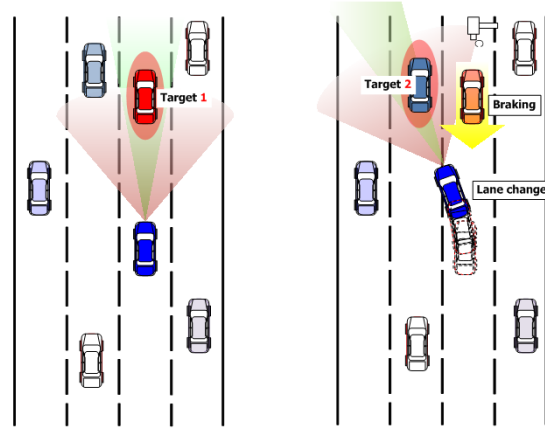
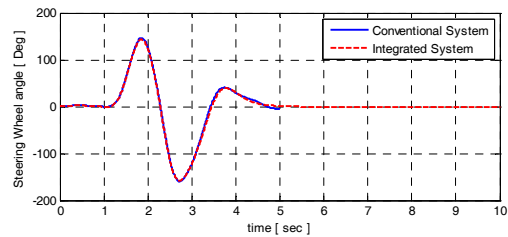


Fig. 7 Test scenario for a single lane change

In this simulation, wheel steering angle is determined by a driver steering model [12]. Fig. 8-(a)-(f) show the steering wheel angle, target on/off, vehicle speed profile for the target vehicles and subject vehicle, yaw rate error, and braking pressure which is control input at the front left tire, respectively. As shown in Fig 8-(a) and (b), the target vehicle was changed to another vehicle by the driver's steering angle. From Fig. 8-(e), it is shown that both the integrated system and the conventional system provide good performance with respect to vehicle lateral stability. However, since, to improve vehicle lateral stability, the conventional system gives up a longitudinal safety control, the rear-end collision occurred at 5 sec. This result can be shown from Fig. 8-(d).



(a) Steering wheel angle

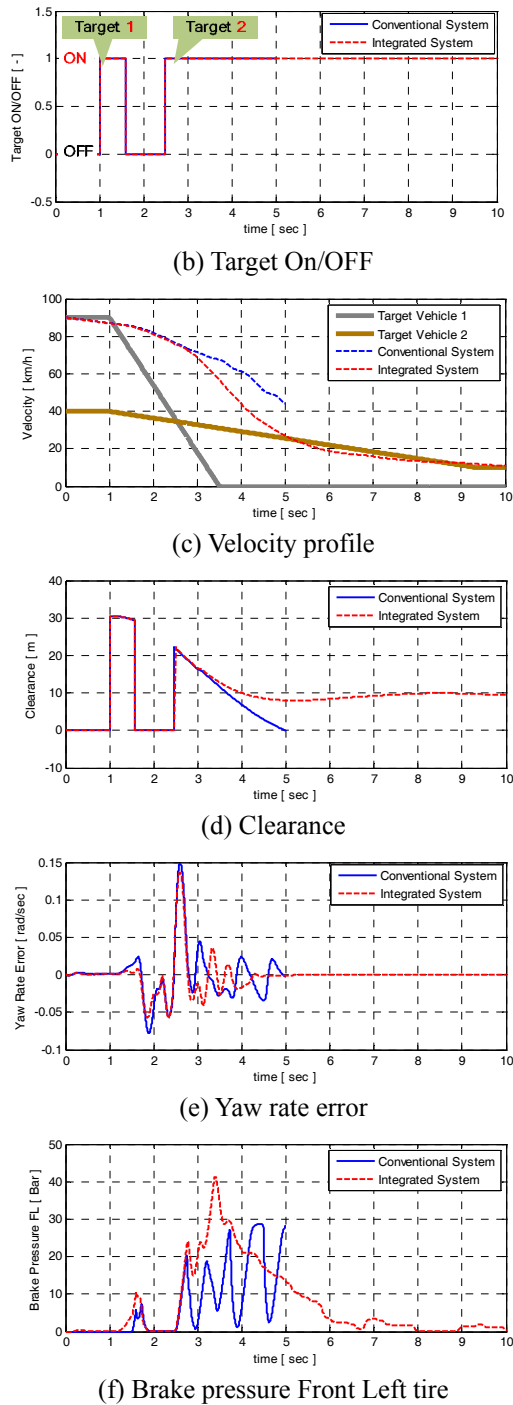


Fig. 8 Simulation results of a lane change with a braking

### Circular Turning Maneuver

A circular turning simulation was conducted to evaluate the performance of the integrated system for the improvement of maneuverability. In this simulation, the steering wheel angle is also determined by the driver steering model. The vehicle

is simulated on a dry road with 90 km/h to following a target vehicle. While following the target vehicle, the target vehicle starts to decelerate with deceleration level of  $-5\text{m/sec}^2$  for cornering. For this situation, braking pressure for the collision avoidance with the target vehicle is applied by the SCC/CA system. Also, the danger of vehicle lateral unstable motion does not exist in this situation. Fig. 9 shows the test scenario.

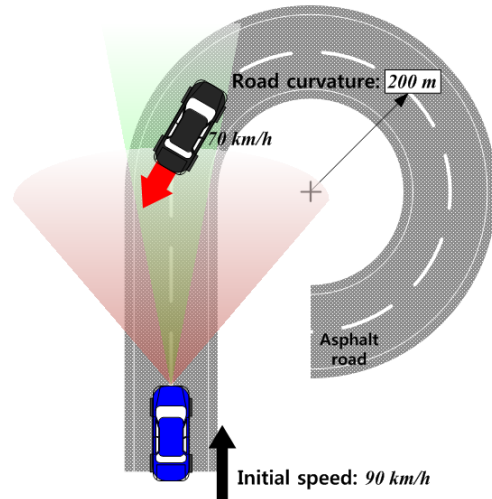
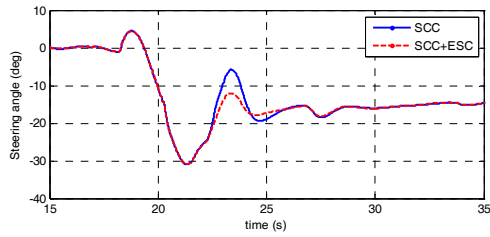


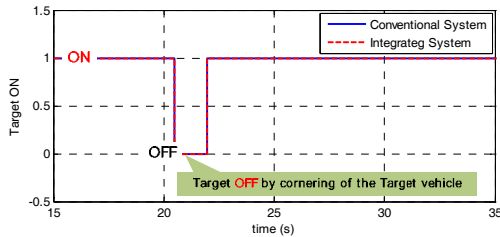
Fig. 9 Test scenario for a circular turning

Fig. 10-(a)-(e) show the steering wheel angle, target on/off, yaw rate error, and braking pressure which is control input at the front left tire, respectively. As shown in Fig. 10-(b) and (c), a target signal was turned off temporarily by cornering of the target vehicle. While the subject vehicle cornered and neared the target vehicle, a target signal was turned on. Since the scenario needs longitudinal safety control for the collision avoidance without lateral stability control, the conventional system determined a braking pressure considering only the collision avoidance. As shown in the Fig. 10-(c) and (d), both the integrated system and the conventional system provide good performance with respect to vehicle longitudinal safety. However, since, to avoid the rear-end collision, the conventional system gives up a lateral stability control, yaw rate error was increased.

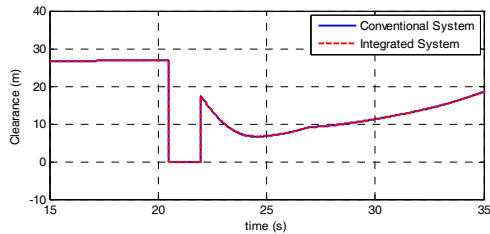




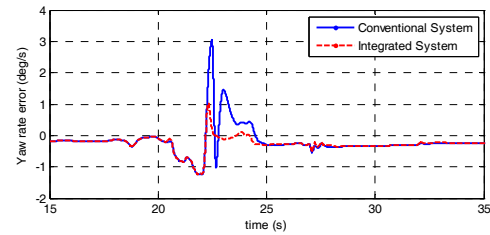
(a) Steering wheel angle



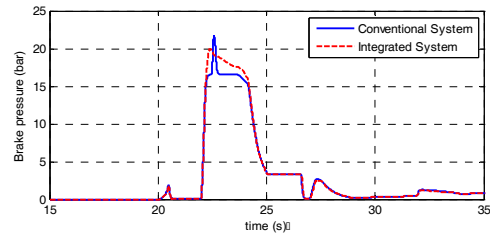
(b) Target On/OFF



(c) Clearance



(d) Yaw rate error



(e) Brake pressure Front Left tire

Fig. 10 Simulation results of a circular turning maneuver

## CONCLUSIONS

An integrated vehicle safety control strategy for vehicle longitudinal safety and lateral stability has been proposed. The proposed control strategy is designed to optimally coordinate the brake actuator inputs to obtain both lateral stability and longitudinal

safety in various driving situations. Normal driving, integrated safety I, and integrated safety II mode have been defined in the index-based plane. To determine the current control mode, the longitudinal and lateral indices are used. According to the selected control mode, the control algorithms calculate the desired longitudinal force and the desired yaw moment. From the desired longitudinal force and yaw moment, the coordinator determines the throttle angle and the brake pressures by using optimal distribution. The proposed the integrated vehicle safety system has been implemented on a SUV vehicle using a radar sensor, a VSC module and a controller. Simulations have been conducted to investigate the performance of the proposed integrated vehicle safety control system in various driving situations. From the simulation, it has been shown that the proposed system assists the driver in combined severe braking/large steering maneuvering so that the driver can keep maneuverability and prevents the vehicle-to-vehicle collision. Especially the proposed control system improves the vehicle safety in severe driving situations in which both longitudinal and lateral motions are to be controlled simultaneously.

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# **SAFETY IMPACT METHODOLOGY (SIM): APPLICATION AND RESULTS OF THE ADVANCED CRASH AVOIDANCE TECHNOLOGIES (ACAT) PROGRAM**

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## **ABSTRACT**

This paper provides a summary of four cooperative research projects conducted under the National Highway Traffic Safety Administration's (NHTSA) Advanced Crash Avoidance Technologies (ACAT) program. The ACAT program sought to determine the safety impact of new and emerging crash avoidance technologies that are intended to help drivers avoid crashes, reduce crash severity, and prevent injuries and fatalities. This research developed and applied a Safety Impact Methodology (SIM) framework to estimate safety benefits for the proposed pre-production crash avoidance systems.

This paper presents the application and results of the Safety Impact Methodology for four different crash avoidance technologies including: Advanced Collision Mitigation Braking System by Honda, Lane Departure Warning by Volvo-Ford, Pre-collision Safety System by Toyota, and Backing Crash Countermeasures by General Motors.

## **INTRODUCTION**

Advanced crash avoidance technologies help drivers to avoid crashes or, if the crash is unavoidable, to reduce the harm of the crash. Crash avoidance systems are able to warn the driver of dangerous situations and pro-actively deploy countermeasures *before* a crash occurs. These countermeasures may include warnings (by means of haptic, auditory, or visual alarms) and/or actively controlling the vehicle (by braking or steering) for a limited time.

Oftentimes, in cases of driver inattention (e.g. driver distraction), the countermeasure would occur prior to the driver sensing a critical situation, giving the driver additional time to react. It is this additional time margin which enables the driver, in coordination with the crash avoidance system, to avoid or mitigate the crash. This is important as it was observed in the

100-Car Naturalistic Driving Study that nearly 80% of crashes and 65% of near-crashes involved some form of driver inattention within three seconds before the event [1].

“Developing approaches for crash avoidance safety technologies is challenging in that, prior to significant market penetration, it is difficult to determine real world effectiveness and safety benefits of new technologies. ... While there are numerous challenges, the agency believes that it has a role in encouraging the development and deployment of all beneficial safety technologies especially, crash avoidance technologies” [2].

Crash avoidance technologies are moving from the development phase to the deployment phase at an accelerated pace. Although the potential of these advanced technologies to reduce crashes, fatalities, and injuries is great, their effectiveness is largely unknown. In order to better understand the potential safety impact of crash avoidance systems, NHTSA started the Advanced Crash Avoidance Technologies (ACAT) program in September 2006.

The ACAT program was established to identify new or emerging advanced technologies and to estimate the safety impact of these technologies. In support of this goal, this research program had two main objectives. The first objective was to develop and utilize a “Safety Impact Methodology” (SIM) to evaluate the ability of advanced technology applications to solve specific motor vehicle safety problems. The second objective was to demonstrate how the results of objective tests can be used by the SIM to assess the safety impact of a real system.

NHTSA entered into a cooperative research agreement with four partners in the automotive industry. The cooperative agreement partners joined with other subcontractors in industry and academia to form the following four teams:

- Team 1: Honda R&D Co., Ltd.-Dynamic Research, Inc. (Honda-DRI) Team for the Advanced Collision Mitigation Braking System (A-CMBS)
- Team 2: Volvo Car Corporation-Ford Motor Company-University of Michigan Transportation Research Institute (Volvo-Ford-UMTRI) Team for Lane Departure Warning (LDW)
- Team 3: Toyota Motor Corporation (Toyota) Team for the Pre-Collision Safety System (PCS)
- Team 4: General Motors Corporation-Virginia Tech Transportation Institute (GM-VTTI) Team for Backing Crash Countermeasures

“[The] Advanced Crash Avoidance Technologies (ACAT) program, in which NHTSA partners with automobile manufacturers to improve information on safety impacts of crash avoidance technologies, is intended to encourage manufacturer efforts to develop such technologies” [3]. This research was completed in the fall of 2009 and final reports from each team have been submitted. This paper summarizes the findings of the four ACAT teams.

Each team carried out the following tasks:

- Identification of the safety problem area
- Description of the advanced technology
- Development of SIM tool
- Development of objective tests
- Conduct and analysis of objective tests
- Estimation of safety benefits using SIM tool

Each team was able to evaluate the estimated effectiveness of their specific pre-production crash avoidance system using their SIM, using the framework described below. Each of the approaches taken by the by the various teams represents a novel method to predict the estimated safety impact of pre-production crash avoidance technologies.

## NHTSA SIM FRAMEWORK

Using the SIM framework shown in Figure 1, each team developed their own computational “SIM tool” based on this methodology. The framework identifies the principle components of SIM and interactions between these components including: Data Usage, Case Scenarios, Objective Testing, Model Creation, Data Generation, Countermeasure Performance Analysis, and Safety Benefits. A short description of each component and its function is given:

**Data Usage** identifies the sources and frequencies of the data used to define the traffic conflict(s) of interest.

**Case Scenarios** describe the specific problem area and corresponding conditions selected for countermeasure application.

**Objective Testing** collects empirical data from test tracks, simulators and other sources to provide distributions of values for model parameters (driver, vehicle, and countermeasure).

**Model Creation** develops a set of computational equations and executable tools to describe driver-vehicle operation in normal and conflict related driving and their respective response both with and without the countermeasure.

**Data Generation** applies the model to the selected scenarios to document the performance of countermeasure operation versus performance with no countermeasure.

**Countermeasure Performance Analysis** compares the number of events (e.g., crashes) associated with presence and absence of the countermeasure to assess system effectiveness.

**Safety Benefits** reports the estimated benefits in terms of quantity of events avoided or mitigated.

The framework does not dictate a specific approach or method. The framework communicates NHTSA’s operational vision of a SIM and the activities NHTSA identified as critical to developing a sound methodology. This framework can be adjusted to accommodate and communicate various approaches to estimate safety benefits. A more detailed description of the SIM framework is given in [4].

## BASIC SAFETY BENEFIT EQUATIONS

The methodologies used to estimate safety benefits are based on the benefits equation [5]:

$$B = N_{wo} - N_w \quad (1)$$

where,

$B$  = benefits, (which can be the number of crashes, number of fatalities, “harm”, or other such measures)

$N_{wo}$  = value of this measure, (for example, number of crashes) that occurs without the system

$N_w$  = value of the measure with the system fully deployed

The benefits equation can be rewritten as:

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

where,

$N_{wo}$  = size of the problem addressed, and  
 $SE$  = effectiveness of the system.

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

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

where,

“ $i$ ” is an index referring to individual scenarios;  
 $N_{wo_i}$  = the number of crashes that occur in scenario “ $i$ ” when the ACAT countermeasure is not available  
 $E_i$  = the effectiveness of the ACAT countermeasure in preventing crashes in scenario “ $i$ .”

### ACAT PROGRAM

The ACAT program was a proof-of-concept effort that sought to determine the feasibility of developing estimates of effectiveness for specific safety technologies in the absence of data from real world crashes or field operational tests. Although these estimates are provided, the focus of this project was on the development of the SIM and linking it to the

results of the objective tests. The SIM used the data available at the time of the study to estimate safety benefits, the calculation of which involved various assumptions and limitations.

Note that each team estimated safety benefits using their own set of equations derived from the basic benefits equations shown. The target populations and addressable crashes for each ACAT were distinctly different as each ACAT team was trying to solve a different safety problem. Team 1 estimated the **overall effectiveness** and safety benefits using the entire US motor vehicle fleet as the baseline population. Team 2, Team 3, and Team 4 estimated the **system effectiveness** and safety benefits using specific target populations as the baseline population, which were different for each technology. Therefore, each ACAT project should be viewed as an independent, stand-alone effort.

All four teams implemented a SIM which can be expressed within the framework stipulated by NHTSA. A summary table comparing the approaches of the four teams and the details of their approaches within the respective components of the SIM framework are shown in Table 1. This is followed by a summary of the implementation of the SIM for each of the four teams, respectively. For more information please refer to the Final Reports of each project.

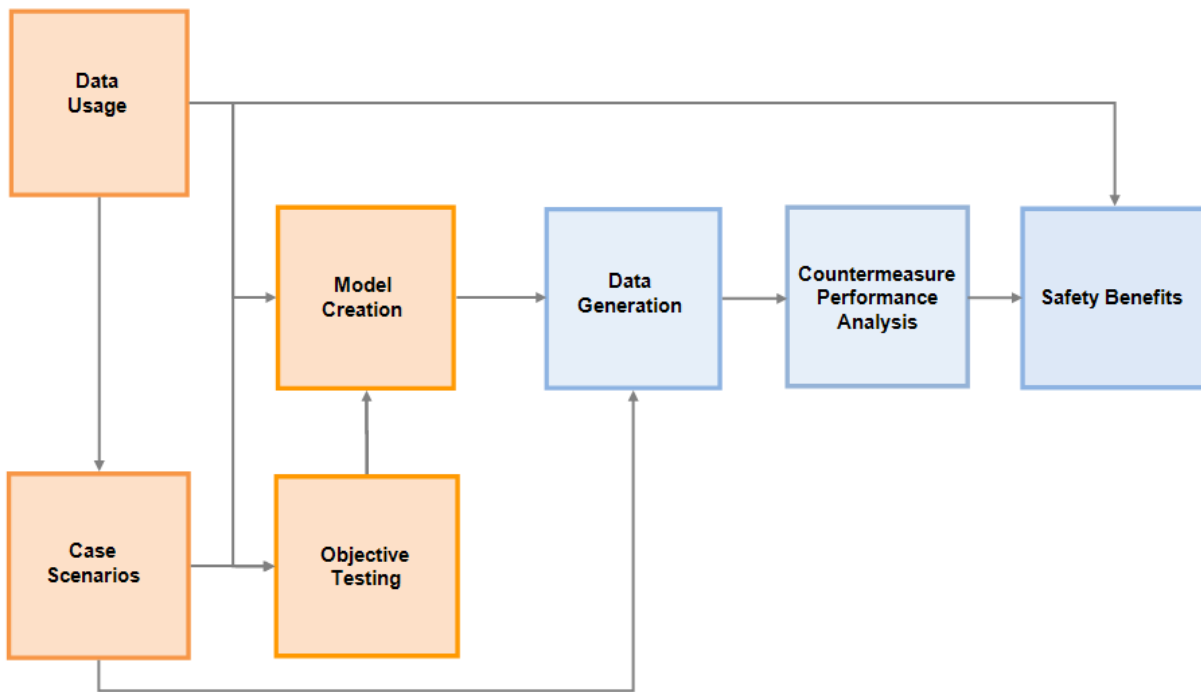


Figure 1. NHTSA SIM Framework

**Table 1.**  
**Comparison of SIM for the four ACAT teams**

<b>SIM Blocks</b>	<b>Components of SIM Framework</b>	<b>Team 1: Advanced Collision Mitigation Braking System (A-CMBS)</b>	<b>Team 2: Lane Departure Warning (LDW)</b>	<b>Team 3: Pre-Collision Safety System (PCS)</b>	<b>Team 4: Backing Crash Countermeasures</b>
<b>Data Usage</b>	Archival Data, Real world data, Corporate body of knowledge and Technology characteristics	NASS/CDS, PCDS, FARS, and GES data	GES, CDS, Highway Performance Monitoring System (HPMS), and RDCW-FOT data	GES, CDS, FARS and Event data recorder (EDR)	FARS, GES, SCI, Public domain research, GM research archives, and VTTI data
<b>Case Scenarios</b>	Breakdown of scenarios, Crash Characteristics and Technology relevant scenarios	- Vehicle-vehicle, intersecting paths - Vehicle-vehicle, rear-end/forward impact - Vehicle-vehicle, head-on - Single vehicle, pedestrian	Inadvertent lane or road departure	SAP-98 Rear-end collision - Lead vehicle stopped - Lead vehicle decelerating Head-on collision Collision to object	10 scenarios (6 pedestrian crashes, 3 vehicle-to-vehicle crashes, and 1 vehicle-to-fixed-object crashes).
<b>Objective Testing</b>	Driving simulator, test track and Lab/HMI test	Driving simulator and lab tests involved. Tests include Guided Soft Target - vehicle conflict tests using naïve and trained driver.	Driving simulator tests with naïve subjects to develop the driver model. Trained driver tests for system validation.	Driving simulator involved. (LVS, LVD). Vehicle tests with -fixed obstacles for system performance	Track and public road tests involved. All 10 scenarios tested. Pedestrian tests conducted using mannequins.
<b>Model Creation</b>	Model definition, validation and calibration	Indigenous simulation model. Cases validated against automated reconstruction and simulation	Using distribution of parameters. Model generated with Matlab/Simulink/CarSIM	Model validated from test track and EDR data.	Matlab/Simulink model. Validated based on previous corporate sponsored research
<b>Data Generation</b>	Digital computer simulation and simulator testing	Reconstructed crashes simulated with and without the ACAT with a sample of typical drivers.	Monte Carlo simulation run with and without ACAT	Simulator Testing results	Monte Carlo simulation run with and without ACAT
<b>Countermeasure Performance Analysis</b>	Without countermeasure, With countermeasure, System effectiveness.	DeltaV, Crash/No crash, Exposure ratio, Prevention ratio	Crash/No, Crash, Exposure ratio, Prevention ratio	Crash/ No crash, Speed reduction Crashes avoided, Fatalities/Injuries reduced	Crash/No crash, Prevention ratio
<b>Safety Benefits</b>	Safety benefits	Crashes, fatalities, injuries (Fatality Equivalents)	Crashes reduced/ mitigated	Crash reduction, fatalities and injury reduction.	Crashes reduced/ mitigated

## TEAM 1: ADVANCED COLLISION MITIGATION BRAKING SYSTEM (A-CMBS)

For the ACAT program, DRI, with support from Honda, developed a tool to evaluate Honda's prototype Advanced Collision Mitigation Brake System (A-CMBS). The A-CMBS addresses four primary collision types including: intersecting paths, rear-end/forward impact, head-on, and pedestrian crashes. The SIM tool provides an estimate of safety benefits in terms of reduction in crashes, vehicles involved, and fatalities [6].

### Data Usage

The Honda-DRI approach begins with the construction of a crash scenario database from archival national accident databases in the United States such as the National Automotive Sampling System/Crashworthiness Data System (NASS/CDS) and Pedestrian Crashworthiness Data System (NASS/PCDS). The CDS database provides detailed descriptions of tow-away crashes involving one or more light passenger vehicles based on in-depth at-scene crash investigations. The PCDS database provides detailed descriptions of vehicle-pedestrian crashes also based on in-depth at-scene crash investigations. These data are also supplemented by information from the Fatality Analysis Reporting System (FARS) for fatal crashes. This crash scenario database contains in-depth information and time-space reconstructions of real-world accidents based on their time-domain relationship. This data was used to classify the crash scenarios in terms of technology relevance and to create sub-samples of cases in each Technology Relevant Crash Type (TRCT).

### Case Scenarios

The characterization of the crash scenarios begins with identifying the combination of driver, vehicle, and environment dynamics presented during the crash. Unlike traditional segmentation processes, Team 1 reconstructs actual scenarios from the NASS/CDS and PCDS databases using the Automated Accident Reconstruction Tool (AART) and segments them into their respective TRCTs. The AART estimates the time-space relationships of the Subject Vehicle and Collision Partner trajectories based on digitized scene diagrams, coded data, and Newtonian physics combined with a number of assumptions. The process adopts a stratified sampling process to select a subset of TRCTs to facilitate simulation. The primary TRCTs from the AART reconstructions used for the safety benefit estimation were:

- Vehicle-vehicle, intersecting paths
- Vehicle-vehicle, rear-end/forward impact
- Vehicle-vehicle, head-on
- Single vehicle, pedestrian

### Objective Testing

The purpose of objective testing in the Honda-DRI ACAT project was to observe and measure the response of an expert driver to the countermeasure intervention; and to observe and measure the response of the vehicle to automatic interventions. A small sample of reconstructed cases was used for this purpose. These response measurements were used for parameterizing and calibrating the driving simulator test conditions and the models in the CSSM. The objective tests included Laboratory Tests, Track Tests, and Driving Simulator Tests.

**Laboratory Tests** were conducted to measure the characteristics of the countermeasure warnings as experienced by a driver during a potential conflict event. The results from these tests were used to create and calibrate the Driving Simulator (DS) as well as to provide parameter values for the CSSM model. Lab tests involved testing the vehicle fitted with ACAT for human factor attributes like warning location, magnitude and spectra as well as vehicle components like vehicle weight, dimensions, etc. that serve as input to the simulations.

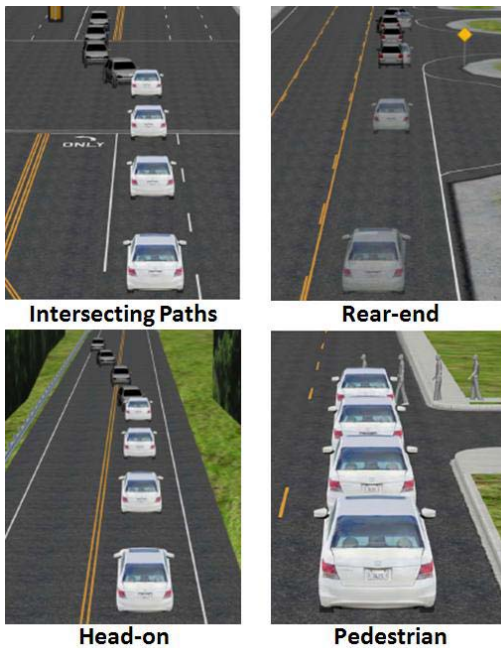
**Track Tests** involved *driver-in-the-loop tests* for expert driver response, delays and magnitudes to warnings and *driver-out-of-the-loop tests* for vehicle response to the ACAT system. The results were used to calibrate the DS and CSSM models of the ACAT system. In order to run the track tests two targets were developed: the Car Guided Soft Target (GST) and the Pedestrian Guided Soft Target (PGST). The GST consists of a self-propelled, self-steering and braking, GPS-guided, low-profile, hardened Dynamic Motion Element chassis, to which soft, 3D targets of a light passenger vehicle (constructed of separable foam panels) are attached as shown in Figure 2.



Figure 2. GST on Dynamic Motion Element base.

The Pedestrian GST consists of a cable-driven, low-profile, hardened “turtle” trolley, the longitudinal position of which is GPS-guided, and to which an inflatable pedestrian form is attached. Both prototypes were instrumental in obtaining driver performance measures for the objective track tests.

**Driving Simulator Tests** involved driver-in-the-loop tests and were used to measure the response of subject drivers to the intervention by the countermeasure system. Both an expert driver and 12 typical drivers were tested. The measurements included the type of driver response (braking, steering or a combination) and the delay and magnitude of each response. 12 cases were selected for the simulator testing, which included three cases for each of the four TRCTs described earlier. An example case used in the driving simulator for each of the four TRCTs is shown in Figure 3.



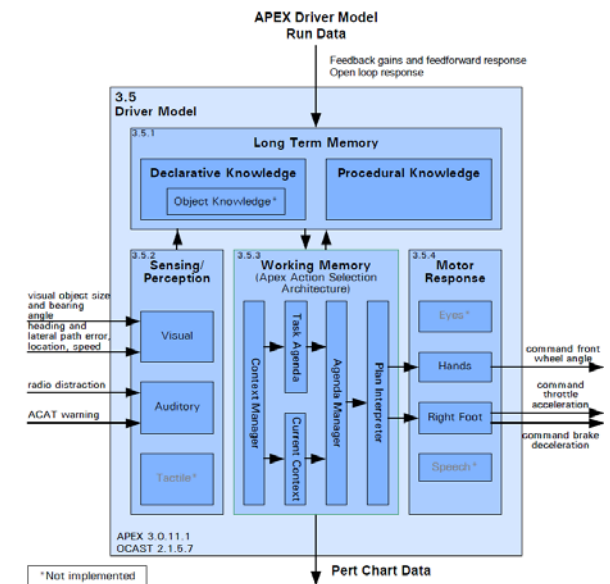
**Figure 3. Illustration of the four primary Technology Relevant Crash Types**

To ensure test reproducibility and repeatability, timing, and consistency of Subject Vehicle (SV) speed, cruise control was used for the SV. A visual distraction task was used in which a light was turned on at 2.0 sec prior to the start of the first expected A-CMBS warning and was turned off at 0.82 sec prior to either the pre-calculated start of A-CMBS braking, or the reconstructed time of impact to the Collision Partner (CP) if there was no A-CMBS braking.

A suite of models form the core of the simulation tool and lie within the framework of development of the

Crash Sequence Simulation Module (CSSM). The core function of the CSSM is a time domain simulation of the *Driver model*, which is based on the NASA Architecture for Procedure Execution (Apex) human operator programming language, the *Vehicle model* (with and without ACAT) and *Environment model* in Matlab /Simulink. The Apex and Simulink models are linked together providing visual object information to the driver model; and driver control to the vehicle model. The virtual reality display used to view the runs is also driven by the Simulink model.

The CSSM has a graphical user interface that enables the user to select the desired crash scenarios and driver behaviors for simulation. The CSSM then initializes and runs the time domain simulations for all desired combinations of crash scenarios and driver behaviors specified by the user. Simulation post processing was accomplished by creating a graphical summary of the driver behavior and other time domain outputs. The CSSM driver model comprises Long term memory, Sensing/Perception, Working memory, and Motor response as illustrated in Figure 4. *Long term memory* comprises declarative knowledge and procedural knowledge, such as vehicle steering and speed control procedures. The *sensing and perception* passes visual, tactile, and auditory information to the long term memory. *Working memory* is implemented in the NASA Apex Action Selection Architecture. The *Motor response* function outputs the commanded steering wheel angle, forward acceleration in g’s, and brake deceleration in g’s to the Simulink vehicle-ACAT-environment model.



**Figure 4. Apex driver model.**



The vehicle dynamics model in the CSSM was constructed as a Matlab/Simulink model. The model uses three inputs: primary control inputs, vehicle states, and a number of vehicle-specific parameters to calculate the vehicle state for each time step. This information is used to calculate values for parameters including: yaw rate, heading angle, and lateral velocity, which is fed back to the model. The vehicle model also includes a distance and azimuth sensor model, control logic, and a brake actuator model, apart from the conventional vehicle dynamics model. The pre-crash vehicle motions are described using quasi-steady state equations-of-motion in terms of state variables.

The countermeasure model was also constructed as a Matlab/Simulink model that allows an interface with the vehicle model and the Apex driver model. The model uses information from the subject vehicle and data from the sensors to determine the state of its outputs. There are many intermediate outputs of the A-CMBS model that are processed further in order to get the final output signals. The resultant final outputs of the A-CMBS model include: braking level, warning, and seat belt tensioner mode.

### Data Generation

A time domain simulation of the driver, vehicle, and environment is conducted by the CSSM. The output from each CSSM simulation includes a yes/no data element that indicates whether or not a crash occurred during the simulation. If a crash occurred then the change in vehicle velocities (i.e.  $\Delta V$ s) for the crash were computed based on the impact geometry and speeds. The  $\Delta V$  values were in turn used to estimate the probability of driver fatality (POF) and injury Fatality Equivalents (FE). If a crash did not occur then the POF and FE are zero. Results for simulations with and without the countermeasure were combined to determine the reduction in the probability of crash, POF and injury FE's.

The advantages of using a sample of “reconstructed crash cases” are that: they include co-variations that have been observed to occur in all the case variables (i.e., not just those judged to be key variables); they are more likely to be “realistic”; currently, they are more recent (e.g., in the case of NASS/CDS) from most regularly updated databases; they have established weighting factors that relate them to national level crash data; and in general, they appear to be nearly the “best available,” most representative and most complete detailed level data for crashes in the United States.

### Countermeasure Performance Analysis and Safety Benefits

The core of the performance analysis lies in the application of the Overall Safety Effects Estimator (OSEE) which estimates the overall safety benefits in terms of the reduction in the numbers of collisions and fatalities at the US level using the fleet systems model. This is based on data for technology effectiveness functions, crash scenarios, retrospective as well as forecasted data. The technology effectiveness functions describe the Exposure, Prevention and Fatality Ratios (ER, PR, FR) for each technology relevant crash type and are based on results from the CSSM simulations.

The estimated safety benefits were computed based on extensions to the baseline benefits equations described in [5] starting with Eq. (3). Depending on the type of benefits (the number of conflicts, crashes, or fatalities) the effectiveness term ( $E_i$ ) is:

$$E_i = \begin{cases} 1 - ER_i & \text{for conflicts} \\ 1 - ER_i \times PR_i & \text{for crashes} \\ 1 - ER_i \times PR_i \times FR_{p,i} & \text{for fatalities} \end{cases}$$

where,

$ER_i$  and  $PR_i$  are the estimated Exposure Ratio and Prevention Ratio, respectively for scenario “ $i$ ” and  $FR_{p,i}$  is the Fatality Ratio for person “ $p$ ” in scenario “ $i$ ”.

The overall estimated safety benefits are the sum of the benefits for each crash type. The benefits for each crash type are equal to the estimated effectiveness ( $E_i$ ) times the size of the problem for each crash type ( $N_{woi}$ ). The overall benefits estimates of the Honda A-CMBS, if it had been installed in the entire US Light Passenger Vehicle Fleet in the 2005 calendar year are shown in Table 2. The baseline population in this table comes from Traffic Safety Facts 2005.

**Table 2.**  
**Safety benefit estimates for the Advanced Collision Mitigation Braking System (A-CMBS)**

	<b>Crash Problem Size for the Entire US Fleet</b>	<b>Estimated Overall Effectiveness for the Entire US Fleet</b>	<b>Estimated Safety Benefits</b>
Crashes	6,146,907	8%	511,000
Vehicles	10,838,878	9%	1,013,000
Fatalities	43,510	4%	1,623

## TEAM 2: LANE DEPARTURE WARNING (LDW)

As part of the ACAT program, Volvo, Ford and the University of Michigan Transportation Research Institute (UMTRI) developed a SIM that addresses lane departure crashes. The Volvo-Ford-UMTRI (VFU) team used interactions between driver, vehicle, environment and technology elements in a Monte Carlo simulation model to estimate safety benefits in terms of crashes avoided [7].

### Data Usage

The VFU SIM was tailored to lane departure crash types. These include road departure and lane departure crashes. The VFU SIM utilizes GES, CDS, Road Departure Crash Warning (RDCW) Field Operational Test data, Michigan State data and a Swedish in-depth crash database (Factors Influencing the Causation of incidences and Accidents, FICA) to establish the typical characteristics of the LDW relevant crash population.

### Case Scenarios

A key component for effective development of a computational model is defining the driving and crash characteristics of the typical scenarios where LDW might be of assistance. These characteristics were captured through a set of *Driving Scenarios (DS)*. Each driving scenario represents a typical combination of driver, vehicle, and environment states that precedes lane/road departures. However, it should be noted that the DS are not pre-crash scenarios as such, since driving under the DS conditions does not automatically result in a crash. Rather they represent combinations of conditions that have the potential to produce lane departures and resultant crashes.

For the purpose of scenario development, baseline population and pre-crash scenario factors were obtained from NASS/GES and NASS/CDS and the Swedish in-depth database. Roadway geometry data were obtained from Michigan State data and Federal Highway Administration (FHWA) Highway Performance Monitoring System (HPMS) data. Vehicle kinematics data were obtained from naturalistic RDCW data. All these sources were used in developing a combination of fixed as well as variant parameters of the DS, that feed into to the SIM model. An example of such a driving scenario would be a vehicle traveling on a dry but curved roadway with two or more divided lanes in daylight with no adverse conditions, with a driver who is not

distracted or fatigued. Overall, 25 such high priority technology relevant scenarios, capturing the typical conditions of slightly more than 90% of the relevant crashes were developed, which form the basis for input to the computational model.

### Objective Testing

Objective tests were performed in the ACAT project in the form of track tests for system performance verification and parameter estimation in the computational model, road tests to establish system availability under different DS's, and two driving simulator studies were conducted to analyze distracted and drowsy driver reactions to various HMI warnings. It should be noted that the outputs of objective tests were not used directly in the computational model, but rather were used to generate parameter values for running simulations as well as to validate and calibrate the computational model.

### Model Creation

VFU's approach focuses on developing a computational model that ties driver, vehicle, environment, and technology elements together to generate realistic interactions between them in a dynamic environment, in order to produce reliable performance outputs. This was accomplished by developing models for the vehicle, technology, and driver, respectively. The Vehicle Model was implemented using CarSIM and was embedded as a subsystem in Matlab's Simulink tool. Output from the driving simulator studies was used to calibrate and validate the Vehicle Model. An illustration of the CarSIM model is shown in Figure 5.

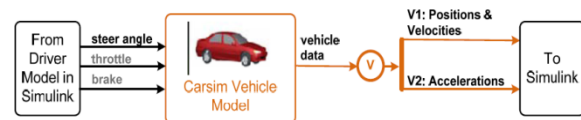


Figure 5. Architecture of the Vehicle Model.

For the countermeasure model, a generic model of the Volvo Lane Departure Warning (LDW) system was developed for implementation in the SIM. The warning algorithm is a function of the lane position and the vehicle's lateral velocity with respect to the lane markings. When the distance between inside of the lane marker and the outside of the nearest front tire is less than the set threshold distance, a lane excursion is flagged, as depicted in Figure 6. While the system was fitted with two levels of sensitivity, the LDW model was implemented with high sensitivity.



**Figure 6. Vehicle location when the lane departure is detected.**

A unique feature of the VFU model is the approach to modeling driver performance. The underlying principle is that drivers leave the lane due to inattention. This principle is coupled with the idea that when drivers become inattentive they switch from a lane-keeping mode, that keeps the vehicle within the lane, to a mode of no action. A return to alertness is modeled by the driver returning to the lane-keeping mode. A warning is one event that will cause a driver to return to alertness from an inattentive state of mind. The modeling utilizes a partitioning of parameters into those that are derived from crash data and those that are derived from quantitative analysis of naturalistic driving data.

### Data Generation

The basic process used for data generation is a Monte Carlo simulation program, which is implemented without and with support from the Lane Departure Warning system. A novel feature of this process is the use of randomly selected cases from the Michigan State crash data files as the means of obtaining variations in key variables such as lane width and detailed road geometry at sampled crash sites. This approach reduces the need for simplified distributions of these key variables which would be used in a more traditional Monte Carlo process.

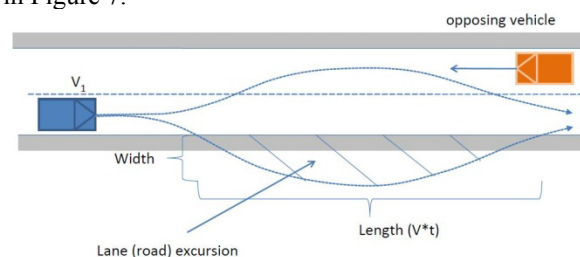
The core of the Monte Carlo process lies in defining and simulating the *virtual driving event*, which is a driving scenario (a combination of the Driver, Vehicle, Environment and Technology (DVET) components) presented as a combination of initial conditions, model parameters, road conditions, and environmental conditions. Each of these parameters is selected randomly for a single run in the simulation. Each simulation is designed to represent a single potential lane or road departure “event” without the technology. Thousands of such runs are executed to form the baseline Virtual Crash Population. Repeat simulations with the technology enabled generates the data required to assess safety benefits estimates.

Some elements that are unique to the VFU ACAT project in the data generation process are as follows:

**Inverse Time to Lane Change (ITTLC)** ITTLC is the reciprocal of the estimated time to lane crossing given the instantaneous position and lateral velocity of the subject vehicle. The ITTLC serves as the primary control variable while sampling initial parameters, which include vehicle kinematic variables obtained from naturalistic driving and parameters obtained by sampling from random distributions.

**Transition Probabilities** In the context of a driving scenario, transition probability is defined as the expected probability of a vehicle transitioning from a normal driving scenario to a crash scenario. This process applies a sampling approach from the ITTLC bins and obtains expectations based on the relative frequencies in those bins. Transition probabilities are an essential component of the VFU SIM methodology, providing an efficient method to amplify crash risk in simulations without introducing systematic bias.

**Crash Metric** As an alternative to generating actual crashes and representing the detailed locations of potential collision objects, a distance-based measure of crash probability was developed. This basic crash risk model associates a crash metric with the lateral or longitudinal distance traversed at various locations outside the desired lane, as shown in Figure 7.



**Figure 7. Crash risk related to trajectory output from simulation.**

The logic behind it is that the lane deviations are unplanned and hold a uniform risk of colliding with a fixed or moving object that is proportional to “exposure”, i.e. the size and duration of the lane excursion. For fixed objects and neighboring lane excursions, this is a distance-based metric based on an arbitrary boundary layer, while for road excursions, the Maximum Road Excursion (MRE) metric is used, which increases linearly within the clear zone (for road departure) to a maximum value at the edge of the clear zone.

## Countermeasure Performance Analysis and Safety Benefits

The basic calculation in this activity is a comparison of crashes that occur without the system to crashes that occur with the system. The VFU team emphasized that this process is different for crash avoidance systems than it is for crashworthiness systems. The difference is that the sequence of relevant events for crash prevention starts with an aberration from “normal” driving. This starting point may lead to a variety of types of crashes or, as occurs most of the time, a corrective action that avoids a crash altogether. The VFU team implemented this process by defining a transition matrix that contained the probability of each type of crash, or no crash, for each type of starting condition, scenario, or event.

The basic benefits equation extends from the original equations such that,

$$B = N - N' = \sum_i \sum_j (T_{ji} - \varepsilon_i T'_{ji}) w_i E \quad (4)$$

where ,

N and N' = the number of crashes with and without the system

E = the Overall system effectiveness

$\varepsilon_i = \frac{w'_i}{w_i}$  is the Exposure ratio

$T'_{ji} = P(C_j | S_i)$  ,  $w'_j = P(S_j)$  Are the transition probabilities and scenario weights with the system.

$T_{ji} = P(C_j | S_i)$  ,  $w_j = P(S_j)$  Are the transition probabilities and scenario weights without the system.

This equation is rewritten into a more general form,

$$B = \sum_j (1 - \varepsilon_j \pi_j) c_j N \quad (5)$$

where,

$$\pi = \frac{P(C|S)}{P(C|S)} = \frac{\sum_j T'_{ji}}{\sum_j T_{ji}} \quad \text{and} \quad c_j = \frac{N_j}{N}$$

Many simplifications and assumptions were necessary to be able to complete the overall project within the time and resources available. These included use of a limited number of driving simulator runs; use of data from one state (Michigan) instead of national data for road environment parameters; no

consideration of fatigue, distraction or non-driving workload in the driver model; and use of a single model of passenger car to represent the entire passenger car fleet. Within the available resources, the team developed models that had adequate fidelity in terms of processes and mechanisms, but otherwise were as simple as possible.

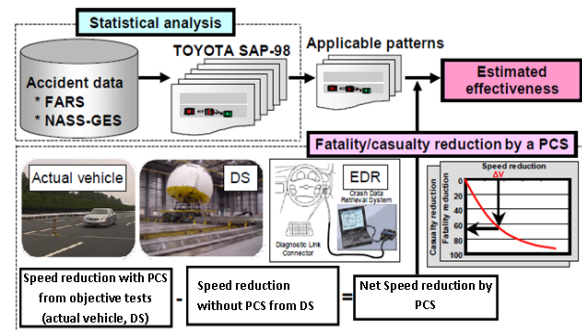
For effectiveness, an initial “raw” estimate of 47% for the 181,000 crashes was calculated. This effectiveness estimate was then refined based on estimates of other influential factors like system availability, driver responsiveness, and driver compliance, which effect the outcome of the benefits estimation process. The resulting range of the final estimate is given below in Table 3.

**Table 3.**  
**Safety benefit estimates for Lane Departure Warning (LDW)**

	Target Population	Estimated System Effectiveness	Estimated Safety Benefits
Crashes	181,000	13% - 32%	24,000 - 57,000

## TEAM 3: PRE-COLLISION SAFETY SYSTEM (PCS)

For the ACAT program, Toyota developed a Toyota SIM (T-SIM) that estimates safety benefits for advanced driver assistance systems such as the Pre-collision Safety System (PCS) that reduces the vehicle impact speed in a crash. The PCS addresses rear-end crashes, head-on crashes, and collision-into-objects. The T-SIM generates estimated safety benefits including the number of crashes avoided, fatalities reduced, and casualties reduced. A graphical view of T-SIM is shown in Figure 8 [8].



**Figure 8. Structure of the T-SIM for the PCS. Data Usage.**

GES, CDS, FARS, and Event Data Recorder (EDR) data were the primary databases used in the development and application of the T-SIM. The SIM process is initiated by classifying the vehicles in GES and FARS crash database as culpable and counter party. Using this classification and crash variables such as accident type, location of crash, and traffic control, the crashes in GES and FARS are grouped into 486 Standard Accident Patterns (SAPs). This set of 486 accident patterns is reduced to 98 SAP by eliminating the minor (representing less than 0.025% of all fatalities in FARS) and unclear cases. The remaining 98 SAPs represent approximately 85% of all crash cases in the accident database. EDR data is used to retrieve information concerning driver performance in baseline crashes.

### Case Scenarios

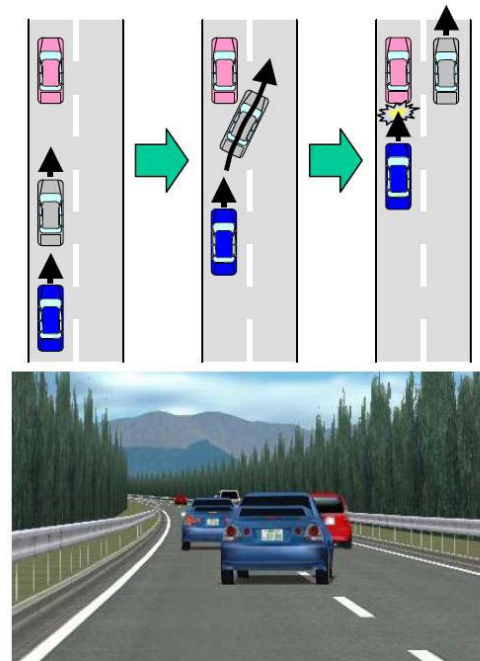
The relevant crashes are separated into three major subdivisions: rear-end (Lead Vehicle Stopped (LVS) and Lead Vehicle Decelerating (LVD)), head-on, and collisions with other objects. Each subdivision is then further subdivided by travel speed ranges (5 mph bins) into the final set of scenarios. Of the 98 SAPs, 15 are considered to be relevant to the PCS. The number of crashes without the countermeasure active ( $N_{woi}$ ) for each one of the relevant scenarios/SAP is calculated from FARS and GES data.

### Objective Testing

The speed reduction attained by Pre-collision Brake Assist (PBA) and Pre-collision Brake (PB) is modeled using the deceleration profiles generated from test track tests, where a PCS equipped vehicle is driven, into a polyurethane-foam pole with a radar reflector, by an expert driver using several different braking levels (e.g. 0.2 g, 0.4 g), including no braking. The driver reaction and brake application profile is modeled using data from the driving simulator study, where the distracted driver reacts to a PCS warning. An example from the Driving Simulator is shown in Figure 9 where a Lead Vehicle Stopped (LVS) scenario is shown.

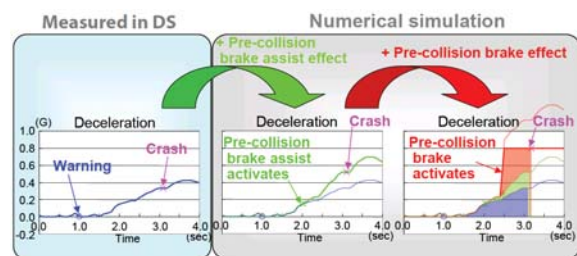
### Model Creation

The model of driver performance consists of a delay after the occurrence of an alert, a warning or other causes that may bring the driver back to alertness, a level of braking and a gradual onset between no braking and the selected level of braking. A key assumption is that drivers react similarly to a



**Figure 9. Driving Simulator LVS scenario showing cut-out revealing stopped vehicle.**

warning, in terms of braking magnitude and application rate, as they would in normal driving when they become aware of an impending crash. The model for the combination of vehicle and countermeasure system has two parts. The Pre-collision Brake Assist (PBA) acts as an amplifier of the driver level of braking and the Pre-collision Brake (PB) produces a constant high level of deceleration, once the respective specified criteria have been reached. The effect of PBA and PB is numerically overlaid on the driver reaction data generated from the Driving Simulator (DS) as shown in Figure 10. The difference in reduction of impact speed between with and without PCS is used to estimate safety benefits.



**Figure 10. Effects of PBA and PB overlaid on the deceleration profile measured in the DS.**

A key element of the T-SIM is the use of EDR data to estimate pre-crash speed reductions when drivers do not have the benefit of the countermeasure.

EDR data were analyzed to estimate speed reduction before crash without a PCS to know the distribution when the drivers stepped on the brake before crash. The result implies that drivers' braking behavior obtained by the DS was similar to the actual situations by EDR. It also implies how much drivers can brake during the crash imminent situation may not be different regardless of the warning. Therefore, the DS data was used for the simulation by weighting the data to have a closer distribution to the EDR data.

### Data Generation

The probability of a fatality or casualty without the countermeasure for each scenario is calculated directly from FARS and GES data. The reduction of travel speed with the countermeasure is determined from the DS tests that determine driver response to a warning and from test track experiments to determine the supplementary impact of the PBA and PB subsystems. The probability of a fatality or casualty with the countermeasure for each scenario is determined by subtracting the reduction in travel speed from the original travel speed (taking into account any pre-crash braking) for each scenario and applying the probability from the original data for the reduced speed. The difference in speed reduction is used to estimate the fatality reduction for accident patterns.

### Countermeasure Performance Analysis and Safety Benefits

The effectiveness of a system can be calculated by multiplying the fatality reduction and the number of fatalities in the applicable accident patterns. The effectiveness in preventing fatalities or casualties for each of 15 scenarios is equal to:

$$E_{fi} = 1 - \frac{P(fatality)_{wo\ i}}{P(fatality)_{w\ i}} \quad (6)$$

where,

$P(fatality)_{wo\ i}$  is number of fatalities for scenario "i" without the countermeasure active.

$P(fatality)_{w\ i}$  is number of fatalities for scenario "i" with the countermeasure active.

and similarly for casualties:

$$E_{ci} = 1 - \frac{P(Casualty)_{wo\ i}}{P(Casualty)_{w\ i}} \quad (7)$$

System Effectiveness is the weighted sum of the effectiveness for the individual scenarios.

While safety benefit estimates were developed by Team 3, the final report was still being reviewed at the time of this printing. Therefore these results are not published here but will be published in the final report for this ACAT project.

### TEAM 4: BACKING CRASH COUNTERMEASURE SYSTEM

As part of the ACAT program, General Motors Corporation (GM) with support from Virginia Tech Transportation Institute (VTTI) developed a basic methodological framework and simulation model to estimate the effectiveness and safety benefits of a prototype backing crash countermeasure system. The SIM tool provides an estimate of safety benefits in terms of reduction in crashes and fatalities [9].

### Data Usage

The data sources that were used were primarily national databases like GES, FARS, NHTSA Special Crash Investigations (SCI) Database; state databases, specifically, Nebraska, Kentucky, and North Carolina; supplemental data sources include data from National Electronic Injury Surveillance System (NEISS), Police Accident Reports (PARs), and death certificates and other non traditional sources including other naturalistic data sources from archives and literature studies. Parametric data sources including: brake reaction time, braking performance, vehicle kinematics, glance distributions, and driver trust, were also used from research archives.

### Case scenarios

The scenario development and crash characterization process was undertaken to aid objective testing of specific countermeasure systems. Since the required data was not captured in the national databases directly, the activity involved a multi-step "reasoned" process that broke down the target population into the following 10 scenarios shown in Table 4. These scenarios were considered to be reasonably representative, but not exhaustive, of the types of backing crash scenarios with emphasis on pedestrian backing crash situations.

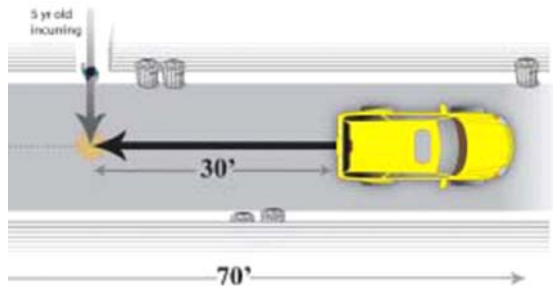
### Objective Testing

The purpose of objective testing is to produce parameter estimates that can populate the SIM model to produce estimated safety benefits applicable to the overall crash problem size.

**Table 4.**  
**Objective test scenarios for Backing Crash Countermeasures**

Test scene #	Roadway Type	Maneuver	Pedestrian Posture/Motion Offset/Direction of Encroachment	Distance from Bumper at Initiation of Backing
P1	Parking Lot	Backing out	Standing on center line	Near (e.g., 5')
P2	Street	Parallel Parking	Sitting on curb, Right (e.g., 2')	Farther (e.g., 30')
P3	Driveway	Backing out	Prone, Left (e.g., 2')	Moderate (e.g., 15')
P4	Driveway	Backing out	Incurring, from right	Moderate (e.g., 15')
P5	Parking Space	Backing out	Incurring from left	Near (e.g., 5')
P6	Long Driveway	Driving in Reverse	Incurring from left	Farther (e.g., 30')
V1	Inter section	Backing	Stopped behind on center line	Near (e.g., 5')
V2	Driveway / Street Junction	Backing out	Approaching from the left	Moderate (e.g., 15')
V3	Parking Lot	Backing out	Parked Behind	Farther (e.g., 30')
FO1	Driveway/ Roadside Junction	Backing out	Utility Pole, encroach to the Right	Moderate (e.g., 15')

An example of such a scenario would be the incurring pedestrian scenario as shown in Figure 11. Here the pedestrian incurs from the left on a long driveway with a distance of 30 feet from bumper at the time of initiation.



**Figure 11. Illustration of the 5 year old incurring pedestrian scenario.**

A highlight of the objective test development process was the development of pedestrian test devices. This involved development and modification of off-the-shelf dummies to develop child pedestrian test devices that have realistic radar cross-sections at the 24 GHz frequency that is used in some rear object detection systems. Test Objects used in Grid tests and Camera Field of View evaluations are depicted in

Figure 12 below.



**Figure 12. Test Objects used during testing (from left to right: Gen II 5 year old, Gen II 2 year old, Cardboard Cylinder, Gen II sitting child, PVC Pole, Gen I Prone 5 year old).**

### Model Creation

A unique feature of the GM-VTTI process was the development of a driver model that has three distinct submodels: the Visibility Model, the Glance Behavior Model, and the Driver Response Model.

**Visibility Model** In the Visibility Model, the parameters define the outside visibility by first determining which “displays” are available to the driver from look-up tables which are used to obtain a probability of visibility. That probability is compared to a pre-determined threshold to ascertain visibility, which includes left mirror, right mirror, rear - view mirror and over the shoulders. In occluding situations, the visibility matrices are zeroed out. The data for the model is obtained from objective testing performed as part of research from other projects as part of GM’s corporate body of knowledge.

**Glance Behavior Model** The Glance Behavior Model not only provides distributions of driver glance behaviors in the presence and absence of counter measure systems but also probabilities of subsequent glance locations based on current glance locations and length of glance. The Glance Behavior Module accomplishes these goals by generating glances and keeping track of when new glances should be generated.

**Driver Response Model** The outputs of the Glance Behavior Model are fed to the Driver Response Model, which determines the presence, type, and level of driver response. The model first determines if the driver has detected the obstacle and countermeasure. If no detection is determined, the simulation proceeds to the next step. If there is evidence of detection, then the model generates a reaction time and braking effort appropriate for the situation and applies these parameters to determine if a crash or no crash occurred. The same process applies for automatic braking as well. A “no crash” situation is detected by the end of simulation time or if the vehicle has stopped before impacting the obstacle. A “crash” situation is identified if the obstacle is within the vehicle’s width, the distance to the object is less than or equal to 0, and the vehicle speed at impact is  $> 0$ .

### Data Generation

The core of the SIM model is the Monte Carlo simulation process exercised in a Matlab/Simulink environment that will extract data from a given set of distributions. The process involves picking values from a given distribution for a given iteration, which are obtained from objective tests and other sources of data. Each iteration is run several times for a new set of parameter values with and without the countermeasure active to account for the variability in outcomes. A comprehensive set of data is produced for all situations which are used in the estimation of safety benefits.

The initial modules of the SIM model define parameters that will remain fixed throughout the simulation (*Non-Variant Parameters*). Subsequent modules define parameters that change as the simulation progresses (*Variant Parameters*), which are defined inside the Simulation Control loops.

Once all the parameters are defined, the SIM starts the Monte Carlo Simulation. The simulation model should be seen as a representation of the overall backing maneuver, from the point where the vehicle is shifted to reverse all the way through to when a crash with the obstacle is recorded or an avoidance of the crash is achieved. The simulation model consists of numerous modules and sub-modules in Matlab that are initialized and called upon repeatedly and are exercised at various points of the iterations. Once all simulation control loops are completed, estimation of safety benefits is performed. A summary flowchart of the SIM flow is shown in Figure 13.

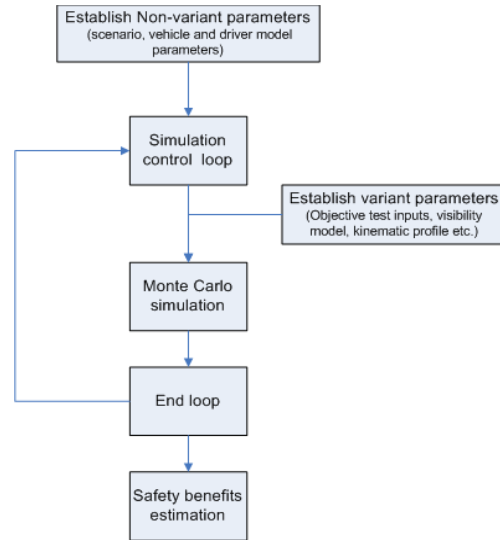


Figure 13. Flowchart of the Monte Carlo process.

### Countermeasure Performance Analysis and Safety Benefits

The main outcome of the countermeasure performance analysis and safety benefits estimation process is the estimated number of crashes avoided annually following the deployment of a particular crash countermeasure. The equations that are used to determine this are given as follows:

$$C_A = C_{wo} \times D_C \times SE \quad (8)$$

where,

$C_A$  = annual number of the type of crashes of interest

$C_{wo}$  = annual number of the type of crashes of interest prior to a countermeasure’s deployment

$D_C$  = potential countermeasure deployment rate

$SE$  = System Effectiveness

Another potential safety benefit is the reduction in fatalities, which is given by:

$$H_R = H_{wo} \times D_C \times SR \quad (9)$$

where:

$H_R$  = predicted annual reduction in fatalities

$H_{wo}$  = annual total fatalities for the type of crashes of interest prior to a countermeasure’s deployment

$D_C$  = potential countermeasure deployment rate in the vehicle fleet.

$SR$  = System Harm-Reduction Effectiveness

Table 5 below summarizes the target crash population, estimated system effectiveness, and estimated safety benefits.



**Table 5.**  
**Safety benefit estimates for Backing Crash Countermeasures**

	<b>Target Population</b>	<b>Estimated System Effectiveness</b>	<b>Estimated Safety Benefits</b>
<b>Crashes</b>	202,000	32%	65,000
<b>Fatalities</b>	182	62%	113

**CONCLUSION AND SUMMARY**

This paper describes a Safety Impact Methodology framework which was used by each of the ACAT teams to estimate safety benefits for pre-production crash avoidance systems. The SIM framework includes the following components: Data Usage, Case Scenarios, Objective Testing, Model Creation, Data Generation, Countermeasure Performance Analysis, and Safety Benefits. The specific extensions to the SIM framework developed in each of the ACAT projects were unique and can be used to estimate safety benefits for various types of crash avoidance systems.

**PROGRAM INFORMATION**

Detailed Final Reports [6][7][8][9] from the teams describing their ACAT projects have been submitted and are in the process of being published. These reports will be available on the NHTSA website at: <http://www.nhtsa.gov/Research/Crash+Avoidance/Office+of+Crash+Avoidance+Research+Technical+Publications>

The ACAT program continues with a second series of research projects known as ACAT-II. This research program involving two teams is currently underway and is set to finish in June 2011. Technical questions on the ACAT program should be referred to James Funke of NHTSA's Office of Vehicle Safety Research at (202) 366-5213 or via e-mail at [james.funke@dot.gov](mailto:james.funke@dot.gov).

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# ON THE USE OF REAL-WORLD ACCIDENT DATA FOR ASSESSING THE EFFECTIVENESS OF AUTOMOTIVE SAFETY FEATURES

## METHODOLOGY, TIMELINE AND RELIABILITY

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### **Abstract:**

During development of innovative automotive safety features (and therefore well before market introduction) it is common practice for OEMs and their suppliers to do predictive analyses of the anticipated benefit of these systems. It is also common practice that stakeholders do a retrospective analysis once the system in focus is in production. Real-world data is then used to identify the “true” effect of the new system. There are however certain constraints to this approach. The varying degree they are met explain the difficulty to find consistent results and also the time span it takes before such results can be taken with any degree of certainty. It is therefore not surprising that even for systems that are now widely recognized as highly efficient it has taken several years before effectiveness numbers turned out to be stable.

### **INTRODUCTION**

During development of innovative automotive safety features (and therefore well before market introduction) it is common practice for OEMs and their suppliers to do predictive analyses of the anticipated benefit of these systems. These analyses are usually limited to “what-if” simulations which is why they are not affected by take rate / fleet penetration issues. Moreover all parameters in the study can be controlled, i.e. the isolated effect of a single system can be easily shown. On the other hand however assumptions, e.g. about long-term driver behavior adaptation, and other simplifications are usually needed even if their validity can not be guaranteed at this stage.

It is therefore also common practice that stakeholders do a retrospective analysis once the system in focus is in production. Real-world data is then used to identify the “true” effect of the new system. There are however certain constraints to this approach:

- the system in focus must be sufficiently frequent in the real world accident data for its effects to be visible.

- it must be possible to distinguish vehicles with the system from vehicles without the system in the accident data since any misclassification of vehicle equipment or accident situation affects the calculated effectiveness. An estimate of the effectiveness can only be reliable if the nature of misclassifications is non-systematic and its extent is limited.
- the effect of a system that is deployed slowly and has small take rates can be “overwritten” by other systems or concurrent developments.
- confounding factors like belt use must be known (minor changes in the rate of non-use can have dramatic effects on fatality rates).
- case group and control group should differ only in terms of presence of the safety feature in focus. Other parameters like distribution of gender, age, vehicle type, mileage etc. should match. If this is not possible multivariate statistical analysis is needed to identify the respective influence of these parameters.
- results obtained from national or regional studies can not necessarily be applied to predict the effectiveness for regions with different fleet, driver population or infrastructure.
- accident data reflects only accidents that have actually happened, i.e., accidents avoided by a certain technology do no longer appear in the databases. This influences the baseline values.
- over time, drivers may get accustomed to the system and change their driving behavior.
- effectiveness figures published by different authors vary widely in terms of the measure they quantify – skidding, loss of control, single ve-

hicle accidents. This makes results hard to compare.

These constraints and the varying degree they are met explain the difficulty to find consistent results and also the time span it takes before such results can be taken with any degree of certainty - systems like antilock brakes and daytime running lights have been around for decades but are still subject to discussion. It is therefore not surprising that even for systems that are now widely recognized as highly efficient (such as ESC) it has taken several years before effectiveness numbers turned out to be stable.

Electronic stability control (ESC) has been developed to assist the driver of a vehicle in critical loss-of-control situation which may lead to a (in many cases serious) accident. A relevant question of course is whether this wanted behavior of ESC can be confirmed from real world accident data. Moreover a thorough quantification of the effectiveness including confidence limits is necessary. Up to today the corresponding literature on vehicle safety contains quite a number of papers dealing with this question. The assured finding of today is that ESC really constitutes a primary safety system which is of high effectiveness in critical loss-of-control situation. The focus of the present paper is to investigate the history of the corresponding research on the quantification of the effectiveness of ESC with special focus on the question how the confidentiality of the results developed over time.

#### AVAILABLE STUDIES

Sferco et al. (2001) is an early paper dealing with the potential effectiveness of ESC in Europe. The paper itself states that in 2001 *it was impossible to undertake a fleet study, i.e. a comparison of accident rates between two fleets of similar cars, one equipped with ESP and the other one not equipped, because at that time too few passenger cars on the road were equipped with ESP. Instead the paper presented an estimate of the potential effectiveness of ESP by analyzing a sample of accidents and relying on experts' opinion deciding, case by case, whether ESP would have potentially influenced the process of the accident or not* (cf. Sferco et al. (2001), p.3). The outcome in the paper on the basis of the so-called EACS (European Accident Causation Survey) data was that ESC could have an influence in about 34% of fatal accidents and 18% of injury accidents. But at that time in 2001 a reliably quantification of the possible effectiveness of ESC was not at all possible.

In November 2002 a press release of Mercedes-Benz (also see Unselt et al. (2004)) again indicated that ESC should be regarded as a driver assistance system which may have a significant impact on of loss-of-control

accidents. ESC is standard equipment of all Mercedes-Benz passenger cars since summer 1999. So the company compared the two groups of Mercedes passenger cars first licensed in the model year 2000/2001 with those first licensed in 1999/2000.

On the basis of a large random sample of police recorded accident data (including not only injury accidents but property damage accidents as well) for the years 1998 – 2001 from the German Federal Statistics Office it could be observed that among all Mercedes-Benz passenger cars the share of those involved in loss-of-control accidents decreased more rapidly than the share of vehicles involved in loss-of-control accidents among all accident involved passenger cars of other brands. More precisely it was observed that for all brands (excluding Mercedes-Benz) the share of passenger cars involved in loss-of-control accidents decreased from 14.5% in 1999 to 14.3% in 2001. The corresponding share for Mercedes-Benz passenger cars only reduced from 15.0% in 1999 over the same time period to 10.7% in 2001.

It is argued in the press release that the reason for the much faster reduction of the share of loss-of-control accidents in Mercedes-Benz passenger cars compared with passenger cars from other brands is mainly due to the ESC safety system. It is worth mentioning that the press release does not contain a serious statistical quantification for the effectiveness of ESC and that only a reduction of a share was reported upon which in theory of course also could be a consequence of an increasing number of others than loss-of-control accidents. Nevertheless the study strongly indicates that ESC might be an effective system avoiding reasonable parts of loss- of-control accidents. But further and much more detailed investigations would be necessary to obtain reliable and statistically significant quantification of the indicated effectiveness of ESC.

So far all investigations obtained rather crude investigations about the possible effectiveness of ESC. No one of the so far reviewed studies take further variables into account. So it is very clear that most vehicles differ not only according to the equipment with ESC or not, but also typically on other equipment. For example at that time ESC equipped vehicles typically belong to an upper (luxury) segment of the car fleet on the roads. Moreover ESC-equipped passenger cars – especially in the year 2002 and earlier – are much newer than vehicles not equipped. Questions of the possible effects of vehicle mass, road conditions, gender and age of the driver and more general driving behavior in different categories of vehicles and so on, have so far not been taken into account.

In the year 2003 a first much more quantitative study of the effectiveness of ESC was presented on the ESV conference in 2003 by Tingvall et al. (2003). This study uses police recorded accident data from Sweden with at least one injured person from the years 2000 until 2002. Only vehicles from the model years 1998 – 2003 were included in the study. The authors build two groups of various case (ESC equipped) as well as control cars (not equipped with ESC) where the controls were selected to be as close as possible to a case vehicle. In total 442 case cars and 1967 control cars are considered in this study. The main idea of the authors is to compare the share of ESC-equipped vehicles in the two accident groups of rear-end accidents and all accidents except rear-end with each other. The reason for this is, that it is assumed that the equipment with the safety function ESC more or less has no potential to affect rear-end accident situations.

Under this assumption the share of ESC-equipped passenger cars in the group of rear-end accidental situations could be regarded as a reliable estimate of the share of ESC-equipped passenger cars on the roads. And of course this share is the quantity to which we can compare the share of ESC-equipped passenger cars among other accidental situations in order to see whether there is a reduction or not. A reduction of the share of ESC-equipped vehicles in a specific accident situation (other than rear-end) will be interpreted as an effectiveness of ESC with respect to the specific accidental situation considered.

To understand better this quite important approach let us consider a simple example, taken from Kreiss et al. (2005) and coming from real accident data. From a large sample of about 690'000 police recorded passenger accidents of the German Federal Statistical Office for the five years period 1988 – 2002 we extract only fatal accidents in which passenger cars are involved for which we most likely know whether these vehicles have been equipped with ESC or not. Moreover we only include involved passenger cars into the study if we most likely know whether ESC has some potential effect on the accident outcome of this specific vehicle (accident sensitive to ESC) or if ESC definitely has no effect on the accident outcome (accident not sensitive to ESC). Doing so we end up from our huge accident data base with a sample of n=432 passenger cars involved in fatal accidents. The results can clearly be arranged as shown in Table 1..

Exactly as described in Tingvall et al. (2003) we use the equipment ratio of  $54/68=79.4\%$  for the vehicles involved in accidents not sensitive to ESC to estimate the ESC equipment ratio for the vehicles on the road. It is stressed that the quantity 79.4% only is an estimator of

the unknown equipment ratio on the market and that this estimator may suffer from systematic (e.g., vehicle selection) as well as completely unsystematic (probabilistic) fluctuations. Since the equipment ratio of  $82/228 = 36.0\%$  for the vehicles involved in sensitive accidental situations is much lower we have an indication of a relevant effect of ESC.

**Table 1.**  
**Cross-tabulation in Kreiss et al (2005)**

<b>Fatal accidents</b>	<b>Vehicle not equipped with ESC</b>	<b>Vehicle equipped with ESC</b>	<b>Total</b>
<b>Accident not sensitive to ESC</b>	68	54	122
<b>Accident sensitive to ESC</b>	228	82	310
<b>Total</b>	296	136	432

For a precise and correct quantification of the effectiveness of ESC note that according to our assumptions ESC only can have an effect on the category of sensitive accidents in ESC-equipped passenger cars. That is only the number 82 in the above Table 1 might be influenced by ESC. Under the assumption that ESC completely has no effect we would expect the same equipment ratio of 79.4% for the passenger cars involved in accidents sensitive to ESC. If this would have been the case we would have expected a number x instead of 82 accidents in Table 1 such that the fictive equipment ratio  $x/228$  equals 79.4%. This leads to  $x=181$ . Thus ESC was able to reduce the fictive number of accidents sensitive to ESC from 181 to 82 which constitutes an impressive reduction rate of 54.7% for ESC in the category of accidents sensitive to ESC. Rewriting the reduction rate as

$$\begin{aligned} \text{Effectiveness} &= 1 - \text{OR} \\ &= 1 - (82 \cdot 68) / (54 \cdot 228) \\ &= 1 - 0.453 = 0.547 = 54.7\%, \end{aligned}$$

where

$$\text{OR} = (82 \cdot 68) / (54 \cdot 228)$$

is the so-called Odds-Ratio of Table 1.

This exactly describes what Tingvall et al. (2003) did. They considered as the category of accidents not sensitive to ESC rear-end accidents on dry roads. This means that the results assume that rear-end accidents on dry roads are not expected to be influenced by ESC. This assumption is justified as long as direct influence is

considered. However ESC is usually combined with some kind of brake assist (BAS). Such a system may have an influence on rear-end accidental situations, so there might be an indirect effect of ESC via the link to BAS. Fortunately it can be seen that such a possible indirect effect typically leads to an underestimation of the effectiveness of ESC. (cf. Kreiss et al. (2005)).

As accidents sensitive to ESC the Swedish study reported upon in Tingvall et al. (2003) selected all accidents except rear-end on dry roads. This means that this study, in contrast to our example from above, considers the effectiveness of ESC to all accidents except rear-end on dry roads.

Since the paper of Tingvall et al. (2003) does not give explicit tables like Table 1 but results of the effectiveness only we could not have used their data for our example above.

The confidence interval [1.1% , 43.1%] for the overall effectiveness of ESC on all but rear-end accidents given in the paper of Tingvall et al. (2003) is quite large. In other words, with 95% confidence we can only state a 1.1% effectiveness of ESC. Concerning the effectiveness on all but rear-end accidents on dry roads the paper states a 95% confidence interval of [-19.0% , 37.6%], which does not state a significant effect of ESC on dry roads at all! On wet roads the study obtained a 95% confidence interval of [7.8% , 55.2% ] for the effectiveness of ESC.

The authors stress that because of the different weather conditions it is impossible to generalize the results of their specific study to all other parts of the world. Moreover it is remarkable that the Swedish study cannot detect a significant effect of ESC on dry roads. Finally the Swedish study does take into account varying road conditions.

In the paper Aga and Okada (2003) the authors report on a study of the ESC effectiveness in Japan. This study not only took accident material (provided by ITARDA) into account. Instead the rate or risk of suffering an accident when driving on the roads is considered and the study gives estimates for this risk of passenger cars equipped and not equipped with ESC by computing the numbers of accidents per 10<sup>7</sup>000 registered vehicles per year. It is obtained that vehicles equipped with ESC have a of about 35% lower risk of suffering a single car accident. The investigation and computation of this risk rates was done in such a way that vehicles registered for the first time in 1994 were investigated according to their accident behavior for the period 1994 – 1998, vehicles registered for the first time in 1995 have been under accident inspection from 1995 until 1999 and so

on. Since ESC have been introduced somewhere in between the study we have to face the fact that in the study older vehicles not equipped with ESC and more recent and modern vehicles equipped with ESC have been considered. And of course and also as already mentioned these passenger vehicles of varying year of manufacture differ according to their safety equipment in more than ESC. Even the mileage per year and this means the time under risk on the roads may differ for the vehicles and would lead to a biased estimator of the reduction of the accident rate! However the paper of Aga and Okada (2003) presented a different and relevant approach for investigating the possible effectiveness of ESC.

In a further paper, Page and Cuny (2004) report on a study similar to the approach of Tingvall et al. (2003) for French cars. In this study the authors compared the Renault Laguna 1 (which was not equipped with ESC) with the newer vehicles Laguna 2 – equipped with ESC. The selected sample consists of 1356 cars involved in injury accidents in 2000 – 2003 in France. In contrast to Tingvall et al. (2003) the authors have thoroughly selected a variety of accidental situations relevant to ESC and/or braking. Even more the authors considered several different scenarios of driver age, vehicle age or year of accident. As described above in detail the authors give 1 – Odds-Ratios as estimates of the effectiveness of ESC in accidents sensitive to this system. Without taking into account any confounding factors (crude approach) Page and Cuny (2004) for example obtain the following 2x2 contingency table.

**Table 2.**  
**Cross-tabulation in Page and Cuny (2004)**

	<b>ESC equipped</b>	<b>No ESC</b>	<b>Total</b>
<b>ESC sensitive accident</b>	22	177	199
<b>Non ESC sensitive accident</b>	71	318	389
<b>Total</b>	93	495	588

which leads to a (crude) Odds-Ratio of  $OR = (22 \cdot 318) / (71 \cdot 177) = 0.56$  indicating that 1 – OR = 44% of all ESC sensitive accident situations could be avoided by the electronic stability program. A corresponding 95% confidence interval for the (crude) Odds-Ratio was given in the paper as [0.46 , 1.29] and meaning that the value OR = 1 could not be excluded on this significance level. This means that we unfortunately do not have a significant effectiveness of ESC on French roads from this study. Of course this is due to the fact that the sample size in this study as well as in all other studies so

far is limited, even so a period of several years of police recorded accidents have been taken into account. The reduction of the accident sample because of the necessity of having knowledge of the equipment with the safety function as well as the selection of sensitive and not sensitive accidents dramatically leads to a reduction of the sample size. This holds true for all studies even in large countries and is not a drawback of the study of Page and Cuny (2004). A very relevant result from Page and Cuny (2004) is the fact that here for the first time we obtain indications that the effectiveness of ESC varies with confounding variables like driver age, vehicle age and year of the accident. Again these results are not statistically significant. A certain drawback of the study of course is that the comparison of the Laguna I and its successor Laguna II leads to the problem that these two passenger cars differ in much more than the equipment with ESC, only.

It shows that with an error probability of 5% we can expect an effectiveness of the new Laguna 2 in comparison with the old Laguna 1 according to ESC-sensitive accidents of at least 7%. Of course this reduction rate of 7% is only valid for the group of ESC sensitive accident constellation and by no means for all accidents as in the study of Tingvall et al. (2003).

Let us see how sensitive the results reported upon in Table 2 are. Sources for uncertainty are

- precision of the ESC-equipment ratio in the category of non ESC sensitive accidents as a surrogate for the equipment rate on the roads
- Misclassification of vehicles according to equipment
- Misclassification of accidents according to type
- Under- or over-reporting of certain accident types
- Influence of additional factors like age or gender of driver, driving behavior depending on vehicle category
- Comparability of vehicles equipped and not equipped with ESC

To investigate possible effects of these facts assume that the equipment ratio of  $71/318=22.3\%$  in the category of non ESC sensitive accidents systematically under- or overestimates the equipment ratio on the roads by about 10%, that is that the equipment ratio on the roads may be either 24.8% or 20.1%. This would immediately lead to a quite substantial uncertainty about the effectiveness of ESC within the range of (38%, 50%).

As a further example let us assume that about 10% of the reduction of ESC-sensitive accidents in Table 2 are completely explained by further safety features (other

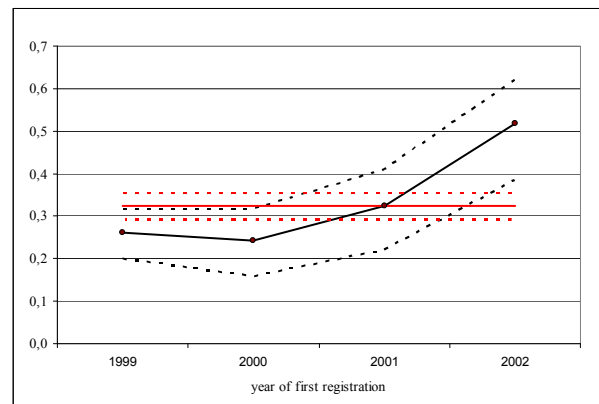
than ESC) and that only the ESC equipped vehicles additionally are equipped with this functions. This would lead to the following modification of Table 2 concerning the pure effectiveness of ESC.

**Table 3.**  
**Cross-tabulation by Page and Cuny (2004), modified to account for non-ESC effects**

	ESC equipped	No ESC	Total
ESC sensitive accident	24	177	199
Non ESC sensitive accident	71	318	389
<b>Total</b>	93	495	588

The same calculation of above would lead to a decrease of the computed effectiveness of ESC to 38%.

Misclassification of vehicle equipment and/or accidental situations of course has an effect on the quantification of the effectiveness of ESC. From Kreiss et al. (2005) it is seen that a completely random misclassification of both mentioned types has the effect that we underestimate the effect of ESC. So this in a sense is not that problematic. Much more delicate would be a situation in which the used accident data base contains some systematic errors or reporting rates of only one type of accident or only one group of ESC- or non ESC equipped vehicles. This would lead to a systematic variation concerning the quantification of the effectiveness of ESC.



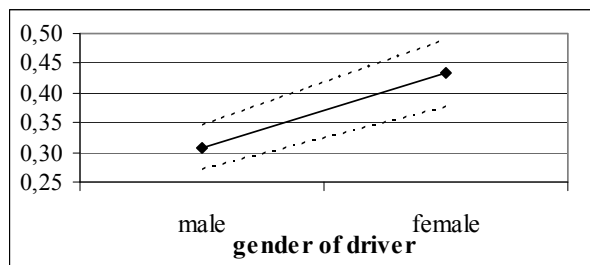
**Figure 1. Effectiveness of ESC for different years of first registration (1999-2002) (black) with 95% confidence limits (dotted) and overall effectiveness including 95% confidence limits (red)**

Further difficult to detect sources of uncertainty in the quantification of the effectiveness of ESC may be

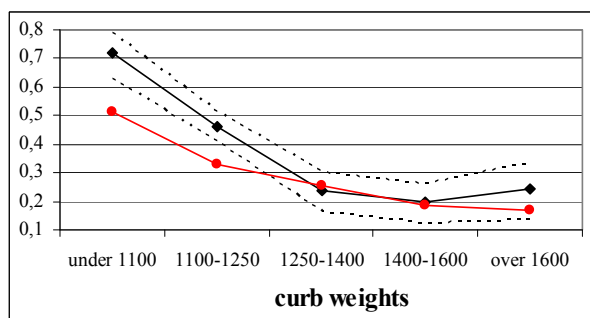
hidden in additional and relevant variables. Some examples are discussed in Kreiss et al (2005). From the already mentioned rather large sample of German accidents for the period 1998-2002 this paper reports that the effectiveness of ESC varies according to a variety of additional variables. For examples the following result is obtained concerning different years of first registration

Figure 1 indicates that either the functionality of ESC systems in vehicles improved over the years or that additional safety equipment in more recent cars has some effects on loss-of-control accidents or even both. Another possible explanation is that the underlying accident data most probably is sampled during the same period, i.e. the 1999 cars may simply be older (and therefore driven by a different driver population) than the 2003 ones.

Concerning the gender of the driver Kreiss et al. (2005) obtain a significantly better effectiveness of ESC in women-driven vehicles, cf. Figure 2.



**Figure 2. Effectiveness of ESC separately for gender of driver including 95% confidence limits**



**Figure 3. Effectiveness of ESC separately for different curb-weights (in kg) including 95% confidence limits (black solid and dashed lines) together with the percentage of female drivers in the respective curb-weight category (red line)**

Since it can be verified at least from accident data that women on average drive smaller sized vehicles than men the effect seen in Figure 2 may be to some extend

or even completely be explained by a possible variation of the effectiveness of ESC according to vehicle size. To this end consider Figure 3 presenting the variation of the effectiveness of ESC in comparison to vehicles size and also the percentage of women-driven vehicles (involved in accidents) according to the different vehicle category.

Finally Kreiss et al. (2005) obtain from the German accident data base that ESC is more effective on dry than on wet or icy roads which is in contrast to the Swedish results of Tingvall et al. (2003) and underpins the remark of the Tingvall paper that results from one country can not easily be extended to other countries!

Weekes et al. (2009) claimed a higher effectiveness rate of ESC for young drivers in the UK. More precisely the study states that the overall effectiveness of ESC for young drivers of about 14% is around double a previously published overall effectiveness of 7% for all ages and all injury severities. Since the paper also states that young drivers commonly drive small used cars with ESC rarely fitted the question arises how far the reported effectiveness is related for example to the smaller vehicle, since ESC if equipped in smaller and lighter vehicles might have a dramatically higher effectiveness (cf. Section 2 and Figure 3).

ESC appeared on the U.S. market a few years later compared to Europe. Farmer (2004) compared on police-reported crashes for seven states from the years 2001 and 2002 crash rates per registration for selected group of vehicles. The main focus was on vehicle models which changed from no ESC or optional ESC to standard ESC in consecutive model years. Concerning the overall crash involvements and the injury crash involvements the papers describes slight effects (which not in all cases are statistically significant), only. Concerning fatal crash involvements the observed effects are larger. A closer look on the reported results shows that the picture is indifferent over the considered vehicle models. For some ESC equipped vehicle models even higher numbers of fatal crashes than expected where observed.

Another inconsistency, likely based on little data, is that the observed effectiveness of ESC was larger in the group of vehicles which changes from optional to standard ESC equipment compared to the group of vehicles for which the equipment changes from no ESC to standard ESC. However the observed effects of for example 41% lower than expected number of single vehicle crashes is quite similar to reduction rates reported for Japan or Europe. Concerning the overall multiple vehicle crash-rates Farmer (2004) reported a little, if any, effect of ESC, which is in contrast to the

studies of Aga and Okada (2003) and Tingvall et al. (2004).

Dang (2004) on the basis of single vehicle crash data from the years 1997-2002 from five US states in her evaluation note reduction rates of about 35% for single vehicle crashes in ESC equipped passenger cars. A 30% reduction is reported for fatal single vehicle crashes (also for passenger cars). For SUV's the obtained reductions rates are higher. The effectiveness of ESC is computed by using multiple-vehicle crashes as control group. Since the belt usage rate among passengers in ESC equipped SUV's (58%) was higher than among passengers in non ESC equipped SUV's (49%) and the small samples do not lead to reliable results for SUV's.

The paper of Bahouth (2005) reported on six US state files of about 14,000 police-reported crashes for the years 1998-2002 and 11.2% reduction in multiple-vehicle frontal crashes as well as a 52.6% reduction in single-vehicles crash rates for ESC-equipped Toyota passenger vehicle models and SUV's in the US. Following the methodology of Tingvall et al. (2003) the study of Bahouth (2005) compares rear impact crashes with multi-vehicle frontal crashes and single-vehicle crashes. The obtained results are similar to the findings of Farmer (2004).

## AVAILABILITY OF REAL WORLD DATA

### 1.1 National statistics

All major developed countries publish their annual road accident statistics, usually based on police accident reports. Although concerns about underreporting have been voiced (and corroborated by hospital and insurance data,[]) the national databases are considered the most comprehensive in terms of case numbers. On the other hand however, they allow only limited or no access to disaggregate data and/or omit detailed injury, technical or reconstruction information. Hence, scientific in-depth databases have been established to fill this gap.

### 1.2 Scientific in-depth databases

These databases cover only a small fraction of all accidents but provide detailed information on the vehicles and their safety features, medical data as well as reconstruction results for the collision and, in some cases, the pre-crash phase. If available, the latter also allow for an analysis of accident causation. There are different sampling philosophies (random, stratified,...) that may or may not allow a projection to national statistics.

GIDAS, the German In-Depth Accident Database is an example of a scientific database. It was launched in

1999 and has BAST (the Federal Highway Research Institute) and FAT (an industry consortium) as sponsors. Two academic institutes, Hanover Medical School and the Technical University of Dresden act as contractors. Each contractor collects about 1000 cases per year, following a common methodology and storing them in a common database. The entry criteria,

- road accident
- involving personal injury (of any severity)
- within defined geographical regions
- while the analysis team is on call

should make sure that sampling is random and hence the sample is representative. This is true for most key variables except accident severity – the more severe an accident is the more likely the GIDAS team will be notified by the police. This causes a certain bias towards severe and fatal cases; however this bias can be corrected by means of weighting factors if necessary.

### 1.3 OEM proprietary databases

Since scientific databases are often designed to be representative of national statistics the vehicles sampled in them also represent a cross-section of makes, models and model years. Manufacturers trying to establish the real-world safety performance of a new model or feature will however look primarily at accidents involving new (and, if possible well-equipped) vehicles from their own model range. This is why some OEMs have set up their own accident investigation teams, often feeding their information into databases even more detailed than the scientific databases discussed previously. Due to their (intentional) bias in terms of vehicle selection and some other (unintentional but sometimes inevitable) bias in terms of geography, accident severity, etc... projection from these data to national statistics is problematic.

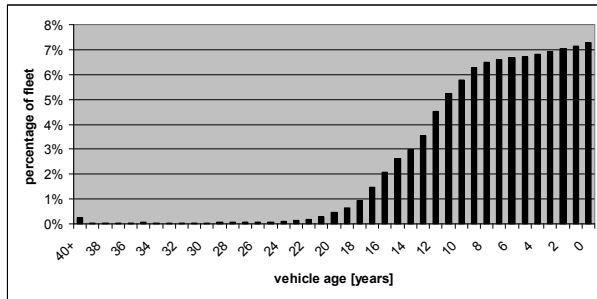
### TIME LAG BETWEEN TAKE RATE AND FLEET PENETRATION

Advanced safety features are usually introduced following a top-down approach, i.e. at first they are offered as an optional extra for luxury executive vehicles, then gradually becoming available in more and more family vehicles until, in many cases, the feature becomes standard equipment even in compact and economy cars. Furthermore, advanced features usually cannot be retrofitted, i.e. their fleet penetration can grow only as fast as old vehicles are replaced by new ones.

Both of these effects cause a substantial time lag between the market introduction of a new technology and the time it can be found in significant numbers in the fleet. The following example illustrates this. For simplicity it was assumed that both the overall number of



vehicles in the fleet and the replacement rate do not change over time. This leads to an age distribution like the one in the following graph (slightly idealized from 2009 German registration data):

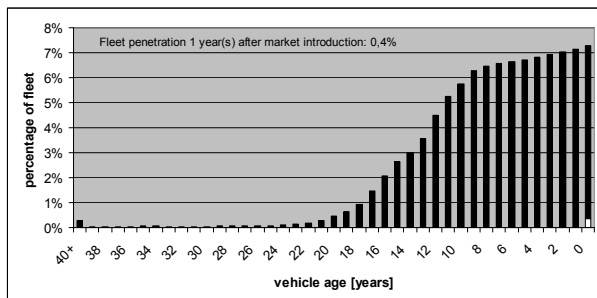


**Figure 4. Sample age distribution of a given fleet of cars**

Let us further assume that a new promising in-vehicle technology will be phased in according to the following scenario. Please note that a time span of 10 years between market introduction and 100% equipment rate is relatively short by comparison - most systems have taken a longer time, some have never become standard.

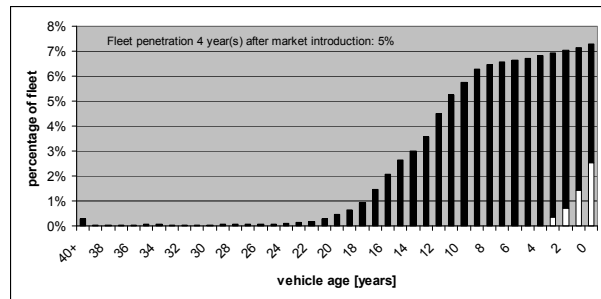
1 year after market introduction	5% take rate
2 years after market introduction	10% take rate
3 years after market introduction	20% take rate
4 years after market introduction	35% take rate
5 years after market introduction	50% take rate
6 years after market introduction	65% take rate
7 years after market introduction	80% take rate
8 years after market introduction	90% take rate
9 years after market introduction	95% take rate
10 years after market introduction	100% take rate, i.e., standard

After the first year approximately 0.4% of all vehicles in the fleet will be equipped:



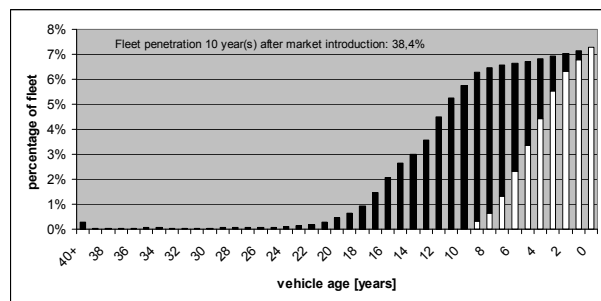
**Figure 5. Age distribution and system fleet penetration 1 year after market introduction**

Another three years later the fleet penetration will still be as low as 5%:



**Figure 6. Age distribution and system fleet penetration 4 years after market introduction**

Even ten years after introduction, i.e., when we assumed the system to have become standard on every new vehicle there will be many more vehicles without the system than with the system on the road:



**Figure 7. Age distribution and system fleet penetration 10 years after market introduction**

This illustrates the difficulty of an early assessment of a newly introduced system, a problem that is often made even worse when the first buyers (“early adopters”) of a new technology are not a representative cross-section of the overall population of customers.

## IDENTIFICATION OF SAFETY FEATURES IN THE ACCIDENT DATABASES

For a retrospective analysis of a given system’s safety benefit it must be possible to identify the presence or absence of this feature in the accident database. Typically, police data do not contain any such information. Given the multitude of makes and models in today’s fleet officers on the scene can not tell with certainty which systems have been present. Arguably this gap could be filled with the help of the respective OEM who might (even years after the accident) look up this information in its production history data. As many systems in question are optional their presence needs to be established on a per-vehicle (i.e., VIN) basis. Different OEMs however have different systems to record

their production history which makes this approach tedious. Moreover, forwarding a VIN list to an OEM raises privacy issues, so this approach is not even legally possible in many jurisdictions.

Generally speaking, scientific databases are facing the same problems. Given the lower case numbers however it is often possible for the investigators to gather the required information from inspecting the vehicle on the scene. In this case however only systems will be identified whose fleet penetration is high enough to justify the effort of introducing the respective variable in the database. This adds to the delay described in the previous section.

### **CORRELATION VS. CAUSATION**

One of the most common errors in statistical studies is the confusion between correlation and causation. Something (e.g. a driver action or a safety system) can cause another action or occurrence, which means that the primary action or occurrence really implies or at least has some influence on another action or occurrence. As an example, a damaged braking system in a vehicle is a possible cause for a rear-end accident in nose-to-tail traffic. And if one action or occurrence causes another, then they are most certainly correlated. Correlation only means that there is some tendency of two or more actions or occurrences to coincide in a (typically complex and random influenced) situation. But just because events occur together this does not mean that one causes the other, even if it may make some sense. If one reduces correlation to the classical statistical correlation coefficient, then correlation even measures linear dependence, only. And it is rather easy to think of variables, which are closely (and even completely) dependent – for example in a quadratic or more complicated nonlinear way – and having a correlation coefficient of exactly zero!

An extreme difficulty in many statistical methods is that they are designed to detect or to test correlation of two or more events only! To obtain evidence that observed correlation comes from causality of two or more factors one has to rule out the possibility that the observed factors are caused by one or more further and typically not observable factors. Strictly and theoretically speaking this really hardly can be done. In some situation causation may be deduced from common or specialists sense, but there are of course many cases in which the existence of causality of events is not so clear. Studies in which only two or a very restricted number of variables are considered are to a large extent not able to give reasonable evidence in direction of causality.

The applied statistical literature recommends so-called controlled studies in order to give evidence that ob-

served correlation is connected to causation. In a controlled study, two or more groups of observational objects (e.g. vehicles with drivers on the road) are created, which in almost every way are comparable (same age and gender of driver, same vehicle and same driving and road conditions and so on) except the one (e.g. a specific safety function) one is interested in. Exactly this is done in serious clinical trials developed in order to detect causation between for example lung cancer and smoking.

For the evaluation of the influence of a specific safety function or a complete safety equipment in vehicles on the road and based on real-world accident data the statistical tool of a controlled study by far is not an option. The selection of accidents, which to a suitable amount coincide in respect to driving situation, weather conditions, driver and vehicle, in many if not all cases is impossible because of a limited number of accidents available and more seriously because of the lack of information. As an example note that the risk of being rather severely or even fatally injured cannot be reliably computed from an accident database in which the information whether the driver was belted or not is not available.

Because of this one has to be really aware of falsely jumping to causal conclusions too early. This seems to be extremely the case when there is some public suspicion about the reasoning for some observed effects.

As an example let us consider once again the situation reported upon in Figure 2 (Section 2). There we find out a statistically significant correlation between the gender of the driver of a vehicle and the effectiveness of the ESC system in loss-of-control accidents. This result does not mean that there necessarily is some causation between the two factors, more exactly that an ESC system works better in a female driven vehicle than in a vehicle driven by men. Of course there may be causality, but the slightly deeper investigation, which includes the size of the vehicle, shows that gender of driver and the size of the vehicle are correlated as well (cf. Figure 3). So it is quite possible that the true causality is between the size of the vehicle and on one hand the gender of the vehicle (women tend to driver smaller cars) and on the other hand between ESC and size of the vehicle (the safety increment by ESC in smaller vehicles is larger than in larger cars typically having more primary and secondary safety equipment on board than smaller cars). This really may be the case and really may lead to the observed pseudo-correlation between gender of the driver and effectiveness of ESC in loss-of-control accidents. Unfortunately, it may be the case that none of the above is true and the true reason for all observations is much more complex. A further more

complex and still plausible explanation for the observed phenomenon may be that women indeed tend to drive smaller vehicles but also tend to drive in different situations and moreover possess a different driving attitude than men and that (young?) men especially in small cars tend to overestimate their and the vehicles possibilities and are much more exposed to loss-of-control accidents.

All this demonstrates how complex reality might be and possible is. Thus a reliable conclusion from a single accident investigation is difficult if not impossible to obtain. It is the variety of accident-based investigations leading to comparable and therefore reproducible results that forms a convincing picture of a causal dependence of the ability specific safety function to partly avoid specific types of accidents.

In case a statistical database analysis shows a positive correlation between two variables a and b it takes engineering judgement (or at least common sense) to determine whether a causes b, b causes a or both a and b must be attributed to a third effect, cf. Zobel (2007)

#### DRIVER EFFECTS VS VEHICLE EFFECTS

To demonstrate that driver effects not taken into account may lead to a substantial bias in statistical conclusions let us consider a thought experiment.

Assume that we have  $n=1.000.000$  vehicles on the road and that 30% of all vehicles are equipped with a specific safety function of interest. Let us think for simplicity of just one driver related variable (Driver) which can attain two value, 0 and 1, say, only. An example is gender of the driver. We restrict our investigation to only to accident scenarios of two types, namely one sensitive to the safety function of interest (Sensitive Accident) and the other one more or less neutral (Neutral Accident) accidental situation. The assumed model to generate accident data is a simple logistic regression model of the form

$$P(\text{Sensitive Accident} \mid \text{Safety Function} = r, \text{Driver} = x) = \frac{\exp(\beta_0 + \beta_1 r + \beta_2 x)}{1 + \exp(\beta_0 + \beta_1 r + \beta_2 x)}$$

for all  $r, x = 0, 1$  and  $\beta_0 = -5$ ,  $\beta_1 = -0.35$  and  $\beta_2 = 0.50$ . This means that we have a positive effectiveness of the safety function as well as of  $\text{Driver} = 0$ . More precisely the effectiveness of the safety function on accidents sensitive to it reads as follows:

$$\text{Effectiveness} = 1 - \exp(-0.35) = 0.295 = 29.5\%$$

Let us further assume that for about 80% of the vehicles  $\text{Driver} = 0$  is true and that we have the following distribution of the variables Driver and Safety Function

**Table 4.**  
**Driver distribution in equipped and non equipped vehicles**

safety Function	gender		total
	male	female	
not present	600,000	100,000	700,000
present	200,000	100,000	300,000
total	800,000	200,000	1,000,000

Table 4 reflects that 30% of the vehicles are equipped with the safety function but that this rate varies according to Driver gender equal to “male” or “female”.

According to our assumption on the probability for an accident we obtain by Monte Carlo simulation the following tables of accidents.

**Table 5.**  
**Simulated number of accidents sensitive to the safety function**

safety Function	gender		total
	male	female	
not present	4,009	1,097	5,106
present	951	779	1,730
total	4,960	1,876	6,836

**Table 6.**  
**Simulated number of accidents neutral to the safety function**

safety Function	gender		total
	male	female	
not present	4,050	2,100	6,150
present	1,350	2,100	3,450
total	5,400	4,200	9,600

The values in Table 6 accurately resemble the equipment rate within the two driver categories (compare the respective columns in Tables 4 and 6). But, the probability of suffering a neutral accident varies within the two driver groups.

Using the standard SPSS-routine *logistic regression* the following estimators are derived:

$$\beta_0 = -0.010, \beta_1 = -0.341 \text{ and } \beta_2 = -0.640.$$

It can be seen that only the estimator for  $\beta_1$  and therefore the effectiveness of the safety function satisfactorily works, while the estimator for  $\beta_2$  completely is misleading.

Now let us see what happens if we apply the logistic regression routine without taking the two different driver categories into account, thus what happens if we do not take gender into account. Doing so we end up with the following 2x2 contingency table of accidents

**Table 7.**  
**Simulated numbers of accidents**

safety Function	accident type	
	neutral	sensitive
not present	6,150	5,106
present	3,450	1,730

The estimator for the effectiveness of the safety function in this simplified situation without any confounding variables is rather easy and reads as follows

$$\text{Effectiveness} = 1 - 6,150 \cdot 1,730 / (3,450 \cdot 6,106) = 39.6\%$$

and therefore overestimates the effectiveness by about 34% when compared to the “true” effectiveness of 29.5% (see above).

This simple example demonstrates that it is rather essential to include confounding variables when they may have a non-negligible influence.

Summarizing one can say, that the effectiveness of a specific safety function reliably can be estimated on the basis of real world accident data only if relevant confounders are included in the investigation. Falsely ignored confounders may lead to substantial errors in estimating the effectiveness of a safety function even in very simple examples.

### SYSTEM A VS SYSTEM B

As already mentioned at several places in this paper it is most wanted to obtain from real-world accident data reliable and significant results on the causal effectiveness of some safety functions or some safety equipments. To do so and especially to obtain enough reasoning for causality it is necessary to include so-called explaining variables in the investigations in order to be able to (at least partly) control for the influence of these covariables. Age and gender of the driver, weather and road conditions, seat belt usage and vehicle age, mileage and vehicle equipment may serve as examples of covariables, which should be included. So far the theory. In real data applications this to a considerable extend is not

possible because of the lack and reliability of information in accident databases.

But even if we assume that we have all these information at hand then in a lot of investigations the total number of accidents tends to be way too small to carry through a very detailed statistical analysis. Of course there exist statistical models, which allow for the inclusion of a lot of variables but most often these models are of so-called parametric nature, like the logistic regression model is. These models and especially the logistic regression model are rather handy to apply to multivariate observed data and the results typically look quite nice and easy to interpret so that one might be tempted to apply these models without further thinking. But a great disadvantage of parametric models is that they by their definition make very strong assumptions on the underlying dependence structure of the various variables. Of course, when dealing with data a linear dependence is the easiest to assume and of course the obtained results look nice because they are linear. But the assumed model does not allow for anything else than linearity! The same objection is true for the logistic regression model, which assume after a certain logarithmic transformation nothing else but a linear multivariate model. At least this linearity assumption has to be checked on the data before the logistic regression model is applied and conclusions are drawn.

### CONCLUSIONS

For a number of years after the introduction of ESC researchers from different regions of the world have published retrospective analyses of this system’s safety benefit. Using different data sources, mathematical approaches and effectiveness metrics the overall results were scattered and, in some respects, contradictive. Some studies found that – with the data available at the time – they could not rule out a *negative* effect on safety at the 95% confidence level. This initial uncertainty is caused by various factors, many of them – by nature – beyond the control of the respective authors. Any early study of a new technology’s safety effect should therefore be taken with care.

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# A GENERATIVE APPROACH TO ESTIMATE EFFECTS OF SAFETY SYSTEMS FOR REAR-END COLLISIONS USING ASSTREET

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## ABSTRACT

Estimating the benefits of advanced safety systems before introducing to markets is useful to develop and enhance the systems effectively. Several estimation methods have been proposed to date. Some are based on comprehensive accident data such as those of NASS-CDS. Others are based on proving-ground test results. However, actual accidents present much more permutations and configurations of striking and struck vehicles than those. Furthermore, driver behavior varies among cases.

This paper presents a proposal of a novel method that addresses the issues described above. First, a virtual traffic flow that represents an actual one is created. Then, the way in which an active safety system is expected to play its role in accidents happening in traffic is measured. The Advanced Safety System & Traffic REaltime Evaluation Tool (ASSTREET) was used to generate road environment, vehicle movements, and driver behavior. In order to show the usefulness of the method, a pre-collision system (PCS) with forward collision warning (FCW), pre-collision brake assist (PBA), and pre-collision brake (PB) functions were applied as the active safety system. The procedure is the following.

A virtual traffic flow was created. On a simple road environment with intersections and traffic signals, numerous vehicles run under traffic rules on ASSTREET. The vehicles' speed distribution and the duration of the stopping period were adjusted to match realistic driving data measured on roadways, by the road parameters such as speed limits and the distance between intersections.

Next, rear-end collisions in the virtual traffic flow were created. Driver errors and braking reaction after

noticing the collision danger were incorporated into the virtual driver behavior. Because most of the driver errors in rear-end collisions are attributable to inattention, the inattention period and the brake reaction time with a convincing distribution were given to the virtual drivers. The braking deceleration distribution, which is also necessary characteristics for pre-collision reconstruction, was obtained using our driving simulator through the ACAT (Advanced Collision Avoidance Technology) program with NHTSA (National Highway Traffic Safety Agency). The distribution of the combination of striking vehicle speed and struck vehicle speed agreed well with actual data. Consequently, rear-end collisions in the simulation were regarded as representing actual ones. Finally, the benefit of PCS was estimated. Rear-end collisions in the virtual traffic flow were generated by vehicles with no active safety systems. After collecting all rear-end collision pairs of striking and struck vehicles, a PCS was installed in striking vehicles. Then the simulation was repeated. Comparing the results obtained with and without use of the system clarifies the PCS benefit.

The advantage of this method is that a mass of rear-end collisions enables evaluation of PCS' specification differences quantitatively. Results clearly indicate circumstances in which the system is expected to function effectively.

Although the current simulation is considered as covering most of rear-end collisions that people might happen to encounter, such scenarios as avoidance by steering, collision during negotiation of a curve, and collision with a cutting-in vehicle have not been simulated yet. Those will be addressed in the near future.

## INTRODUCTION

Estimating the benefits of advanced safety systems before introducing to markets is useful to develop and enhance systems effectively. The basic approach of estimation is to take advantage of accident data and simulate a collision to determine whether accidents could have been avoided with the system equipped with a vehicle. The main problem of the approach is that it is difficult to acquire cases with detailed kinetic information needed for the simulation. The other problem is that accidents seldom occur in actual traffic. For instance, in the 100-car study conducted by National Highway Traffic Safety Administration (NHTSA), only 27 rear-end collisions were observed among their records of one hundred vehicles during one year [1].

Two kinds of approaches were proposed to solve the problem. One approach is to make use of the in-depth accident data [10] which has been accumulated year by year. However, lack of detailed driver behavior in the data remains to be a major disadvantage. The other approach takes advantage of near-crash cases instead of accident cases [11] [12] [13]. Although near-crashes occur more frequent than accidents, their amount is still limited. Even in the 100-car study, only 60 cases were available for analyses [11].

Therefore, a generative approach is proposed. This paper first describes how a rear-end collision model was built based on the analysis of ITARDA (Institute for Traffic Accident Research and Data Analysis) micro data. Then, it describes how virtual rear-end collisions were generated and the results are compared with actual statistics. In the last section, the benefit of the proposed method is demonstrated by applying it onto a PCS (pre-collision system). The micro data analysis result was brought from the collaborative research with ITARDA, "Investigation of Human Factors in Traffic Accidents for Driver Assistance systems". ASSTREET (The Advanced Safety System & Traffic REaltime Evaluation Tool) was used to generate virtual collisions.

## ACCIDENT MODEL

### Kinetic Model

A simple kinetic model with no human-related factors is considered to simulate a rear-end collision. In terms of geometry, a collision is the state in which the distance between objects becomes zero. Therefore, any vehicle-to-vehicle collision process can be described with their trajectories. For further simplification, rear-end collisions are assumed to be caused between only two vehicles on a straight road. Then, a collision

is expressed as a crossing point of the two vehicles' trajectories, as shown in Figure 1.

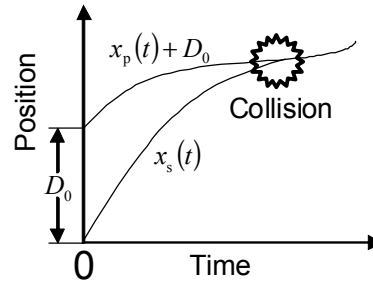


Figure 1. Rear-end collision model.

Equation (1) describes a simplified rear-end collision model.

$$\exists t, (x_p(t) + D_0) - x_s(t) = 0, \text{ where } x_p(0) = x_s(0) = 0 \quad (1).$$

Here,  $x_p$  and  $x_s$  are the time-variant positions of a leading vehicle and a following vehicle respectively, their positions at time 0 is 0.  $D_0$  is the initial distance between the vehicles.

The equation indicates that  $x_p$ ,  $x_s$  and  $D_0$  are the least variables to describe a rear-end collision. Although the model assumes that both vehicles' lengths are zero, substituting zero length for non-zero length will not affect the calculation. If three variables  $x_p$ ,  $x_s$ , and  $D_0$  of all rear-end collisions occurred in the real world are known, then kinetic models are consequently created and the benefits of the rear-end collision prevention systems could be assessed precisely.

However, as it is not realistic to know them, ITARDA micro data analysis and normal driving data analysis were used for the substitution. The procedure is addressed in the next section.

### Accident Data Analysis

To clarify the vehicles' behavior before rear-end collisions, 98 of ITARDA micro data were analyzed. The result is shown in Figure 2.

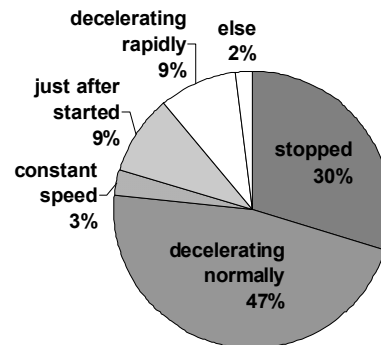


Figure 2. Driving behavior of leading vehicles before crashes (Source : ITARDA).

It was found that more than 90% of the leading vehicles were regarded as normal driving maneuvers. They were either stopped, decelerating normally, moving at constant speed, or had just started. Their velocity before starting deceleration is also distributed within a normal range of approximately from 40 to 70 km/h. These facts indicate that the leading vehicle behavior  $x_p$  could be replaced with the normal driving behavior data. The same conclusion is reported in the analyses conducted by ITARDA [2].

Considering an actual collision scene, following vehicle behavior  $x_s$  would be divided into four sequences. They are initial state, inattentive state, reaction state, and evasive braking state, as depicted in Figure 3.

The initial state consists of distance  $D_0$  and initial velocity  $v_0$ . It should be noticed that both are the representatives of normal driving.

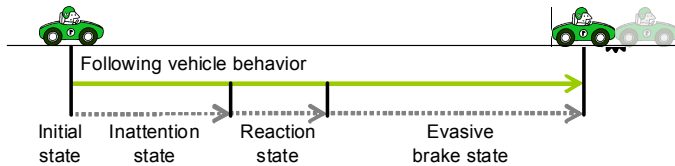
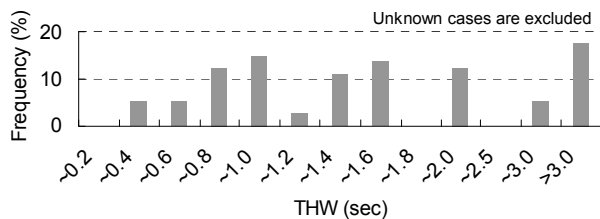
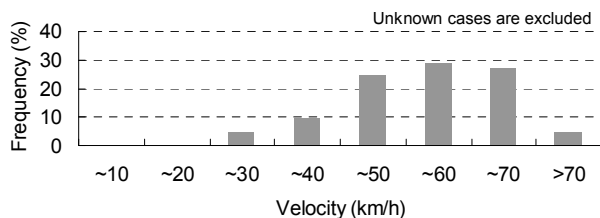


Figure 3. Driver state sequence of a following vehicle.

Then, as shown in Figure 4, the distance  $D_0$  should be distributed approximately 1-2 seconds in terms of the Time Head Way (THW) and the velocity  $v_0$  should be distributed mainly from 40 to 70 km/h.



(a) Time head way before collision danger was noticed



(b) Following vehicle's velocity before collision danger was noticed

Figure 4. Initial states of the following vehicles.

The following vehicle behavior  $x_s$  should be described as Equation (2), using four variables: the initial

velocity  $v_0$ , inattention period  $\lambda$ , reaction time  $\tau$  and the evasive deceleration by braking  $a(t)$ . For simplification, it is assumed that the vehicle maintains at a constant velocity when the driver is in inattentive state. Therefore when the braking starts,  $a(0)=0$ .

$$x_s = v_0 t + \int \int_0^t a_s(t) dt dt,$$

$$a_s = \begin{cases} a(t - \tau - \lambda) & t - \tau - \lambda \geq 0 \\ 0 & \text{otherwise} \end{cases} \quad (2).$$

In summary, the rear-end collision model is defined by Equation (1) and by Equation (2).

As for the leading vehicle behavior  $x_p$ , the initial distance  $D_0$  and the initial velocity  $v_0$  can be identified with those data during normal driving.

The other variables in the model, those are, the inattention period  $\lambda$ , the reaction time  $\tau$ , and the evasive deceleration by braking  $a(t)$  could not be measured in normal driving, but can be identified by a driving simulator experiments, etc.

## GENERATE VIRTUAL ACCIDENTS

### Generation Process Overview

As the leading vehicle behavior  $x_p$ , the initial distance  $D_0$  and the initial velocity  $v_0$  are highly correlated, it is necessary to assign an appropriate joint probability distribution for the calculation. To solve the problem, The Advanced Safety System & Traffic REaltime Evaluation Tool (ASSTREET) had been developed and introduced.

As depicted in Figure 5, ASSTREET is based on a traffic simulator which includes a driver model [4] [6] and a virtual road environment. The driver model generates plausible behavior in response to traffic situations by simulating drivers' internal processes of perception, cognition, judgment, and operation.

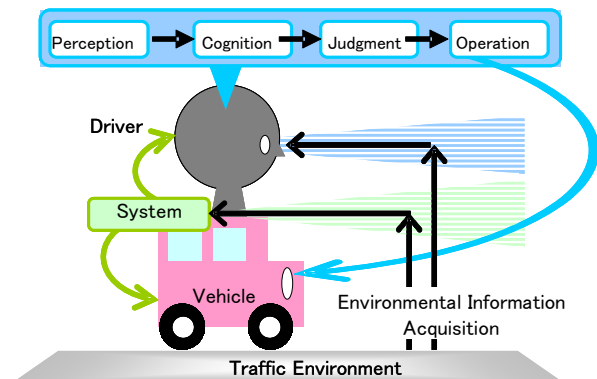


Figure 5. Advanced Safety System & Traffic REaltime Evaluation Tool (ASSTREET).



To simulate a following vehicle behavior before collision feasible in real world, it is essential to assign probability densities to the inattention period  $\lambda$ , the reaction time  $\tau$ , and evasive deceleration by braking  $a(t)$ . For the inattention period  $\lambda$ , we adopted the density estimated by Morita et al. [7]. The reaction time  $\tau$  and the evasive deceleration by braking  $a(t)$  are modeled based on results obtained from driving simulator (DS) experiments [8]. Here, as shown in Figure 6, evasive deceleration by braking  $a(t)$  is approximated by jerk  $j$  and maximum deceleration  $d_{\max}$  for easier calculation. Then, the deceleration is reconstructed from the probability densities of both parameters.

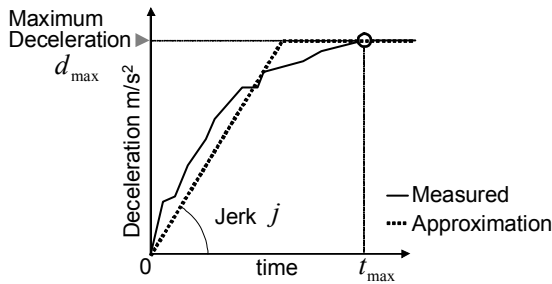


Figure 6. Approximation of evasive braking.

The following steps and Figure 7 explain the simulation procedure.

#### A. Normal traffic flow simulation process

Simulate a normal traffic flow using ASSTREET under the road environment which will be discussed in the next subsection.

#### B. Collision generative simulation process

- B-1. Select an arbitrary pair vehicles which have leading-following relation.
- B-2. Assume a parallel street. On the street, just the selected pair of leading-following vehicles is running.
- B-3. Substitute the following vehicle behavior on the parallel street for inattentive driver's behavior defined as Equation (2).

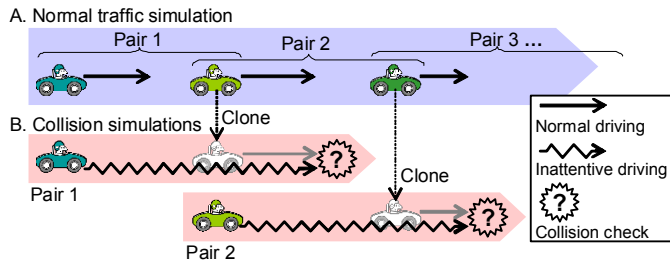


Figure 7. Simulation procedure.

- B-4. Save the pair of vehicles' kinetic information as one virtual accident if they collide.
- B-5. Repeat calculation from step B-1 to B-4 till sufficient collisions are accumulated.

The collision generative simulation was performed at the back of the normal traffic flow simulation so that the occurred collisions do not spoil the normal traffic flow.

The conspicuous benefit of the separation is described here. The existing simulator donates human errors to the drivers in the virtual traffic and collects the collisions when they happened during the calculation, which is a time consuming effort [3]. On the contrary, the collision generative simulation can generate a lot of virtual accidents in a short time.

In fact, as the parallel simulation is done for different pairs or sampling at different timing, two hundred thousand virtual accidents, which is roughly equivalent to the number of rear-end collisions occurred in a year in Japan, were generated within 20-hour using a Xeon X5482 3.2 Hz processor (Intel Corp.) and 4 GB memory.

#### Road Environment Model and Its Validation

To simulate a normal traffic flow, it is necessary to apply an appropriate road environment into ASSTREET. As it is apparently impossible to reproduce whole road environment across the country, factors affecting the rear-end collision should be considered.

There are two clues to determine the factors. One is that the collision model treats only longitudinal motion. The other is that the majority of the leading vehicles are stopping or decelerating before collisions. These facts suggest that the essential factors are the velocity change that represents decelerating to a stopping state. The road environment was modeled by two steps. First, a base structure of the road environment was determined. A street with intersections controlled by traffic signals permitting right and left turns as shown in Figure 8 is adopted. The street also has a speed limit for each section. The street will naturally induce vehicles to decelerate and to stop.

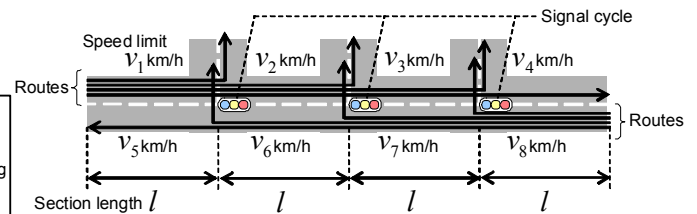
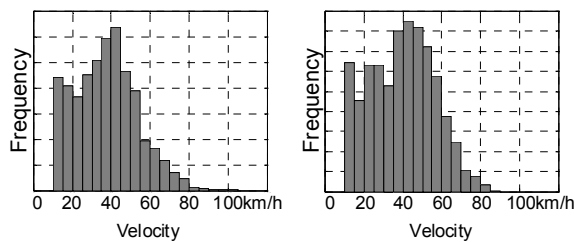


Figure 8. Virtual traffic.

Then in the second step, the section length, speed limit, signal cycle and amount of traffic flows were adjusted referring to the analytical result of naturalistic driving behavior database [9], which is provided by the Research Institute of Human Engineering for Quality Life (HQL).

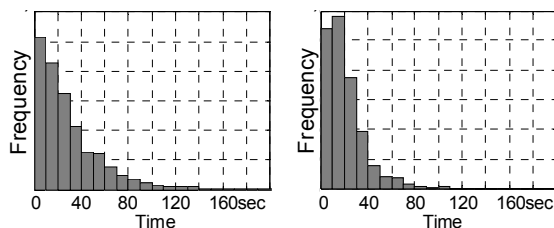
Two properties were used to assess the reproducibility. One is the histograms of the velocity before deceleration and another is the stopping period. Figures 9 and 10 present comparisons between calculation and the analytical result of the naturalistic driving behavior database (DB).

As for the histograms of the velocity before deceleration, though simulation result has more peaks than the naturalistic driving behavior database, both have the same maximum peak at around 40 km/h.



(a) Naturalistic driving DB (b) Simulation result

Figure 9. Comparison of the velocity before deceleration.



(a) Naturalistic driving DB (b) Simulation result

Figure 10. Comparison of the stopping period.

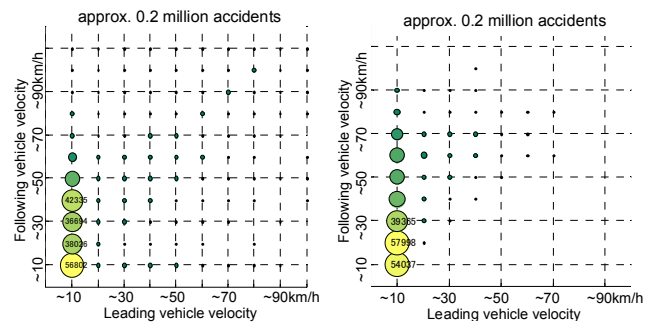
As for the histograms of the stopping period, though simulation result has a peak slightly longer than the naturalistic driving behavior database, and simulation result shows narrower time range than the naturalistic driving behavior database, both results show the similar distribution.

The road environment model is considered to reproduce the actual traffic flow well.

### Collision Representation and Its Validation

To validate the generated collision counts, the simulation result is compared with the nationwide traffic accident statistics in Japan compiled by ITARDA. The statistical attribute shown here for comparison is the distribution of velocities when the leading vehicle driver and following vehicle driver

recognized collision danger. Figure 11 shows the collision count distributions.



(a) Rear-end collision statistics (b) Simulation result (2008, Source : ITARDA)

Figure 11. Accident distribution comparison.

For the simulated data, the velocity of the leading vehicle at impact is used as substitution and the initial velocity of the following vehicle is used as substitution. It can be seen that both have a majority in a range less than 10 km/h of leading vehicle velocity. When compared by the following vehicle velocity, the simulation result shows a good resemblance to the actual statistics. Both have a peak at the low-velocity range and decrease towards high velocity.

For the area in which both vehicles have low velocity, the simulation result has more collisions than the actual statistics. It is known that the traffic accident statistics is based on accidents reported to the police by drivers. It is also known that drivers tend not to report to the police for trivial collisions [1]. The difference may be derived from the fact.

### PCS BENEFIT ESTIMATION

#### Specification difference Study

As the generated collisions have kinetic histories, the benefit of the safety system can be estimated by adding a system effect onto the following vehicles. Three different PCS specifications; A, B and C were examined. Here,

System A. The system activates just Forward Collision Warning (FCW). When collision risk is judged increased, FCW issues an alarm.

System B. Pre-collision Brake Assist (PBA) is added to System A. PBA is activated after FCW and assists a driver's braking depending on the amount of his or her braking.

System C. Pre-collision Brake (PB) is added to System B. PB is activated when collision is judged unavoidable. It automatically brakes irrespective of a driver's braking.

The onsets of FCW, PBA, and PB are shown in Figure 12. To understand their difference easily, functions are assumed to be activated for full speed range. The sensors equipped to vehicles are also assumed to function with no error and with no false detection.

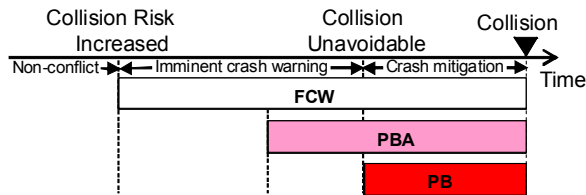


Figure 12. Onsets of FCW, PBA and PB.

Figure 13 shows the result. The benefit is compared by relative speed.

It can be seen that System A (FCW) shows higher collision avoidance ratio in lower speed range and System B (System A+PBA) helps System A for all speed range. System C (System B+PB) is expected to show higher reduction than System A and System B do without doubt, its benefit is shown as speed range expansion rather than as reduction expansion. Thus, the proposed method enables to compare the system difference quantitatively.

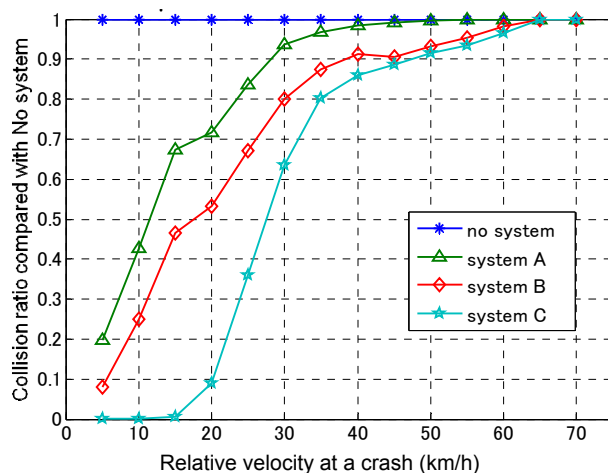


Figure 13. Collision avoidance ratio comparison.

### Sensitivity Evaluation Study

Unlike passive safety systems, most of the active safety systems have functions to affect drivers. Therefore, driver properties are considered to have impacts on system benefit estimation. Furthermore, driver properties are usually identified not in actual accidents but in proving ground or driving simulator experiments. Although subjects for these experiments are chosen carefully, the measured properties may contain some bias compared to those in actual collisions. In this section, the driver property influence is addressed

which can only be achieved by simulation. Figure 14 presents the results. The vertical axis shows the ratio compared with System A, B and C without offset.

Figure 14 (a) shows the effect of the inattention period  $\lambda$ . The result indicates that the effect is small for all systems. The reason is considered as follows. As inattention period gets longer, the collision count of no system increases, but is soon saturated. However, drivers are assumed to react to the warning in System A, B and C before inattention period ends, collision count will not be affected so much by the inattention period extension. The result reflects the mechanism.

Figure 14 (b) shows the effect of the reaction time  $\tau$ . The result indicates that the effect is large for System A and B, while is small for System C. It is because System A and B depend on drivers' reaction that the reaction time increase consumes the time available for evasive braking. The result of System C indicates that automated brake could compensate drivers' reaction delay.

Figure 14 (c) shows the effect of the jerk of braking  $j$ . The result indicates that the jerk affects relatively dull on all systems. It is considered that the deceleration by driver's brake reaches its maximum in a short period, and the jerk has only a slight effect on the total amount of deceleration.

Figure 14 (d) shows the effect of the maximum deceleration  $d_{max}$ . The result indicates that the maximum deceleration is the most contributing factor to PCS.

In summary, it became clear that the driver's maximum deceleration is the most contributing factor to PCS, followed by the driver's reaction time.

### CONCLUSIONS

A novel method to estimate the effects of active safety systems was proposed. The characteristics of the method is that rear-end collisions are reproduced through a combination of normal traffic flow simulation process and collision generative simulation process.

For normal traffic flow simulation process, a simulator ASSTREET was introduced. In the generated traffic flow by ASSTREET, leading-following vehicle pairs were selected one by one. Next in the collision generative simulation process, by substituting following vehicle behavior for inattentive driver's behavior, a mass of rear-end collisions were generated. As the collision generative simulation was performed at the back of the normal traffic flow simulation, the collision occurrence does not spoil the normal traffic flow. The results of both processes were verified with actual data.

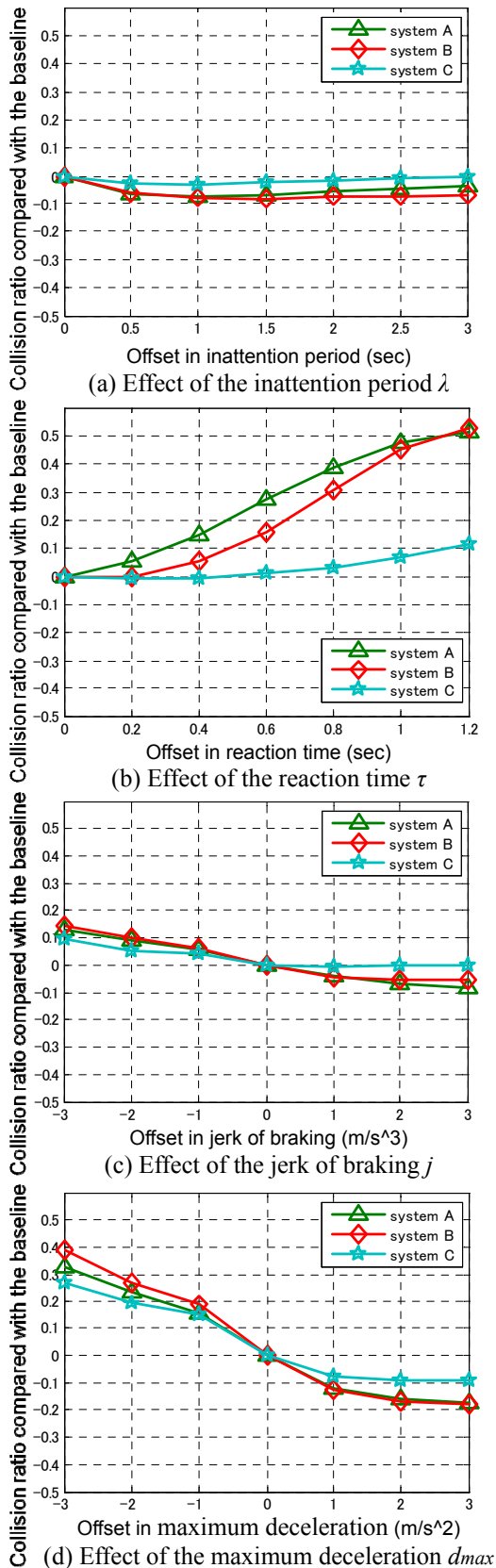


Figure 14. Sensitivity evaluation.

To demonstrate the benefit of the proposed method, a Pre-collision System (PCS) was applied as an example. Although PCS applied for the evaluation is a virtual one, the result revealed how each PCS function is expected to work effectively. The sensitivity evaluation study revealed that the driver's maximum deceleration is the most contributing factor to PCS, followed by the driver's reaction time.

We believe the simulation is regarded to generate most of rear-end collision patterns, however, certain particular scenarios such as avoiding maneuver by steering, collision during negotiating a curve and collision with a cutting-in vehicle have not been simulated yet. Those issues will be addressed in the near future.

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# DEVELOPMENT OF A TARGET PROPULSION SYSTEM FOR ASSESS

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## ABSTRACT

The ASSESS project is a collaborative project that develops test procedures for pre-crash safety systems like Automatic Emergency Braking (AEB). One key criterion for the effectiveness of e.g. AEB is reduction in collision speed compared to baseline scenarios without AEB. The speed reduction for a given system can only be determined in real world tests that will end with a collision. Soft targets that are crashable up to velocities of 80 km/h are state of the art for these assessments, but ordinary balloon cars are usually stationary targets. The ASSESS project goes one step further and defines scenarios with moving targets. These scenarios define vehicle speeds of up to 100 km/h, different collision scenarios and relative collision speeds of up to 80 km/h. This paper describes the development of a propulsion system for a soft target that aims to be used with these demanding scenario specifications.

The Federal Highway Research Institute's (BAST's) approach to move the target is a self-driving small cart. The cart is controlled either by a driver (open-loop control via remote-control) or by a computer (closed-loop control). Its weight is limited to achieve a good crashability without damages to the test vehicle. To the extent of our knowledge BAST's approach is unique in this field (other carts cannot move at such high velocities or are not crashable).

This paper describes in detail the challenges and solutions that were found both for the mechanical construction and the implementation of the control and safety system. One example for the mechanical challenges is e.g. the position of the vehicle's center of gravity (CG). An optimum compromise had to be found between a low CG oriented to the front of the vehicle (good for driveability) and a high CG oriented to the rear of the vehicle (good for crashability).

The soft target itself which is also developed within the ASSESS project will not be covered in detail as this is work of a project partner. Publications on this will follow.

The paper also shows first test results, describes current limitations and gives an outlook. It is expected that the presented test tools for AEB and other pre-crash safety systems is introduced in the future into consumer testing (NCAP) as well as regulatory testing.

## INTRODUCTION

Advanced driver assistance systems, collision mitigation systems and anti-collision systems have been part of the research community since the beginning of the last decade (see e.g. [1] p.541). They promise a sustainable decrease of road traffic fatalities all over the world. Today's production systems will apply full brake deceleration up to a few 0.1 seconds before an unavoidable accident in the full speed range (see [2]), some production systems are already able to completely avoid an accident in the speed range of up to 30 km/h [3].

No manufacturer would only start selling a system before its functionality has been validated, so all systems will have passed extensive testing with proprietary dummy targets during the development phase (see e.g. [1] p. 43). These dummy targets will have been adjusted to the sensor technology used by the specific system (see e.g. [4]).

However, there is no harmonized and universal test procedure (based on a common agreement of all stakeholders) available neither for regulatory testing (e.g. for the verification whether a system conforms to future UN ECE regulations) nor for consumer testing (e.g. Euro NCAP test procedures beyond the generic "Beyond NCAP"-procedure).

Without this, it will not be possible to compare different system designs in their functionality and liability.

This is where the EC-funded framework project "ASSESS – Assessment of Integrated Vehicle Safety Systems for improved vehicle safety" comes in (see [5]). This project, in cooperation with other initiatives, develops an integrated test methodology for advanced safety systems. Accident research leads to the definition of relevant test scenarios, test tools for the scenarios are being developed and validated, recommended adaptations for current crash test procedures are investigated, and a way to estimate the socio-economic benefit of each tested Advanced Driver Assistance System (ADAS) is proposed.

The methodology will be applicable for all kinds of systems. That means that not only will the test tools have to be compatible for different sensor technologies, but also the driver behaviour needs to be taken into account.

This paper describes the development process for one part of the ASSESS project – one of three target propulsion systems.

The target in that context can in general be some random mock-up appearing to ADAS as a relevant vehicle. There is only one (soft-crash) target developed within the ASSESS project. The three test labs TNO, BAST and IDIADA are responsible to provide for the propulsion of that target, capable of dealing with the test scenarios defined within the project.

After a survey of available systems, BAST decided to develop a relatively simple system almost from scratch.

Development processes are usually structured according to the V-model for product development, and so is this paper. The start of all development is the definition of the requirements (what should the product do?) and validation test criteria (does it do what it should?). The next step is the definition of specifications (how will the product do that?) and verification criteria. The link between definition phase and testing phase is the implementation phase.

The development process is still ongoing by the time of paper preparation (March 2011), so no final validation can be presented.

This paper will present the requirements and specifications, briefly describe how the system is implemented, show verification results and give an outlook on validation tests. Since the topic is relatively broad, the paper will focus on the development process of a system for rear-end collisions.

## REQUIREMENTS

The target propulsion system to be used within the ASSESS project needs to be able to perform the test scenarios defined within the project, as well as other scenarios that might become standard test scenarios for Autonomous Emergency Braking systems in the future. The main purpose is the evaluation of ADAS from a regulatory point of view and it is not designed for development purposes.

In particular, the system is not intended to be a multi-purpose propulsion system for complex situations with various vehicles, and it is also not intended to be operable in a fully automated test setup. Other approaches fulfil these requirements very well but are relatively complex and expensive to use for possible test labs or are not able to achieve the necessary decelerations and driving dynamics (see e.g. [6]).

Requirements are derived top-down from the scenario definitions from the ASSESS project. Key

domains in the propulsion system development process are the crash performance, the driving dynamics and the reproducibility. These three domains (and also other important domains) will be traced during the development phases.

## Scenario definitions

This paper focuses on rear-end collisions, relevant scenario definitions are given in Table 1. A full set of the scenario definitions is available in [7], available for download on the ASSESS website. Almost all of the scenario definitions will be tested with fast, slow or no driver reaction. Experiments with no driver reaction and with failing autonomous brake systems will certainly be the worst case for the target propulsion system development, so the requirements will point towards these scenarios. Scenarios with a stationary target do not require the propulsion system and therefore do not affect the system's requirements.

**Table 1.**  
**Relevant rear-end scenario definitions (see [7])**

Ego Vehicle Behaviour	Target Behaviour	Comments
Constant velocity, 50 km/h	Constant velocity, 10 km/h	Initial TTC > 3 s, no and 50% lateral offset
Constant velocity, 100 km/h	Constant velocity, 20 km/h	Initial TTC > 3 s
Constant velocity, 50 km/h	Braking 4 and 7 m/s <sup>2</sup> from 50 km/h	Initial distance 14 m
Constant velocity, 80 km/h	Braking 4 and 7 m/s <sup>2</sup> from 80 km/h	Initial distance 45 m

A test run can only be valid if specific accuracy requirements are met. These requirements are summarized in Table 2. The requirements affect not only the measurement equipment used for both vehicles, but also the design of the kart (e.g. chassis stability, steering actuators) and control systems as well as the whole experiment setup.

**Table 2.**  
**Preliminary accuracy requirements (see [7]).**

Parameter	Control-ability	Repeat-ability	Measurement Accuracy
Test Velocity	$\pm 1.0$ km/h	$\pm 0.5$ km/h	$\pm 0.1$ km/h
Distance (longitudinal)	$\pm 0.50$ m	$\pm 0.20$ m	$\pm 0.03$ m
Distance (lateral)	$\pm 0.20$ m	$\pm 0.20$ m	$\pm 0.03$ m
Acceleration / Deceleration	$\pm 0.5$ m/s <sup>2</sup>	$\pm 0.2$ m/s <sup>2</sup>	$\pm 0.1$ m/s <sup>2</sup>

### Crash performance

Vehicle tests will need to cover the full timespan from first detection of a target to the collision. Neither vehicle under test nor the soft-crash target system should suffer significant damage during the tests.

Therefore the most demanding requirement for the combination of target system and soft-crash target is the maximum impact velocity to be endured. An impact velocity of 40 km/h is required to perform most of the scenarios.

Probably the most important contributing factor to crash performance is the design of the soft-crash target. The ASSESSOR soft-crash target will be designed within the ASSESS project as a universal target for all test scenarios. The development is done by a project partner and will not be described in detail, however the basic principle and the implications for the propulsion system need to be discussed.

During a collision of two vehicles, energy needs to be transferred between the faster vehicle under test and the slower soft-crash target system. The vehicle under test would then be decelerated and the target system accelerated. The distribution of the accelerations and decelerations between the two vehicles depends on stiffness and masses.

An ideal soft soft-crash target system or a soft-crash target system with no mass would be accelerated to the test speed with no significant speed reduction for the vehicle under test – in this case the forces acting on the vehicle would not be significant, it would suffer no significant damage.

The whole soft-crash target system therefore needs a relatively low stiffness and low mass – stiffness is a parameter of the soft-crash target, while the mass is mainly a parameter of the propulsion system.

### Driving dynamics

Also quite demanding are the driving dynamics requirements: the whole system needs to be able to reach a maximum speed of 80 km/h and a maximum deceleration of 7 m/s<sup>2</sup>.

Lane-change manoeuvres and oncoming collisions will also need to be performed but are not subject of this paper.

### Sensor visibility

The test procedures developed in the ASSESS project aim at consumer and regulatory testing where no modifications to the vehicle under test are allowed, and where the vehicle under test should have no chance to detect an ongoing test. That means that any combination of propulsion system and soft-crash target needs to appear like a car – to all kinds of autonomous emergency brake sensor systems. Sensors available on the market today are e.g. RADAR, LIDAR, video and fusion approaches involving these technologies.

## SPECIFICATIONS

### Concepts

Several methods for moving the soft-crash target are already being used for development purposes. The methods can be divided into three groups: self-propelled soft-crash targets, soft-crash targets fixed to a crane that is carried by a vehicle driving parallel to the soft-crash target, and methods where the vehicle under test is running on a test-bed with objects moving in front of the vehicle. The target supporting structure for crane-fixed soft-crash target can be very light, but they require a vehicle driving in a parallel lane. This vehicle will need to be masked in order to not confuse the ego vehicle's systems.

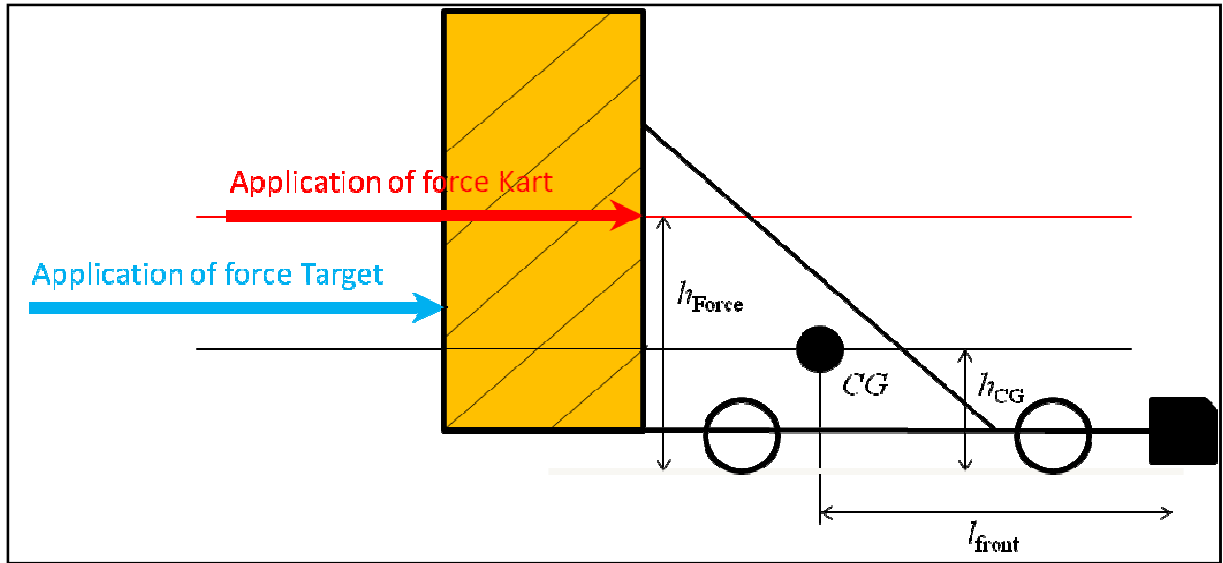
The mass of self-propelled target systems will very likely be significantly higher compared to the other methods, but they do not need a vehicle driving in a parallel lane. Any other vehicles need to be masked to all sensor technologies that could possibly be used. Vehicles running on a test-bed could have a chance to detect an ongoing test by evaluating the satellite navigation signals.

A crane-supported target will also be used within ASSESS and is described in [7], and also test-bed experiment setups will be carried out.

Different approaches either do not deliver the necessary crash performance [8] or are not able to drive at a constant speed [4].

The BASTKART propulsion system belongs to the group of self-propelled systems. It is based on a standard race kart driven by a 125 cc two-stroke engine and equipped with a supporting rear frame and carrier plate to carry the soft-crash target.





**Figure 1. Forces acting on the kart during impact of the vehicle under test.**

Future versions will very likely be able to withstand oncoming collisions, however this is not the focus of this paper.

### Crash performance

A maximum impact velocity of 50 km/h will be required for the ASSESS test scenarios. Requirements and development of a similar soft-crash target itself have already been published by [6]. The paper primarily addresses the development of the propulsion system, however the propulsion system does significantly contribute to the achievement of a sufficient crash performance.

Basically the soft-crash target is a pneumatic spring-damper. The intruding vehicle deforms the soft-crash target and thus builds up air pressure in the moment of the impact. Venting holes in the target introduce a damping effect. Finally, the air pressure inside the target generates a force on the carrying plate. This force's point of attack is assumed to be the centre point of the plate. Other forces acting on the kart are the inertia force (opposite to the direction of acceleration) and gravitation force. The situation is shown in Figure 1.

The equations of motion (neglecting pitching motion) are

$$m \cdot \ddot{x} = F_{Target} \quad (1).$$

$$F_{Target} \cdot h_{Force} - m \cdot \ddot{x} \cdot h_{CG} - m \cdot g \cdot l_{Front} \stackrel{!}{=} 0 \quad (2).$$

Any arm between the propulsion system's centre of gravity and this force would generate a pitching moment, finally a pitching motion, a lift-off of the whole kart – which would then be uncontrollable. Hence, pitching motions definitely need to be

avoided. The maximum acceleration limit that would not result in pitching motions is given by

$$\ddot{x}_{max} = g \cdot \frac{l_{Front}}{h_{Force} - h_{CG}} \quad (3).$$

There would be no limit if the height of the target force matches the kart's centre of gravity.

The centre of gravity of the BASTKART propulsion system would need to be in the height of the supporting plate centre point in order to let the BASTKART withstand high impact velocities without pitching movements. However, the high masses are the kart's chassis and engine, almost at road level.

### Driving dynamics

Accident scenarios demand a relatively high deceleration of up to 7 m/s<sup>2</sup> and driving speeds of up to 80 km/h. The achievable deceleration does not depend on the vehicle's centre of gravity, as long as both axles are braked and the brake force distribution is adjustable.

The maximum velocity is limited by the air drag resistance of the vehicle. An approximation of the power needed for a specific velocity is

$$P = c_w \cdot A_{Front} \cdot \frac{\rho}{2} \cdot v_{rel}^3 \quad (4).$$

with the air drag coefficient  $c_w$ , the front surface  $A_{Front}$ , air density  $\rho$  and relative velocity  $v_{rel}$ . With the assumption for the product of air drag and front surface (worst case: 2 m<sup>2</sup>) the power necessary for a velocity of 80 km/h (= 22 m/s) is 13 kW.

The scenarios do not demand a specific maximum lateral acceleration of the kart, however manoeuvrability and lateral stability are important for safe testing. For sufficient manoeuvrability, the

wheel load on the front axle is important – this contradicts the crashability requirement to have the center of gravity relatively near to the rear axle.

### Measurement accuracy and reproducibility

Inertial measurement units (IMUs) supported by Differential GPS are state of the art in vehicle dynamics testing. They deliver accuracies well below 10 cm, they are lightweight and relatively easy to use. IMUs will be used in the propulsion system as well as in the vehicle under test.

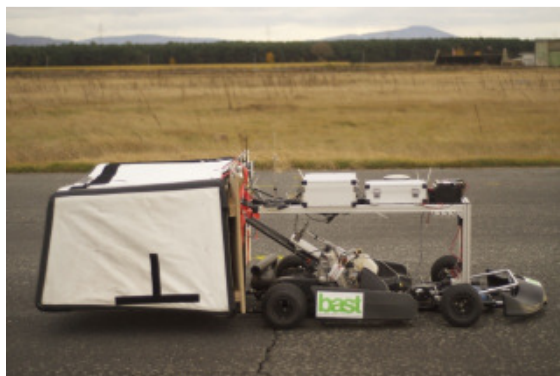
The final test results will very likely be sensible to variations in the propulsion system's velocity and deceleration. A closed-loop control would be needed to achieve a relatively high reproducibility.

The main requirement for lateral stability is to stay in a corridor with a width of 40 cm throughout a test run. It will certainly be possible to maintain this requirement with manual steering control of the kart. The kart should always be under command of the kart operator, so manual control is also a good choice from the safety perspective.

## IMPLEMENTATION

### Vehicle Concept

This first implementation of the BASTKART propulsion system focuses on rear end collisions only but will be adopted to other accident scenarios in the future. It is based upon a FIA-approved race kart of the class KF3 (125 cm<sup>3</sup>, up to 30 hp) and can be equipped with either a 21 kW or a 15 kW two-stroke engine, both of which deliver enough power to reach a velocity of more than 80 km/h. Two brake circuits brake either the front or the rear axle with adjustable brake force distribution. Steering and braking system are actuated by powerful (but rather slow) servo motors, the engine's throttle is actuated a light servo motor.



**Figure 2. Overview over the BASTKART propulsion system, including the rear of the soft-crash target.**

An additional structure to carry the soft-crash target is made from steel pipes and rectangular steel profiles. This structure has been designed to endure a maximum target force of up to 50 kN without significant distortion. Taking into account a mass of around 200 kg, this would result in a possible acceleration of up to 25 g, which is roughly the acceleration that occurs for a crash velocity difference of 50 km/h (see [6]).

The supporting structure and the engine accumulate to a relatively low center of gravity. All additional equipment is mounted as high as possible in order to move the system's center of gravity as high as possible. An additional 'equipment frame' is introduced for this purpose.

Position and movement of the BASTKART as well as of the vehicle under test is measured by means of two GeneSys ADMA inertia & DGPS platforms which also have trigger inputs (e.g. for the touch sensor on the soft-crash target, for the warning sound detection on board of the vehicle under test etc.). All measurements are synchronized via the GPS satellite time signal. A CAN-WiFi-bridge transmits all measured data from the propulsion system to the vehicle under test for recording and display.

The kart is mainly controlled by a human operator. The operator will be assisted by deceleration and cruise control for the actual manoeuvres, however lateral control will always be done manually, and the operator can always override the controller settings. The advantage of this concept is to have all relevant persons on board of the vehicle under test. Test results can be evaluated immediately after each test run, and it is not necessary to implement desired trajectories for the BASTKART system for quick tests.

Manual control is done via a RC Control regularly used for model planes. In addition, a second remote control can independently start or stop the kart's engine and actuate an emergency brake. Both remote control devices use different radio channels and operate independently. The steering remote control's transmission distance is greater than 1000 m.

The gross mass of the final propulsion system (excluding the soft-crash target) is 224 kg, with 43% on the front / 57% on the rear axle (this will be shifted to the rear axle when the soft-crash target is mounted).

The BASTKART propulsion system with soft target attached is shown in Figure 2.

## VERIFICATION

### Crash Performance

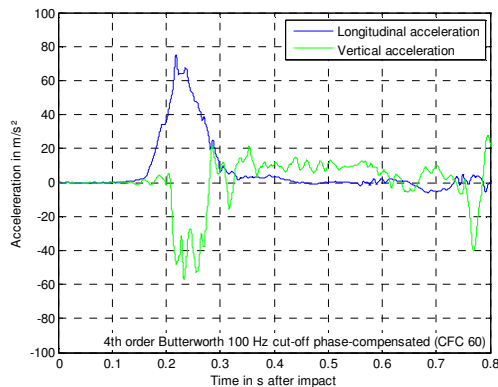
Theoretical considerations have led to the definition of the system's maximum acceleration without pitching movement. If these considerations are true,

it would be possible to calculate the maximum acceleration for different configurations.

Two different system setups with different positions of the center of gravity have been tested in BAST's crash facility. Kart and soft-crash target were equipped with crash acceleration sensors, especially in longitudinal and vertical directions. The intruding vehicle was a regular passenger car, its velocity was measured with a light switch. Time of impact was sensed with a touch sensor attached to the kart. The experiment setup is shown in Figure 3, a typical graph is shown in Figure 4.



**Figure 3. Test setup for crashability verification, early configuration.**



**Figure 4. Typical plot of an impact test. Note longitudinal acceleration rises some 150 ms after the time of impact, the vertical acceleration (pitching movement) does increase only after the longitudinal acceleration has reached the threshold given by eq. (3).**

The longitudinal acceleration threshold after which pitching occurs has been calculated according to eq. (3) for two different configurations. Calculated values lie well within the spread that was observed in each series of tests. Results therefore do not lead to a falsification and the theory can be used for further optimization of the kart system.

The actual kart configuration has been tested up to impact velocities of up to 40 km/h without major pitching movement.

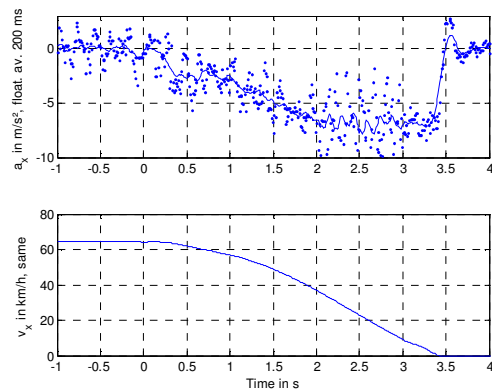
## Driving dynamics

Manoeuvrability is sufficient, the turning radius of approximately 10 m is also sufficient for practical considerations.

As of February 2011, a velocity (cruise) controller and a brake deceleration controller will need to be implemented. They will probably be available for the final validation testing (which will be finished by the time this paper is published). System identification data has been collected.

These tests show a maximum deceleration of 7 m/s<sup>2</sup> (see Figure 5 for plots of a deceleration step from 0% to 100% brake actuation) which satisfies the specifications derived from the ASSESS scenario definitions.

The maximum velocity is far beyond 80 km/h, however lateral stability on uneven roads is still a problem to be solved, and the brake swell time will need to be improved.

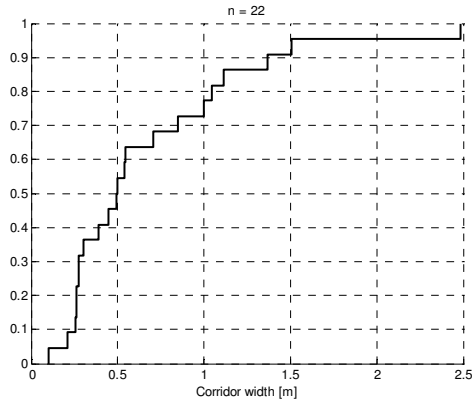


**Figure 5. Deceleration (upper plot) and velocity (lower plot) during a braking manoeuvre.**

## Reproducibility

While velocity and deceleration of the BASTKART will be controlled, the lateral control will – mainly for safety reasons - stay within the hands of the kart operator.

During pre-tests, 22 test runs on a relatively uneven road have been investigated for corridor widths and relative deviations during full test runs. Figure 6 shows a summary of the results.



**Figure 6. Cumulated maximum corridor width for 22 pre-test runs. 40% of all test runs are within the limit of 40 cm defined within ASSESS.**

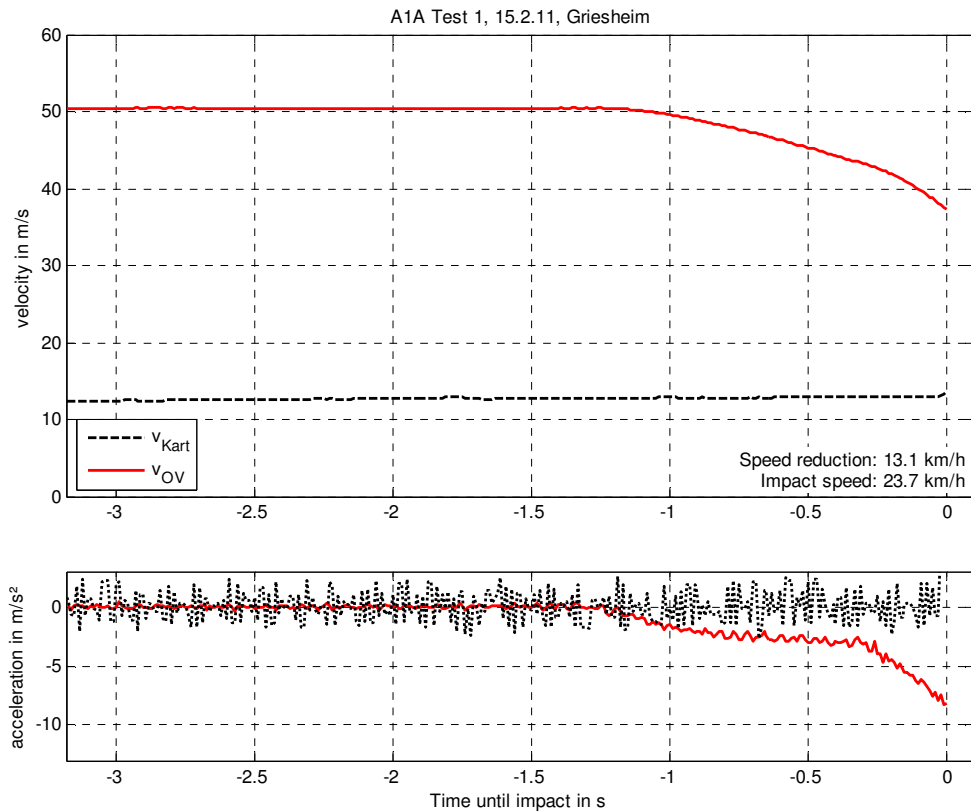
For the investigation, a virtual center line of the test run is defined by averaging the kart and vehicle positions for the last three seconds before impact (individually per test run). The absolute corridor width then is the addition of the maximum lateral deviations of each vehicle during that last three seconds.

The absolute corridor width (black plot in Figure 6) lies within 40 cm (borders according to reproducibility requirements for ASSESS test scenarios, see [7]) in 40% of all test runs. This means that – right before vehicle stability improvements that will also contribute to a better reproducibility) at least 40% of all test runs would have been valid test runs.

### FIRST VALIDATION RESULTS

The validation process ensures that the system fulfils the requirements: it can be used to test advanced driver assistance systems according to the test procedure defined within the ASSESS project. The propulsion system and the soft-crash target itself are still under development. A full validation has not yet been carried out, but a few tests have already shown the potential of the test method. Figure 7 shows a full test run performed according to ASSESS test scenario A1A (first row of Table 1).

A slower lead vehicle travels at a velocity of 10 km/h and is being approached by the vehicle under test with 50 km/h. The fictive Time-To-Collision is a common measure for distinct points



**Figure 7. Plot of velocity (upper) and acceleration (lower) of a typical vehicle under test, ASSESS scenario A1A. No manual brake actuation during the experiment. Note that the parameter time refers to real time, not to time-to-collision.**

in time. It is given by

$$TTC = \frac{x_2 - x_1}{\dot{x}_2 - \dot{x}_1} \quad (5).$$

with the longitudinal distances and velocities of both vehicles.

The initial TTC is greater than 2.6 s. The vehicle under test is equipped with an autonomous emergency brake system that starts to brake around a TTC of 1 second (if both vehicles maintain a constant velocity, the collision would occur in 1 second). The BASTKART was controlled manually and maintains a constant velocity slightly higher than 10 km/h, the vehicle under test maintains a constant velocity of 50 km/h due to the use of an active speed limiting device.

It can be observed that autonomous braking occurs around a TTC of 1 s, with a peak deceleration of 4 m/s<sup>2</sup>. In total, a speed reduction of 10.9 km/h has been achieved purely with autonomous braking, and the impact velocity of 27.4 km/h did not cause any damage to the BASTKART and soft-crash target combination.

## SUMMARY

A method to test autonomous brake systems has been developed. This method uses a modified kart that carries a soft-crash target. The development process has been presented in detail. The method is a simple but yet efficient way of testing AEB systems.

First tests show the potential of the method. Further research in the soft-crash target characteristics is needed, and also improvements for the reproducibility of velocities and decelerations need to be achieved.

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# Pre-Crash Scenario Framework for Crash Avoidance Systems Based on Vehicle-to-Vehicle Communications

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United States

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## ABSTRACT

This paper prioritizes and statistically describes pre-crash scenarios as a basis for the identification of crash avoidance functions enhanced or enabled by vehicle-to-vehicle (V2V) communication technology. Pre-crash scenarios depict vehicle movements and dynamics as well as the critical event immediately prior to the crash. The prioritization of pre-crash scenarios is based on the societal harm from persons who were injured in pre-crash scenarios involving at least two vehicles. The crash must also involve at least one light vehicle (e.g., passenger car, van, minivan, sport utility vehicle, or pickup truck) with a gross vehicle weight rating less than 4,536 kg. This paper also introduces a framework that serves to connect pre-crash scenarios to crash avoidance functions and provides information that will enable the identification of appropriate functional requirements, performance specifications, objective test procedures, and initial system effectiveness benchmarks. The framework incorporates crash statistics about the driving environment, contributing and causal factors, and kinematic information. In addition, time-to-collision equations for each pre-crash scenario are derived to identify key variables that must be measured to recognize and assess the crash threat of driving conflicts. Crash statistics are obtained from national crash databases including the 2004-2008 General Estimates System, the National Motor Vehicle Crash Causation Survey, and the Event Data Recorder database. A set of ten pre-crash scenarios are identified as a priority for the development of V2V-based safety applications. These priority scenarios are arranged into five crash avoidance packages that consist of rear-end, lane change, opposite direction, junction crossing, and left turn across path/opposite direction crash countermeasures. This paper delineates the priority

pre-crash scenarios and maps them to V2V-based safety applications under development.

## INTRODUCTION

This paper describes a pre-crash scenario framework that facilitates the development and evaluation of crash avoidance systems based on vehicle-to-vehicle (V2V) communications using dedicated short-range communications at 5.9 GHz. This framework is constructed in support of the V2V safety application program as part of the United States Department of Transportation's Intelligent Transportation System program [1]. Safety applications will be designed to increase situational awareness and reduce or eliminate crashes through V2V data transmission that supports driver advisories, driver warnings, and vehicle controls. It is envisioned that each motor vehicle on the roadway will be able to communicate with other vehicles, and that this rich set of data and communications will support a new generation of active safety applications and systems.

The pre-crash scenario framework is established to further define the crash problem and identify new crash avoidance capabilities. It serves to connect pre-crash scenarios to crash avoidance safety applications and provide information that will enable the identification of their functions that address the most pressing aspects of the crash problem, performance guidelines, and initial effectiveness benchmarks. This framework also contributes to the classification and grouping of crash avoidance technology so deployed crash avoidance systems can be ranked for their ability to reduce the likelihood and severity of crashes. This framework will be used to determine requirements for safety applications and set priorities for investment.

The following five steps were performed to develop the pre-crash scenario framework for V2V-based crash avoidance systems:

1. Identify target pre-crash scenarios for V2V-based safety applications
2. Describe target pre-crash scenarios based on national crash statistics
3. Prioritize and rank target pre-crash scenarios by frequency and severity
4. Depict priority pre-crash scenarios and determine crash avoidance needs and countermeasure profiles
5. Highlight V2V-based countermeasures for priority pre-crash scenarios

The pre-crash scenario framework was developed separately for light vehicles and heavy trucks. Light vehicles encompass passenger cars, vans, minivans, sport utility vehicles, and light pickup trucks with gross vehicle weight ratings of less than or equal to 4,536 kg. This paper summarizes the results of the five steps listed above for light vehicles only.

## TARGET PRE-CRASH SCENARIOS

V2V-based safety applications predominantly apply to crashes that involve multi-vehicle pre-crash scenarios. This criterion recognizes that, in general, V2V-based systems require two equipped vehicles in communication to be effective. The exception is the broadcast of control loss message in the single-vehicle control loss pre-crash scenarios. This analysis adopted the control loss warning function under investigation by the Crash Avoidance Metrics Partnership (CAMP) in the Vehicle Safety Communications – Applications (VSC-A) project [2]. Consequently, a total of 22 pre-crash scenarios were deemed applicable to V2V-based safety functions. These target scenarios form a subset of the 37 pre-crash scenarios that were developed by the National Highway Traffic Safety Administration to establish a common crash avoidance research foundation for prioritization of traffic safety issues and development of concomitant crash avoidance systems [3]. The 37 pre-crash scenarios depict vehicle movements and dynamics as well as the critical events occurring immediately prior to most police-reported crashes.

Based on statistics from the 2005-2008 National Automotive Sampling System (NASS) General Estimates System (GES) crash databases, V2V-based safety applications would potentially address about 4,336,000 police-reported light-vehicle crashes annually, with the 95 percent confidence interval between 3,691,000 and 4,981,000 [4]. Considering the 22 target pre-crash scenarios, V2V systems have the potential to deal with 76% of all crashes involving at least one light vehicle.

The 22 target pre-crash scenarios were down-selected to 17 pre-crash scenarios for further analysis [5]. Control loss (with or without prior vehicle action), backing, parking, and “other” pre-crash scenarios were excluded because they may be more efficiently addressed by autonomous vehicle-based systems or because additional V2V data about a vehicle losing control serve as an input to advisory systems rather than crash imminent warning systems. The remaining 17 target pre-crash scenarios are listed below:

1. Rear-end crash/lead vehicle stopped (LVS)
2. Rear-end crash/lead vehicle moving at slower constant speed (LVM)
3. Rear-end crash/lead vehicle decelerating (LVD)
4. Rear-end crash/lead vehicle accelerating (LVA)
5. Rear-end crash/following vehicle making a maneuver
6. Opposite direction/no vehicle maneuver
7. Opposite direction/vehicle making a maneuver
8. Left turn across path from opposite directions (LTAP/OD) at signalized junctions
9. LTAP/OD at non-signalized junctions
10. Straight crossing paths (SCP) at non-signalized junctions
11. Turning at non-signalized junctions
12. Turning right at signalized junctions
13. Running red light
14. Running stop sign
15. Changing lanes/both vehicles traveling in same direction
16. Drifting/both vehicles traveling in same direction
17. Turning/both vehicles traveling in same direction

Vehicle maneuver in the list above refers to a vehicle passing, parking, turning, backing up, changing lanes, merging, or making a successful corrective action to a previous critical event.

## PRE-CRASH SCENARIO STATISTICS

The 17 target pre-crash scenarios were statistically described in terms of their driving environment, driver characteristics, contributing and causal factors, and kinematic information. Data sources included the 2004-2008 GES, National Motor Vehicle Crash Causation Survey (NMVCCS), and Event Data Recorder (EDR) crash databases. The EDR database contains a subset of cases from the 2000-2007 NASS Crashworthiness Data System (CDS) crash databases.

### GES Statistics

The GES crash database estimates the national crash population each year based on a weighted sample of about 55,000 police-reported crash cases that include all vehicle types and injury levels [6]. This paper presents results based on an average annual estimate from yearly crashes over a five-year period including 2004-2008 datasets. These crash estimates do not account for non-reported crashes. The GES was selected for this study because it is updated annually, is nationally representative, and includes attributes for crash type, pre-crash detail, driving environment conditions, driver and vehicle contributing factors, and injury levels of persons involved. Table 1 lists the GES variables that were queried for this analysis.

**Table 1. Queried GES Variables**

Category	GES Variable
Driving Environment	Roadway Alignment
	Roadway Surface Conditions
	Atmospheric Conditions
	Relation to Junction
	Traffic Control Device
	Lighting Condition
	Speed Limit
Driver Characteristics	Age
	Gender
Driver Contributing Factors	Police-Reported Alcohol Involvement
	Police-Reported Drug Involvement
	Person's Physical Impairment
	Violations Charged
	Speed Related
	Driver's Vision Obscured By
	Driver Distracted By
Vehicle Factors	Vehicle Contributing Factors
Driver Action	Corrective Action Attempted

Key observations about the driving environment from the analysis of all 17 pre-crash scenarios are [5]:

- Most crashes occur on a straight road and dry surface in clear weather.
- Many rear-end pre-crash scenarios are reported at intersections controlled by 3-color signals, particularly LVS and LVA scenarios.
- Most crashes occur in daylight. Opposite direction pre-crash scenarios happen more in dark conditions than any other scenario.
- A large portion of crashes associated with changing lanes/same direction, drifting/same direction, rear-end LVM, and rear-end LVM pre-crash scenarios occur at speed limits greater than or equal to 55 mph (88 km/h).
- A very large portion of crashes tied to running stop sign, turning/same direction, and LTAP/OD, SCP, and turning at non-controlled junction pre-crash scenarios are reported at speed limits less than or equal to 35 mph (56 km/h).

Statistical observations of driver characteristics, crash contributing factors, and causes were obtained from the vehicle/driver of interest. Drivers of interest refer to light-vehicle drivers who were charged with traffic control device violation, attempted a maneuver, or were in the following vehicles in rear-end pre-crash scenarios. Demographics of drivers of interest are:

- 31.6% younger drivers ( $\leq 24$  years old), 59.7% middle-age drivers (25-64 years old), and 8.7% older drivers ( $\geq 65$  years old).
- 56% male drivers and 44% female drivers.

Crash contributing and causal factors are [5]:

- About 3% of all drivers were cited with alcohol. Higher involvement rates are coded in running stop sign, drifting/same direction, opposite direction, lead vehicle moving, and turning right at signalized junction pre-crash scenarios.
- Drugs are implicated in only 4% of all drivers.
- Violations are cited to about 42% of all drivers.
- Speeding is attributed to 13% of all vehicles. Striking vehicles in rear-end pre-crash scenarios account for 89% of all speeding vehicles.
- Inattention is noted by 27% of all drivers. Higher inattention rates emerge in running red light, running stop sign, rear-end, and turning in LTAP/OD at non signalized junction pre-crash scenarios as compared to other scenarios.
- Vehicle contributing factors account for 0.6%.



## NMVCCS Statistics

The NMVCCS data provide detailed information about different aspects of the crash including pre-crash movement, critical pre-crash event, critical reason, and associated factors [7]. On-scene information was collected on the events and associated factors leading up to 6,949 crashes that involved light vehicles during a three-year period from January 2005 to December 2007. Of these, 5,470 crashes comprised a nationally representative sample. Table 2 lists the NMVCCS variables that were investigated in the analysis.

**Table 2. Investigated NMVCCS Variables**

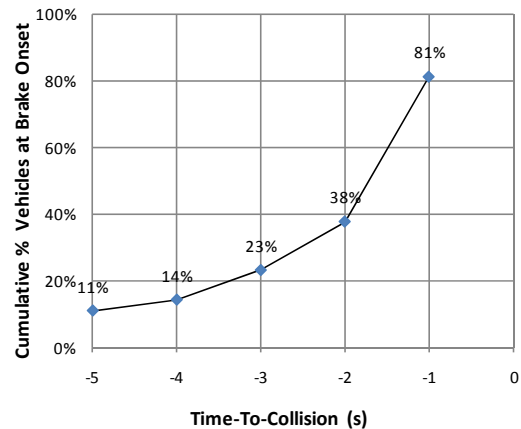
Category	NMVCCS Variable
Critical Reason	Critical Reason for the Critical Pre-crash Event
Driver Condition	Fatigue
Driver Recognition Error	Inattention
	Driver Conversing
	Inadequate Surveillance
	Other Driver Recognition Factor
Driver Decision Error	Misjudgement of Distance/Speed of Other Vehicle
	False Assumption of Other Road User's Action
	Following Too Closely
	Other Driver Decision Factor
Driver Action	Inadequate/Incorrect Evasive Action

The analysis of NMVCCS causal factors revealed the following key observations [5]:

- Fatigue is a factor in about 10% of all drivers. Higher fatigue rates are noted in opposite direction (27%), changing lanes/turning/drift – same direction (15%), rear-end LVD (13%), and rear-end LVS (13%) pre-crash scenarios.
- Inattention is cited in 15% of all drivers. Higher inattention rates are observed rear-end LVS (23%), running red light (23%), and rear-end LVD (18%) pre-crash scenarios.
- Inadequate surveillance is implicated in 55% of all drivers. Rates over 65% show up in running red light/stop sign, LTAP/OD, and SCP/turning at non-signalized junction pre-crash scenarios.
- False assumption of other road user's action is mentioned by 13% of all drivers. This rate amounts to 26% in LTAP/OD at signalized junction by left turning and other vehicles, 30% in turn right at signalized junction, and 25% in rear-end LVS pre-crash scenarios.
- Inadequate evasive action by all vehicles is 5%. This rate is highest in opposite direction pre-crash scenarios at 24%, followed by rear-end LVS pre-crash scenario at 13%.

## EDR Kinematic Data

EDR records were analyzed to quantify driver speed and braking response to an imminent crash from 5 seconds before the crash [8]. A sample of General Motors EDR vehicle cases from the 2000-2007 CDS databases were used in the analysis. Pre-crash data such as brake switch status and vehicle speed are recorded and stored at 1-second increments for 5 seconds from the start of a triggering event (i.e., crash). This analysis assumed that the start of this triggering event coincides with the exact instant of the collision; i.e., time-to-collision equals to zero. Figure 1 illustrates the proportion of vehicles that braked in response to a lead vehicle stopped from 5 seconds before the crash [5]; 3 seconds before the crash, only 23% of the vehicles initiated a brake response. The intensity of braking exerted by the vehicles was also computed by taking the difference in speeds over one second between five and four, four and three, three and two, and two and one second before the crash when brakes were applied. Similarly, the effective deceleration was calculated from the change in velocity over the five one-second intervals immediately before the crash.



**Figure 1. Illustration of Brake Response by Striking Vehicles in Rear-End LVS Scenario**

Quantitative crash data on speed, driver braking response, and brake intensity support the development of performance guidelines and objective test procedures for crash countermeasure systems, and enable system developers, for instance, to set minimum operating speeds and determine alert

timing for crash warning algorithms. Moreover, travel speed information helps to project the potential safety benefits of safety applications based on V2V communications.

### PRIORITY PRE-CRASH SCENARIOS

Ten scenarios with the greatest societal harm were prioritized from the 17 target pre-crash scenarios for further examination so as to gain the most benefit by reducing the occurrence of these crashes. The cost of pre-crash scenarios was estimated from the 2004-2008 GES as a function of two harm measures: comprehensive economic cost and functional years lost. These harm measures were derived from the maximum injury severity of all injured persons in a crash according to the Abbreviated Injury Scale – a classification system for assessing impact injury severity developed by the Association for the Advancement of Automotive Medicine.

Table 3 lists the 17 target pre-crash scenarios in a descending order in terms of their comprehensive cost based on 2007 economic values. It should be noted that these cost estimates reflect the injury levels of persons involved in police-reported crashes only. This analysis excluded the cost of crashes that were not reported to the police. The total cost of the 17 pre-crash scenarios account for 73% of all cost derived from the original 22 V2V target scenarios. The excluded control loss scenario contributed to about 24% of the comprehensive cost [5].

The 17 target V2V pre-crash scenarios were organized into six target pre-crash scenario groups as seen in Table 4. These groups were logically organized by their crash characteristics including movement and relative positioning between vehicles prior to impact. The traffic control device (TCD) violation group is different from the other five groups as it requires a specific driver violation at junctions controlled by 3-color signals or stop signs. This particular group was excluded from further analysis since its pre-crash scenarios are best addressed with safety applications based on vehicle-to-infrastructure communications such as the cooperative intersection collision avoidance system for violations developed by CAMP [9].

**Table 3. Societal Harm of Target Scenarios**

Pre-Crash Scenario	Annual Crashes	Comprehensive Cost	
		Total	Portion
SCP @ non signal	647,000	\$ 41,095,000,000	14.95%
Rear-end/LVS	942,000	\$ 29,716,000,000	10.81%
Opposite direction/no maneuver	118,000	\$ 29,558,000,000	10.75%
Running red light	237,000	\$ 18,274,000,000	6.65%
LTAP/OD @ non signal	184,000	\$ 15,481,000,000	5.63%
LTAP/OD @ signal	204,000	\$ 14,777,000,000	5.37%
Rear-end/LVD	398,000	\$ 12,215,000,000	4.44%
Rear-end/LVM	202,000	\$ 10,342,000,000	3.76%
Changing lanes/same direction	336,000	\$ 8,414,000,000	3.06%
Turning/same direction	202,000	\$ 6,176,000,000	2.25%
Opposite direction/maneuver	11,000	\$ 3,500,000,000	1.27%
Drifting/same direction	105,000	\$ 3,483,000,000	1.27%
Running stop sign	41,000	\$ 3,075,000,000	1.12%
Rear-end/striking maneuver	83,000	\$ 2,381,000,000	0.87%
Turn @ non signal	45,000	\$ 930,000,000	0.34%
Turn right @ signal	31,000	\$ 908,000,000	0.33%
Rear-end/LVA	21,000	\$ 667,000,000	0.24%

**Table 4. Target Pre-Crash Scenario Groups**

Pre-Crash Scenario	
Group	Scenario
Rear End	Rear-end/LVS
	Rear-end/LVD
	Rear-end/LVM
	Rear-end/striking maneuver
	Rear-end/LVA
Lane Change	Changing lanes/same direction
	Turning/same direction
	Drifting/same direction
Opposite Direction	Opposite direction/no maneuver
	Opposite direction/maneuver
LTAP/OD	LTAP/OD @ non signal
	LTAP/OD @ signal
Junction Crossing	SCP @ non signal
	Turn @ non signal
	Turn right @ signal
TCD Violation	Running red light
	Running stop sign

The 15 remaining target pre-crash scenarios were selected down to a total of 10 priority pre-crash scenarios for V2V-based safety applications [10]. This reduced selection excludes target pre-crash scenarios that contributed to less than 1% of the annual societal harm listed in Table 3. In addition, the two LTAP/OD pre-crash scenarios were combined as one since they have similar kinematics.

The 10 priority pre-crash scenarios are arranged below by their respective group in a descending order of societal harm:

1. Rear-end: cost = \$52,273,000,000 and frequency = 1,542,000
  - a. LVS
  - b. LVD
  - c. LVM
2. Junction crossing – SCP at non-signalized junctions: cost = \$41,095,000,000 and frequency = 647,000
3. Opposite direction: cost = \$33,058,000,000 and frequency = 129,000
  - a. No vehicle maneuver
  - b. Vehicle making a maneuver
4. LTAP/OD: cost = \$30,258,000,000 and frequency = 388,000
5. Lane change: cost = \$18,073,000,000 and frequency = 643,000
  - a. Changing lanes/both vehicles traveling in same direction
  - b. Turning/both vehicles traveling in same direction
  - c. Drifting/both vehicles traveling in same direction

The rear-end pre-crash scenario group is comprised of multiple-vehicle crashes that occur longitudinally while traveling in the same lane in the same direction. The junction crossing SCP group incorporates the scenario in which the two vehicles approach each other from perpendicular directions at non-signalized junctions. The opposite direction pre-crash scenarios involve two vehicles approaching each other from opposite directions, either in the same lane or adjacent lanes prior to the critical event, typically away from road junctions. The LTAP/OD pre-crash scenarios consist of two vehicles approaching each other from opposite directions, initially in adjacent lanes, with one vehicle initiating a left turn maneuver across the path of the other. Lane change crashes are characterized by predominantly laterally-oriented two vehicles traveling in the same direction in adjacent lanes.

## PRE-CRASH SCENARIO DEPICTIONS

The 10 priority pre-crash scenarios were depicted to convey information that will be helpful in the development of functional requirements, performance specifications, objective test procedures, and

estimation of safety benefits for V2V-based safety applications [10]. The depiction of pre-crash scenarios consists of the following four key elements:

- General crash characteristics
- Relative location and motion of involved vehicles
- Supporting demographic data
- Kinematic crash representations

## General Crash Characteristics

Each pre-crash scenario group was depicted in a typical configuration to illustrate the common kinematic and time-dependent elements. Generic illustrations were created to show the simplest roadway geometry and define the critical quantitative physical parameters. Each pre-crash scenario group was also linked to a primary critical event that made the crash imminent:

1. Lane departure leading to encroachment onto the travel lane of another vehicle. The two vehicles may be traveling in the same or opposite directions.
2. Approaching a vehicle in the same lane. The two vehicles may be traveling in the same or opposite directions.
3. Encroaching onto the travel lane of another vehicle at junctions including turning across the path or straight crossing paths. In turning across the path, the two vehicles may be initially traveling from the same or opposite directions.

## Relative Location and Motion of Vehicles

The location and trajectory of the subject vehicle and other relevant vehicles are the essence of the mathematical description for the time-to-collision (ttc) variable. The initial state of the vehicles must be understood and the potential influence of other driving factors must be estimated in order to predict possible intersection of their paths. In addition to the subject vehicle, other vehicles of interest include target vehicles located ahead, behind, and to either side of the subject vehicle. Moreover, the front or rear offset of target vehicles must be considered. V2V-based safety applications must be able to

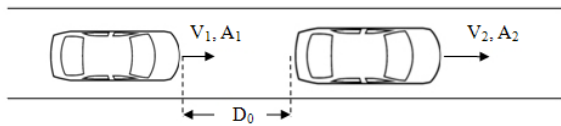
ascertain each vehicle's relative position including elevation, velocity, heading, range rate, position in lane, acceleration (longitudinal and lateral), and yaw rate.

### Supporting Demographic Data

Pre-crash scenario depictions included supporting demographic data from the GES and NMVCCS databases, where available. Such information provides insight into the most common crash contributing factors and primary causes.

### Kinematic Crash Representations

Kinematic representations consist of three elements: scenario configuration, timeline, and mathematical description. The scenario configuration is depicted by a generic diagram, similar to Figure 2, to represent each pre-crash scenario.



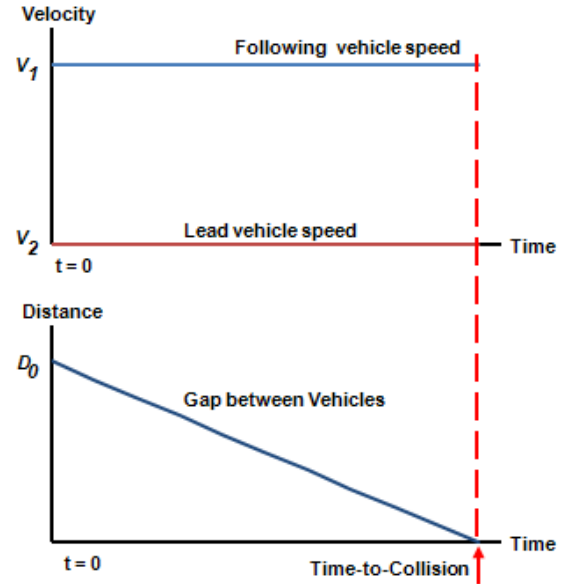
**Figure 2. Rear-End Pre-Crash Scenario Diagram**

The timeline of each pre-crash scenario illustrates the behavior of each vehicle involved in the scenario to highlight the speeds and distance between vehicles as a function of time. Figure 3 shows the crash timeline for the rear-end LVS scenario.

Each kinematic depiction concludes with a mathematical description of the ttc equation for each scenario. Equation (1) illustrates a sample ttc equation for the rear-end LVS scenario:

$$ttc = \frac{D_0}{V_1} \quad (1)$$

ttc = Time-to-collision  
 $D_0$  = Distance between vehicles  
 $V_i$  = Vehicle i speed



**Figure 3. Timeline of Rear-End LVS Scenario**

### Crash Avoidance Needs

From the kinematic crash depictions and time-to-collision equations, various crash avoidance needs were identified for each priority pre-crash scenario group. The information needs were organized by crash kinematic, driver intent, and demographic needs. Vehicles in all pre-crash scenarios must collect the following information:

- Vehicle position
- Velocity
- Longitudinal acceleration
- Lateral acceleration
- Heading
- Position in lane
- Yaw rate
- Turn signal use
- Brake activation
- Throttle position
- Wiper state, temperature, etc.
- Vehicle size

Driver intent could be deduced from the use of vehicle controls and signals such as turn signal use, brake activation, and/or throttle position. Each vehicle must also compute different variables such as range, range rate, and time-to-collision to all vehicles in close proximity.

**PRIORITY PRE-CRASH SCENARIO COUNTERMEASURES**

The VSC-A project developed and tested six safety applications for autonomous vehicles to work in conjunction with vehicle communications and positioning systems [2]. The following is a brief description of five of these related safety applications that were selected for a test bed in the VSC-A project:

- **Emergency Electronic Brake Light (EEBL):** This application enables a host vehicle to broadcast a self-generated emergency brake event to surrounding remote vehicles. Upon receiving such event information, the remote vehicle determines the relevance of the event and provides a warning to the driver if appropriate.
- **Forward Collision Warning (FCW):** This application warns the driver of the host vehicle in case of an impending rear-end collision with a remote vehicle ahead in traffic in the same lane and direction of travel.
- **Intersection Movement Assist (IMA):** This application warns the driver of a host vehicle when it is not safe to enter an intersection due to high collision probability with other remote vehicles at stop sign controlled and uncontrolled intersections.
- **Blind Spot Warning (BSW) + Lane Change Warning (LCW):** This application warns the driver of the host vehicle during a lane change attempt if the blind spot zone into which the host vehicle intends to switch is, or will soon be, occupied by another vehicle traveling in the same direction. The application also provides the driver of the host vehicle with advisory information that a vehicle in an adjacent lane is positioned in the blind spot zone when a lane change is not being attempted.
- **Do Not Pass Warning (DNPW):** This application warns the driver of the host vehicle during a passing maneuver attempt when a slower moving vehicle, ahead and in the same lane, cannot be safely passed using a passing zone that is occupied by vehicles in the opposite direction of travel. The application also provides the driver of the host vehicle with advisory information that the passing zone is occupied when a passing maneuver is not being attempted.

Table 5 highlights potential crash countermeasures by mapping VSC-A’s V2V-based safety applications to the 10 priority pre-crash scenarios [11].

**Table 5. Mapping Priority Pre-Crash Scenarios to VSC-A Safety Applications**

Priority Pre-Crash Scenarios		VSC-A Safety Applications				
		EEBL	FCW	IMA	DNPW	BSW+ LCW
Rear-End	Lead Vehicle Stopped		✓			
	Lead Vehicle Moving		✓			
	Lead Vehicle Decelerating	✓	✓			
Junction Crossing	SCP @ Non Signal			✓		
LTAP/OD	LTAP/OD					
Opposite Direction	Opposite Direction/ No Maneuver					
	Opposite Direction/ Maneuver				✓	
Lane Change	Changing Lanes/ Same Direction					✓
	Turning/Same Direction					✓
	Drifting/Same Direction					✓

As seen in Table 5, VSC-A safety applications address 8 of the 10 priority pre-crash scenarios. Two scenarios, LTAP/OD and opposite direction/no vehicle maneuver, would require the development of new applicable crash countermeasures. VSC-A safety applications would still require some further development to deal with the different crash characteristics and kinematics of the pre-crash scenarios already addressed by these applications, especially in the alert decision making area by considering distinct dynamic states of the vehicles.

## CONCLUSIONS

This paper delineated a pre-crash scenario framework for the development and evaluation of crash avoidance systems based on V2V communications. Crash statistics were provided for 17 target pre-crash scenarios based on national crash data in the 2004-2008 GES and NMVCCS databases. The crash analysis focused on multiple-vehicle, police-reported crashes that involved at least one light vehicle. Moreover, comprehensive economic costs based on 2007 economic values were utilized to quantify and rank the societal cost of the 17 pre-crash scenarios. The pre-crash scenario framework statistically described the 17 target pre-crash scenarios in terms of their driving environment, driver characteristics, contributing and causal factors, and kinematic information about travel speed, brake application, and deceleration level over a period of 5 seconds prior to the crash.

This paper identified 10 priority pre-crash scenarios that were arranged into five pre-crash scenario groups as a basis for the development of future V2V-based crash avoidance systems. The five pre-crash groups included rear-end, lane change, opposite direction, LTAP/OD, and junction crossing pre-crash scenarios. The rear-end and lane change groups consisted of pre-crash scenario groups traveling in the same direction, in the same or adjacent lanes and are differentiated by their crash modes, rear or side-impacts respectively. The opposite direction group involved vehicles moving in the opposite direction in the same or adjacent lanes. The LTAP/OD and junction crossing pre-crash groups occurred at junctions such as intersections or driveways, differentiated by the primary other vehicle's initial orientation, opposite and parallel versus perpendicular to the subject vehicle.

Crash avoidance needs for the V2V-based crash countermeasures were derived from kinematic equations that represent the time-to-collision and suitable avoidance maneuver for each target pre-crash scenario. These equations incorporated key parameters that the countermeasures must measure to decide on whether a crash is imminent in a specific scenario and to determine when to assist the driver.

CAMP's VSC-A project investigated and built V2V-based safety application prototypes that addressed rear-end, lane change, junction crossing SCP, and opposite direction/vehicle making a maneuver pre-crash scenarios. The remaining two priority pre-crash scenarios, opposite direction/no vehicle maneuver and LTAP/OD, were not directly addressed by the VSC-A project. Thus, further development is recommended to build V2V-based safety applications that address these two remaining scenarios.

This paper presented a pre-crash scenario framework that will be used to identify intervention opportunities and define crash countermeasure profiles based on V2V communications. The statistical and kinematic depictions of priority pre-crash scenarios will enable the development of countermeasure functional requirements and minimum performance specifications, objective test procedures, and the estimation of potential safety benefits.

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# CAR-TO-PEDESTRIAN CONTACT SITUATIONS IN NEAR-MISS INCIDENTS AND REAL-WORLD ACCIDENTS IN JAPAN

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## ABSTRACT

The number of traffic deaths in Japan was 4,863 in 2010. When looking at the number of the road accident fatalities (4,863) in 2010, it reveals that pedestrians account for the highest number (1,714, 35%). To reduce the severity of injuries and the number of deaths, active safety devices providing pedestrian detection are considered to be ones of the effective countermeasures. The detailed features of the contact scenarios in car-to-pedestrian are necessary to develop the safety devices. Since the information on the real-world accidents was limited, the authors focused on the near-miss scenarios captured by drive recorders installed in passenger cars.

The first purpose of the present study is to ascertain the utility of using near-miss scenarios for understanding the features of the contact situations between cars and pedestrians. In the present study, the authors investigated the similarities between the data of near-miss incidents including motion pictures captured by drive recorders and the data of national traffic accidents based on real-world fatal pedestrian accidents in Japan. This study used 163 motion pictures of near-miss car-to-pedestrian incident data collected by the Society of Automotive Engineers of Japan (J-SAE) from 2005 to 2009. The results indicated that 70% pedestrians at intersections or on straight roads were crossing the roads in front of the forward moving cars both in accidents and near-miss incidents. Considering the features of pedestrians' behaviors from this result, the authors found similarities between accidents and near-miss incidents. It was made clear that one could estimate the situations in pedestrians' accident from the near-miss incident data which included motion pictures capturing pedestrian behaviors.

The second purpose of the present study is to estimate the time to collision (TTC) from the near-miss incident data. This study analyzed 103 near-miss car-to-pedestrian incident data in which pedestrians were crossing the roads in front of the forward moving

cars at intersections or on straight roads. We calculated the TTC from the velocity of a car with an installed drive recorder and the distance between a car and a pedestrian at the moment a pedestrian initially appeared on a motion picture captured by the drive recorder. As a result, the average TTC was 1.7 seconds (SD 1.3 seconds). The average TTC was 1.8 seconds in cases that pedestrians were walking across a crosswalk, which was longer than the average TTC 1.4 seconds in the cases that pedestrians were walking across the roads without a crosswalk. The authors propose that the specifications of the safety device for the pedestrian detection and for automatic braking should reflect the detailed information including the TTC obtained by the near miss situations, in which the worst situation was assumed that the cars were moving toward pedestrians without braking due to car driver's inattentiveness.

## INTRODUCTION

The number of traffic deaths in Japan was 4,863 in 2010. When looking at the number of the road accident fatalities (4,863) in 2010, it reveals that pedestrians account for the highest number (1,714, 35%)<sup>1)</sup>. The Japanese government has an aim to reduce the annual fatality count to less than 2,500 till 2018<sup>2)</sup>. For example, since head injuries were the most common causes of pedestrian deaths in car-to-pedestrian accidents, the Japanese Ministry of Land, Infrastructure, Transport and Tourism (J-MLIT) started to assess the safety performance of the bonnet top of a vehicle. To reduce the severity of injuries and the number of deaths, active safety devices such as the crash severity mitigation system using sensors for pedestrian detection is regarded as an effective countermeasure. Currently, cars with the crash severity mitigation system with a sensor of a stereo camera and automatic braking installed are produced in Japan<sup>3,4)</sup>. Those cars are expected to be developed in consideration of car-to-pedestrian contact situations including the time to collision (hereafter referred to TTC). However, the contact situations in accidents have not been made clear so far, because the detailed



information on the real-world accidents is limited. For example, Rosen et al.<sup>5)</sup> investigated the pedestrian locations and car locations one second prior to their impacts that resulted in fatal accidents, but there have been few other representative examples. Hence this study focused on the near-miss incidents captured by drive recorders installed in passenger cars.

The near-miss incident is the situation that a car accident involving a pedestrian is avoided by the attention and braking of a driver. Near-miss incidents occurred more frequently than accidents. Recently, drive recorders were installed in taxis in Tokyo area for the purpose of investigating causes of car accidents and educating car drivers. The data of the drive recorder consist of forward moving pictures captured by its camera, and the cars' velocities, accelerations, and braking signals. If the near-miss incidents were similar in the feature to the accidents, we determined that the car-to-pedestrian contact situations or the TTC could be estimated from the near-miss incidents. So the authors analyzed the near-miss incident data captured by drive recorders installed in taxis.

The first purpose of the present study is to ascertain the utility of using near-miss situations for understanding the features of contact situations between cars and pedestrians. In this study, the similarities were investigated between the data of near-miss incidents including motion pictures captured by drive recorders and the data of national traffic accidents based on real-world fatal pedestrian accidents in Japan.

The second purpose of the present study is to estimate the TTC from the near-miss incident data so as to help develop the crash severity mitigation system of active safety cars in the future. This study analyzed near-miss car-to-pedestrian incident data in which pedestrians were crossing the roads in front of the forward moving cars at intersections or on straight roads. The authors calculated the TTC from the velocity of a car with an installed drive recorder and the distance between a car and a pedestrian at the moment a pedestrian appeared on a motion picture captured by the drive recorder. The worst situation was assumed when a car was moving toward a pedestrian without the attention and braking of the car driver. In the present study, the authors used and analyzed the near-miss car-to-pedestrian incident data by the Society of Automotive Engineers of Japan (J-SAE) from 2005 to 2009 in order to estimate the TTC considering the worst situation.

## NEAR-MISS IN-DEPTH DATA

J-SAE has collected near-miss incidents data<sup>6)</sup> consisting of forward movie pictures, and the cars' velocities, accelerations and braking signals which are obtained from drive recorders which has been installed in over one hundred taxis in Tokyo from 2005. The drive recorder was installed on the inner side of the front glass and consisted of a camera and three dimensional accelerometers. The near-miss data include contact events of car-to-car, car-to-pedestrian, car-to-bicycle, and car-to-motorcycle impacts.

Table 1 Vehicle-to-pedestrian near-miss data

Daytime (n=77 incidents)				
Adult or child	Location	Crosswalk	Pedestrian moving direction	Number
Adult (n=72)	Straight road (n=28)	None (n=24)	Go straight	4
			Across	20
		Yes (n=4)	Across	4
	Intersection (n=42)	None (n=4)	Go straight	1
			Across	3
		Yes (n=38)	Go straight	2
			Across	36
Other* (n=2)	None (n=2)	Across	2	
Child (n=5)	Straight road (n=5)	None (n=5)	Across	5

Other\*: in parking areas

Nighttime (n=86 incidents)				
Adult or child	Location	Crosswalk	Pedestrian moving direction	Number
Adult (n=83)	Straight road (n=32)	None (n=29)	Go straight	-
			Across	29
		Yes (n=3)	Across	3
	Intersection (n=51)	None (n=3)	Across	3
			Yes (n=48)	Go straight
		Across	48	
Child (n=3)	Straight road (n=1)	None (n=1)	Across	1
	Intersection (n=2)	None (n=2)	Across	2

The drive recorder's collection of data is triggered by a driver's sudden braking of over 0.5 G deceleration, and the recorder can keep capturing the data for 10 seconds beforehand and 15 seconds after the triggering. In the present study, the authors used 163 near-miss car-to-pedestrian incident data from 2005 to 2009 consisting of 77 incidents in daytime and 86

incidents in nighttime. Table 2 summarizes the age-group (adult or child), near-miss incident location (straight road or intersection), crosswalk, and pedestrian moving direction. In reviewing Table 2, it is seen that the majority of the pedestrians were crossing the roads in front of forward moving cars at intersections or on straight roads regardless of whether it was daytime or nighttime.

### CONTACT SCENARIOS IN REAL-WORLD ACCIDENTS AND NEAR-MISS INCIDENTS

To clarify the utility of using near-miss car-to-pedestrian incident data, the authors investigated the motion pictures captured by drive recorders of 163 near-miss incidents from 2005 to 2009 and the national traffic accidents records based on 12,283 real-world fatal pedestrian accidents from 1999 to 2003 in Japan<sup>7)</sup>. The relationship of moving directions between vehicles and pedestrians on straight roads and intersections is defined as shown in Figure 1. On the straight roads, the cases that pedestrians were crossing the roads in front of the forward moving cars were defined as “A”, and the cases that pedestrians were walking at the same direction with the moving cars were defined as “C”. At the intersections, cars moved in three directions: forward, turning right, and turning left. The cases that pedestrians were crossing the roads in front of the forward moving cars were defined as “B”, and the cases that pedestrians were walking at the same direction with the initial moving cars which later turned right or left were defined as “D”.

The distribution of moving directions between vehicles and pedestrians in accident data and near-miss data is shown in Figure 2. When focusing on the distribution ratio of the cases pedestrians were crossing the roads in front of the forward moving cars (“A” and “B” in Figure 1), it is seen that these were 67% (fatal) vs. 74% (near-miss) in daytime, and 78% (fatal) vs. 69% (near-miss) in nighttime, respectively. The results indicated that approximately 70% pedestrians at the intersections or on straight roads were crossing the roads in front of the forward moving cars. Considering the features of pedestrians’ behaviors from this result, similarities are observed between accidents and near-miss incidents. It was determined that one could predict the pedestrian accident situations by analyzing the near-miss incident data containing motion pictures capturing the pedestrian behaviors. Therefore, in the next section, the authors investigate the detailed situations from the near-miss incident data that cars and pedestrians approached each other.

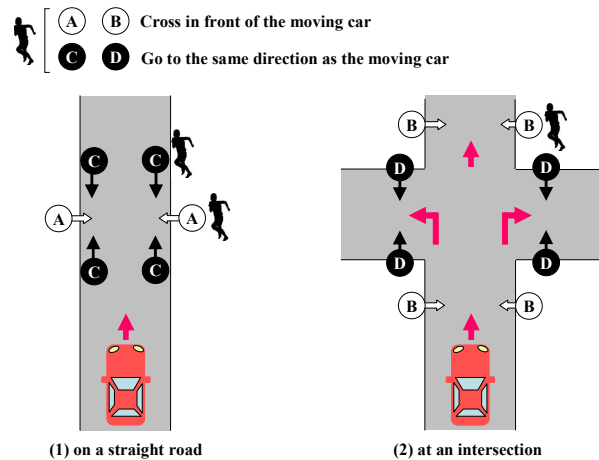


Fig. 1 Relationship of moving directions between a vehicle and pedestrian

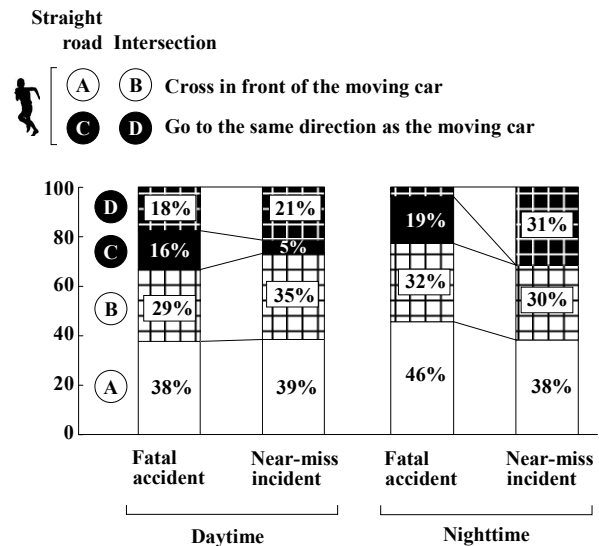


Fig. 2 Distribution of moving direction between a vehicle and pedestrian in accident data and near-miss data

### NEAR-MISS IN-DEPTH ANALYSIS

#### Near-miss in-depth data

In this section, the time to collision (TTC) is estimated from the near-miss car-to-pedestrian incident data in which pedestrians were crossing the roads in front of the forward moving cars at the intersections or on straight roads. Basically, the near-miss incident was in such a situation that the car accident was avoided due to the attention and braking of the car driver. In the present study, the TTC was estimated from the near-miss data considering the worst case that a car moving toward a pedestrian would result in accident without the car driver’s braking.

Table 2 Summary of in-depth analysis of vehicle-to-pedestrian near-miss data (n=103 incidents)

Location	Straight road (n=55 incidents)				Intersection (n=48 incidents)				Total
	Daytime (n=28)		Nighttime (n=27)		Daytime (n=23)		Nighttime (n=25)		
Across from	Right	Left	Right	Left	Right	Left	Right	Left	
Adult pedestrian	10	14	12	14	12	11	13	10	96
Child pedestrian	2	2	0	1	0	0	0	2	7
<b>Total</b>	<b>12</b>	<b>16</b>	<b>12</b>	<b>15</b>	<b>12</b>	<b>11</b>	<b>13</b>	<b>12</b>	<b>103</b>

The near-miss incident data that cars and pedestrians approached each other were selected for the purpose of analysis. As a result, 103 out of 163 near-miss car-to-pedestrian incident data were used; pedestrians were crossing the roads in front of the forward moving cars at the intersections or on straight roads. The age group and near-miss location of the 103 incidents are summarized in Table 2. The numbers of the near-miss incidents were similar in daytime (28 cases) and night time (27 cases) at straight road and in daytime (23 cases) and night time (25 cases) at intersections. The numbers of incidents involving adult and child pedestrians were 96 and 7 cases, respectively.

**Calculation of TTC**

The TTC (second) was calculated by the following formula using the velocity (V: m/s) of a car with an installed drive recorder and the forward distance (L: m) between a car and a pedestrian at the moment a pedestrian appeared on a motion picture captured by the drive recorder as shown in Figure 3.

$$TTC = L/V \quad [1]$$

Here, V is the running velocity of the car just before the driver applies the brake after realizing the existence of a pedestrian. It was determined whether a driver applied the brakes by checking the braking signal and deceleration signal recorded in the drive recorder.

The authors also investigated the lateral distance (Ld: m) between one side of the car and the pedestrian by using the following formula.

$$Ld = LL - 0.85 \quad [2]$$

Here, LL (m) is approximately 1.7m which is the distance between the center of the drive recorder camera (the center of the car) and the pedestrian, and 0.85 m of the half distance of the full width of the car.

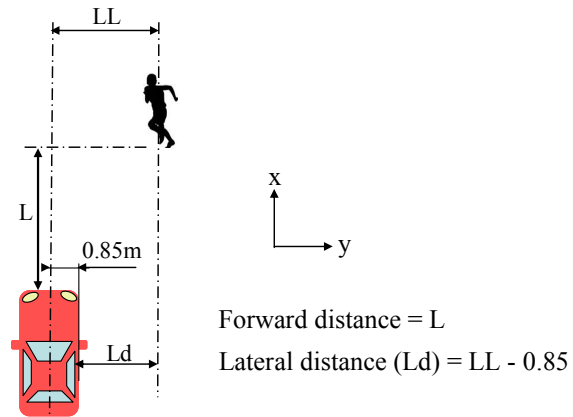


Fig. 3 Definition of a lane and distance

Figure 4 shows the estimated TTC distribution of the lateral distance (Ld) from the one side of a car to the pedestrian at the moment that the pedestrian appears on a motion picture captured by the drive recorder. The TTCs ranged from 0.5 seconds to 5.0 seconds. In determining the location of a pedestrian relative to the center of a car, it is observed that 49 cases were on the right hand side and 54 cases on the left hand side. The average TTC was 1.8 sec (SD 1.5 sec) for the cases on the right hand side, and 1.6 sec (SD 1.0 sec) for the cases on the left hand side. Since the average TTC was similar on both sides, the following analyses were performed regardless of whether the pedestrian was located on the right or left hand sides. The average TTC was 1.7 sec (SD 1.3 sec) for the total 103 cases.

The distribution of the estimated TTC and forward distance (L) between a car and a pedestrian is shown in Figure 5. Looking at the figure, one could observe a linear correlation between the forward distance and TTC theoretically.

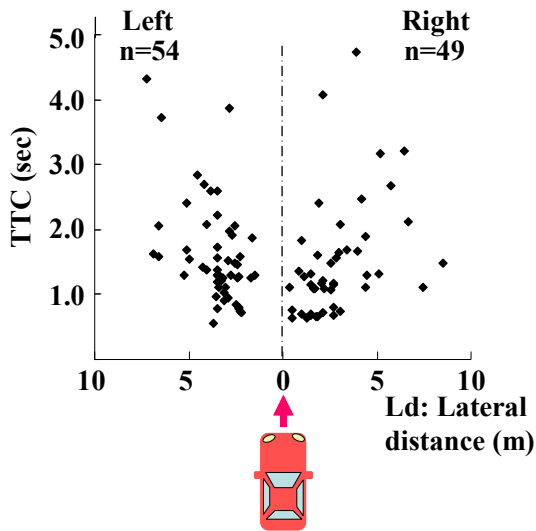


Fig. 4 Distribution of the estimated TTC and lateral distance (Ld)

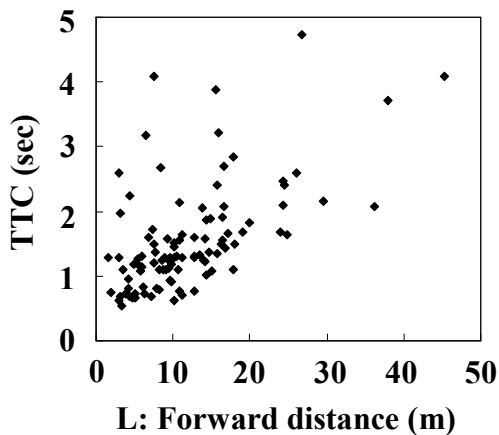


Fig. 5 Distribution of the estimated TTC and the forward distance (L)

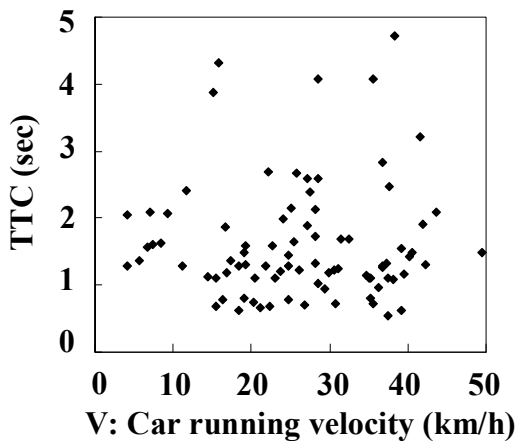


Fig. 6 Distribution of the estimated TTC and the car running velocity (V)

The distribution of the estimated TTC and the car running velocity (V) is shown in Figure 6. Theoretically, the TTC became shorter if the car running velocity was getting higher. On the other hand, no linear correlation between the car running velocity and TTC is observed. One could speculate several reasons for the widely-scattered coordinates in Figure 6. Therefore, in the next section, the authors investigate the detailed features of pedestrian behaviors.

#### Detailed Feature of Pedestrian Behaviors

The authors classified the pedestrians' popping out patterns in front of the drive recorder installed in a car into four categories as shown in Table 3. The classified patterns are (1) unobstructed view, (2) from behind a building, (3) from behind a parked vehicle, and (4) from behind a moving vehicle. The average of the TTC, the forward distance between a car and a pedestrian, and the car running velocity in classified 4 pedestrian pop out patterns are shown in Figure 7. Looking at the average TTC, the unobstructed view (1) was longest as 2.9 seconds, which was presumably caused by the longer forward distance (Ave 16.2m) regardless of the relatively higher running velocity of a car (Ave 30.3 km/h). The average TTC 1.4 seconds from behind a building (2) was similar to the average TTC 1.3 seconds of from behind a parked vehicle (3). And from behind a moving vehicle (4) was the shortest at 1.2 seconds, which was presumed to be caused by the higher running velocity of a car (Ave 32.9 km/h).

The average of the TTC, the forward distance between a car and a pedestrian, and the car running velocity in classified two pedestrian locations at crosswalk or without crosswalk of each classification is shown in Figure 8. The average TTC in the cases that pedestrians were walking across a crosswalk was longer than the average TTC in the cases that pedestrians were walking on the roads without a crosswalk. It was assumed to result in the effect of a crosswalk that a car driver would have enough time to put on the brake for the crosswalk ahead. When one focuses on the location of a crosswalk, it is observed that the average TTC 1.9 seconds in cases at intersections was longer than the average TTC 1.6 seconds in cases on straight roads. It was assumed that a car driver would recognize that he or she were in more danger of hitting a pedestrian at an intersection than on a straight road. So, it was determined that a car driver would put on the brake and have enough time to reach a crosswalk at an intersection. On the other hand, the average TTC in cases that pedestrians were walking across the roads at an intersection without a crosswalk was shortest as 1.2 seconds in the

four categories described in Figure 8. Even though these were near-miss incidents, it revealed that this condition had the high potential of causing an accident at an intersection without a crosswalk.

Table 3 Classified 4 pedestrian popping out patterns in front of a car installing the drive recorder

(1)	(2)	(3)	(4)
Unobstructed view	From behind a building	From behind a parked vehicle	From behind a moving vehicle

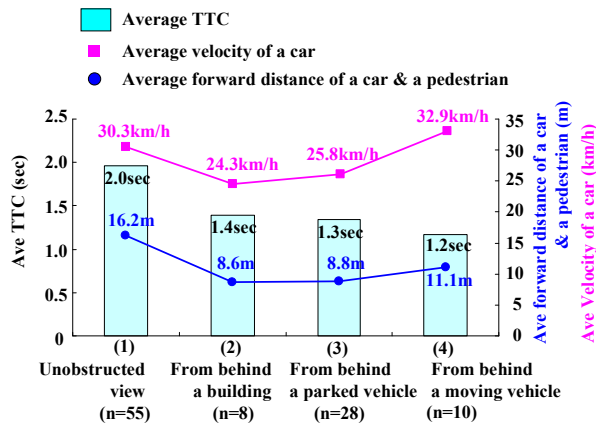


Fig. 7 Averages of TTC, forward distance between a car and a pedestrian, and the car running velocity in classified 4 pedestrian popping out patterns

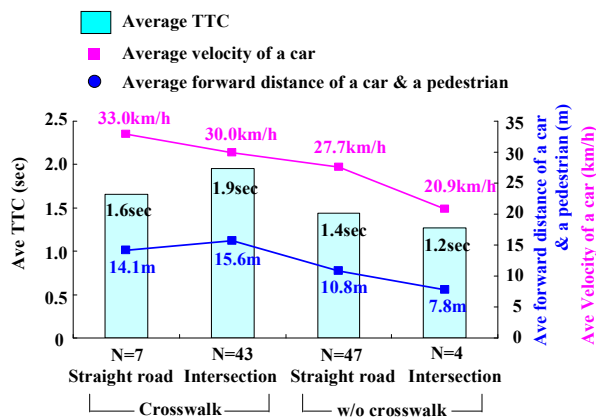


Fig. 8 Averages of the TTC, distance of a car and a pedestrian, and velocity of the drive recorder installed in a car on roads with or without crosswalk

## DISCUSSION AND CONCLUSIONS

In the present study, the authors investigated the utility of near-miss situations for understanding the features of the contact situations between cars and pedestrians, and estimated the time to collision (TTC) by focusing on the near-miss incident data. Basically, the near-miss incident was in such a situation that a car accident was avoided by the attention and braking of the car driver.

1) The similarities between the data of near-miss incidents including motion pictures captured by drive recorders and the data of national traffic accidents based on real-world fatal pedestrian accidents in Japan were investigated. The results indicated that 70% pedestrians at intersections or on straight roads were crossing the roads in front of the forward moving cars both in accidents and near-miss incidents. Considering the features of pedestrians' behaviors from this result, similarities were found between accidents and near-miss incidents. It was determined that one could estimate the situations in car-to-pedestrian accidents from the near-miss incident data which included motion pictures capturing pedestrian behaviors.

2) The authors analyzed 103 near-miss car-to-pedestrian incident data in which pedestrians were crossing the roads in front of the forward moving cars at intersections or on straight roads. In the present study, it should be noted here that the TTC could be estimated from the near-miss data considering the worst case that a car moving toward a pedestrian would result in accident without the car driver's braking. The TTC was calculated from the velocity of a car installing a drive recorder and the distance between a car and a pedestrian at the moment a pedestrian initially appeared on a motion picture captured by the drive recorder. From the results, the average TTC was 1.7 seconds (SD 1.3 seconds). When one focuses on the pedestrians popping out patterns in front of the cars, it is observed that the average TTC was the shortest at 1.2 seconds in the cases that pedestrians popped out from behind moving vehicles on the opposite lane. The authors propose that the specifications of the safety device for the pedestrian detection and automatic braking should reflect the detailed information including the TTC obtained by the near miss situations.

3) In the present study, the authors focused on the 103 near-miss car-to-pedestrian incident data in order to obtain the TTC. Since the feature of the 103 near-miss car-to-pedestrian incident data was similar to the feature in accident records, the authors could define the available near-miss incident level for estimating accident situations based on the present analysis results such as the average TTC was 1.7 seconds (SD 1.3 seconds).

## ACKNOWLEDGMENTS

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# INFLUENCE OF DRIVER ASSISTANCE SYSTEMS ON REPAIR COSTS

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## ABSTRACT

The growing proliferation of driver assistance systems in vehicles has made an increasingly significant contribution to the reduction in the number of fatalities and severities in traffic accidents. Driver assistance systems, such as autonomous pre-crash braking systems can reduce the impact velocity (particularly the impact energy) or can even avoid the crash completely. Thus, by reducing the impact speed in order to decrease the number of serious accidents, the subsequent repair costs of the crashed vehicle can also be lowered.

In the following article, based on a crash test (following Euro NCAP with a frontal impact) the influence of driver assistance systems on repair costs after an accident are described and discussed. Particularly, the potential of an integrated safety approach regarding repair cost reduction is described, focusing on an autonomous emergency braking system. The system of an actual BMW 5 Series model will serve as an example.

The repair costs of two vehicles crashed with and without an autonomous pre-crash braking system are compared here. The relevant test results are described and discussed, quantifying the effect of the autonomous emergency braking system on the impact speed and, consequently, on the repair cost reduction. Furthermore, an estimate of the benefit of the system in real-world crashes is given.

One major result of the test was that with an autonomous emergency braking system, an impact speed reduction of up to 40% (based on the initial speed according to the Euro NCAP test procedure) can be achieved. The benefits generated concerning the damage to a BMW 5 Series are also described.

## INTRODUCTION

So far systems that help to prevent accidents (active safety) and systems to minimize the consequences of accidents (passive safety) have clearly been separate fields. The isolated treatment of those two safety pillars became difficult with more and more components merging the borders established by the definitions. The integrated safety approach was born. Sensors, finding their way into the vehicle through active systems are simultaneously used for passive safety systems.

Automatic braking and pre-crash occupant positioning are systems offered by an increasing number of automobile manufacturers in their high class vehicles. Based on the experience with other safety systems the new systems will soon find their way into all vehicle classes. The benefit potential of passive safety systems like airbags or seat belts with their surrounding components is identified in crash tests.

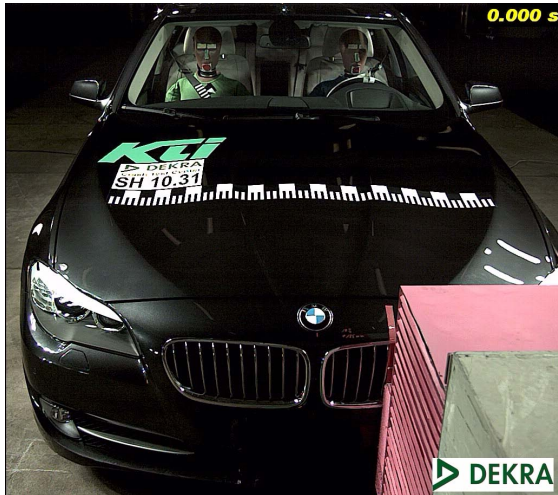
The benefit potential of active safety systems like ESP is analyzed in driving maneuvers. To test active and integrated safety systems in a reproducible way requires crash tests allowing a pre-crash reaction on the part of the car. So far no test standard, neither for homologation nor for consumer testing, allows a reliable statement about the effectiveness of active and integrated safety systems. Their benefit potential has not been verified yet. To define test standards for driver assistance systems with a main focus on forward-looking systems, the vFSS working group was founded in 2009.

The first results of the vFSS working group (advanced Forward-looking Safety Systems) encouraged them cause to test the effectiveness of an autonomous braking system and the influence on the occupant load outcome. Therefore, the DEKRA Crash Test Center modified its hauling system to automatically react on the braking of the test vehicle by adapting the hauling speed. KTI and DEKRA carried out the first crash test with an automatic braking car.

This paper gives an overview of the frontal impact accident scenarios and describes the crash test with automatic braking and its results relating to vehicle damage and potential benefits on repair costs.

## CRASH TEST

The tested vehicle was a BMW 530d, type F10, equipped with a prototypic collision imminent braking system. The test set up followed the Euro NCAP frontal impact configuration. This is an offset crash test with 40% overlap against a deformable barrier and Hybrid III 50<sup>th</sup> percentile male dummies on the driver's and passenger's seats. The collision speed is given at 64 km/h. This speed was chosen as the initial speed for the autonomous braking. For comparison, a similar car was crashed without the activation of an active safety system. The test set-up is shown in Figure 1.



**Figure 1. Impact position with 40% overlap.**

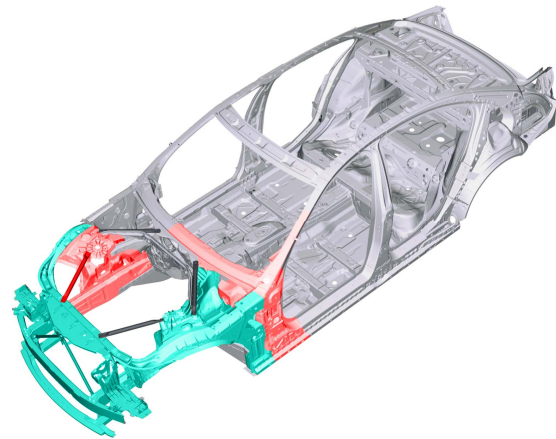
Approaching the barrier the sensor detected the obstacle and the full braking power was automatically triggered 0.9 seconds before the impact. The collision speed was reduced to 40km/h. The collision energy was, thus, reduced far more than 50% from 343kJ to 133kJ. The different deformation patterns are shown in Figure 2.



**Figure 2. Different deformations resulting from the 64 km/h impact (orange) and the 40 km/h impact (black).**

The results showed the effectiveness of a pre-crash braking system. The vehicle damage could clearly be reduced due to the reduction of impact speed. The damages on both cars were analyzed. It turned out that the car at 64 km/h impact suffered additional damage, among other things, on the front bulkhead, A-pillar, windscreen, right side member and left front door (Figure 3).

The software "Audatex AudaPad" was used to calculate the damages on both vehicles. AudaPad is a special software used for calculating repair costs on vehicles. The comparison of these results with the ones of a similar crash test with deactivated systems and a collision speed of 64 km/h showed significant differences. The repair costs were reduced by more than 25% in the 40 km/h test.

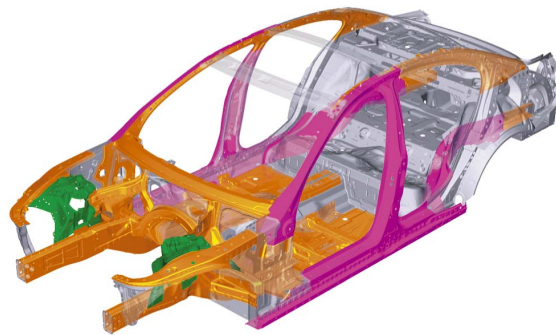


**Figure 3. Comparison of damage on the body structure resulting from the 64 km/h impact (red) and the 40 km/h impact (green).**

## REPAIRS

### Preliminary consideration

Steel-aluminium composite construction is used on the BMW 5 Series (F10), Figure 4. The BMW (F10) has a stiff passenger cell, increased use of high-strength multi-phase steel and hot-moulded ultra-high-strength steel, giving the safety passenger cell maximum stiffness on relatively low weight. The front side panels, bonnet, the doors and the front spring supports on the body of the new BMW 5 Series sedan are made of aluminium.



**Figure 4. Aluminium (green), multi-phase steel (orange) and hot-moulded ultra-high-strength steel (pink) used for the BMW F10 body structure [Source: BMW]**

The OEM's introduction of new materials and production techniques in cars makes it increasingly important so that the repair of such vehicles is carried out with the appropriate techniques and quality [1]. Therefore, OEM information was used during the repair. The damaged car was repaired with an Inverter type welding machine with 10 kA maximum current and a variable pressure (maximum force 5 kN) to join the high-strength steel safely. Because of aluminium's electrical flow



characteristics, welding is not permitted anywhere on the front structure of the BMW F10; front end components are partially attached with rivets and a high-strength glue. Therefore, it is a requirement that appropriate technical equipment and parts are used, such as rivet insertion and extraction tool, factory-specified structural adhesive and silicon-coated rivets.

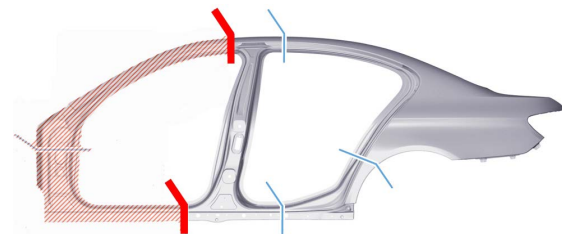
### Repair after the impact at 40 km/h

Initially, for proper diagnosis an electronic measurement of the car body was carried out. After additional check with a tear test-spray-set, we found that the right aluminium front shock tower section was not damaged. After removal of exterior attachment parts (such as bumper, headlights, fender, bonnet), the car was fixed on a bench. The repair started with a raw reshaping of the car chassis on a universal straightening bench. During straightening, we measured the dimensions at reference points. The vehicle was then raised on a lift. Windscreen and dashboard were removed (access and front-seat passenger airbag had been deployed). The engine was also removed in order to properly access the damaged components. The engine and front suspension were then removed. The front end of the car was fully disassembled while mounted on the Car-O-Liner bench to ensure manufacturer's tolerance would be met. To prepare the new parts, marked the cutting lines and then cut them at those points. We then made a rough cut of the brace (between firewall and strut tower), side member and inner fender apron near the installation area. Welded connections were open and wheel arch with engine support was removed. In order to replacement part correctly, we used alignment brackets to mount to the firewall. To preparation of new parts, were severance cut marked and cut. By repairing this vehicle on a bench, we were able to restore it to factory specifications. New components were attached with welding, adhesive and rivets. Thereby, to avoid contact corrosion, we grinded the new wheel arch part in the area of the bonding surfaces. The vehicle had to remain on the bench for 12 hours (at a temperature of 20°) after the structural adhesive was applied to allow it to set properly. The car was then taped and protected so that it could be primed. A factory-recommended seam sealer was then applied to all new joined seams and painted. Then, the engine and front suspension were installed as a single unit; all systems were installed and checked prior to painting. Finally the errors were deleted in the error memory.

### Repair after the impact at 64 km/h

In comparison to the crash at 40 km/h, there was a substantial difference, with far more

comprehensive deformation of the car body after the 64 km/h impact. The A-pillar was damaged, especially at the lower part at the connection with the sill and the roof side rail was deformed. Other differences were noticeable at the side member which displayed severe deformation on the front floor under reinforcement not seen in the first crash at 40 km/h. It was also noticed that the firewall was damaged in the second crash. The progress of repair was basically the same as the repair after the crash at 40 km/h. However, additionally it was necessary to repair the firewall, right front side member, right front spring supports and A-pillar. In order to do this, the interior up to the B-pillar area had to be removed. It was, different from the repair on the car at 40 km/h impact, carried out a roughly cut the side member and front shock tower near the installation area also on the right-hand side. In order to replace the A-pillar, the spot-welded adhesive joints were open and the side frame connection cut, Figure 5. At the A-pillar was the bonded connection with MAG weld seam was replaced and sealant was applied to the cavity sealing.



**Figure 5. Red marked severance cuts at the side frame (blue marked: further preferred cuts) [2].**

The new parts were in accordance with marked severance cuts and cut and adjusted with alignment brackets. Fundamentally, the complete front including some parts of the firewall were removed. The assembly was carried out again, similarly to the other BMW, which crashed at 40 km/h.

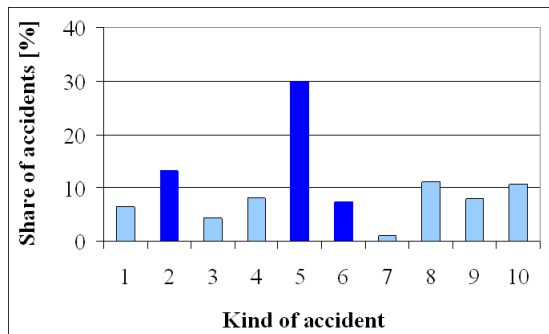
## ACCIDENT OCCURRENCE

In the year 2009, 41 million cars were registered in Germany (79% of all motorized vehicles). In the same year the German police registered 2.3 million accidents. 73% of all accidents, occurred in urban areas, followed by 20% in rural areas (not on motorways) and 7% in motorways [3].

Furthermore, several of the accidents reported to insurance companies were not recorded by the police. On the other hand, certain cases were recorded by the police but not reported to insurance companies if no claim for compensation was expected [4]. In Germany for example, the number of accidents reported by insurers was about 3.371 million (of motor car liability insurance case, 2.656

million of them passenger cars) in 2009 [5]. The average loss per car accident in motor liability insurance amounted to 3,520 €.

The right parameter to estimate the benefit potential of active safety systems is the kind of accident. In the official statistics of road traffic accidents in Germany, 10 kinds of accidents can be distinguished. The distribution of the individual accidents (with severely injured people and severe accidents involving material damage) is shown in Figure 6.

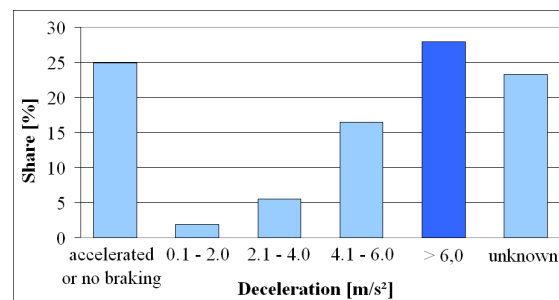


**Figure 6. The share of accidents with severely injured persons and severe accidents involving material damage (n=310,810).**

Three kinds of accidents were identified, which could potentially have been influenced by Collision Imminent Braking Systems (Type 2, 5 and 6). They are highlighted in dark blue in Figure 6. According to the German Federal Statistical Office, Type No. 2 "Collision with another vehicle moving ahead or waiting" describes accidents caused by a rear-end collision with a vehicle, which was either still moving or stopping due to the traffic situation. The kind of accident No. 5 includes collisions with crossing vehicles and with vehicles which are about to enter or leave from/to other roads, paths or premises. Collisions between vehicle and pedestrian belong to the No. 6 kind of accidents. More than half of all accidents belong to this three kinds of accidents (50.5%). For these crash types the automatic emergency braking systems can reduce the collision speed and can prevent the accidents or mitigate its effects.

Another important factor is the vehicle's braking before the impact. In most cases the vehicles are decelerated before the impact. Within the vFSS working package accident analysis was evaluated the GIDAS (German in depth Accident Study) data in regard to the pre-crash braking behavior in selected kinds of accidents (including the car-against-pedestrian accident). This current study is based on a total of 1,492 car accidents with frontal car impacts (single front or first impact of multiple collisions) against rear of 2-track-vehicles (a total

of 13,433 of reconstructed accidents, years 2000 - 2007). In about 25% of the 1,492 cases the bullet vehicle was not decelerated before the impact. In another 23% of the cases the data did not contain information about the pre-crash braking behavior. In all other cases the cars were decelerated before the impact. About 30% of the cars braked with an average acceleration of less than  $4\text{m/s}^2$ . This is only half of the possible braking acceleration under good conditions. In nearly 28% of the cases, the deceleration was greater than  $6\text{m/s}^2$ , Figure 7. Further analysis of accident databases corroborated these results [DEKRA, GDV, AZT]. These results will help to estimate the real world effectiveness of automatic emergency braking systems.



**Figure 7. Deceleration of the bullet vehicle (n=1,492) [Source: vFSS].**

#### POTENTIAL BENEFIT OF AUTOMATIC EMERGENCY BRAKING SYSTEMS

About 50% of all drivers braked with an average acceleration of less than  $6\text{m/s}^2$  [Source: vFSS]. In order to help drivers during braking maneuvers, cars can be fitted with a collision imminent braking system. In this respect, more than 50% of the accidents can be immediately addressed. We did not check the conditions on the spot. However, it is advisable to consider the road surface conditions in future analyses.

Certainly, there is less damage on the car with reduced collision speed. Figure 8 shows the known correspondence between the impact speed and the repair costs. The vehicles were crashed at 10 to 22.5 km/h over the front surfaces [6, 7, 8]. The RCAR speed test was used as this basis for these tests. The test conditions are shown in table 1.

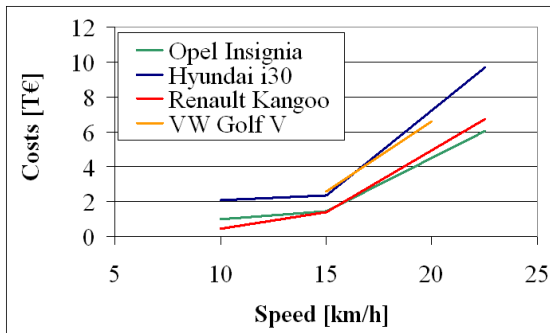


Figure 8. Correspondence between the impact speed and the repair costs [6, 7, 8].

Table 1. Test conditions

Collision speed	slope	overlap
10 km/h	0°	100%
15 km/h	10°	40% left side
20 km/h	10°	40% left side
22.5 km/h	10°	40% right side

In the frontal impacts, there is a direct relationship between the impact speed and the repair costs. Moreover, the evolution in costs for frontal impacts is very similar in the vehicles. The crash management modern cars are the reason for this performance. New vehicle bumpers are designed to withstand minor impact without significant damage (except scratches, notches and the like). Energy-absorbing bumpers in some form, are capable of absorbing impact of up to 5 km/h. Then, is there very little difference in the vehicles between the impacts at 10 and 15 km/h. At this speed range most of the parts that were damaged were easy to replace. The repair costs increased with increasing collision speed, since the side beam was damaged, and the mechanical units had to be replaced. With regard to the restraint systems, the driver's airbag, the front passenger airbag, and the safety belt pretensioners were activated.

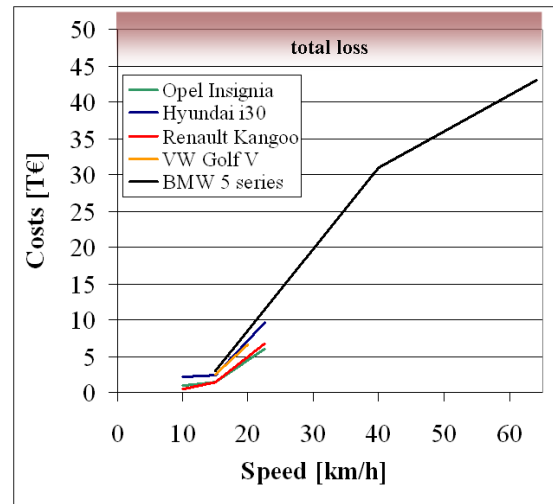
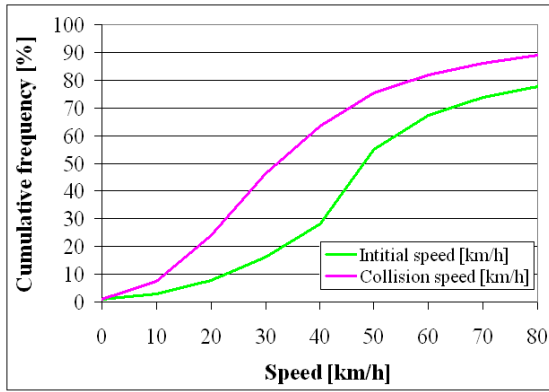


Figure 9. Correspondence between the impact speed and the costs for a speed range of 10 km/h to 64 km/h.

The repair costs as a result of the crash tests at 40 km/h and 64 km/h are also shown in figure 9, which shows an S-shaped (run of the) curve. This is largely due because the outer parts of the car (so called "crumple zones") controlled the weakening of this area, while strengthening and increasing the rigidity of the inner part of the body of the car. This turns the passenger cabin into a "safety cell", by using more reinforced beams and higher-strength steels to improve the resistance of the occupant compartment against mechanical loads in the event of a crash and which leads to less deformation.

In addition, it needs to be considered that repair costs not only occur on the bullet cars, but also on the target vehicles. The repair costs are limited by total loss. Nevertheless it is possible that the repair costs are lower, if according to the insurance company the current value of the vehicle goes below the repair costs (total loss).

The distribution of the driving speed of the car is of great interest. Figure 10 shows the distribution of the driving speed of the bullet vehicle. It is obvious that 40% of the cars have collision speeds of 40 km/h or below and the majority of impacts happen at initial speeds below 50 km/h.



**Figure 10. Initial speed and collision speed of the bullet car (unknown excluded,  $n \approx 1,000$ )**  
[Source: vFSS]

Assuming that all target vehicles were standing at the impact, the deceleration and resulting probable collision speed can be calculated when using an autonomous pre-crash braking system (in reality nearly 65% of the rear impacted vehicles were stationary at the impact). The speed reduction can easily be calculated as shown below:

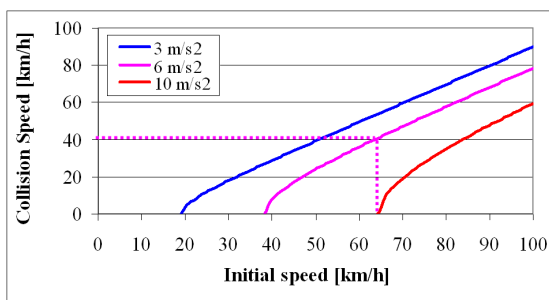
$$v_c = \sqrt{v_i^2 - 2 \cdot a \cdot s} \quad (1)$$

Where:

$$s = v_c \cdot t \quad (2)$$

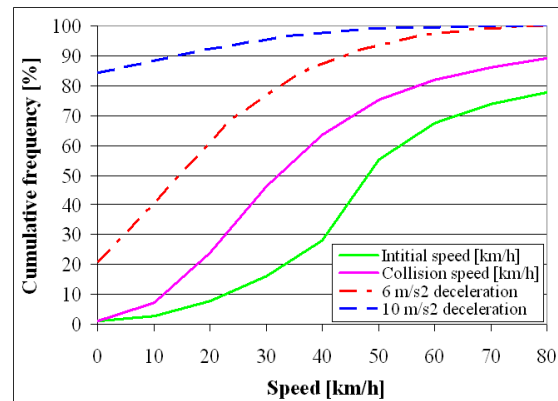
- $v_c$  = collision speed
- $v_i$  = initial speed
- $a$  = deceleration
- $t$  = time to collision

The reduction of speed is shown in Figure 11 for a braking deceleration of 3, 6 and 10 m/s<sup>2</sup>. 3 m/s<sup>2</sup> is a typical deceleration for an autonomous cruise control system and 10 m/s<sup>2</sup> are achievable under best conditions (dry road surface). The speed reduction in the test with autonomous braking of the BMW is highlighted in pink (6 m/s<sup>2</sup>). This deceleration can be achieved even on a wet road surface.



**Figure 11. Speed reduction for a braking deceleration of 3, 6 and 10 m/s<sup>2</sup> (rounded) and time to collision  $t = 0,9$  s.**

Figure 10 shows the distribution of collision speed and initial speed of the bullet car. The possible collision speed, under best conditions, is additionally shown in figure 12 provided that at all events the car decelerates by using an autonomous pre-crash braking system (for car accidents in the used database). Note: about half of all accidents are kinds of accidents with severely injured people and severe accidents involving material damage could potentially have been influenced by Collision Imminent Braking Systems (Figure 6). In reality, the benefit is dependent on a variety of parameters (such as road surface conditions, point of time when the system reacts and the intensity of reaction).



**Figure 12. Possible collision speed deceleration at usage of an autonomous pre-crash braking system (deceleration of 6 and 10 m/s<sup>2</sup>, time to collision  $t = 0,9$  s, unknown excluded).**

The curve moves toward lower collision speed, by means of better utilization of the road friction coefficient. The number of cars that come to a standstill before the impact is noticeable ( $v_c = 0$  km/h). This is the share of accidents, where a collision could completely be avoided using an autonomous braking system at a low speed (in this example with the BMW at nearly 38 km/h initial speed, see Figure 11).

Figure 12 shows that nearly 40% from all accident cars (in this example cars they have initial speeds 44 km/h or below) the collision can speed reduced below 15 km/h as critical speed in respect of repair costs. In real accidents occurrence these succeeds only approximately 15% of all drivers. Thereby, the automatic full emergency braking system can speed reduced below 15 km/h (as critical speed) of up to additionally 35% of in this study investigated accidents is possible (nearly 15 to 20% of all accidents involving cars with severely injured people and severe accidents involving material damage). In this speed area where often only parts damaged, which are easy to replace and very rarely structure parts. Furthermore, an autonomous

emergency braking system (with a deceleration no more than  $6 \text{ m/s}^2$  and time to collision  $0,9 \text{ s}$ ), could completely avoiding approximately 20% of accidents in this study (approximately 10% of all accidents involving cars with severely injured people and severe accidents involving material damage). If all cars were fitted with Collision Imminent Braking Systems, up to 80% (40% of all accidents involving cars with severely injured people and severe accidents involving material damage) of all car accidents in the current database could have been avoided under best conditions (dry road surface, deceleration  $10 \text{ m/s}^2$ , time to collision  $t = 0,9 \text{ s}$ , optimal system reaction).

## CONCLUSIONS

Apart from ESP systems, emergency braking systems and collision warning systems are those with the greatest safety potential in the field of active safety in cars.

In a recent study conducted by KTI, it was found that with the help of the Collision Imminent Braking Systems, ten to forty percent of car accidents could have been prevented in Germany alone. The benefit is established a variety of parameters such as road surface conditions and system reaction.

The findings were based on a crash test of a BMW 5 Series equipped with a prototypic pre-crash system and automatic full emergency braking.

Subsequent it was performed a predictive calculation of the usefulness of automatic full emergency braking system regarding repair cost reduction. Factors taken into account during the research included both official statistics and the analysis of the traffic accidents which have so far been studied within the framework GIDAS (German In-Depth Accident Study).

The automatic full emergency braking system is capable of braking the vehicle to a complete standstill. In the event the traffic following slows too rapidly, the system provides a warning and calculates the required brake pressure required to safely stop the vehicle which is then provided instantaneously by the emergency braking system as soon as the brake pedal is depressed.

Approaching the obstacle the sensor detected the obstacle and the system warn the driver by illuminating a red light in the instrument panel and the Head-Up Display 2.1 seconds prior to the impact. 1.7 seconds before impact the system give an alarm by adding a warning signal. The full braking power to be automatically triggered  $0.9$

seconds before the impact. Should the driver disregard the warning, the emergency braking system performs an emergency partial braking maneuver, significantly reducing the severity of the impact. The systems reaction but varies from manufacturer to manufacturer.

The analysis of the real life accident occurrence potentially show the influenced of automatic full emergency braking systems: More than half of all accidents are kinds of accidents (50.5%, note: accidents with severely injured people and severe accidents involving material damage) which could potentially have been influenced by Collision Imminent Braking Systems. Furthermore, in the analysed accident data, a braking with an average acceleration of more than  $6 \text{ m/s}^2$  before the impact could be observed in only nearly 27%. These accidents immediately can be addressed with a Collision Imminent Braking System.

Assuming that all cars (100%) are equipped with an autonomous emergency braking system, speed could be reduced below  $15 \text{ km/h}$  as critical speed, in nearly 25 to 45% of all car accidents involving severely injured people and severe accidents involving material damage. If all cars were fitted with Collision Imminent Braking Systems, dependent on conditions, 10 to 40% of all car accidents in Germany could be avoided.

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## **CARS ARE DRIVEN ON ROADS, JOINT VISIONS AND MODERN TECHNOLOGIES STRESS THE NEED FOR CO-OPERATION.**

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### **ABSTRACT**

Today traffic safety is a major health issue. The numbers of killed and injured in traffic accidents globally every year are staggering. The World Health Organization WHO has estimated the number of fatalities to approximately 1.2 million and the numbers will increase by 65% over the next 20 years. (Peden et al.).

Realizing that this is unacceptable, a number of countries and organizations, among them Sweden and Volvo Car Corporation, have adopted visions aiming towards the goal of no serious injuries and fatalities in traffic (Johansson R, 2009).

The European Commission, in its communication on road safety 2011-2020 to the European Parliament, (SEC (2010) 903) did clearly state the goal of a drastic reduction of the number of fatalities and serious injuries in traffic in line with the visions of reaching zero.

Traffic safety has taken major steps during the last four decades and the risk of being killed or seriously injured as an occupant in a passenger car has been cut down to one third from the early 1970s, (Beckmann, 2009). This has been done basically through separate efforts by each stakeholder in the safety community operating independently (focusing users, roads and vehicles).

Improving road traffic safety towards the target of zero deaths and serious injuries will pose many challenges and obstacles to governments, road authorities and car manufacturers globally. Modern active and integrated safety systems carry a hope of substantially contribute to better safety. However no individual part in society can achieve the demanding goals on its own. Systematic co-operation will be essential to progress. These co-operations need initially to establish shared views on strategies forward, agreements on division of responsibilities, and a shared view on the interfaces between the cars and the infrastructure. A joint view on the demands put on the drivers is also essential. Stringent targets can only be met in an efficient way by a holistic view on road design, vehicle design and user capabilities.

In 2008 the Swedish Transport Administration and Volvo Car Corporation signed an agreement on co-operation. This co-operation rests on the two separate visions of the parties involved, i.e. Vision Zero, for the Swedish government and Vision 2020 for Volvo Cars. An important part of the co-operations is the establishment of quality and demands on the interfaces between the vehicle and the road for instance , road design, road lane markings, road friction measuring, division of responsibility, speed limits etc.

### **WHAT ARE THE CHALLENGES FACING US?**

Mobility is a cornerstone for modern society. In the industrialized parts of the world transportation play a key role in mobility. In developing countries an expansion of the road transport system is foreseen. More cars have in the early days of motorization been linked to higher risks. In the industrialized world that pattern was broken around 1970. Since then a safer road traffic has been achieved even though the amount of traffic has increased.

The challenge is to live up to the modern demand that mobility should be safe and not pose risks to life and health. This has also to apply when using a global perspective. In the future the road transport system must cope with more mobility, more mixed traffic situations, higher demands on safety and demands on lower environmental impact.

It is often stated that the vehicle design changes that would be necessary in order to reduce the environmental footprint of motor vehicles are in conflict with improved road safety. Given the advances in new modern technologies the challenges linked to reduced vehicle size and weight are likely to be overcome. The required performance needed in order to meet the visions of zero fatalities and serious injuries is thus possible to be achieved within the next 10-20 years.

The road transport system is open and complex. No single body has control over it. It is also characterized by its size. Any activity aiming at change of the system must be cost effective and robust.

## **THE NEED FOR CO-OPERATION BETWEEN THE STAKEHOLDERS RESPONSIBLE FOR TRAFFIC SAFETY.**

Ever since the introduction of motor driven vehicles in the early 1900s, manufacturers, responsible for designing and producing the cars and authorities, responsible for designing the infrastructure, have been, to a large degree, working independently. The generic approach has been to redesign cars and roads when needed in response to encountered problems and conflicts.

The road users play an important role to contribute to a safer road transport system. However the demands put on the users in the past have been excessive. Training and information campaigns have been used to make the driver to become 'safe'. The responsibility put on the driver have been formulated as if the drivers never made errors or mistakes. The Swedish Vision Zero approach is stating that road users make mistakes and misjudgements. The human nature cannot be considered to be completely reliable. Humans are sometimes irrational and have spells of distraction and lowered driving task focus. The driving capability of humans also varies considerably in time given different circumstances. A safe system must therefore adapt to the capabilities of the users.

Motor vehicle driver education, traffic education in schools and campaigns are and will continue to be important. Although improved safety training and traffic education can help to reduce the road casualties the potential is limited and the big push towards zero must come from safe vehicles and safer infrastructure.

Society wants the road transport system to be open to the majority of the citizens. It is clear that no significant change in the access to the traffic system, compared to the present situation, will be generally acceptable.

As an effect of modern cars with better road handling and improved crash performance, in combination with gradually improved infrastructure, the numbers of injuries and fatalities have decreased over the last decade.

The societal needs point at one direction, only zero fatalities and zero severely injured in road traffic may be accepted. This is basically already the status of the railway traffic and aviation where any deviation from the present status cannot and will not be accepted by the society. The approach from railroad and aviation safety must therefore also be the aim for all efforts for road traffic. With a beginning in Sweden back in 1997, many countries

have today formally adopted a vision aiming at zero fatalities and injuries.

Stakeholders involved realize that new strategies and new technologies need to be developed to achieve stringent targets. Consequently, both new ambitious strategies and advanced technologies are being developed that have the potential of assisting significantly towards the zero target.

The Swedish Vision Zero has led to changes in the philosophy of road design. The approach is not aiming at zero crashes, it is instead aiming at lowering the number of severe injuries and fatalities. The same approach has led many countries to adopt strategies for replacing in-plane crossings with roundabouts thus reducing the risk for severe injuries in side and rear impacts. Speed limits matching travel speed with crash capabilities of modern cars and speed management has also been used extensively to reduce fatality risks in traffic. This change is in need of good estimates of the future development of cars.

The emergence and market introduction of so called active safety systems for motor vehicles have clearly shown a substantial potential to reduce the number of injuries and fatalities. These systems are, however, in some cases depending on the road infrastructure to perform their tasks well and in a quality assured manner. Features such as lane markings, traffic signs, information displays, etc. have to be designed and constructed in a logical, obvious, detectable and consistent manner. This is essential for technical systems to be able to read and understand the features and information. The road to vehicle interface must also have a predictable and acceptable life-span or follow a maintenance level adapted to the needs and design pre-requisites of the vehicle systems.

If advanced systems are not matched with reliable and available infrastructure features the confidence of users will quickly be eroded and this trust will be difficult re-establish.

In the light of the rapid development and increased market penetration of the advanced systems using the infrastructure features, the pace of efforts to adapt and align both the systems and infrastructure features to each other need to be increased and intensified.

When looking at traffic in a holistic perspective, it is clear that a common view of the division of responsibilities in reaching zero would benefit all involved stakeholders and the society. Such a division could be to assign responsibility to the vehicle for protecting the occupants in a frontal collision up to certain impact speed and then having

the infrastructure responsible for preventing higher impact speeds. Another case can be for side impacts, the vehicle responsible for protecting the occupants up a certain impact speed and the infrastructure preventing side impacts at higher speeds.

A clear and agreed division of responsibilities has the potential of introducing safety measures in the most efficient way and reduce levels of redundancy when applying a holistic approach. For example, a more narrow focus on crash energy when designing a motor vehicle could result in reduced vehicle weight, a more optimized safety system design and more compact vehicles. This in turn could lead to lower CO2 and regulated emissions, lowered vehicle purchase, operational and maintenance costs, lowered societal costs, improved comfort and reduced risk of congestions.

The way ahead for reaching zero fatalities and injuries will be to accept the error and mistake levels of road users and concentrate on the improved performance of other parts of the system. This does not exclude the drivers from responsibility to follow rules and regulations. Operational errors, misjudgements and mistakes, however, should be managed by the system in a way to eliminate harm to life and health.

## THE DRIVING PROCESS

Using a common model is one way for stakeholders to better understand and focus the work with safety. A model often used is the model showing phases leading up to a potential crash.

When looking all the sequences leading up to an impact, these can be divided into the preventative, dynamic, avoidance and mitigation phases. After impact there is the post-crash phase where the aspect of quickly locating and in an efficient manner treat accident victims to avoid fatalities, life-threatening conditions and long-lasting disabilities. See figure 1.

The preventative phase is characterized as a non-conflict phase, whereas the dynamic, avoidance and mitigation phases are conflict phases. The preventative phase is what is considered to be the phase where normal driving occurs, i.e. the vast majority of the time on the road.

The mission of the motor vehicle and the infrastructure must always be to assist the driver to stay within the zone of normal driving, that is in the non-conflict part of driving sequences. Vehicle design, road design and speeds should be optimised to ensure comfortable and safe drive under normal driving conditions. If the car and driver has strayed away from this safe zone and towards a conflict

phase the task of the vehicle and the infrastructure is to 'push' the car and its occupants back into the 'normal driving' phase.. This can be done in different ways, e.g. stabilizing the cars, steering away from a threatening object, braking the car thus avoiding an impact, etc.

If the car has passed into a conflict phase and there is no possibility to return it back to the 'normal driving phase' the joint efforts of the vehicle and infrastructure must be to lessen the consequences of an impact by mitigation efforts, for instance, reducing the impact severity, removing hard and stiff objects in the zone of impact, designing forgiving road sides that guides the car to reduce the crash energy in a controlled manner.

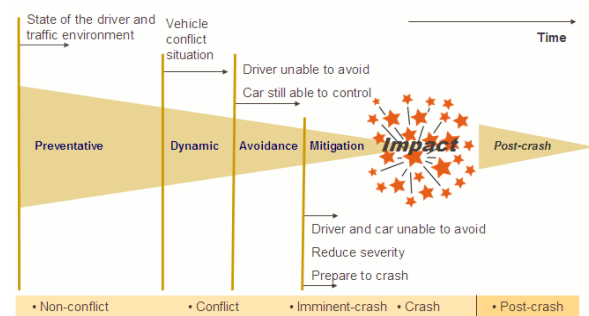


Figure 1. Phases leading up to an impact.



## **THE AGREEMENT ON CO-OPERATION**

The Swedish government and Volvo Car Corporation both have visions with the ultimate goal to eliminate fatalities and severe injuries in the road transport system. As the authority with responsibility for road safety the Swedish Transport Administration (STA) has a good dialogue with many industry partners. Volvo Cars and the STA have signed an agreement to better understand how a modern cars and modern roads best co-operate.

The agreement between the Swedish Transport Administration and Volvo Car Corporation was signed in September 2008 by the STA Administrator Mr. Ingemar Skogö and the Volvo Car Corporation CEO, Mr. Fredrik Arp, at a ceremony linked to the annual road traffic safety conference in Tylösand, Sweden.

Because of the identified need for this co-operation both from the perspective of STA and from Volvo Cars and the expectations from the safety community and the Swedish government the will and determination of the involved parties to produce results were clearly demonstrated already in the beginning of the co-operation.

### **Principles of the agreement**

In the framework of the agreement, a number of areas were identified and in need of being investigated.

One of the main tasks is to establish boundary conditions and interfaces for modern vehicles and modern infrastructure. Other tasks to share are vehicles and legislation and vehicles and other road safety stakeholders. The collected knowledge will enable a common view on the potential division of responsibilities between the traffic safety stakeholders. An agreed division of responsibility will open up the possibilities for more harmonised and optimized vehicle and infrastructures designs. Included in the discussions on establishing boundaries between vehicles and infrastructure are also the aspects of setting the basic requirements and identifying the expectations on the driver's area of responsibility, expected driver performance, and driver limitations. The research findings on the expected levels and span of driver performance will be an important aspect in identifying the levels of responsibilities of the other traffic safety stakeholders.

In designing the infrastructure there are a number of features that play an important role in the interaction with vehicles. Among those are; protective railings, lane markings, street signs and the generic design of streets and adjacent areas.

Field data is to be continuously monitored and shared between the participants.

It is clearly stated that the aim of the co-operation is to strive towards that all driving is done within the safety boundaries of the system. The definition of violations in contrast to misjudgements, mistakes and minor errors is important in the work towards defining the responsibilities of the stakeholders.

## **STRUCTURE OF THE GOVERNING BODY AND WORKING GROUPS**

The co-operation between the Swedish Transport Administration and Volvo Cars has been shaped in a very open and constructive manner. The governing body for the co-operation is a steering group that consists of key traffic safety experts and responsible from both parties involved, in all around ten people. These represent the different areas involved in shaping the strategies for enhancing road traffic safety and also have the authority to make the necessary decision needed in order to move forward towards the common visions of zero injuries and fatalities.

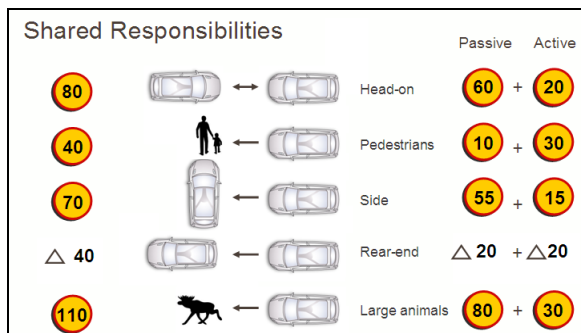
The steering group is setting up and controlling working groups.

### **The working group on boundary conditions**

As discussed earlier, setting the boundary conditions for the division between the responsibility of the infrastructure and the vehicle for different crash types and injury creating mechanisms can potentially mean enhanced and optimized overall traffic safety and fewer redundancies in the design of both vehicles and infrastructures.

In the start-up the working group set out its task by carefully analyzing available data for potential conflict situations. In order to get a more complete and holistic picture of the conflict situations representatives from both heavy vehicle manufacturers and the urban infrastructure were invited to complement the members from Volvo Cars and the road authority. The heavy vehicle side was represented by the staff working with traffic safety and accident analysis at Volvo Truck Corporation and the urban infrastructure side was represented by the local road traffic section at the City of Gothenburg.

The resulting product, once this working group is ready to deliver its analysis and recommendations is expected to be in the form illustrated in figure3.



**Figure 2. Examples on how the responsibilities can be divided between infrastructure and vehicles.**



**Figure 3. Road with a wire rope median guard rail to avoid head-on collisions.**

The basic concept of this approach is that the speeds illustrated in figure 2 representing a safe speed limit. This illustrates a division of responsibilities between the vehicles and the infrastructure. For the case of head-on collisions this means that below the speed that will be eventually agreed upon, in this example set to 80 km/h, the car will be responsible and the infrastructure design will be responsible for safety above this speed. Any road where it is normally possible to drive above 80 km/h will need to be equipped with measures to avoid frontal-collisions. In the case in the figure 3 this is done by using a wire rope median divider making head-on collisions virtually impossible.

For the vehicle the safety of the occupants can be delivered in different ways. One way is to reduce the speed by before impact. By reducing speed the crash protection will be sufficient. The car can also steer away from the potential conflict.

For conflicts between pedestrians and vehicles the proposed boundary conditions in the working group is set at a speed of 40 km/h, i.e. above this speed the pedestrians need to be separated from the traffic. Up to 40 km/h the car can manage the impact with the pedestrian either by passive protection using

soft and energy absorbing structure or devices creating no serious injuries to the pedestrians at this speed or by first reducing the impact severity and then creating no harm at the remaining speed. In the example in Figure 2 the speed change for reducing energy by braking before hitting the pedestrian is set at 10 km/h and the remaining speed thus becoming 30 km/h.

The work in this working group is continuing with the goal of reaching an agreed set of boundary conditions that is to be used as a base standard for future road and street designs in Sweden and for the design of the future Volvo vehicles.

### Working group for interfaces cars/ infrastructure

Traditionally, lane markings, rumble strips, road signs (such as speed limit signs, directional signs, restriction signs and information signs) all have been designed in ways suitable for driver recognition and what is practicable when applying them to the infrastructure. Very limited considerations have been given to the interfaces with the vehicle system since they have not appeared until the five to ten years. There are already vehicle systems that are depending on certain features in the infrastructure to perform their task. In the future there be even more vehicle systems needing support from road features. Examples of such systems are Lane Departure Warnings systems (LDW), driver drowsiness systems, lane keeping aid systems and speed limit sign recognition systems. The usability of these systems is depending on a number of factors linked to the design of the infrastructure features. For instance, for systems depending on lane markings for their performance the contrast to the road surface, the spacing between the dashed lines, the link up between lanes and exits are essential and could decide if a lane departure system will be an efficient driver support aid or will be practically unavailable for the majority of the road usage.

The outcome of the discussions in this working group so far has been a set of recommendations on the contrast, shape and spacing of the road lane markings. Once implemented, this will potentially have an effect on the availability and performance of a number of systems that are depending on the lane markings.

Discussions are also ongoing on the shape and placement of road signs. One strategic decision taken in Sweden is that speed limits will always be posted by a circular shaped speed limit sign. Some countries have adopted principles for advertising speed limits in towns and cities by posting special signs for urban areas when entering a town, which

does imply a speed limit of 50 km/h. This strategy will be problematic for road sign recognition systems looking specifically for signs with a rounded shape which is the shape commonly used for indicating restrictions in many parts of the world. A recommendation from the group is that any change in the set speed limit should always be indicated by a speed limit sign.

### **Working group on violations**

A basic philosophy both in the Vision Zero as adopted by the Swedish Transport Administration and the Volvo Vision 2020, is that the road traffic system should be tolerant to errors caused by what can be referred to as normal human behaviour. This means that those who are playing by the rules and doing their best to use the system should be offered a safe journey.

Obviously, there are, however, some road users that are deliberately breaking the rules and regulations of the system. It is essential that a clear definition is made to distinguish between these violations of the system and the 'normal' or 'ordinary' errors, mistakes and misjudgements.

Involved in the task of setting the targets for zero deaths and serious injuries is the discussion on if zero is truly in all respects zero regardless of if the road users have stepped over a clear boundary into the area of severe violation. Although it has not been ultimately decided, setting the target also to zero for the case of serious violations does appear to be neither logical nor realistic. A violation is characterized in that it is:

- Deliberate and is following a strategic decision
- Breaking the legal rules of the system

Errors, mistakes and misjudgements are:

- Random and not planned
- Independent of the legal rules

One issue that will pose an interesting and onerous task in deciding on the violation issue is how to categorize non-belt usage. Obviously, seat belt usage laws for front seat passengers exist in most countries and it is considered to be the 'normal' driver behaviour to buckle up. All governments and safety organizations around the world strongly recommend using the seat belts. Still we know that, in many countries, the belt usage rate for drivers is 80 percent or even lower. We also know that the properties for protecting the occupants improve significantly for belted occupants. It cannot be considered optimal for any society to adopt rules requiring protection for un-belted occupants to the same level as for belted occupants. However, is non-belt usage to be considered as a violation to the

same degree as excessive speeding? Logically, a somewhat lower safety level need to be considered but non-belt usage must still be part of the analysis and performance setting when designing for protecting the occupants.

However, disconnecting a seat belt reminder system should be considered a violation.

### **NEXT STEPS IN THE CO-OPERATION.**

The work in the three working groups will continue towards a common view of the issues discussed and the responsibilities. The working group discussing interfaces, i.e. lane markings, street signs, etc., is closest in its tasks of finalizing a recommendation. The working group dealing with violations is gaining momentum and will be monitored closely by the parties in the agreement. The discussions in this group are challenging and can have implications on a number of areas, e.g. restraint designs, road speed designs, etc.

The co-operation, as it exists today, mainly includes the national government agency, Swedish Transport Administration and one representative from the passenger vehicle manufacturer side. In one group Volvo Trucks and the City of Gothenburg, are represented. Desired would be to expand the entire co-operation to include more parties when relevant.

An expansion to other parties outside of Sweden would also be desired. An international perspective will give an added merit to any recommendations from the working groups. Better co-operation between vehicle manufacturers and road authorities is recommended by the European Council in their communication on road safety.

## DISCUSSION

In this paper the societal demands of lowered emissions, improved fuel economy, reduced congestion, improved comfort *and* zero severe injuries and fatalities have been stated as inevitable and necessary. The obvious question is: will the transportation sector be able to meet the demands of the society and will this be met in an acceptable time frame.

When analyzing the traffic safety it becomes clear that the low-hanging fruits of actions already have in many countries been managed and what now remains to reach the goals are much more onerous tasks requiring advanced engineering, new approaches and new ways of thinking.

Efforts are needed aiming at cutting away unnecessary redundancies and adapting all elements into one common model where the borderlines for the responsibilities of all stakeholders are easily identified and decided in the, for the society, most optimal way. This is the basic view point of and the reasoning behind the co-operation between Swedish Transport Administration and Volvo Car Corporation.

The approach of dividing the responsibilities is shaped around the belief that once divided, the stakeholders will base and adapt the development according to the agreements. There is an apparent risk, however, that the adaptation to the area of responsibilities for the car and the infrastructure will not go hand in hand and thus, there exists a risk that there will be a misalignment in the design approach over time between the two stakeholders.

Even if the standards for design of roads to avoid frontal crashes are adopted and in effect, the risk is that the actual building of the measures necessary will be delayed and take time. It can then be argued that the reduction of road casualties would be more rapid if there would be an overlap in the responsibilities between infrastructure and the vehicles. Vehicle design, road design and timing should be aligned.

There are also voices raised claiming that road users will adapt to a more protective road environment and will be less careful and observant and depend too much on the technologies. Substantial research and many strategic decisions are therefore needed in order to give proper consideration to these aspects and the steep learning curves in the paths towards zero need to be climbed in small steps, each step carefully evaluated and adjustments should be made according to lessons learned.

## CONCLUSIONS AND RECOMMENDATIONS

The challenges of finding a widely accepted strategy for road traffic with zero serious injuries and fatalities at the same time as meeting the demands on increased mobility, improved comfort, reduced emissions and improved fuel economy will necessitate more close co-operations between the different road safety stakeholders.

One of the goals for this kind of co-operation will be to will be to define interfaces and division of responsibilities between vehicles and the infrastructure.

In order to facilitate this in Sweden the Swedish Transport Administration and Volvo Car Corporation in 2008 signed an agreement on such a co-operation. The work is governed by a steering group which has three working groups dealing with the different aspects as defined in the agreement. Although progress has been made more efforts are needed in order to reach the desired results.

Expansion of the work to both heavy vehicles and also more international co-operation would contribute towards a more wide spread and holistic perspective.

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## TWO METRICS OF NIGHT VISION SYSTEM PERFORMANCE

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### **ABSTRACT**

We have developed a pair of metrics for the quantitative evaluation of the performance of pedestrian detection systems. The Metric of Similarity was designed to be used to assess how well the pedestrian-detection output of an infra-red Night Vision system matches its ground truth, that is, the relative level of fit or agreement between the locations in an image frame (measured in pixels) where the system indicates it has detected pedestrians and the locations in the frame where there actually are pedestrians. In contrast, the Metric of Saliency was designed to be used to infer the level of acceptance of the system by a typical driver. These are complementary dimensions of system performance.

### **INTRODUCTION**

The design of active safety systems is an iterative, evolutionary process. Designers continually strive to improve sensor technology, alerting software, and display design, leading to the production of new generations of commercially available systems. In response, system users (drivers, customers) become more sophisticated and demanding, providing feedback to designers and establishing a self-reinforcing cycle of system improvement.

Successive generations of systems need to be compared to ascertain not only their strengths and weaknesses but also their relative levels of driver acceptance (Källhammer, Smith, Karlsson, & Hollnagel, 2007). Designers seek to compare systems developed by different providers. The process of comparing the strengths, weaknesses, and relative levels of driver acceptance of active safety systems requires objective, replicable, and readily comprehensible metrics. This paper discusses the development of two complementary metrics designed to enable both designers and safety raters assess

successive generations or alternative active safety systems.

The occasion that prompted the development of the metrics was an EU-sponsored project aimed at demonstrating the feasibility of fusing two infra-red 'Night Vision' pedestrian detection systems that use different sensor systems (European Union 7th Framework Programme, 2011). In the discussion that follows, we focus on pedestrian detection systems but mean to imply that our discussion generalizes to a wide range of active safety systems. Further, we use the verb 'detect' to mean not only that the sensor has picked up a pedestrian but also that the software and in-vehicle display have highlighted the detected pedestrian to the driver.

### **The role of metrics in system comparison**

Figure 1 is a Venn diagram of a situation frequently faced by designers seeking to assess the relative merits of two pedestrian detection systems. System X and system Y are represented by the two large overlapping squares. The letters and symbols represent 10 pedestrian encounters. There are nine instances of pedestrian detection, seven by each system. Five pedestrians are detected by both systems but one is detected by neither. Both systems appear serviceable but in need of improvement. If designers were presented with systems X and Y, they would face the quandary of weighing the relative merits of two imperfect systems. Given the non-hypothetical nature of this quandary, designers need metrics that enable them to identify classes of events (pedestrian encounters) or incidents for which one system or the other excels. The system that performs better in more situations is likely to be preferred.

If systems X and Y were to represent successive generations of a commercial product, its designers would likely need metrics that enable them to scan large volumes of field data to identify when, where their system failed to detect a pedestrian who should have been detected, and the relative severity of that

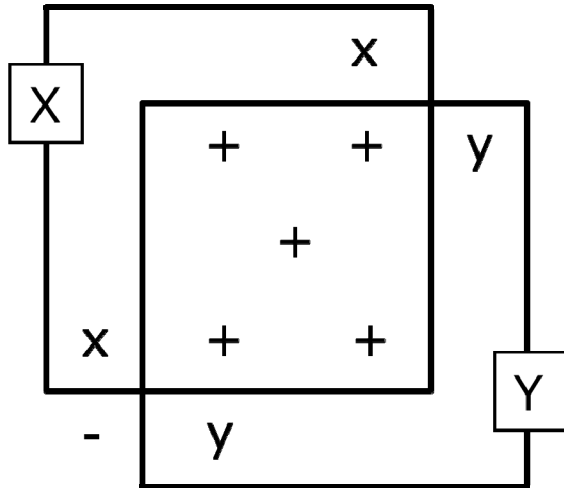


Figure 1. Venn diagram of two capable systems, system X and system Y. While both systems correctly detect most pedestrians, each misses some that the other detects. x: correct detections by system X only. y: correct detections by system Y only. +: correct detections by both systems. -: a pedestrian missed by both systems.

failure. A simple error count is not sufficient, as the severity of each error is not uniform; a system with fewer errors may have more severe failures. Further, system designers need to know whether or not drivers consider a detected pedestrian to be worthy of an alert. It does no one any good to market a system that issue alerts that drivers deem to be nuisances (Källhammer, in press).

The only time when metrics are not needed is the rare case sketched in Figure 2 in which the performance of one system dominates the other.

### Data

The metrics were developed given firm constraints imposed by the nature of the data. For system X, a Far Infra-Red (FIR) pedestrian detection system, we were provided three sets of data, sequences of FIR images containing pedestrians and two sets of numerical data. The first set of numerical data was a list of the frame-by-frame coordinates of rectangles surrounding the actual locations of pedestrians in the images measured in pixels with respect to the upper left corner of the image. This data set we call the 'Ground truth', set G. The second set of numerical data was a list of the 'System output', set S, the coordinates of rectangles used by the system to highlight detected pedestrians to the driver. All entries to both numerical data sets consisted of (x,y) pairs of coordinates that contained no direct information about the distance to a pedestrian.

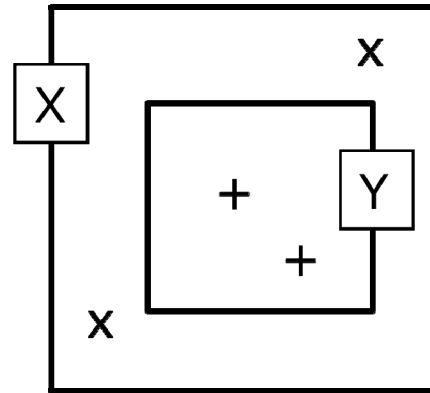


Figure 2. Venn diagram of two systems, X and Y, in which system X dominates system Y. x: corrected detections by system X only. +: correct detections by both systems.

The data constrained our task to devising quantitative metrics that define the fit of set S to set G. The degree of fit between sets affords identification of pedestrians that the system detected and those that it missed. It also affords discrimination of the similarity of the pedestrians' actual locations in the images and the locations highlighted by the system.

We were also provided a second set of system output data from a prototype system Y. These data were acquired at the same time as set G. This afforded comparison of the performance of systems X and Y.

### METHOD

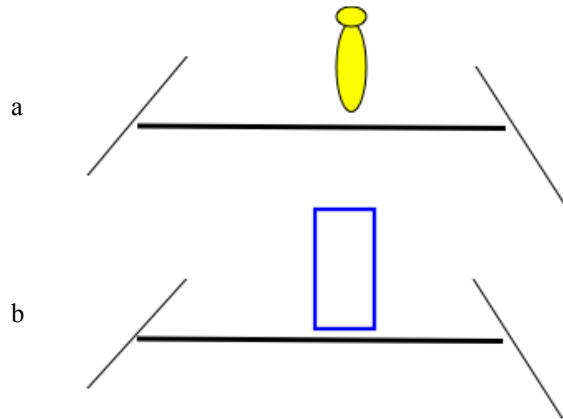
In this section we discuss our approach to developing the Metrics of Similarity and Saliency. We begin by discussing a series of thought experiments, and a lab experiment, and their implications for the formulation of the metrics. We introduce the mathematical foundations of the metrics before turning to their formulations.

### Thought experiments

The first step was to conduct thought experiments about the constraints on system performance imposed by drivers and system designers. We considered one constraint imposed by engineering concerns - the differential impact of misses and false alarms - and two constraints imposed by driver concerns - pedestrian location and proximity.

**Miss detections and false alarms** The first thought experiment addressed whether the two types of error that might be observed in the data - missed detections and false alarms - are equally important to system designers (and drivers). Figure 3 sketches our

thinking. In the upper panel, Figure 3a, a pedestrian is visible (set G) but is not highlighted by the system - there is no detection box from set S. This is a missed detection and is an error that, in certain circumstance, drivers and system designers would surely want to avoid.



**Figure 3. (A) An unhighlighted pedestrian (a miss) is worse than (B) a false alarm.**

In contrast, Figure 3b shows a scene where there is no pedestrian but there is a detection box. This situation is a false alarm; the system issued an indefensible alert. Our analysis suggested that engineers will continue to refine their algorithms to suppress it (Smith, 2010).

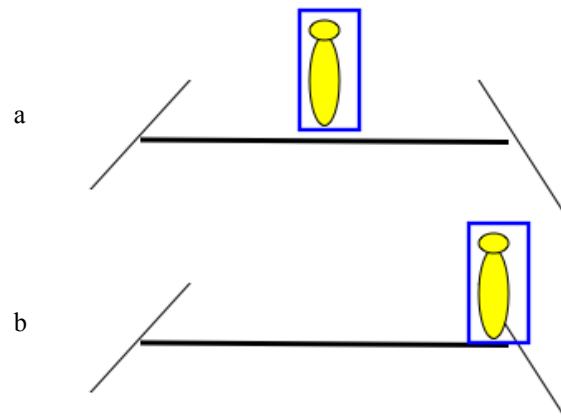
Accordingly, this thought experiment led us to conclude that missed detections matter more than false alarms when it comes to pedestrian detection and to develop metrics that reflect this asymmetry.

**Directly ahead is highly salient** The second question we addressed was whether the location of the pedestrian matters to drivers (and system designers). This question has two parts. Does translation in the vertical dimension matter? Does lateral position matter? Our answers were No to the vertical dimension and Yes to lateral position.

We answered the first by finding descriptive statistics for the vertical locations of pedestrians in data set G. We found that the variance of the location of pedestrians' feet in the vertical direction was small. This means that pedestrians in our data set do not translate vertically in the images. Generally, they do not start at the top of the frame and migrate to the bottom. They usually stand or walk somewhere below the middle of the frame. We concluded that our metrics did not have to consider the vertical component of pedestrian location.

Figure 4 sketches our thinking about the lateral component of pedestrian location. In Figure 4a, a

pedestrian is detected near the center of the image. In practice this means the pedestrian is more or less directly in front of the car. If the pedestrian stood still and the car continued straight, there would be a collision. This is a situation for which an alert would certainly be welcomed by drivers, system designers, and safety raters. In contrast, Figure 4b shows a pedestrian near the edge of the image. In an urban environment such a pedestrian might be walking on the sidewalk. Drivers seldom want to be alerted to pedestrians on the sidewalk. In contrast, in a rural environment, the pedestrian would likely be walking on the edge of the road, facing traffic. Drivers would likely welcome an alert to this pedestrian. This thought experiment led us to conclude that the salience of lateral location is contextually sensitive. Accordingly, we assign a greater weight to pedestrians in the center of the image than to those near the edges and retain the ability to adjust the weighting formula as a function of traffic context.

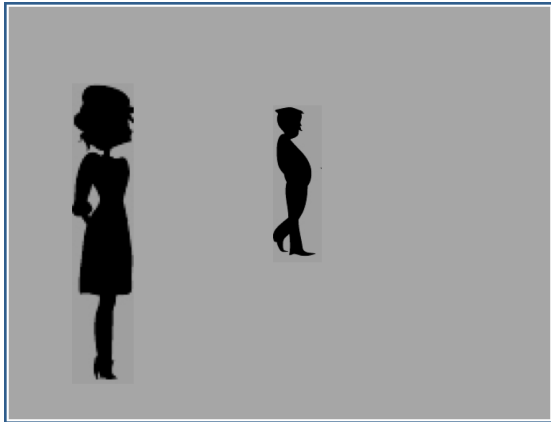


**Figure 4. (A) A pedestrian in the center of the image is more salient than (B) a pedestrian on near the edge of the image.**

**Near is more salient than far** The final thought experiment that shaped the development of the metrics concerned the proximity of pedestrians. A pedestrian who is relatively close to the car is at a greater risk of being hit by the car than a pedestrian at a greater distance. This situation is illustrated in Figure 5.

As the raw data are two dimensional projections of three dimensional space and the objects within it (e.g., pedestrians), there is no direct information about distance to pedestrians in the images. There are however two alternative approaches to inferring distance. The better method is to define the horizon and to find how far below the horizon the pedestrian is standing. This method was unavailable to us as the data sets do not contain information about the location of the horizon. The fall-back method is to

use pedestrian height as a proxy for proximity. As the car approaches, a pedestrian's apparent height increases. Both sets G and S contain information about pedestrian height.

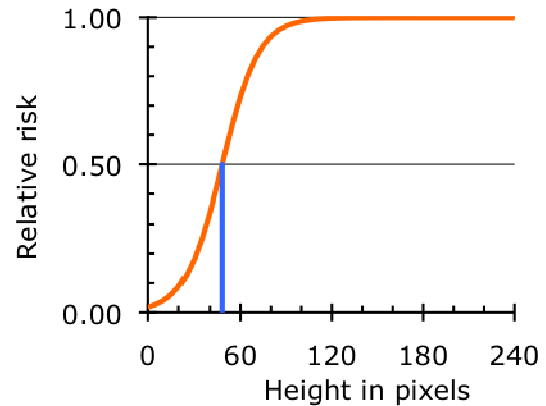


**Figure 5. Closer people pose a greater risk of collision. Closer people appear taller.**

A pedestrian in the far distance is only a few pixels high. Our analysis suggested that the salience of a distant pedestrian to the driver is minimal. In contrast, there comes a time (distance) when the pedestrian becomes salient to the driver. At this ill-defined threshold, represented by the blue line in Figure 6, the pedestrian becomes a meaningful object that may influence driving behavior. Pedestrians closer than this threshold are only marginally more meaningful than they were at the threshold. These considerations suggest that the subjective mapping from height to the relative level of perceived risk is not linear. Rather, it is more likely to have a sigmoid form where the steep ramp occurs in the vicinity of the threshold distance, as sketched in Figure 6. This thought experiment led us to develop a sigmoid weighting function of pedestrian height to capture the influence of pedestrian proximity on driving behavior.

### Laboratory experiment

The second step in the development of the metrics was to conduct a laboratory experiment that asked a representative sample of adult drivers to view a selected set of 15 second-long videos of pedestrian encounters recorded by the pedestrian detection system. Output (colored rectangles) from the pedestrian detection system, set S, was superposed on the videos. The participants viewed a sequence and then, individually, immediately rated the performance of the system. The procedure is discussed in detail by Källhammer & Smith (in press) and Smith and Källhammer (2010).



**Figure 6. A sigmoid function relating height - our proxy for proximity - to relative risk.**

Two findings emerged from this study. First, the participants reinforced our conclusions from the thought experiments. As expected, they were relatively unconcerned about false alarms but rated the system poorly whenever pedestrians went undetected. It appears that drivers do find missed detections more salient than false alarms. Further, the participants were less tolerant of missed detections when pedestrians stood in or crossed the road than when they stood or walked on the side of the road. We were unable to test for differential responses to proximity and distance because every pedestrian in the video clips initially appeared in the far distance and loomed large as the vehicle drove past.

Second, participants were sensitive to both the recency and duration of the missed detection. Recency and duration are two factors long known to influence the memorability of stimuli (e.g., Baddeley & Hitch, 1993; Greene, 1986; Pavlov, 1927; Pieters & Bijmolt, 1997; Seamon, March & Brody, 1984). Recency refers to the time gap between the experience and its recall. Duration refers to the amount of time consumed by an event. For our application, recency reflects the time between (a) the last frame in the video clip in which a pedestrian was not detected and (b) the act of rating system performance for that clip. Similarly, duration is the composite time that a pedestrian went undetected in the video clip. This finding led us to conclude that recency and duration influence drivers' perception of the salience of missed detections and, hence, the relative levels at which they rate system performance.

### Asymmetric distance between sets

When the system fails to detect a pedestrian, set G contains more elements than set S. Set S contains



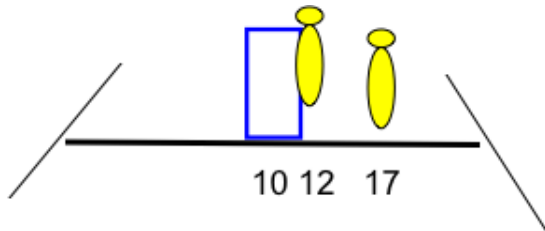
more elements when the system posts a false alarm. The expectation of inequality in set size led us to use a MaxiMin formula to compare sets.

We calculate the distance  $D$  from one set to the other using the MaxiMin expression of Equation 1:

$$D(A,B) = \max_{a \in A} \{ \min_{b \in B} [k \times d(a,b)] \} \quad (1).$$

where  $a$  and  $b$  are points in the sets  $A$  and  $B$ , respectively, and  $d(a, b)$  is the Euclidian distance between them. The free parameter  $k$  is a sigmoid weighting function that ranges from 0.0 to 1.0, like that shown in Figure 6, to map pedestrian height to the relative level of perceived risk.

When there are a different number of elements in sets  $A$  and  $B$ ,  $D(A,B)$  is generally not equal to  $D(B,A)$ . To appreciate this fundamental asymmetry, consider the situation sketched in Figure 7. Here there is one member of  $S$  at 10, and two of  $G$  at 12 and 17: the system finds one pedestrian but there are actually two in the image. Assuming for simplicity that  $k = 1$ , the distance  $D(G, S)$  is 7, the maximum of two values (12-10) and (17-10). In contrast, the distance  $D(S, G)$  is the maximum of the minimum of the couplet (10-12, 10-17), that is, the minimum of 2 and 7. [Euclidean distance is always positive as it is in the world.] The minimum of the couplet is 2 and the maximum of this minimum is also 2. Hence in this example the distance  $D(G, S)$  is 7 and the distance  $D(S, G)$  is 2.



**Figure 7. A hypothetical case with one system detection (set  $S$ ) and two pedestrians (set  $G$ ).**

The important point here is that the situation shown in Figure 7 represents a miss - there are fewer elements in the system output than in the ground truth. The asymmetry of the distance calculation allows us to differentiate the effects of misses and false alarms. The calculation  $D(G, S)$  is a measure of the effect of a miss. The calculation  $D(S, G)$  is the measure of the effect of a false alarm. Here there is a miss and, accordingly,  $D(G, S) > D(S, G)$ . This is a useful characteristic given that drivers and safety raters can be expected to show greater concern for misses than for false alarms (Smith, Schweiger, Ritter & Källhammer, 2011).

## The Metric of Similarity

The Metric of Similarity is the normalized sum of two weighted MaxiMin distances, Equation 2. We apply two sets of weights. The free parameter  $\alpha \in [0, 1]$  differentially weights misses and false alarms. For the pedestrian detection task, a miss receives the greater weight (e.g.,  $\alpha = 0.9$ ). The differential weighting emphasizes the asymmetry of the two components of the sum. The second weight  $k$  (shown in Equation 1) scales pedestrians by their height in the ground-truth image using a sigmoid function. Normalizing by the half-width of the image  $W/2$  constrains the metric to values between 0.0 and 1.0. Because distance is a measure of difference and our goal is a metric of similarity, the normalized sum is subtracted from 1 to produce a Metric of Similarity,  $M$ .

$$M = 1 - \frac{[\alpha \times D(G, S) + (1 - \alpha) \times D(S, G)]}{W/2} \quad (2).$$

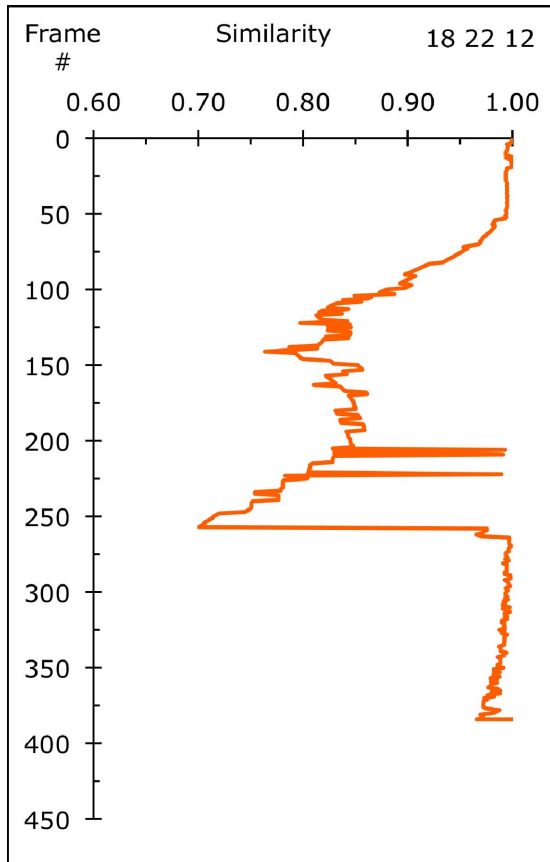
The metric equals 1.0 when the system highlights every pedestrian at the same position as the ground truth. It equals  $1 - \alpha$  in the worst case - the situation shown in Figure 3a in which an undetected pedestrian is standing directly in front of the vehicle at a distance where collision is immanent. To understand why the minimum value of the metric is  $1 - \alpha$ , assume that the image frame shown in Figure 3a is 20 pixels wide and that the undetected pedestrian is standing directly in front of the vehicle at pixel 10. Further, in this worst case, the value of  $k$  is 1.0 because the pedestrian is near the vehicle. The value of  $D(G, S)$  is  $\max \{ \min [10] \}$  and the value of  $D(S, G)$  is zero. Substituting into Equation 2 yields  $1 - [\alpha \times 10 + 0] / (20/2)$  which equals  $1 - \alpha$ .

The Metric of Similarity is calculated for each frame in a sequence and plotted as function of time. An example is shown in Figure 8. If desired, the values can be summed using moving window to provide an aggregate measure of system performance per unit time.

## The Metric of Saliency

The Metric of Saliency aims to predict the relative level of post-hoc saliency of a pedestrian event to the average driver. Saliency is expected to increase as the subjective experience of risk increases.

The formulation of the Metric of Saliency reflects the importance of recency and duration on the memorability of failures to detect pedestrians. Equation 1 is used frame-by-frame to find the pedestrian in each frame who is associated with the



**Figure 8. A time trace of the metric of similarity. Similarity, the goodness of fit of system output to the ground truth, increases to the right.**

greatest distance from a system detection rectangle. We identify that pedestrian as  $\text{Max}(D(G,S)_t)$  – the most salient pedestrian in the image at time  $t$ . We then find the duration of sequential frames in which a pedestrian qualifies as  $\text{Max}(D(G,S)_t)$  and multiple the duration by a sigmoid function of recency that preferentially emphasizes missed detections late in the sequence of frames. The product is a single number that predicts the relative level of salience of missed detections by the system during sequence of frames.

## RESULTS

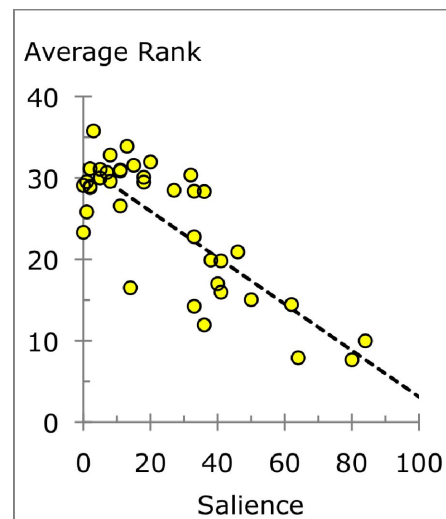
We have applied the Metric of Similarity to 57 digital recordings of the output of an FIR pedestrian detection system and the corresponding ground truth data set. The sequences contain both urban and rural driving.

Low values of the metrics pointed to two opportunities for improving system performance: reducing the lag in system response and training the system to highlight pedestrians who assume odd

poses. The metrics have led designers to focus on these issues as they develop the next generation of Night Vision systems with pedestrian detection.

We have also used the Metric of Similarity to scan a large data set that made it possible to compare the output from two Night Vision systems, an FIR system and a prototype system. Both systems performed well but, on occasion, failed to detect pedestrians. The metric simplified the task of identifying classes of encounters associated with missed detections. These classes were found to be essentially mutually exclusive. This result is ably represented in schematic form by Figure 1.

Figure 9 shows the match between the Metric of Salience and the average ranks of the ratings provided by participants in the laboratory study. We converted raw ratings data to ranks to correct for individual differences in scale use across participants. The lower the rank, the greater the satisfaction with the performance of the Night Vision system. Video clips that received low ranks contained undetected pedestrians that our raters expected the system to highlight. The high level of concordance among raters justifies aggregation of the ranks to calculate the average rank. The correlation between the metric salience and the average ranks of the reviewers' rating is high,  $r = .81$ . It appears that the metric predicts the relative level with which drivers are likely to be displeased when a system fails to issue an alert to an at-risk pedestrian.



**Figure 9. Cross-plot of the metric of salience and the average ranks of the ratings provided by reviewers of video clips containing pedestrian encounters.**

## DISCUSSION

The primary limitation of the methods is their reliance on the height of a pedestrian as the proxy for risk. This shortchanges children. Accordingly, we plan to revise the metrics by replacing pedestrian height with the distance estimate used by the systems in their detection task.

The two metrics quantify system performance along complementary dimensions. The Metric of Similarity provides a time-trace and composite score of system performance. The Metric of Saliency provides a snap-shot prediction of driver acceptance of system output. By applying the metrics, original equipment manufacturers and suppliers have been able to identify factors that contribute to user acceptance of Night Vision systems and their performance.

## ACKNOWLEDGEMENTS

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# ANALYSIS AND VALIDATION OF PERCEPTION SENSOR MODELS IN AN INTEGRATED VEHICLE AND ENVIRONMENT SIMULATION

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## 1 ABSTRACT

The number of Advanced Driver Assistance Systems (ADAS) in future vehicle generations will increase steadily in order to support drivers by means of comfort-, safety- and ecology-functions. Along with the ascent of ADAS functions, the challenge for developers to prove the safety and reliability of the overall system increases. The risk for people and test equipment involved in potentially dangerous real world test scenarios and the great efforts required to achieve reproducible results in real driving tests make an alternative test method necessary.

Therefore, Audi is working together with partners on the development of "Virtual Test Drive" (VTD) [VIR01], a modular, computer-based system for the integrated simulation of a virtual vehicle in a virtual environment. VTD supports engineers throughout the development, testing and validation process of ADAS. It contains reusable components, interfaces, models and tools which can be shared by different simulation variants (Software-, Hardware-, Model-, Driver- and Vehicle-in-the-loop) and applied at different stages of the development and testing process. The VTD simulation environment enables realistic closed-loop simulations to analyze the interaction between simulation components, such as sensor systems, actuators and a model of the vehicle environment as well as the assistance or safety functions under test.

This paper presents in particular a method for the analysis and validation of perceptive sensor models generating synthetic sensor data (e.g. Video Camera, RADAR, LIDAR, etc.) in VTD. The

simulated perception sensor data is compared to real sensor data in a number of selected scenarios.

The process of generating synthetic sensor data with VTD using perception sensor models starts with the recording of a real vehicle test drive in a real world test scenario. GPS trajectory coordinates as well as vehicle state data and perception sensor data are recorded during defined approach and collision scenarios between the ego-vehicle and target objects. In a second step, these data is imported into VTD and synthetic sensor data is generated by feeding the recorded trajectory and vehicle state data through VTD sensor models. In a final step the synthetic sensor data is converted to the same format as the recorded real sensor data. The aim of this conversion step is to evaluate and validate the synthetic data by using the same toolchain as it is done for the real sensor data.

The novelty of the method presented in this paper is its reusability for different sensor models, functions and test scenarios and moreover the high level of automation reachable.

## 2 INTRODUCTION

New generations of ADAS systems are designed towards supporting vehicle drivers in a situation dependent manner by means of safety-, comfort and ecology functions, e.g. Emergency Braking, Left Turning or Traffic Jam Assistant, see Figure 1. The driving force behind the proliferation of such ADAS systems is on the one hand, the increasing performance and integration level of Electronic Control Units (ECUs) and related sensor equipment, and on the other hand, the desire for more

safety and comfort in everyday traffic situations on customer side and a growing awareness of energy-efficient and environmentally friendly driving.

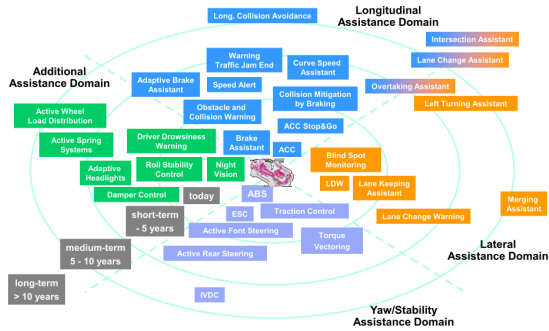


Figure 1. Roadmap for ADAS [EVA01].

The new generations of assistant systems are characterized by relying on the continuous perception of the vehicle environment through one or more ambient sensors (Video Camera, RADAR, LIDAR, etc.). These sensors acquire data about the vehicle’s surrounding field, e.g. the position of other traffic participants, obstacles, traffic signs, etc.. Dependent on the specific assistance function, the evaluated sensor data is used for notification and warning purposes or also for actively influencing the vehicle’s longitudinal and/or lateral driving dynamics, e.g. by executing an emergency braking, to mitigate or avoid a collision.

### 3 CHALLENGES

Closely connected to the increase of ADAS functions in vehicles is the growing challenge for developers to prove the reliability and safety of such advanced systems. The rising number of assistance functions integrated into a vehicle combined with the requirement of close function interconnection and the overall trend towards more vehicle variants per OEM results in significantly higher testing efforts for a vehicle’s electronics in order to validate the correct functioning, safety and reliability of ADAS under the broad scope of everyday driving conditions.

Due to the great effort related to time, personnel and material resources, which is necessary to obtain reproducible test results from real world test drives and the potential risk for people and test equipment involved, especially in case hazardous traffic situations have to be simulated, an alternate, less dangerous and automatable test methodology is required for ADAS systems. This paper presents a computer-based simulation and validation methodology to address the outlined challenges in the process of developing and testing ADAS.

It is crucial for the applicability of such computer-based simulation environments as a partial sub-

stitute for real test drives to ensure that the generated simulation data can be validated against real measurements.

The validation shall ensure a high degree of correspondence between recorded sensor data of real world test drives and synthetically generated sensor data from the sensor models used in the vehicle and environment simulation system. This leads to the following requirements concerning the simulation environment:

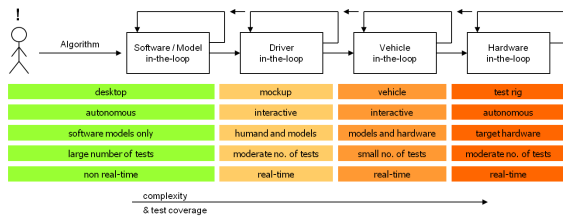
1. The usage of virtual test scenarios which reproduce the essential aspects of the real test drive with respect to experimental setup, object trajectories and environment modeling of the test ground (see section 5.2.2)
2. The usage of validated models for the perception sensors, which show a similar measurement signal and timing behavior to the real sensor device (see section 5.2.3)
3. Automation of the comparison of real and synthetically generated sensor data (validation), due to anticipated frequent adjustments to the real sensor during the development and testing process
4. Non-proprietary specifications and interfaces for test scenarios and sensor models

Within the process of testing ADAS a particular challenge lies in the safeguarding of predictive assistance and safety functions, which actively affect the vehicle dynamics, e.g. an automatic emergency braking system. Such systems must meet very high requirements in terms of reliability and robustness. To ensure the fulfillment of those safeguarding requirements, high test space coverage needs to be achieved. As real test drives on test sites and public roads usually only permit very limited influence on test conditions such as traffic congestion, weather conditions, exact behaviour of other traffic participants, etc., the computer-based vehicle and environment simulation acts as an important additional tool for achieving high test space coverage. A vehicle and environment simulation software like “Virtual Test Drive” (VTD) therefore allows the simulation and reproduction of critical test scenarios under a wide range of parameter variations.

The simulation and testing of ADAS that actively affect the vehicle’s driving dynamics, furthermore requires the usage of closed-loop simulations (see Figure 2). Only in this simulation mode the effect of the vehicle’s lateral and longitudinal dynamics, e.g. a damped pitch angle pulse during braking, has direct influence on the synthetically generated sensor data.

A further reason for the application of software like VTD is the intention to accelerate the ADAS testing process. It allows for example the investigation of different sensor concepts and algorithm parameterizations in a safe und reproducible manner even before the availability of actual hardware prototypes.

To address the challenges identified above, in the course of this paper we use VTD as an integrated vehicle and environment simulation system serving as a platform for perception sensor model validation tasks.



**Figure 2. ADAS development process supported by VTD [VIR01].**

## 4 OBJECTIVES

The work described in this paper pursues the following objectives based on the challenges outlined in section 3:

- Description and implementation of a methodology for the semi-automated generation of synthetic sensor data based on recorded vehicle and object reference trajectories of real world test drives
- Specification and implementation of a methodology for the semi-automated comparison of real and synthetically generated perception sensor data on object list level
- Execution of experiments for the analysis of a sensor model with respect to the correspondence of generated data in comparison with real sensor data
- Specification of a software interface to analyze both real and synthetically generated sensor data in a unified evaluation tool

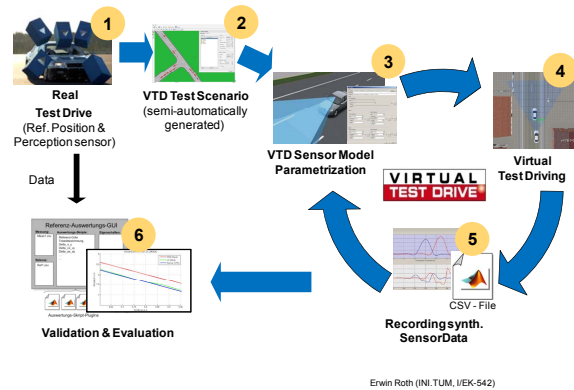
## 5 METHODOLOGY

### 5.1 Overview

This section gives a short overview about the crucial steps to analyze and validate sensor models according to the methodology proposed (see Figure 3) in this paper:

1. Carrying out real test drives on the basis of a previously defined test maneuver catalog, see section 5.2.2. Logging experimental parameters and recording perception sensor and position reference sensor data during the test drive, see section 5.2.1
2. Automated generation of the virtual test scenario data for the simulation toolchain based on the recorded position reference sensor data, see section 5.2.2
3. Parameterization of the VTD sensor models according to the parameters of the real test drive setup and sensor equipment properties, see section 5.2.3
4. Execution of virtual test drives in VTD on the basis of the virtual test scenario data generated beforehand, see section 5.2.4
5. Recording synthetically generated predictive sensor data while running a virtual test scenario in VTD, see section 5.2.5
6. Comparison of real and synthetically generated sensor data by means of MATLAB-based analysis functions, see section 5.2.6

Steps 3 to 5 shall be repeatable in a short time frame with the aim to achieve a high degree of correspondence between the real and simulated test drive for different sensors and sensor configurations.



**Figure 3. Methodology for sensor model validation.**

The execution of the described steps requires several hardware and software tools, that were integrated into an overall process and data workflow as shown in Figure 4. The numbers within the figure reflect the corresponding process steps illustrated in Figure 3.

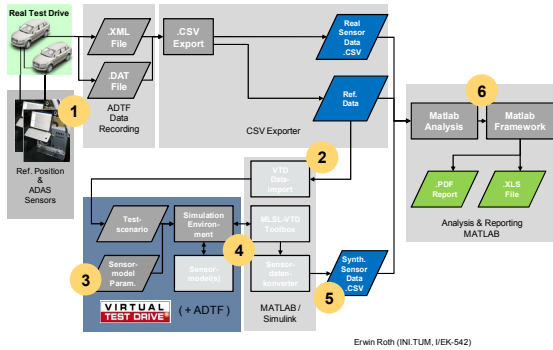


Figure 4. Toolchain integration for sensor model validation.

## 5.2 Procedure

### 5.2.1 Real Test Drive Data Recording

The recording of reference position and environmental sensor data during the actual test drive takes place by means of the so-called RefBox [TUM02]. The RefBox is installed in the ego-vehicle and if necessary also in other moving vehicles taking part in the test scenario. The RefBox system uses Differential GPS and acts as a reference for the ego-vehicle's or other moving objects' temporal change in position. Static reference objects, e.g. a pylon, which might also be involved in the test scenario are measured preliminary to the test drive by the ego-vehicle.

During the actual test drive the RefBox records reference position and perception sensor data (see Figure 5) at defined time intervals for the subsequent offline analysis. The time stamp of the RefBox is used as a global time base for the collected sensor data.

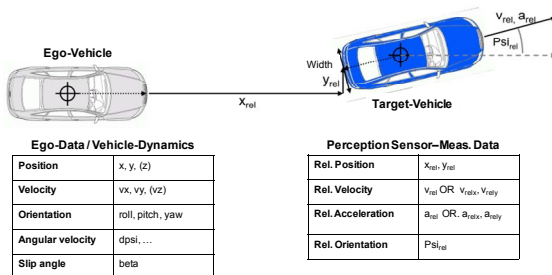


Figure 5. Parameters recorded by the RefBox-System [TUM01].

### 5.2.2 Automated Generation of virtual Test Scenario Data

In terms of a standardized approach for comparing synthetically generated VTD sensor data with real sensor data, an initial set of test scenarios for the import into VTD and the subsequent data comparison was defined.

A *test scenario* is described by the following characteristics in this context:

- Type of the test run
 

The type of test run describes the overall category of variations in different parameters (e.g. velocity or distance variations) of the conducted real test drive. For the subsequent analysis, the test run types "straight frontal collision with a centered static object" and "curved frontal collision with a centered static object" were used.
- Discrete absolute coordinates and orientation data concerning the ego-vehicle and target objects

The data recorded during the real test drive, as described in section 5.2.1, represents the temporal change in position of a defined vehicle body or a body-fixed reference coordinate system. It is unambiguously described by the absolute coordinates of the origin in the three spatial directions X, Y and Z of a global earth-fixed coordinate system and the three Euler angles (yaw, pitch and roll angle) of the local coordinate axes. All six variables are available for each object and each test run as discrete time series at a defined sampling rate.

- Dimensions of ego-vehicle and target objects
 

The dimensions of the ego-vehicle and the target objects are known a priori and denote the dimensions of a rectangular bounding box around the vehicle or object.
- Sensor position, viewing direction and field of view

In terms of the forward-looking sensors used, the individual test scenarios differ in the mounting location of the virtual sensor in relation to a vehicle-body-fixed reference coordinate system and its viewing direction relative to the coordinate system axes. Furthermore the sensor field of view is specified by the parameters minimum and maximum range as well as horizontal and vertical aperture angle.

Furthermore, the following supplementary Data is recorded with a *test scenario*:

- Type-specific data of the sensor
 

The recorded real data is always associated with a defined sensor revision, which identifies the sensor for the respective test or reference scenario unambiguously.
- Specific information concerning the ego-vehicle
 

Relevant parameters related to the real vehicle such as vehicle type, weight, used ECUs and the type of installed measuring equipment represent further information describing the test setup.
- Specific information concerning the target objects
 

The target or collision objects are specified by geometry and material data.
- Specific information concerning the environment
 

The boundary conditions of the real test run in terms of local time, temperature, weather and road conditions are additional parameters describing the test scenario.

The recorded trajectory and position data of the various test runs is converted in a subsequent offline process by a MATLAB framework into a data format readable by VTD. The framework provides a GUI to adapt the conversion process to some of the specific test run conditions outlined above.

During the import process the measured data is manipulated (coordinate transformations, sorting, resampling, ...) according to configurable parameter files and converted into a format readable by VTD. Based on this data format VTD is able to play back the test scenario within the measurement accuracy of the position reference sensors, exactly as it has been recorded on the real test ground (see section 5.2.1).

According to the current methodology the data import and playback take place waypoint-based using discrete position data which may be linearly interpolated. The data used for this study was measured on a flat test site, so that the subsequent analysis is limited to phenomena in the plane. The recorded reference data for the analyzed test scenarios only includes target objects, e.g. cuboids, which were positioned by test personnel. So far no natural obstacles, e.g. roadside vegetation or other interfering objects occurring in public road traffic are included. The subsequent testing and analysis steps are based on a single reference or collision object for the corresponding scenario. The

automatic import of weather condition parameters is not yet possible and the parameters for the virtual sensors have to be set by hand.

### 5.2.3 Parameterization of perception Sensors

The parameters for the virtual perception sensors in VTD in accordance with the real sensors used in the test scenarios are configured by means of a XML configuration file or via a graphical user interface (GUI), as shown in Figure 6.

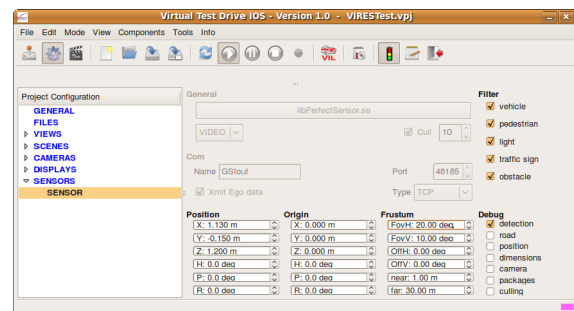


Figure 6. GUI for virtual sensor parameterization.

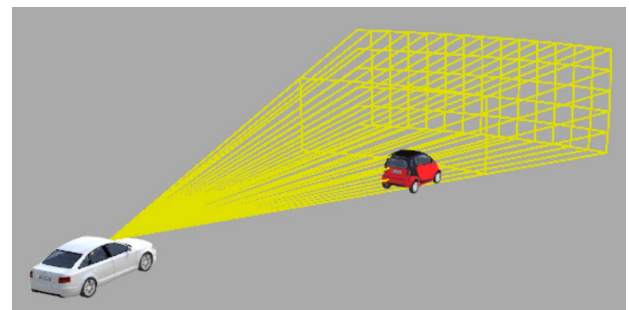


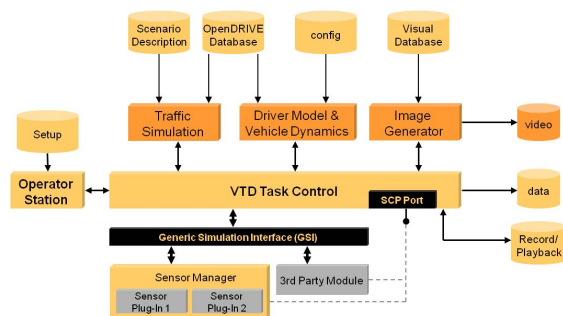
Figure 7. Target-Vehicle within sensor cone of Ego-Vehicle

The idealized sensor models included in the default distribution of VTD, which were used as a basis for the consequent analysis in this paper, use a frustum of pyramid as an approximation for the sensor field of view (see Figure 7) which is truncated on the basis of both minimum and maximum sensor range. Furthermore the aperture angle can be specified in horizontal and vertical direction. The sensor position and spatial orientation relative to the vehicle as well as the coordinate system in which the sensor indicates the measured position data can be parameterized according to the real conditions of the emulated sensors.



## 5.2.4 Execution of Virtual Test Drives

In order to replay the imported real test for the generation of synthetic sensor data the VTD software is used. VTD as an integrated vehicle and environment simulation tool chain provides a modular architecture (see Figure 8) for the simulation of vehicle dynamics, sensor systems, actuators and traffic scenarios with multiple vehicles and parameterizable environment conditions. The environment can be adjusted in terms of weather, light, road and traffic conditions and visualized accordingly.



**Figure 8. Modular "Virtual Test Drive" (VTD) architecture [VIR01].**

With its reusable models, components, interfaces and tools VTD supports a number of open and closed simulation variants (Software/Model-in-the-loop, Driver-in-the-loop, Vehicle-in-the-loop and Hardware-in-the-loop) [TUM01] as shown in Figure 2.

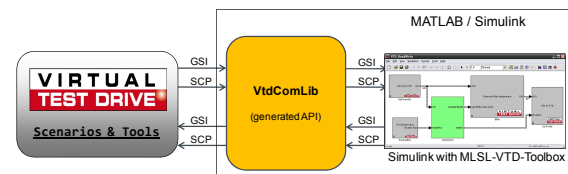
For the task of analyzing synthetically generated sensor data VTD provides the Generic-Simulation-Interface (GSI), a software API that allows the reading and writing of a large number of simulation variables. In the described use case the writing of data to the GSI is used to do the positioning of the objects (ego and target vehicles) in the same way within the virtual test scenario (static or dynamic) as in the real test scenario. The necessary position reference data over time is acquired as described in section 5.2.1.

The execution of simulation scenarios within VTD can be controlled via the Simulation-Control-Protocol (SCP), which allows the querying and setting of model and simulation parameters in order to influence the global simulation behavior, e.g. simulation start/stop, setting of event triggers, etc..

## 5.2.5 Recording of synthetic Sensor Data

For the analysis of the synthetically generated sensor data simulating signal characteristics as they occur in real test drives, the virtual sensor data is recorded by means of the MATLAB/Simulation-VTD-Toolbox (MLSL-VTD-TB) (see Figure 9) on the same sample time basis, as the real sensor data [TUM03].

At each simulation time step the recorded data of the real test drive is imported into MATLAB and the measured values are analyzed in terms of object position and object dynamics. Subsequently the calculated data is sent via GSI using a TCP/IP based network connection to VTD.



**Figure 9. MLSL-VTD-Toolbox: bi-directional communication between MATLAB/Simulink and VTD.**

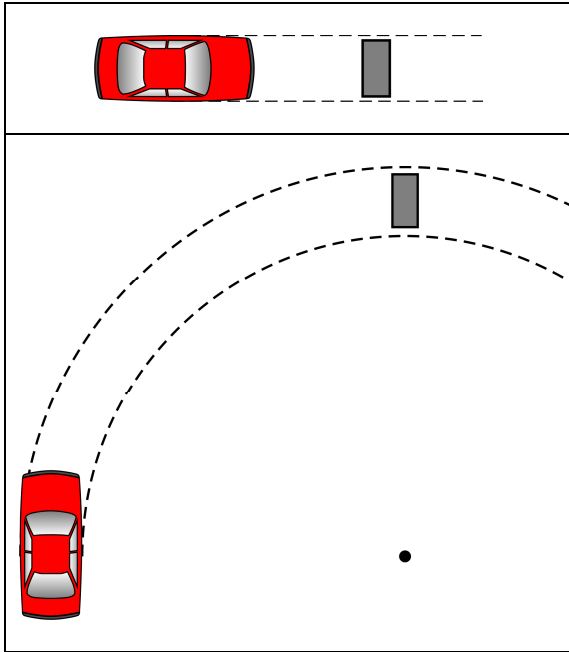
The measured objects are simulated and visualized in VTD on the basis of the values given above. Furthermore they are used to generate synthetic sensor data for the current sample time by means of the parameterized sensor models. In a subsequent step, the synthetic sensor data is sent back to the Simulink simulation model via the GSI interface. In Simulink the received sensor data is recorded synchronously to the time basis of the real test drive. The usage of the same global time basis for real and virtual test scenarios allows the direct comparison of real and synthetic sensor data.

## 5.2.6 Analysis and Validation of virtual and real Sensor Data

The sensor data analysis is accomplished by the use of MATLAB scripts. For this purpose both individually created scripts as well as scripts of an organization wide sensor data analysis toolbox (called "RefReport GUI") can be applied.

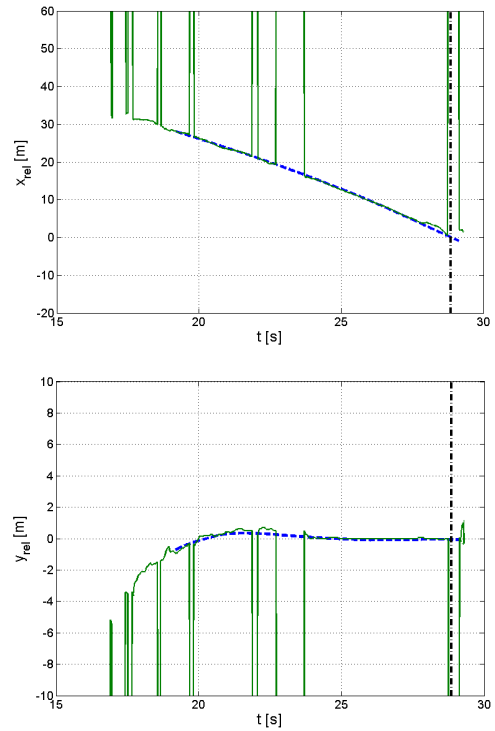
## 6 RESULTS

In the following the results of two exemplarily selected test scenarios imported in VTD are presented. The first scenario is a "straight frontal collision with a centered static object", the second is a "curved frontal collision with a centered static object" (see Figure 10. a, b).

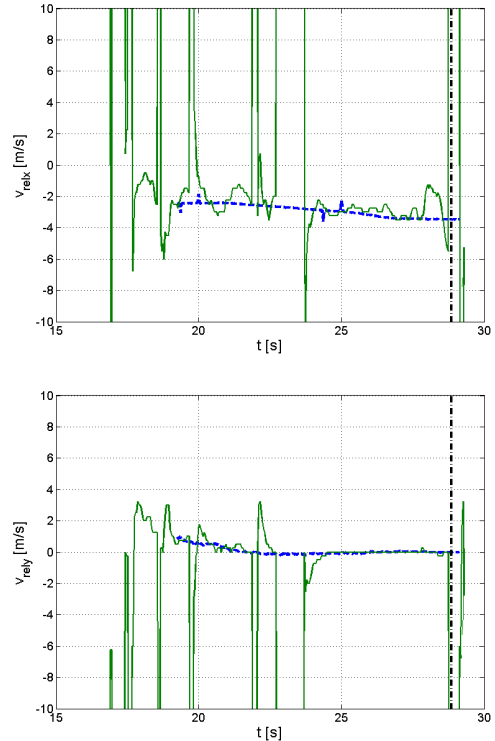


**Figure 10. Test scenario type: a) Straight frontal collision with a centered static object (top); b) Curved frontal collision with a centered static object (bottom)**

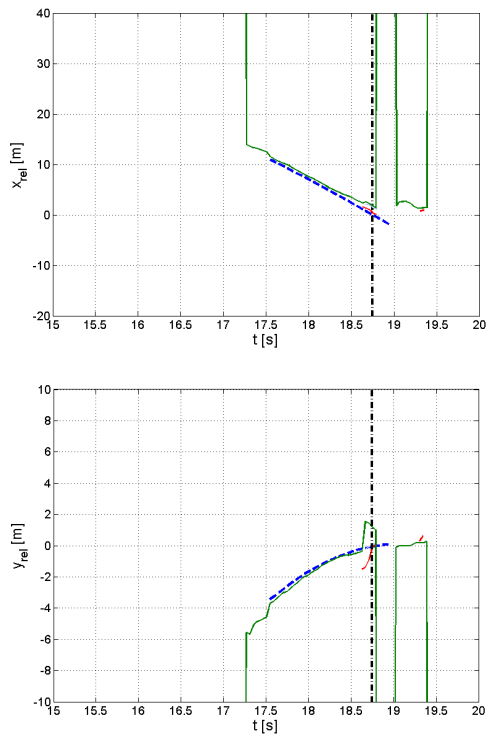
In the following plots the measured data for the relative position in x- and y-direction ( $x_{rel}$ ,  $y_{rel}$ ), as well as the relative velocities in x- and y-direction ( $v_{relx}$ ,  $v_{rely}$ ) are shown. The dashed blue line represents the synthetic sensor data generated with VTD. The perpendicular dashed black line at 28.9 sec. in Figures 12 and 13 and at 18.8 sec in Figures 14 and 15 represents the time of collision between the ego-vehicle and the static target object.



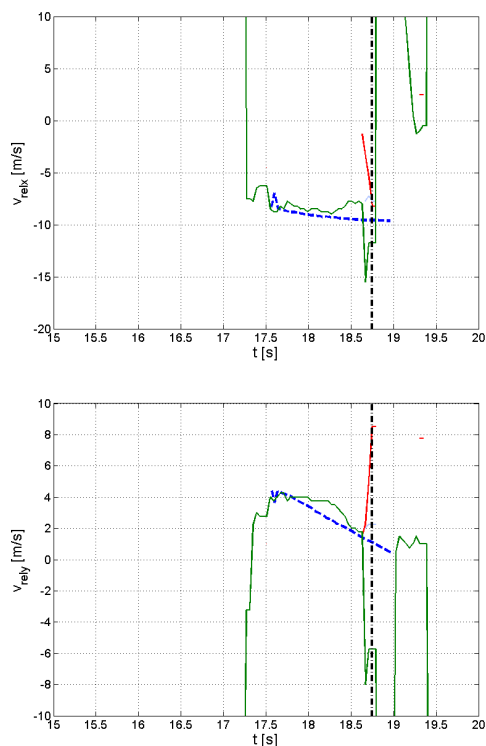
**Figure 11. Real and synthetic sensor data for the relative position in the test scenario "straight frontal collision with a centered static object"**



**Figure 12. Real and synthetic sensor data for the relative velocity in the test scenario "straight frontal collision with a centered static object"**



**Figure 13. Real and synthetic sensor data for the relative position in the test scenario “Curved frontal collision with a centered static object”**



**Figure 14. Real and synthetic sensor data for the relative velocity in the test scenario “Curved frontal collision with a centered static object”**

The data values recorded directly after the time of collision result from the missing model for mechanical interaction between the collision partners in VTD or in the case of the real sensor data from the back-bumping of the hit target object.

All plots show a good correspondence of the measured and synthetically generated sensor data in both position and velocity values at distances larger than approx. 5 meters. Throughout the whole set of real sensor measurement data temporary target object tracking losses can be recognized. Shortly before the time of collision significant deviations of the measured and synthetically generated sensor data values are visible.

The plots of the curved driving scenario (Figures 13 and 14) show that the target object is only detected at a significantly later point of time (smaller distance to the ego-vehicle) compared to the straight driving scenario. This results from the circumstance that the target object enters the pyramidically formed sensor cone at a later point of time, as shown in Figure 7.

Moreover the circular driving scenario shows that the real sensor detects the target object as several objects shortly before the actual time of collision, as shown in Figures 14 and 15 with a red and bright blue line.

All diagrams depict the behavior that the statically parameterized sensor model in VTD has a slightly lower distance range in the specified scenarios compared to the real sensor.

## 7 CONCLUSION AND OUTLOOK

The steady growth in the number of predictive driver assistance functions in new vehicle models combined with the trend towards a higher number of vehicle variants per model leads to a significant rise in testing requirements in order to assure the correct functioning, reliability and robustness of such ADAS under a wide range of traffic conditions. The testing requirements can't be covered anymore in an efficient manner by solely using real test drives. Therefore a methodology is presented to support the ADAS development and testing by using a software tool for the integrated vehicle and environment simulation. The focus of the paper lies on the method for performing semi-automated analysis and validation of perceptive sensor models. The sensor model validation process makes use of reference position and perception

sensor data recorded during real test drives and allows the comparison and evaluation of the real sensor data with synthetically generated sensor data from sensor models on object list level.

The first results of a sensor model validation based on the described methodology with an idealistic sensor model of a prototypical real perception sensor are promising and confirm the basic applicability of the integrated vehicle and environment simulation for the development and testing of ADAS functions. Furthermore the results show current limitations of the approach which need to be addressed in future improvement steps.

The essential use of the presented validation methodology is related to the following aspects:

- Significant time savings through the replication of real test drive scenarios as virtual ones
- Possibility to create validated statements concerning the limitations / application range of the sensor models
- Inclusion of existing and approved tools for analysis, comparison and evaluation of sensor data
- Usage of a unified format for real and synthetically generated sensor data

Furthermore during the implementation of the described methodology several working fields were identified, which should be addressed in successive projects in order to increase the usability of the simulated sensor data for the testing of ADAS:

- Implementation of sensor models which model the most relevant sensor properties and disturbance effects as they occur on object list level of real sensor data
- Extension of the toolchain regarding the analysis and comparison of sensor raw data, e.g. camera images, radar locations, etc.
- Extension of the validation methodology to the level of functions and algorithms
- Improve the grad of automated sensor validation concerning the process- and tool-wide support of parameters related to the sensor and vehicle configuration and test scenario conditions (weather, target object properties, etc.)

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