Don’t sleep and drive – VW’s fatigue detection technology

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Summary

This paper takes an in-depth look at an innovative driver state monitoring system, which VW has developed to assist drivers. The system is designed to help drivers manage their physical and mental resources properly when they are behind the wheel.

The article begins by explaining the motivation that led to the development of the system and then goes on to discuss the characteristics of the physical and cognitive states under observation as well as the system hardware and software components. The reader is given an insight into the empirical derivation of the prediction algorithm. The article also presents the results of the initial customer survey.

1 The human factor in car accidents

Human error is known to be a causal factor in many accidents. There are, however, various aspects of driver error, and an analysis of these aspects can be used to derive better engineering solutions for human-machine interaction. Various proposals have been put forward as the basis for an analysis of human error including Norman (1981), Rasmussen (1982) and Reason (1990). Human error is explained by shortcomings in perception, interpretation of information, decision-making, information recall and direct performance of an action. However, general physical and cognitive aspects such as attention and fatigue also play an important role, because they affect other cognitive processes. The driver’s state has a crucial influence on performance reserves at any point in time and consequently on the conditions that determine the driver’s ability to operate the vehicle safely.

Accident statistics provide grim evidence of the effects that driver fatigue can produce. The percentage of accidents caused by fatigue varies between 5 – 25 % depending on the individual study. One essential characteristic of these accidents is the disproportionate severity of injuries, as can be seen from the graph (Fig. 1). The explanation for this phenomenon can be derived directly from the effects of fatigue. When drivers are tired, they fail to take any action at all to avoid an accident (especially braking or steering). Fatigue impairs perception and the ability to make the decision to react, and it also degrades actual performance of the action(s).

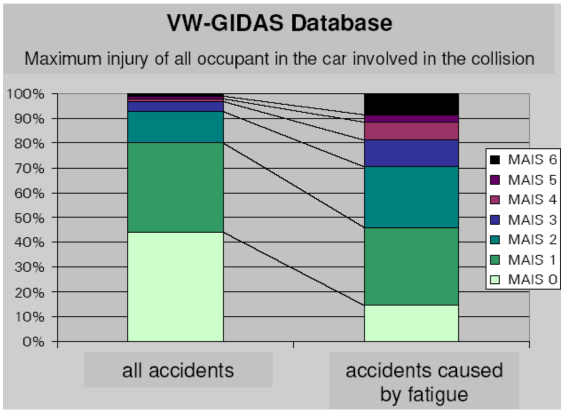

Fig. 1: Maximum injury in car collisions overall in relation to maximum injury in car collisions caused by fatigue

These facts motivated the research team at VW to investigate driver state recognition systems and look for suitable solutions to the problem.

1.1 Driver state recognition as an active safety measure

A whole range of improvements in vehicle design and the provision of airbags and safety belts as standard equipment are safety measures, which have helped reduce the effects of accidents on vehicle occupants in general and drivers in particular. However, it takes active safety measures to actually provide a chance of preventing accidents. Active safety systems, which have proven to be effective such as ESP and ABS help the driver control the vehicle. Driver state monitoring can also be regarded as an active safety measure, because the goal is to evaluate the driver’s performance resources. It can provide prospective information to drivers about their condition, and the vehicle can automatically adapt to changes in the driver’s performance capabilities. Other driver assistance systems can, for example, provide warning in a more timely fashion to give the driver more time to react.

There are difficulties with the methods that are used to assess the driver’s state and the driver’s fatigue level in particular. This in turn creates a problem when an attempt is made to test the suitability of fatigue recognition technology. At first, the answer to the question “what is fatigue?” appears to be quite straightforward. However, research on this phenomenon is still incomplete, and it is not possible at this time to provide an exact, quantitative assessment of fatigue. There is no generally accepted "golden rule" and no fatigue metrics that can be used to calibrate a fatigue recognition system (Bittner et al., 2000).

There are also limits to the effectiveness of attention monitoring systems in real-life driving situations. Monitoring the gaze position or head orientation is one plausible method, which can be used to assess visual attention and ensure that drivers have access to essential information. Ease-of-use considerations dictate that the assessment must take place without contact and without the need for calibration by the driver, and this presents an additional engineering challenge. One fundamental problem with this type of measurement is that "looking at something" does not necessarily mean, "being aware of something".

1.2 What do we mean by attention and fatigue

Attention is a concept, which we have all experienced and which seems plausible to us. However, it actually refers to a multi-faceted phenomenon. Attention is an essential prerequisite, which enables a person to select information, which is coming from the person's surroundings, process the information and control action (James, 1890). Attention can be focused intentionally in an attempt to locate information or unintentionally as a result of physical stimulus. Attention can be focused on one specific area, or it can be divided to a certain extent between several areas. Training and factors such as fatigue and motivation can influence the degree to, which attention and cognitive resources can be divided. Another aspect of attention is vigilance, which means maintaining focus. A person needs to be vigilant to perform a task over a long period of time. All of these factors are important for drivers, because they make available the cognitive and physical resources needed to carry out an activity.

Fatigue is another phenomenon that influences a person's ability to perform a task on various levels. Hacker (1989) defined fatigue as a "state in which performance capabilities are temporarily impaired by continual activity demands which exceed the ongoing capacity to restore performance capabilities." A dangerous situation occurs when the driver of a vehicle suffers from psychological fatigue (temporary impairment of information acquisition and processing capabilities).

The effects of psychological fatigue manifest themselves in four categories:

(1) *physiological* (regulation of the vegetative and nervous system)

(2) *cognitive* (perception and information processing)

(3) *motor* (behavior)

(4) *subjective* (experience)

Changes in the first three categories are generally accessible for observation and "objective" measurement, but this is not the case for the subjective experience of a fatigued person. In addition, there is often no direct correlation between "objective" parameters and subjective experience ("Paradoxien des Müdigkeitsgefühls", Hacker, 1980, pp.70ff.).

Because the terms are not clearly defined, the boundary between the symptoms and the effects of fatigue is not well-defined. In practice, there is actually no need to make a theoretical distinction. The symptoms and effects of fatigue can be summarized as follows (Tab. 1; refer to FHWA, 1997):

Category	Symptoms and effects of fatigue
physiological	• reduced psycho-physiological stimulation
cognitive	• reduced alertness and vigilance • information processing and decision-making takes longer
motor	• reaction time increases when critical events occur • control reactions are more variable and less effective • reduced preparedness to react

Tab. 1: Classification of fatigue symptoms and effects

Brown (1994) believes that the main effects of fatigue are a progressive withdrawal of attention from traffic and what is happening on the road combined with a more risky approach to decision-making.

Brown (ibid) suspects that reduced alertness is most often the result of eyelid closure, which accompanies fatigue. He also describes another effect of fatigue on drivers as "driving without awareness" (DWA). When road and traffic conditions are not very demanding, the driver's attention is gradually diverted from traffic to distracting thoughts. This state of inattentiveness is caused by the fact that visual search behavior in the presence of highly repetitive and predictable visual stimulus is determined to an increasing extent by internal oculomotor control (top down) rather than by the actual task at any moment in time. Regarding the practical effects of this state, Brown (ibid) concludes that DWA will increase the probability of rear end collisions in particular, whereas the likelihood that the vehicle will leave the road without another vehicle being involved will increase if drivers close their eyes.

Knowledge about how fatigue progresses over time is vital for the development of a fatigue recognition system. Many studies have shown that driver fatigue occurs intermittently. There is not a linear increase in fatigue level when drivers with sleep deprivation are at the wheel for long periods of time. Instead, there is a sequence of episodes involving fatigue and reduced alertness with a general tendency towards increased fatigue (e.g. Hargutt & Tietze, 2001; Bittner et al., 2000; Richardson et al., 1997). These findings are in agreement with "classical" results from general fatigue research, which describe repeated short blocks or lapses during vigilance tasks interspersed between periods of normal performance (Warren & Clark, 1937).

The theoretical explanation for these observations is that fatigue does not develop as part of a passive process. What we actually see is interaction between deactivation processes and compensation processes. A driver can, for example, react when he realizes that he is getting tired and change the way he is driving to compensate for the (perceived or suspected) impairment of his ability to react. As a result, it is much more difficult to demonstrate a fatigue-related decrease in performance under realistic conditions than during "artificial" trials under laboratory conditions. According to Hockey (1993), people adopt a *performance protection strategy* when they are doing something that they perceive as being important. A modified action strategy can to some extent compensate for reduced performance capabilities. Determining where the limits of this ability to compensate lie is subjective and dependent on the situation. The limits vary and are difficult to predict.

As a result of interaction between the deactivation and compensation processes, fatigue manifests itself more as an increasing variability in performance than a steady decline in performance (Dinges & Kribbs, 1991).

The factors, which systematically determine the variation between alertness and blockages from one minute to the next remain unknown. Technology designed to recognize blockages in information processing and the activity of drowsy drivers must be designed to monitor changes continually (Dinges et al., 1998).

A fundamental problem in the validation of fatigue recognition technologies is the selection of a suitable criterion (Hartley et al., 2000). The difficulty stems from the fact that "fatigue" is a vague concept, which is used as a general term to describe phenomena, which result from a variety of factors. Literature published in English uses the following terminology in this context: "*fatigue*", "*sleepiness*", "*drowsiness*", "*microsleeps*", "*attention*", "*alertness*", "*vigilance*", "*hypovigilance*", "*performance variability*", "*error vulnerability*" etc. These terms or more or less used synonymously.

At first, the answer to the question "what is fatigue?" appears to be quite straightforward. However, research into this phenomenon is still incomplete, and it is not possible at this time to perform an exact, quantitative assessment of fatigue level. There is no generally accepted "golden rule" and no fatigue metrics that you can use to calibrate a fatigue recognition system (Bittner et al., 2000).

2 VW's approach to (in)attentiveness and fatigue

As can be seen from the information presented in the previous sections, fatigue in general is a very complex phenomenon. It has been the subject of intense scientific study, and drowsiness at the wheel is a very familiar cause of accidents. Fatigue and the resulting microsleeps are merely a subset of the potential causes of accidents, which can be traced to a lack of fitness or performance capability on the part of the driver. From the pragmatic standpoint, fatigue and lack of alertness and the effects on driving may be summarized under the term inattentiveness. To put it another way, fatigue is one of a number reasons for inattentiveness (Brown, 1994). Inattentiveness is a major cause of accidents and can occur when the driver is reading traffic signs or talking with passengers in the vehicle. Unless an accident or dangerous incident occurs, the driver is unlikely to even notice the inattentiveness. That is one of the reasons why our customers perceive fatigue to be a more significant problem than inattentiveness. Nearly all drivers can remember a situation when they were driving while they were tired whether or not they had trouble controlling the vehicle as a result of fatigue. This means that a system that addresses the general problem of inattentiveness would be more effective in increasing traffic safety. Customers are more concerned with fatigue and microsleep, and media reports tend to reinforce this attitude.

To make a valid assessment or relatively reliable estimate of a driver's fatigue level and provide a timely recommendation for action to be taken before a dangerous situation arises, represents a significant challenge (see section 1). Deciding whether a driver is paying sufficient attention to traffic is far more complicated.

What is the best way to assist the driver, give him information about his condition and help him drive the vehicle? To find an answer to this question, we will start by using a pragmatic conceptual model. How, for example, can we tell whether persons attending a meeting are attentively following what is going on or instead have nearly fallen asleep? We can find out or at least make a reasonable assessment by watching their faces. Are they looking at the speaker's charts at the front of the room? Are they looking out the window or flicking through their notes with a bored expression of their faces? Do they already have "heavy" eyelids that open and close slowly and almost remain closed?

This tells us that one way to assess the fitness level of another person or a driver is to observe the face, head and eyes. We can draw conclusions about a driver's alertness if we can determine what seems to be holding the driver's attention, what direction he has turned his head in or where he is looking. If we can determine whether and how a driver's eyelids are moving or whether they are actually closed, we can assess whether the driver is tired. The VW approach is to transfer this human assessment capability to a technical system, which vigilantly observes the driver.

The on-board equipment needed to monitor and assess or estimate the driver's state is as follows:

- a **video sensor (camera)**, which can provide an image of the driver in all lighting conditions and with sufficient resolution, and **image processing software** as part of the camera, which identifies parameters such as eyelid opening, head position and gaze position.
- a **prediction algorithm**, which calculates or estimates the driver's fitness/fatigue level based on eye closure data
- logic or an algorithm, which accepts the various inputs and provides a suitable output to a **human-machine interface**.

Proposed solutions for a driver state monitoring system, the associated difficulties with the system and the resulting technical requirements are presented below. We will also describe our first on-board engineering prototype and what our customers think of this approach.

2.1 Video sensor (camera) and image processing

We use a video camera, which is suitable for vehicle-based applications to monitor the driver. The camera is positioned so that we can monitor the driver's head and especially the eyes. We want to measure the movement of the head, eyes and eyelids with the aid of the camera. The output should include parameters such as the position of the head with relation to the chassis, gaze position parameters and eyelid data. The change in eyelid spacing (the distance between the upper and lower eyelid) over time can be used to calculate the frequency and duration of eyelid motion and other parameters. Parameters derived from eyelid motion are then used to generate an estimate of the driver's fitness/fatigue level. An assessment of attentiveness is based on head and gaze position.

The on-board system also includes an image processor, which analyzes the images and performs the necessary calculations.

The way in which the camera is integrated into the vehicle is largely determined by the cabin design and the need to position the camera so that it can monitor the head and especially the eyes. The camera's location, orientation and field of view must be adapted to suit the particular vehicle.

Once the system is activated, the image processor reads the data that is sent periodically from the camera and performs the necessary processing steps. The processor must be able to calculate the parameters in real time. The system also includes light sources to provide adequate illumination under all ambient conditions.

The data from the system is fed into a fatigue monitoring system and the result (e.g. a warning) is passed onto a human-machine interface.

The observation camera system mounted in the cabin contains the following components:

- camera
- image processor
- light sources

Similar camera systems and video sensors are already being used in laboratory trials in a wide range of applications. The challenge is to adapt these systems to the vehicle and make them suitable for use in that environment. We also have to be able to produce sufficient quantities of the camera in high volume production.

2.1.1 System components

2.1.1.1 Camera

A camera is mounted in the cabin to supply a video signal, which provides an image of the driver's head, the area around the eyes and certain facial features to the image processor. The camera is connected directly to the processor's video input, and it must meet certain technical requirements including for example adequate resolution, frame rate and sensitivity.

The field of vision must include the driver's face in all seating positions if possible without the need for any camera adjustments. The camera must be able to accommodate variations in the size, possible seating positions and posture of different drivers. Body sizes can range from the 5% female to the 95% male. Possible body and head posture must also be taken into account. The camera must offer a certain depth of field because the distance between the camera and the driver can vary depending on the driver's seating position. The camera's peripheral field of view also must be defined.

Additional simulation and in-vehicle testing are required to arrive at a precise definition of the required field of vision. Fig. 2 shows a sample study.

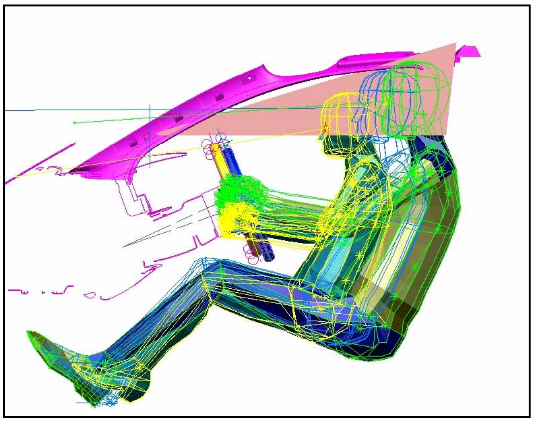

Fig. 2: Example - camera integrated in the A-pillar, Volkswagen Phaeton

2.1.1.2 Light sources

Light sources are needed to ensure sufficient illumination of the object under all ambient conditions. They must be adapted to suit the size and shape of the particular vehicle. The amount of light emitted in the visible spectrum must be so low that the driver does not notice it. The light sources must be safe for the eyes, and they must comply with applicable legislation.

2.1.2 Image processing functional requirements

The cabin-mounted camera system must essentially perform the following functions:

- It must detect whether someone is sitting in the driver's seat.
- It must determine the approximate position of the driver's head in space (x,y,z).
- It must provide current eyelid opening data in millimeters for both eyes. Minor latency is acceptable if an exact eyelid opening value is required.
- A status value should be made available with very low latency. The status should include data on the driver's current position, approximate orientation and eyelid opening status.
- The system must reliably flag measurement dropout or errors.
- It should provide data on head position particularly on the x-y axis (left and right rotation) over a wide range and within a relatively small angular drift. Head orientation in the x-z axis (nodding) over a small range is also important.
- Using the head position as the basis, the next step is to determine the gaze position relative to a fixed, defined cabin element. Qualitative differentiation is required to determine whether the driver is looking at the instrument panel (multi-function control, radio, etc.), looking out at traffic through the windshield on the driver's side, looking through the windshield on the passenger side or looking out the side window. Testing must be carried out to check whether it is possible to reliably determine when the driver is looking at the inside or outside mirrors.
- Capability to perform additional functions such as driver identification would increase customer benefit.

Only specific operational criteria will be added to this long list of requirements.

2.1.2.1 Operational criteria

The functional requirements must be fulfilled in a variety of situations. These operational criteria are essentially divided into ambient criteria and person-related criteria.

2.1.2.2 Ambient criteria

The system must continue to operate reliably regardless of ambient lighting conditions. It must be able to handle the full range of light intensity that is likely to occur during vehicle operation, ranging from total darkness to direct sunlight. The system must also be able to handle rapidly changing lighting conditions (e.g. travel along a tree-lined road with sunlight from the side). On systems that operate in the near-infrared range, consideration must be given in particular to near-infrared interference and the effect of the windows in the target vehicle.

The system is designed for use on the road. Typical vibration must not impair system reliability or cause system failure.

During vehicle testing, the system must operate in the standard test temperature range without any restrictions.

2.1.2.3 Person-related criteria

There must be no dependence on the driver's physical appearance including hair style. Ethnic origin (Asian, African or Central/South/North European/American), sex, make-up and prosthetic changes to the person's face must not affect system performance. We should attempt to provide unrestricted functionality for persons wearing glasses, and this is currently the most difficult image processing challenge. Reflections from the lenses or frame cause errors during image processing and evaluation. The system must be able to measure eyelid spacing through glasses even in unfavorable lighting conditions. It has to accommodate different styles of glasses and lens types (mineral glass, plastic and tinted/untinted lenses) and prescriptions. The only exception relates to sunglasses that filter out a significant amount of infrared light.

2.1.2.4 Measuring eyelid opening

Precision measurement of eyelid movements is a basic prerequisite for determining the driver's fatigue level. The distance between the eyelids is used for example to calculate lid opening and closing speeds, eyelid closure time and blinking frequency. It is also used to determine how wide the eye is opened and other parameters. The system must provide the current distance between the eyelids for both eyes at the camera frame rate. Output must not exceed a defined latency level.

2.1.2.5 Accuracy

The image-processing unit should be capable of detecting the position of the eyelid edges with an accuracy of less than one pixel. Variation in measurement errors is particularly critical. Rapidly changing measurement errors create major problems during fatigue monitoring. Key parameters such as eyelid opening speed are derived directly from the distance between the eyelids, and false discontinuity on the blinking curve leads to very critical measurement errors. Measurement errors that remain constant over time are somewhat less critical. A small, constant offset or factor on eyelid opening data can be tolerated.

2.1.2.6 Quality indicator

It is important that the system is able to recognize and flag unavoidable dropout and large measurement inaccuracies to ensure that the downstream unit that monitors fatigue and detects head and gaze position does not misuse the data or misinterpret it. A differentiated, conservatively designed quality indicator should be used for this purpose.

2.1.2.7 Determining the 3-dimensional position of the driver's head

In a number of applications, it is important to know the approximate position of the driver's head. If possible, there should be no need for ranging sensors other than the camera. When these criteria are met, the camera image along with biometric assumptions (e.g. spacing between the eyes) can be used to determine the approximate distance of the face from the camera. The distance and the position of the face in the camera image can then be used to determine the other two coordinates.

2.1.2.8 Status output

The system should provide a status signal, which is output in real time or nearly so. This is necessary to achieve reliability and an alarm rate, which is acceptable to the customer in a number of situations, which occur when the vehicle is in traffic.
The table below (Tab. 2) shows a sample status value:

Status	Description
Base view	The face of the driver is in the field of view. Both eyes are detected in the camera image
Blink	The face of the driver is within the field of view. The eyes are closed
Turn out of range	The driver has turned his head. The head is still in the field of view, but the eyes are not visible from the camera, and the distance between the eyelids cannot be determined
Occlusion	The eyes are covered by an object, but they are otherwise within the field of view
Lateral out of range	The driver has moved to the side out of the camera's field of view
No person	No one is within the camera's field of view
Measurement error	The face is in the field of view, but the eyes cannot be located

Tab. 2: Output of the driver state

2.1.2.9 Reliability of the status value

The “Blink” status is used to trigger a warning as soon as the driver’s eyes have been closed for a certain length of time. Latency must be minimal in order to provide timely warning to the driver. The fatigue level is determined by measuring the distance between the eyelids (see section 2.1.2.4). Latency is less critical here.

The “Blink” status must be highly accurate. If “Blink” remains set for a defined length of time, a downstream unit (a suitable HMI) will warn the driver. Long blinks will lead directly to a driver warning. If the “Blink” status erroneously indicates a long blink, a false alarm would be sent to the driver. The “Blink” status must never lead to a warning if the eyelids were not actually closed for the defined length of time. However, long blinks should always be detected if possible. 95% of long blinks should be detected using the “Blink” status.

This issue presents also a big challenge for the image processing functions. The requirements placed on other status values are less stringent.

2.1.2.10 Calibration

The system design must ensure that no calibration is needed over the system’s lifecycle. However, automatic calibration without the need for user intervention is acceptable. There should also be no need for calibration during installation or service. The camera lens aperture angle should ensure that there will be an adequate field of view despite the usual installation tolerances.

2.1.3 Sensor tests and outlook

The requirements we have outlined for an on-board video sensor used for driver state monitoring are partially taken from a standard specification list, which applies to any new electronic component or system, which is to be integrated into a vehicle during the course of the development process. VW has also conducted a large number of tests in-house on video sensor prototypes (Fig. 3 shows an example).

Without going into the details of the trials, we would at this point like to briefly explain some of the problems that still need to be resolved before we can consider widespread use of this technology in vehicle applications.

The sensor system should work with drivers who are wearing glasses. Current image processing systems on prototype sensors have the disadvantage that they generate false interpretations or reflections coming from the lenses or frames. These reflections can be confused with the reflections, which normally come from the pupil, for example, at a time when the eye behind the lens may actually be closed. The frame can be misinterpreted as the upper or lower edge of the eyelid. This could lead to generation of false data relating to the spacing between the eyelids or the gaze position.

Fig. 3: Prototype of a video sensor in a VW car

The availability of the sensor signal in all lighting conditions poses another problem. What we are talking about here is lighting conditions that are related to the weather conditions, time of day (sun low on the horizon at sunrise or sunset) or ambient conditions (e.g. rapid transition between light and shadow on tree-lined roads) and differences in lighting conditions that are related to geographical location.

Whether or not we will see this type of system in future cars depends to a large extent on our ability to find satisfactory vehicle-based solutions, which meet the requirements described above and which eliminate the current problems.

2.2 Prediction algorithm

We will now take a look at the methodology, results and conclusions from trials, which were conducted at VW to determine the driver’s state, and his fitness/fatigue level in particular, using eye closure data. An appropriate prediction algorithm was developed and tested in a vehicle application.

2.2.1 Methods and results

The behavior of drivers suffering from extreme fatigue was investigated in a driving simulator during the first phase of the project. In addition to looking at other driving parameters, the study focused on blinking and identification of fatigue indicators.

The pilot study, which ended in 2002, demonstrated a significant correlation between blinking parameters and fatigue. These results were validated in another trial. The wealth of data available from these trials was used to develop a fatigue prediction algorithm, which is based on driving and eye parameters.

In parallel, a prototype sensor was tested and evaluated. Up to that point, complex video analysis was needed to accurately detect blinking. The sensor was designed to perform this function automatically. A prototypical sensor was used to detect blinking. Raw data from the sensor was processed and parameterized during the project.

The algorithm was intended to provide accurate state evaluations for all drivers if possible. The fatigue behavior of a variety of persons was studied at different times. A broad, varied sample of drivers was selected for the study, which roughly represented the population of persons holding driving licenses in Germany. Trials were conducted at various times during the day to ensure that parameter differences, which are related to time of day were identified. Monotonous travel on a freeway was selected to maintain strict control of simulated situations and conditions. Otherwise it would not have been possible to relate parameter differences to a single cause. Thus the results of the study can be generalized to apply to various test persons and times of the day, but it is only valid for a monotonous stretch of freeway.

A third goal was to establish additional fatigue criteria, which were missing from the pilot study. For algorithm training, prediction variables that can be established in the vehicle have to be linked with a fatigue or alertness level criterion. Since no generally valid measurement standard for fatigue exists, three different criteria were established to compensate for the advantages and disadvantages of each criterion. Firstly, the drivers taking part in the study were asked to assess their level of alertness. Secondly, following training on a defined set of observation criteria, neutral observers used video analysis to evaluate driver fatigue. The third "objective" standard was measurement of brain activity (EEG), which was applied in some tests.

A total of 83 persons, who were specifically selected from a large database containing information from responses to an ad campaign, took part in the series of experiments. The participants appeared for testing at three different times during the day: 8 A.M., 1 P.M. and 10 P.M. Each person drove for about two hours on a monotonous stretch of freeway.

The data collected during the experiments was processed and parameterized to provide a basis for prediction models (prediction algorithms), which use a variety of mathematical methods.

The methods used in experiment 1 include:

- threshold analysis
- a C5 decision tree
- multiple regression

These methods were used to construct the prediction algorithms. The approach taken was to use half of the test persons to "teach" the algorithms. The other half was used to test the quality of the predictions. The prediction is retrospectively based on all data collected during the preceding 60 seconds, and it is re-calculated every second (frequency = 1 Hz). Sensitivity and specificity criteria taken from signal detection theory (Green & Swets, 1966) were used to assess the quality of the prediction. To calculate the quality of the prediction, the output of the algorithm is categorized into correctly detected, missed, correctly rejected and false alarm events. Specificity gives an indication of the extent to, which an event was only and exclusively detected when a microsleep phase actually occurred. It can also be expressed as a percentage value for correctly categorized event-free time segments. Sensitivity is a ratio of the number of correctly identified events compared to the total number of events expressed as a percentage.

$$Specifity = \frac{correct\_rejection}{correct\_rejection + false\_alarms} \bullet 100\%$$

$$Sensitivity = \frac{hits}{hits + mis\sin gs} \bullet 100\%$$

Algorithms in this study should have a maximum value for sensitivity and specificity.

Fig. 4 below shows how results were classified. It indicates when a prediction is counted as a hit, false alarm, correct rejection or missing in relation to the 5-minute prediction interval.

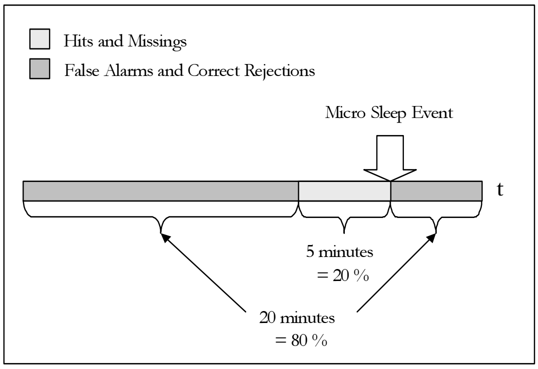

Fig. 4: Evaluation of driver's fatigue recognition algorithm

Prediction algorithms were developed and tested on the basis of this methodology. The best results were achieved when the results of different algorithms were merged into one consolidated algorithm. This is discussed in more detail in the next section.

Indicator models were developed during the 2002 pilot study. Parameters and their fatigue-dependent variation were systematized. Experiment 1 was then conducted to develop algorithms to predict an immanent sleep event. Experiment 2, which followed in 2003/2004, was conducted essentially to repeat the testing and improve the reliability and validity of the algorithms that were developed during the previous experiment. A further experiment was conducted in 2004 to study the effect of warnings on the prediction quality.

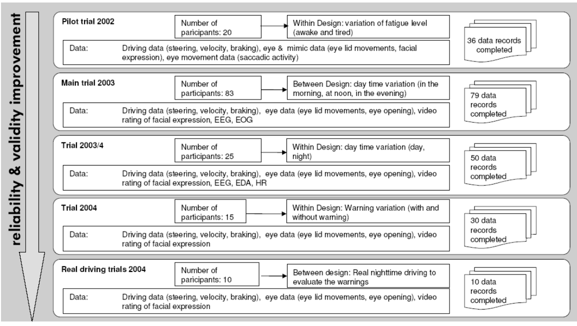

Fig. 5: Empirical basis of driver's fatigue recognition algorithm

2.2.2 On-board implementation

Tests under real driving conditions were carried out to evaluate the data processing and algorithm framework. The general framework is shown in the diagram below (Fig. 6).

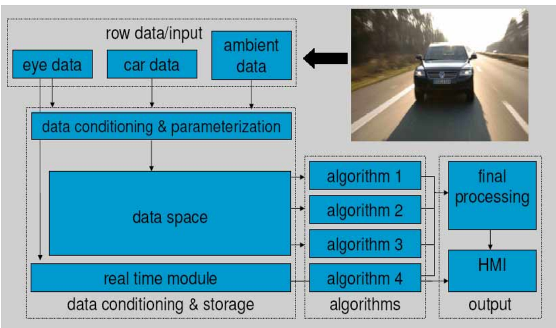

Fig. 6: Framework of driver's fatigue recognition algorithm

Eye data captured by the video sensor was fed into the system. Eye opening as a function of time and the parameters derived from that data are used during calculation of the fitness/fatigue level. Data smoothing has to be performed in order to generate meaningful parameters from the raw data signal. Then compensation must be added for missing input data. After these steps are performed, the quality of the input data is adequate to detect blinking events (event detection). A check should be made to determine the extent to which data from the left and right eye vary. Once eye closing events have been identified, they can be parameterized (the duration of the blinking event or speed at which the eyelid is opened can be determined). The quality of the measurement performed on each blinking event can then be evaluated. The quality assessment is performed during algorithmic processing. Once the significant statistical values per event for the preceding minute have been generated, the data is exported to the data pool and is available to the algorithm modules for further manipulation.

Vehicle and ambient data are placed on the CAN bus (**C**ontroller **A**rea **N**etwork) and fed into the framework. Vehicle data is used to determine activity patterns, which can then be used to perform an additional check of the fatigue prediction. Ambient data such as the time is used to generate the prediction depending on what time of day it is. The prediction takes into account circadian rhythm (our internal time-dependent clock).

Initial development of the prediction algorithm took place under controlled conditions in the simulator. The effect of warnings and feedback on drivers and on the validity of the prediction was also tested in the driving simulator before a test series was carried out on the road.

The results of evaluations conducted on the newly developed warning system under actual conditions were encouraging. The calculation of the quality indicator as well as feedback from test drivers who gave an assessment of the warning system indicate that at the current stage development the system is already producing satisfactory results and is something that customers would like to have.

In principle, the algorithm is transferable to actual behavior in traffic. It is still difficult to capture eye data without error when the driver looks away. This problem was discovered under real-world conditions where more stimuli were present. It did not occur in the carefully controlled environment of the simulator.

It also became clear that the way fatigue progressed under actual road conditions was different from what was observed in the simulator. Drowsiness came on significantly faster in the simulator if the assessment is based on the final fitness value of the prediction algorithm. Subjective self-assessment by the participants indicated that the fatigue level increased over the course of the test drive. Sensitivity and specificity calculated on a minute basis were both above 90 %. These results show that the prototype delivers satisfactory performance.

There is however still scope to improve detection of eye behavior for persons who are wearing glasses. It is also clear that it is not possible to develop an algorithm, which can be used to predict the fitness/fatigue level for the entire driving population. Some drivers do not exhibit the type of behavior, which indicates fatigue to a sufficient extent, and this makes it impossible to develop a universally valid assessment. Results of the testing completed so far indicate that the fitness/fatigue level could be predicted for about 80% of the participants. Ways in which a warning could be issued to the rest of the drivers when microsleep incidents occur are outlined in Section 2.3.

2.3 Other applications for a camera mounted in the cabin to monitor the driver

For this group of less-predictable drivers we are looking at various scenarios and strategies to generate a benefit from the fatigue/alertness assistant.

One possibility is to develop a long blink or doze-off alarm (please refer to section 2.1.2.8). The fatigue/fitness level can be used to produce a warning before the driver falls asleep. In contrast, the long blink or doze-off alarm does not produce an alarm until the eyes have remained closed for a predefined length of time. A high frequency is not needed to determine the eyelid spacing sequence. The system needs “only” to determine whether the eyes are open or closed. However, this decision must be made in a very short time, because a warning must be transmitted to the driver as quickly as possible. The danger for the driver and others becomes acute once the eyes have closed. False alarms are not acceptable, because this would significantly reduce confidence in the system and thus customer acceptance. This scenario places high demands on the image processing function, which must be very precise and accurate. Other scenarios, which make use of the camera in the cabin to monitor the driver, are shown in Fig. 7. The goal is to provide more information on the driver’s alertness by determining the head orientation and gaze position.

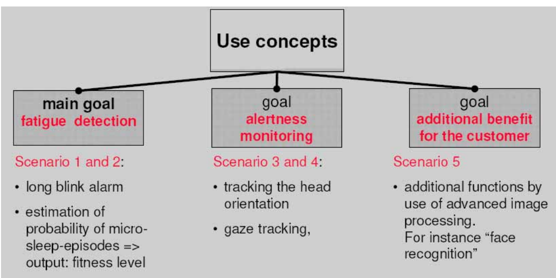

Fig. 7: Use concepts for an in-cabin camera

These use concepts will not be presented in more detail in this paper because the applications are still under development.

3 What does our customer want? Some results of a customer opinion survey

It takes more than a demonstration of technical feasibility to achieve a successful transition from a research project to a product strategy and from there to volume production. Creating a link to the customer and the market is at least as important, and this is why we used marketing techniques to include customer preferences and requirements in the project. In collaboration with our market research and product marketing teams, we designed and carried out an online questionnaire-based survey. The advantage of this type of study is the ability to survey a large number of customers in a relatively short period of time. The disadvantage is that, despite the use of today’s computer and animation technology, the respondents only get a virtual impression. The customers have not used the product or experienced its features, and they can only evaluate the concept. The responses do, however, provide information about expectations associated with the product. They also identify any aversion to this type of technology and shed some light on the reasons behind this attitude.

In the summer of 2004, a standardized online interview was used to survey 431 Volkswagen and Audi drivers in all product segments. The table below (Tab. 3) shows the details of the interview sample.

SEGMENTS	A	B	C	D	MPV/A-MPV	NFZ	TOTAL
Targeted sample size	80	80	80	40	80	80	**440**
Actual sample size	83	83	82	37	81	65	**431**
Sex Male (Female) [%]	59 (41)	71 (29)	66 (34)	84 (16)	62 (38)	89 (11)	**70 (30)**
Ø Age [years]	29	33	36	49	35	42	**36**
Private car (business car) [%]	78 (22)	84 (16)	74 (26)	54 (46)	86 (14)	60 (40)	**78 (22)**

Tab. 3: Sample population

In very general terms, the goal was to solicit opinions from our customers on the alertness/fatigue assistant. Various usage models were presented (refer to Fig. 7). Scenario 1 was given the working title “doze off alarm”, Scenario 2, calculation of the fatigue/fitness level, was called the “fatigue detector”, Scenarios 3 and 4 together were called “alertness assistant”. The scenarios 1 and 2 were the best accepted ones by the customers surveyed, because they were expected as the most helpful functions. The approval level for the alertness assistant was also high, but clearly behind the doze off alarm and the fatigue detector. Respondents were allowed to select more than one item. Another question is whether customers accept the idea of having a camera in the cabin to monitor the driver. They were specifically asked whether they would accept a camera to assess fatigue/alertness and if necessary infrared light sources in the vehicle as well. Over 80% of customers surveyed think that a camera and the necessary infrared lighting in the vehicle are a good idea. This means that only a minority of those surveyed rejected the concept.

Finally, we can say that there is demand for a fatigue/alertness assistant in markets where there is high customer acceptance of technology, such as Germany. There is a need to take a critical look at the expectations that customers place on this type of system. Customers have indicated that the doze off alarm is more important than the fatigue detector. This function should be available on the system to ensure that customers believe that it will provide tangible support.

Authors' note:

The technical requirements and specifications regarding fatigue detection and monitoring outlined in this paper reflect current thinking based on research activities conducted to date. These requirements are subject to change based on ongoing and future research and development efforts in technical disciplines as well as in the behavioral and medical sciences. The development of such systems is necessarily an iterative process that can be described only in broad terms. Individual results over time will determine the nature and content of specifications that can form the basis of production systems.

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BEHAVIOR ADAPTATION TO CAR IMPROVEMENT

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ABSTRACT

Compared to cars designed in the 80[ies] or in the early 90[ies], new cars exhibit major improvements, especially in terms of driver assistance and road handling. To quantify the influence of these developments on drivers' behavior, a study was carried out on a test track with two cars of different generations in the summer 2004.
36 male drivers, from 28 to 52 years old, were recruited in the general public to participate to the experiment. They were dispatched in two homogenous groups. For each group, drivers were asked to drive twice the same car: the first time, they familiarized freely with the car and the road during about one hour ("free driving phase"); three weeks later, they were invited to drive on the same road as if they were late or in a hurry ("rush driving phase"). The track is divided in two portions: a "main road" (3.5 km) and a "secondary sinuous road" (1.9 km). There is no traffic on the test track. Drivers' actions on the car's controls were recorded and synchronized with dynamic parameters and video recordings.
This paper is focused on the influence of car modernity and driving consigns on longitudinal and lateral solicitations of the car. Driver's behavior is analyzed in terms of longitudinal acceleration, deceleration (braking) and lateral acceleration when negotiating short curves.

Key words: driver behavior adaptation, longitudinal acceleration, lateral acceleration, ESP, test track, normal driving, emergency driving

INTRODUCTION

Most previous studies focused on the effect of one driving assistance systems and tend to compare driver's behavior with and without the system. The originality of our research is that it takes into account not only the global effect of cars' improvements (road handling, vehicle chassis including steering wheel assistance, suspension, braking, soundproofing...), but also drivers' "psychological" effects (anticipated confidence, external aspect, dimension of the tires…) before and during driving.
The effect of cars' improvement on driver's behavior is not usually quantified. Only a few studies were carried out around this important topic. For example, Stein Fosser [1] has studied some effects of particular measures to improve safety, like Antilock Braking Systems (ABS) or airbags. He presumed that such systems *produce changes in behavior that reduce the effects of the measures or counteract them entirely. The behavior adaptation that follows such measures is often termed "risk compensation" and it can partly or completely offset the intended safety effects of measures*. In this same study, the author showed the importance of being, or not, aware of the safety measure on someone's car (for example, airbags) which would be more important than the measure's feedback (for example, ABS on a slippery road in terms of steering performance and braking).
New cars exhibit major improvements in terms of driver assistance and road handling. To quantify the influence of these developments on drivers' behavior, a study was carried out on a test track with two cars of different generations: Renault MEGANE 1 and Renault MEGANE 2 (Figure 1) are chosen as an example of cars of 90[ies] and 2000[ies]. The two vehicles have almost the same power to mass ratio. By observing several driving measures on these cars, it is possible to compare the use of them by two homogenous groups of drivers. Each subject drives one car twice.

Renault MEGANE 1 (old vehicle) — Renault MEGANE 2 (recent vehicle)

Figure 1. Two experimented cars

MATERIALS AND METHODS

Even this study is related to the effect of car improvement on driver behavior in general, accidentological stake concerning lateral control of vehicles has guided some choices in the experimental protocol. For example, in France, Loss of control-induced accidents represent 20 % of personal injury accidents. This rate is close to 40 % in curves [2]. A statistical study conducted recently by the LAB using real-world accident database [3] showed that in accidents with only one vehicle:

- drivers having 25-54 years old represent 52 % of accidents,
- male drivers are implicated in 76 % of the cases,
- 69 % of accidents happen out of agglomerations,
- for this kind of accidents, 10 % are fatalities and 80 % are injured (20 % severely).

This information is needed for example in the choice of drivers' population, test track characteristics…

Test track driving

To be able to compare the effect of car developments on drivers' behavior, the track was the same for all of them. The road has a length of 5.4 km - 3.5 km "main road" and 1.9 km "secondary sinuous forest road" (Figure 2). Straight lines have a maximum length of 350 m and short curves have radius from 30 m to 200 m. For safety reasons, there is no traffic on the test track.

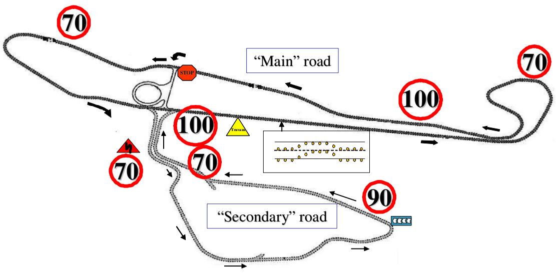

Figure 2. Test Track

- Main road (3.5 km): Figure 3 and Figure 4
- Secondary road (1.9 km): Figure 5 and Figure 6.

Figure 3. Main straight road

Figure 4. Main sinuous road

Figure 5. Secondary sinuous road

Figure 6. Secondary sinuous road

Test vehicles

The vehicles chosen for the experiment were MEGANE 1 and MEGANE 2. MEGANE 1, produced in 1998 (approximately 8 years old) is selected as an "old" car and MEGANE 2 produced in 2004, is selected as a "recent" car. Both cars have ABS. The recent one also has ESP (Electronic Stability Program). The power of general two cars is 66kW (137Nm) and 83kW (152Nm) respectively and engine capacity of both of them is 1.6L. "General performance" [1] is 140. The general performance of recent car is 150, 7 % higher than old car.

Table 1.
Test Vehicles characteristics

	MEGANE 1	MEGANE 2
Birth	1998(8 years old)	2004
Mileage	55000 km	3000 km
Engine capacity	1.6L	1.6L
Power	66kW / 137Nm	83kW / 152Nm
Equipment	Air conditioning +ABS	Air conditioning+ ABS + ESP
General performance	**140**	**150 (+7%)**

Embedded sensors allow to measure drivers' actions on the car's controls (steering wheel and pedals). These measures are recorded and synchronized with dynamic parameters (speed, accelerations…) and video recordings. Four

[1] criterion based on tire characteristics, aerodynamic, maximum speed and time to run 100, 400 or 1000m…, and used by Renault dynamic experts

cameras and a microphone record events taking place inside the car and on the road.

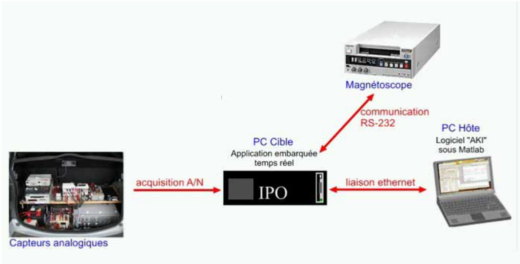

Figure 7. Instrumentation of MEGANE 1 (old vehicle)

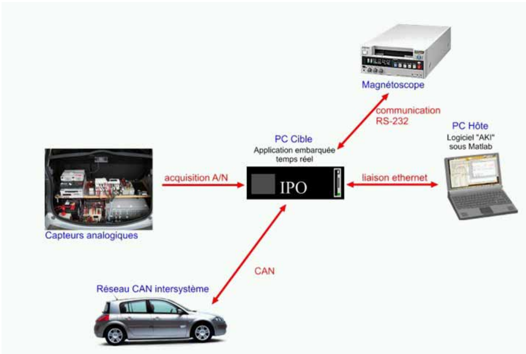

Figure 8. Instrumentation of MEGANE 2 (recent vehicle)

Figure 9. Example of driving video recording

Drivers

36 male drivers (volunteers) participated in the experiment. They were recruited according to their age, driving license acquisition year and annual mileage so as to be representative of drivers involved in loss of car control accidents in France. Their ages vary between 28 and 52 years old (Table 2). The license years vary between 10 and 24 years (median of 19 years), and their annual mileage is between 2000 and 32500 km a year (average of 17000 km). The sample is divided into two homogeneous groups:. nineteen (19) volunteers of group 1 were asked to drive MEGANE 1 and seventeen (17) volunteers of group 2 were asked to drive MEGANE 2.
In all the Tables, Group 1 means old car (MEGANE 1), Group 2 means recent car (MEGANE 2).

Table 2.
Drivers' characteristics

	Age (year)		Driving License (year)		Annual miles (km/year)	
Group	**G1**	**G2**	**G1**	**G2**	**G1**	**G2**
Minimum	29	28	18	10	2000	2000
Maximum	52	52	24	23	32500	25000
Medium	39	39	19	19	20000	16500

Experimental protocol

After brief questionnaire and alcohol test, each group is asked respectively to drive MEGANE 1 and MEGANE 2. Each group drives twice respectively. At the first time, they are asked to drive freely to be familiarized with the car. They are free to choose their driving rhythm ("free driving phase"). In this phase, they drive first lap without data acquisition, and then they have one hour for normal driving with a short rest (30 seconds) after each lap. This phase allows us to collect enough data on the driving style and physical state of the subject.
Three weeks later, they were invited to drive on the same road as if they were late or in a hurry ("rush driving phase"): they had to drive on the same track with a temporal objective they did chose. They have not to take unmeasured risk. This phase allow to see what margin they keep when negotiating curves, and how they will accelerate/decelerate in straight road. They were asked to drive 3 laps 3 times (a short rest after every 3 laps). In conclusion, all subjects drove about 16 laps with data acquisition: **7 laps** for "free driving phase" and **9 laps** for "rush driving phase". At the end of the task, they were interviewed by a psychologist about their feelings and their driving experience.

DEFINITION OF VARIABLES

Variables can be divided into two dynamics groups: speed and acceleration. Acceleration variables can be divided in two groups: longitudinal and transversal acceleration variables (Figure **10**). Both longitudinal and transversal acceleration are measured. All variables are calculated for each subject and for **each lap**. This paper is focused on eleven variables:

(Longitudinal) Speed variables

- VmoyTour : average speed (by lap)
- VmoyLD : straight road average speed
- VmoyVG : curve road average speed

Longitudinal acceleration variables

- ALPerc80: longitudinal acceleration 80percentile
- AccelMax: maximum longitudinal acceleration

Longitudinal deceleration variables (braking)

- ALPerc8: longitudinal acceleration 8 percentile
- DecelMax: maximum deceleration

Transversal acceleration variables

- ATPerc92: transversal acceleration 92 percentile (left turn)
- ATMaxG: maximum transversal acceleration (left turn)
- ATPerc4: transversal acceleration 4 percentile (right turn). It corresponds also to 96 percentile if absolute values are considered
- ATMaxD: maximum transversal acceleration (right turn).

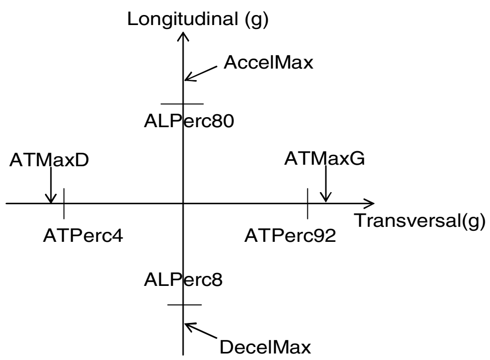

Figure 10. acceleration variables

STATISTIC TEST

To study the difference in the use (driving) of the 2 cars by the 36 volunteers, the eleven variables described above are chosen (Figure 11). Pink lines mean subjects of group 1 and black lines mean subjects of group 2. Red lines mean characteristic values of Group 1 and Blue lines mean those of Group 2. **Bold lines mean average value** of each group, dotted lines mean plus (minus) of variance value of each group.

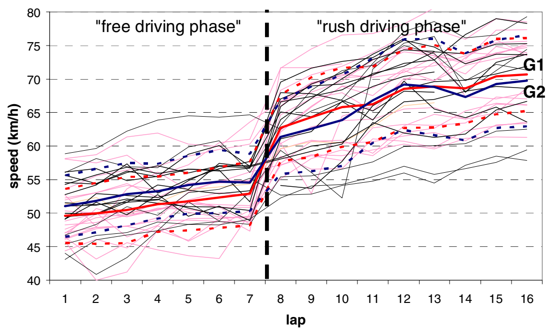

Figure 11. Example data of each variable

Data selection

To eliminate bias due to stabilized / not stabilized driving rhythm, it was decided for the two driving phases ("free" and "rush") that statistical tests are systematically conducted using, in one case all the data collected in all laps, and in the other case only the data on last laps: the 4 last laps for "free driving phase", the 3 last laps for "rush driving phase".

Statistic method

Generally speaking, to compare performance of two cars, comparison of mean is common. This method is largely divided into two parts: nonparametric and parametric ANOVA. Parametric method is used when data are normally distributed, otherwise nonparametric method is recommendable. To characterize the type of data distribution (normality test), "Kolmogorov-Smirnov test" and "Sharpiro-Wilk test [1]" were used.
If data are normally distributed, repeated ANOVA is used. Otherwise, after Mann-Whitney test for each lap is executed, all significances of each lap are integrated. Integrated level is made using the following formula:

Integrated p-value= $1-(1-P_1)\cdot(1-P_2)\cdot\ldots\cdot(1-P_n)$

where p-value corresponds to the Mann-Whitney test result when comparing recent car with old one.

Lap (test track)	1	2	…	n
p-value	P_1	P_2	…	P_n

RESULTS

Graphs

Following graphs give a comparison between the real use of the two cars, in the two driving phases, and for the eleven variables:

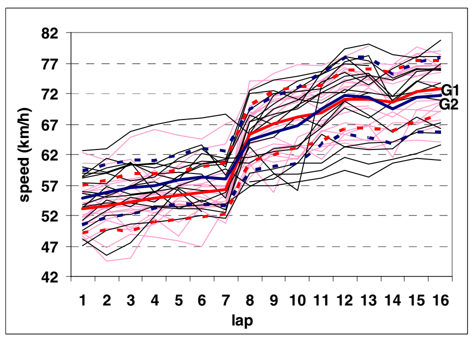

Figure 12. VmoyTour

[1] Shapiro-Wilk test is appropriate when the number of total population is less than 50.

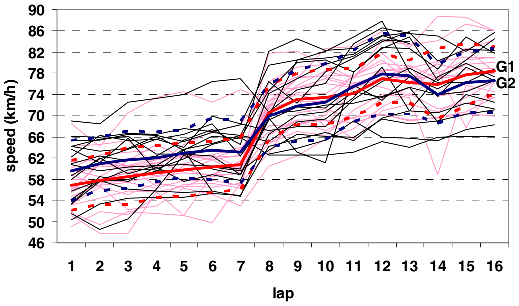

Figure 13. VmoyLD

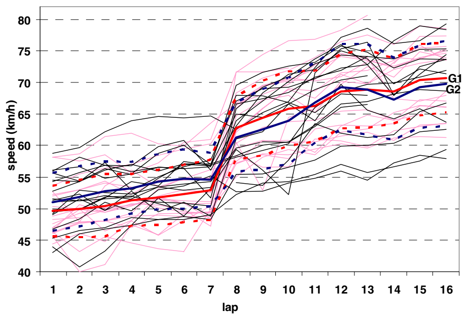

Figure 14. VmoyVG

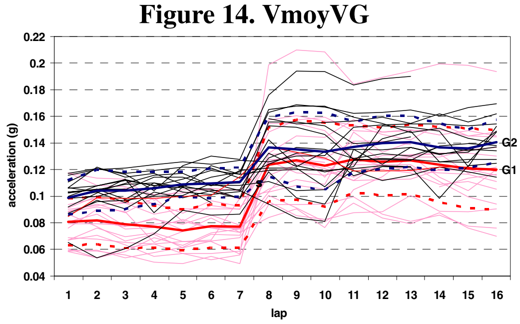

Figure 15. ALPerc80

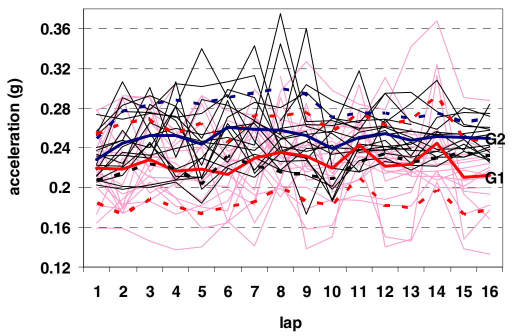

Figure 16. AccelMax

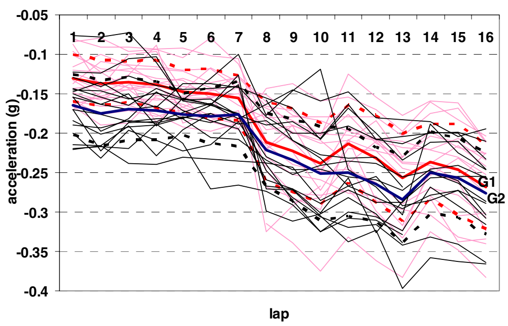

Figure 17. ALPerc8

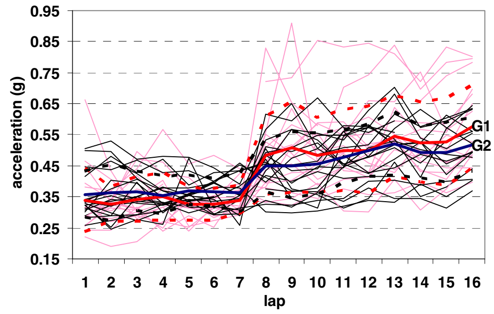

Figure 18. DecelMax

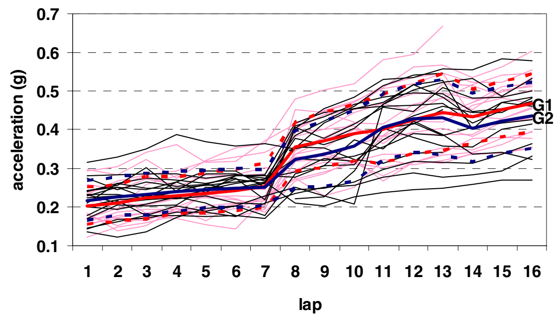

Figure 19. ATPerc92

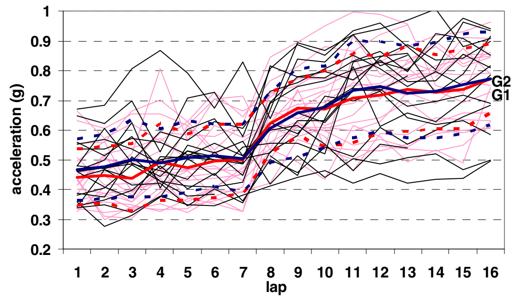

Figure 20. ATMaxG

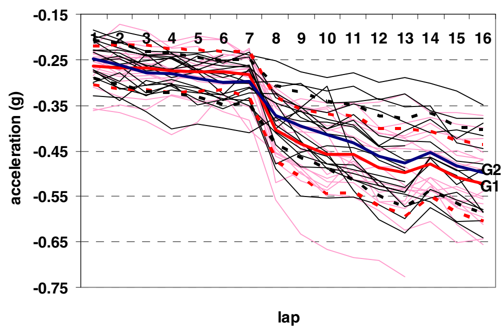

Figure 21. ATPerc4

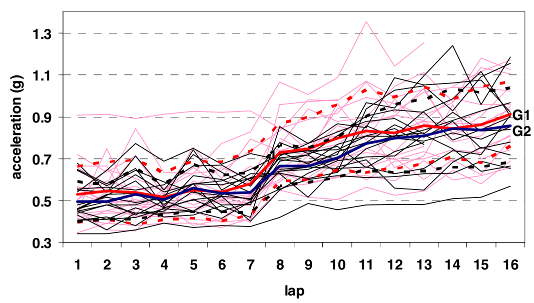

Figure 22. ATMaxD

Statistical Results

If p-value is less than 0.05 (significance level), there is significant difference between the 2 groups of drivers. In **Table 3**, results are described:

Table 3.
p-value of each variable

Variable	p-value of free driving phase: With all data (all laps)	p-value of free driving phase: With 4 last laps data	p-value of rush driving phase: With all data (all laps)	p-value of rush driving phase: With 3 last laps data
Vmoy	.656*	.457*	.999*	.570
VmoyLD	.075	.086	.561	.380
VmoyVG	.729*	.487*	.999*	.952*
ALPerc80	.002*	.000	.722*	.069
AccelMax	.547*	.196	.692*	.100*
ALPerc8	.248	.516	.386	.556
DecelMax	.992*	.980*	.999*	.979*
ATPerc92	.996*	.980*	.480	.290
ATMaxG	.999*	.996*	.999*	.887
ATPerc4	.986*	.883*	.413	.401
ATMaxD	.999*	.999*	.514	.647

* means nonparametric repeated ANOVA

- Average speed: in the 2 driving phases, there is no significant difference on drivers' behavior between old and recent car for the three speed variables (all the lap, straight lines only, curves only). That is, we can not say that drivers in the recent car tend to drive faster than those in old car. For the three last laps of phase1, the average of speed of Group 1 is 55.3, 55.8 and 56.4 km/h while 57.8, 58.3 and 58.1 km/h in Group 2 (Table 4).
- Longitudinal acceleration: in both phases, there is no significant difference between two cars in AccelMax. The only significant difference between these cars is observed in ALPerc80 parameter (which could be explained by certain differences in performance between two cars?) in free driving phase, but it is not the case in rush driving phase. For example, for the three last laps of "free phase", the average of 80 percentile of acceleration of G1was 0.074g, 0.078g and 0.077g while 0.109g, 0.109g and 0.110g in G2 (Table 4). It is also interesting to note that for the two cars, there is no significant difference on maximum acceleration between the two driving phases. This could be explained by car acceleration "limit" (depending especially on the engine power).
- Longitudinal deceleration: both DecelMax and ALPerc8 have no significant difference between the 2 groups in both phases, despite the difference between braking systems of the 2 cars. For the three last laps of phase 1, the average of 8 percentile of acceleration of G1 was -0.148g, -0.150g and -0.156g while -0.176g, -0.178g and -0.176g in G2 (Table 4).
- Transversal acceleration: In both phases, there was no significant difference between two cars in all transversal acceleration variables. For example, for the three last laps of phase1, the average of 92 percentile of lateral acceleration of G1 was 0.234g, 0.243g and 0.254g. Those of G2 were 0.245g, 0.249g and 0.249g (Table 4).

Table 4.
Average values of free driving phase

Variable	Group	"Free driving phase" 4th	5th	6th	7th
VmoyTour (km/h)	1	54.9	55.3	55.8	56.4
	2	57.0	57.8	58.3	58.1
VmoyLD (km/h)	1	59.3	59.7	60.3	60.9
	2	62.1	62.8	63.5	63.1
VmoyVG (km/h)	1	51.3	51.7	52.3	52.9
	2	53.3	54.2	54.7	54.6
ALPerc80 (g)	1	.077	.074	.078	.077
	2	.106	.109	.109	.110
AccelMax (g)	1	.217	.219	.213	.229
	2	.253	.243	.261	.258
ALPerc8 (g)	1	-.138	-.148	-.150	-.156
	2	-.172	-.176	-.178	-.176
DecelMax (g)	1	.351	.325	.326	.340
	2	.355	.371	.365	.363
ATPerc92 (g)	1	.230	.234	.243	.254
	2	.240	.245	.249	.249
ATMaxG (g)	1	.492	.473	.495	.501
	2	.490	.509	.514	.506
ATPerc4 (g)	1	-.274	-.275	-.275	-.283
	2	-.279	-.291	-.300	-.297
ATMaxD (g)	1	.552	.543	.579	.579
	2	.558	.532	.537	.537

Table 5.
Average values of rush driving phase

variable	group	"Rush driving phase" 7th	8th	9th
VmoyTour (km/h)	1	70.6	72.4	72.8
	2	69.5	71.4	71.8
VmoyLD (km/h)	1	76.0	77.8	78.4
	2	74.0	76.3	76.6
VmoyVG (km/h)	1	68.6	70.4	70.7
	2	67.3	69.3	69.8
ALPerc80 (g)	1	.124	.120	.120
	2	.136	.136	.141
AccelMax (g)	1	.245	.210	.212
	2	.252	.250	.250
ALPerc8 (g)	1	-.237	-.247	-.268
	2	-.250	-.257	-.277
DecelMax (g)	1	.524	.526	.576
	2	.492	.492	.517
ATPerc92 (g)	1	.434	.451	.469
	2	.404	.422	.436
ATMaxG (g)	1	.727	.737	.772
	2	.731	.754	.772
ATPerc4 (g)	1	-.479	-.508	-.521
	2	-.452	-.482	-.497
ATMaxD (g)	1	.842	.862	.912
	2	.843	.836	.858

DISCUSSION

With this macroscopic analysis level, we didn't demonstrate significant differences in the use of the two different cars, except in maximum longitudinal accelerations. However, the comparison between average speed in straight lines is at the limit of the statistical significativity (p=0.08) which could be explained by the probable quite difference between car's performances. This result must be relativized: no significant difference between average speed in the curves of the test track. In addition, it is possible that the presence of an experimenter next to the driver in the vehicle, especially in rush phase, can induce an over-confidence, and maybe unmeasured objective risk.

It is probable that representation of everyone when driving a car for the first time is confirmed or infirmed, positively or negatively, with the experience (driving). It seems among this study that driver, even if he drives a new modern car with more assistance systems (vehicle chassis, soundproofing, braking) and a better external aspect, (aerodynamic shape, dimension of the tires…) than old vehicle, he does not have systematically a different behavior in both, normal (free phase) and hurry driving (rush phase). We can assume that global representation before and during driving would mostly condition his behavior adaptation (with a more or less risk taking) more than his just awareness about this or that assistance.

These interpretations are based in a great part on the exploitation of the interviews with the psychologist at the end of the driving tasks. For example: from the interview with the psychologist at the end of "rush driving phase", some drivers were very surprised (positively) by the road handling of the old car, which is opposite to what they supposed it to be before driving. But of course, in all cases, the driving profile or style ("slow", "normal" or "active") has also an evident influence on the use of the vehicle, independently of its characteristics.

As in any test track experiment, some bias can not be avoided. People don't drive their own cars, they are asked to drive "freely" or "in a hurry" with an experimenter in the car, on a test track they don't know. The "free" phase is very important: subjects take one hour to "test" the vehicle, to memorize the road and its environment, and also to discuss a little with their passenger. We can assume that these bias will decrease with time (or laps), and drivers will use their own driving habitudes as in real road.

In this paper, guidelines about drivers' behavior are presented. There is a probability to be exaggerated in some variables in rush driving phase. Generally people drive their own cars with more care because they don't want to change regularly car accessories (like tires or brakes) nor losing money because fuel consummation.

The result of this pilot experiment on the effect of car improvements must be taken with care regarding to its limits: representativity of drivers (especially their number) and the test track (in terms of geometry, state of the road…), lack of traffic…

The LAB conducted in 2003 another experiment with 83 drivers on a 50 km real road including highways and secondary roads. Subjects drove a Peugeot 307 vehicle. Even experimental protocol is different from the present study, it is interesting to observe that the medians of maximum transversal acceleration are quite similar: 0.55 g against 0.59 g respectively (Figure 23).

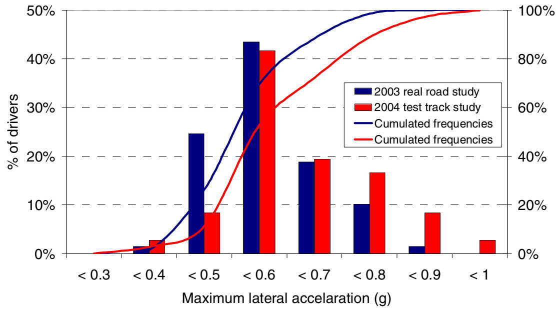

Figure 23. Comparison with another study

CONCLUSION

In the respect of longitudinal acceleration, there is significant difference between the use of the 2 cars in 80 percentile of longitudinal acceleration (ALPerc80) by the 2 groups in "free driving phase", but not in "rush phase". However, there is no significant difference between general driving behavior of the 2 groups in speed variables and transversal acceleration variables.

To analyze this part, deeper inspection is necessary. In addition, big dispersion between the drivers, even in the same Group, are observed at least on the eleven variables analyzed in this paper.

This study using general or macroscopic variables such as average speed per lap must be continued by a more detailed or microscopic analysis of the driver behavior and his strategies when negotiating some particular curves for example.

This study was conducted for instance only with objective variables. Further analysis will integrate subjective data collected by the psychologist at the end of all driving tasks. This would give relevant information about the real use of the vehicles and how drivers perceive/choose the level of solicitations in the two driving tests, and also a comparison between the two cars

Despite the lack of quantitative studies on the effect of cars' improvements, and even if some active safety devices or any other driver assistances would change their driving behavior, it must be kept in mind that improvements in passive safety by reducing the number of injuries today allow an

important compensation of any perverse effect of assistances.
The first macroscopic results of this study on behavior adaptation to car's improvements shows the interest of focusing on the global representation of the car than on an isolated effects of this or that assistance.

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EMERGING CCD-CMOS TECHNOLOGY:
AN OPPORTUNITY FOR ADVANCED IN VEHICLE SAFETY SENSORS

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ABSTRACT

Passenger airbags are currently designed for the optimal support of a 50-percentile adult in a crash, reducing the risk of severe injury for a maximum range of occupants. However, such a fixed-level, high-energy airbag deployment can be extremely dangerous for very small occupants, for example the 5-percentile woman or children in infant seats. For this very reason, new standards such as FMVSS 208 (Federal Motor Vehicle Safety Standard No. 208) include differentiated airbag deployment strategies according to occupant classification.

IEE, Luxemburg, develops and manufactures such occupant classification systems. An example of which are the sensor mats made by IEE, which tier one automotive suppliers use globally for their seating systems. These mats measure the two-dimensional pressure profile in the seat area, and deliver these values for a pattern recognition algorithm as basis for occupant classification. An innovative development project, currently being conducted by the company, is an optical system which can provide three-dimensional information on the occupant, enabling highly differentiated classification. This system is projected to become commercial by 2007.

LEGAL AND SENSOR REQUIREMENTS FMVSS 208

According to FMVSS 208, restraint systems have to be designed in such a way that, in the event of an impact, they create less risk of airbag induced injuries, particularly for small women and young children.

To achieve these goals FMVSS 208 proposes three airbag deployment strategies in the event of a crash:

'Suppression In Case Of Presence', if sensors detect an infant seat, occupied by a child up to six years old, and deployment of the airbag, if a person in the range of a 5-percentile woman or taller is detected,

'Low Risk Deployment' (LRD) means that the airbag deployment does not harm an occupant at close range from the airbag module. For verification a dummy is positioned close to the dashboard while the airbag is deployed and the corresponding dummy injury criteria must not bypass certain values to be in line with the low risk deployment strategy. Sensing technology can be used to switch the airbag to a low output mode.

'Dynamic Automatic Suppression Strategy' (DASS), meaning that in addition to a qualitative occupant classification (as with LRD), the occupant's current position in relation to the airbag deployment door (in-position, out-of-position) has to be traced and the airbag is suppressed if the occupant is at close range to the airbag deployment door.

'FULL' LRD, as well as the sophisticated DASS strategy, require highly-sensitive, advanced occupant classification systems, which can deliver the complex data set necessary to take the best possible decision.

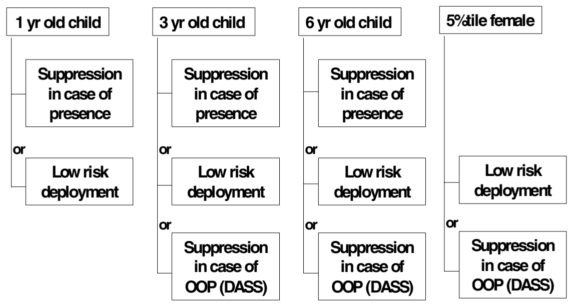

Figure 1: Different certification strategies proposed by the NHTSA FMVSS208 final rulemaking

For the standards '3 year-old child', '6 year-old child' and '5-percentile woman', the LRD strategy is already widely used. For the 1 year-old child in a rear-facing infant seat (RFIS) and placed on the passenger seat, both 'Suppression' and LRD are also included in the standards. However, airbag technology does not yet permit energy limitation, as required by LRD. In such cases, today's systems are changed to a controlled switching off of the airbag. This ensures at least a certain minimal security for all accident scenarios.

Dynamic Automatic Suppression Strategy (DASS) provides considerably more opportunity. The newly-developed IEE 3D-System provides the necessary information for differentiated recognition. In all cases of occupation, including the RFIS and out-of-position occupation, this system provides the essentials to adapt correspondingly-modified airbag modules to the 'Low Output Mode'.

Although a DASS strategy for the 1 year old child is not yet approved and optimized, an airbag strategy for real life child seat scenarios could be as follows:

- an RFIS is always considered as 'out-of-position',
- for a FFCS a specific airbag suppression zone (ASZ) could be defined. Only if the child is out of this area, the airbag will be deployed (with less energy).

Accordingly, the 3D system allows an airbag strategy matched to the situation (RFIS / FFCS / person OOP / person in position), rather than the presently insufficient differentiated strategy based on age. Suggestions for respective test procedures have been submitted for assessment by the US NHTSA (National Highway Traffic Safety Administration).

Requirements for the specific sensors may distinctly differ, depending greatly on the OEM's own safety strategy and the individual design of the car (small roadster or large truck). On the other hand, the installed sensor families should meet differing safety requirements in the US and other parts of the world.

RELATED WORK

Current technology for occupant classification systems is mainly based on pressure sensors installed inside the vehicle seats, for e.g. , the IEE OC® sensor. However, with vision based system, the position of the occupant and orientation of the child seat can be also be determined. Different approaches in the vision systems can be broadly divided into different categories based on the sensing technology. Sensing technology is either based on the video camera (for example see [1]) or on stereo-vision based range images ([2], [1], [3], [4]). In the reference [2], a 3-D vision system using stereo cameras was developed. It was argued that stereo vision offers a potential to produce detailed results within real-time constraints and it suited for irregular environment. In references [3] and [4], stereo-based range data was used to detect whether and where humans are inside a vehicle. In [1], Krumm and Kirk developed a system based on both intensity (2-D) and stereovision-based (2 and half-D) range data and found for each class the principle components, with which nearest neighbor classification was performed. However, these methods are based on stereo vision which are sensitive to varying illumination conditions inside the car. Furthermore, extra equipment and processing is required to capture 3-D information from the stereo images. Another important aspect for a serial production is the cost of such a system. Hence, above systems are definitely not cost effective as they require two cameras for capturing the scene, and the need of important processing power and time.

REAL TIME 3D TIME-OF-FLIGHT IMAGING

Key element of the new optical occupant classification system developed by IEE is a 3D Modulated Light Intensity (MLI) System. The system's ability to deliver three dimensional images is based on the measurement of the phase shifts of the modulated emitted light signal and its reflection by the object. The smaller the difference, the shorter the distance between the object (the occupant or the infant seat) and the sender/recorder-combination. Thus every snap-shot delivers an image with differentiated depth information for the complete detection area.

Other time of flight (TOF) technologies apply a different principle emitting a short pulse of high optical intensity (Figure 2). The light velocity turns into a flight time of only 66ps per meter distance (resolution 1cm). These short periods require sensors of extremely high sensitivity. In order to obtain a resolution in the 1 cm range, the frequency bandwidth has to be greater than 10 GHz. This in turn creates high energy consumption, which is difficult to supply in the automotive industry.

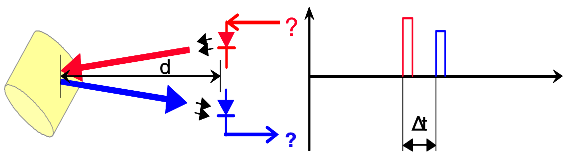

Figure 2: Light pulse based time of flight. The turn around time of an emitted light pulse is measured and put into relation of the distance $d=c\cdot\Delta t/2$

The IEE MLI System uses a different approach. By emitting a continuous wave-modulated cone of light, with a defined wave length, the phase difference between sent and detected signal can be measured and to generate a topographic image provided afterwards to the classification algorithm (Figure 3). This principle, which consumes much less energy, is the basis on which the IEE system works.

A key feature is an active, non-scanning light source, which emits amplitude modulated near infrared light (NIR) and thus delivers a homogeneous illumination for the camera field of vision (FOV).

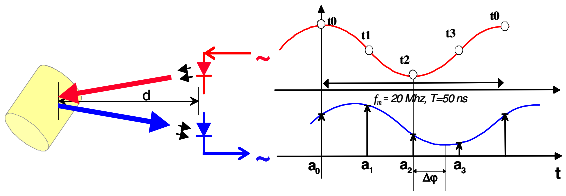

Figure 3: Detected light intensity as a function of time. The sinusoidal modulation (top curve) of the illumination causes a periodically modulated signal in the receiver (lower area). The phase offset can be computed by evaluating the signal amplitudes a_0, . . . ,a_3 at 4 different temporal positions t_0, . . . ,t_3.

Due to the travel time of the light to and from the target, the phase of the detected beam is retarded compared to the phase of the modulation signal in the transmitter (see Fig. 3). This phase delay can be measured and directly converted into the distance between the target and the camera. The amplitude and phase of the received signal can be retrieved by synchronously demodulating the incoming modulated light within the detector. Demodulation of a received modulated signal can be performed by correlation with the original modulation signal (cross-correlation). The measurement of the cross-correlation function at selectively chosen temporal positions (phases) allows the phase of the investigated periodical signal to be determined [5]. With the selected temporal positions t_0 = 0°, t_1 = 90°, t_2 = 180°, t_3 = 270°, one can calculate the phase offset via the formula

$$A = \arctan\left[\frac{a_3 - a_1}{a_2 - a_0}\right] \quad (1)$$

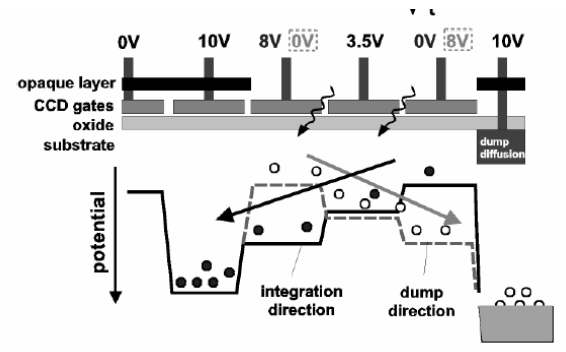

Figure 4: Cross sectional view of the CCD pixel layout

Figure 4 shows the layout and a cross-section view of the pixel. By applying proper gate voltages to the photo gates, the potential gradient in the semiconductor is influenced. If the voltages of the photo gates are changed synchronously with the modulated light, optically generated charge carriers move either to the integration gate (IG) or are dumped to the dump diffusion. This process is repeated until the integration gate has accumulated a sufficiently large signal. The four amplitudes a0; : : : ; a3 are obtained by subsequently repeating this process at 4 different phase offsets [5]. The IEE sensor is based on a 4 tap-pixel sensor, a design which acquires the 4 amplitudes simultaneously.

With regards to system accuracy, the assumption is made that depth is not limited by electronics/noise of the detection system but only by the photon shot noise (a physical limit). Achieved accuracy can therefore be calculated, and depends on

- background illumination and other noise sources, and
- on the object reflectance and its distance to the sensor.

The dependence of reflectance and background noise is calculated and read out as relative fault of the amplitude value. This ensures adequate action can be taken should measurement error become too great.

Moreover, the mean amplitude value per pixel (corresponding to the intensity of the reflected light) allows the generation of a grey scale image of the complete detection area.

In summary, the main advantages of the IEE 3D-Camera-Solution are the simultaneous provision of distance information and accuracy, combined with a real life b/w image.

CAMERA HARDWARE

A monocular camera is integrated in the vehicle's center overhead module, enabling a field of view of 120° × 90° (136° in the diagonal) with a resolution of 50 by 52 pixels. Using a near infrared light, unperilous to the human eye, at a wavelength of around 890nm, sensing range is up to 750cm (limited by the modulation frequency of the light). At a distance of 150cm, depth accuracy is at 2.2cm.

The sensor as key component of the whole system is realized in a 4-tap pixel architecture. This 4-tap pixel is built in form of two single 2-tap structures. These two structures are controlled in a way that the phases 0° and 180° as well as the phases 90° and 270° can be captured in parallel.

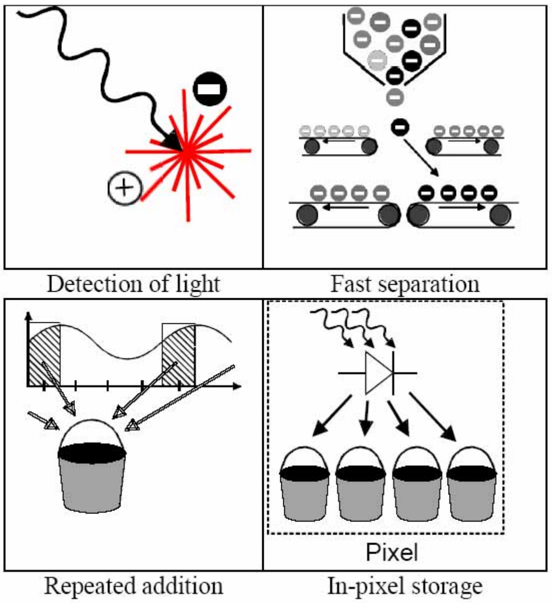

Figure 5: Key function of the imager: Detection of light, fast separation of the generated electrons into the 4 different taps; repetition of the measurement until reliable signal generated and storage in of signal in pixel before reading out complete imager

The sensor transforms the incoming optical signal into electron-hole pairs. The efficiency of this process is basically limited by the inherent quantum efficiency of the chosen semiconductor material and the fill-factor of the optical sensor. In order to demodulate the incoming 20MHz signal, a fast charge separation and transport has to take place within each pixel. The sensor's ability to separate and transfer the charges to the corresponding output node represents the demodulation contrast (2), which is defined as the ratio of the demodulated amplitude A (1) and the acquired offset signal B,

$$C_{\text{demodulation}} = \frac{A}{B} \qquad (2)$$

Within one single modulation period of 50 ns (corresponds to the modulation frequency of 20 MHz) typically only a few photons impinge on each individual pixel and hence only a few photoelectrons are generated in the pixel. For a broad range of operating conditions – statistically spoken – even less than one electron is generated per modulation period. The repeated addition of the electrons generated over numerous modulation periods is thus necessary and represents a very important feature of the current embodiment. The approach of adding charges almost noise-free at the pixel level is tightly linked to the CCD pixel realized in a CMOS technology. This CCD pixel represents a key element to the success of the present technique. Moreover, the in-pixel storage and the processing of the different signal samples allow a high degree of flexibility in the readout process.

An automotive occupant monitoring system requires the development of a specific lens for the imager. The optical field of view for an occupant classification system must have an opening of at least 120° in the horizontal x-axis of the vehicle. The point spread function, a low f-number and an application specific anti-reflection coating are only some of the elements which characterizes this lens development.

The active light emitter is realized on a single board. The module is built in a chip-on-board (COB) technology. The illumination unit is covered by a structured lens in order to distribute uniformly and to guide the optical power to the regions of interest defined by the type of the application. The lens provides and additional safety margin to the requirements of the eye-safety norm EN 60851 class 1. The developed system emits a sinusoidal wave illumination front with a total mean power of 600mW.

STATIC CLASSIFICATION ALGORITHM

The algorithm related to the *static* occupant classification is a three step process (Figure 6): The pre-processing of the data recorded by the camera is followed by a feature determination step and the classification step. In a fourth step, the localization and the *dynamic* tracking of the occupant's head position complete the process

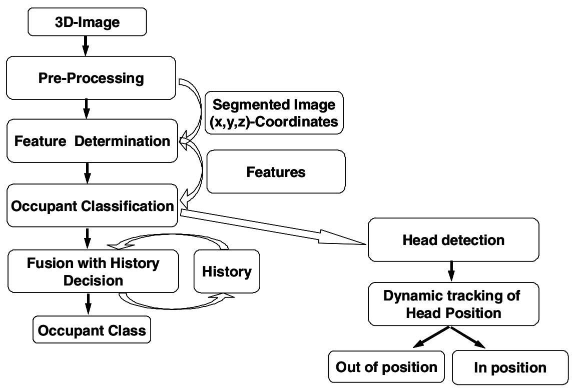

Figure 6: Algorithm flowchart for static and dynamic classification

Step 1: Preprocessing

Step one starts with a pre-processing algorithm to reduce the image noise and to eliminate the background. This involves a distance clipping of the range images; with this operation, range measurements are compared at each pixel location with a reference distance image that corresponds to the empty car interior. This allows removing any information regarding the background (or objects outside the car), i.e. a binary image can be generated where all background pixels are set to 0 and non-background pixels to 1. Once this is done they are then transposed as a three dimensional matrix in a Cartesian coordinate system (Figure 8).

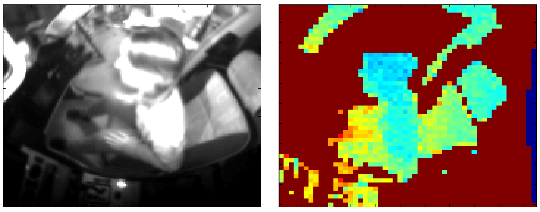

Figure 7: (left side) intensity image of the scene. (right side) color coded distance raw image before preprocessing

As the comparison with the inserted b/w image in Figure 7 and 8 proves, multiple information is available about the occupant's head, hands and shoulder position, as well as the occupant's position in relation to the car seat backrest.

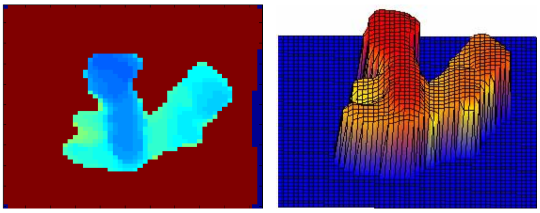

Figure 8: (left) preprocessed distance image; (right) topographical view

Step 2: Feature Computation

The second step covers the feature determination. For this purpose the recorded patterns are compared with basic patterns stored in a database, and subsequently characteristic analogies are used to characterize the content of the recorded image. As an example, the comparison of the patterns of an RFIS and a small adult who is sat upright uses indicators like the angles between the typically fixed structures (seat and backrest) and the variable structures, determined by the characteristic seat occupation (slope of the infant seat backrest, position of the person in relation to the car seat backrest). Once the differentiation between infant seat and person has been completed, and a person has been identified, the position of the person's head is detectable.

Feature computation aims in obtaining a compact representation of significant information required to describe the relevant parts of the original image. The goal is to preserve as much classification information as possible contained in the original image. This representation in terms of features should be computationally inexpensive so as to fulfill the real-time requirement. Descriptors are used that are either derived from the range frame itself or from the representation of the data in the Cartesian vehicle coordinate system. Shape features can be calculated directly from a binary 2D range image. By keeping only pixels in the vicinity of a discontinuity in range, an edge image can be calculated, for which contour descriptors can be derived, e.g. area, height and orientation of ellipsoidal contours. Additional features can be gained from the distribution of scatter points in the 3D vehicle coordinate system. Therefore, the coordinates are projected on certain planes and then fitted to different shapes like ellipses or planes. From the fitted shapes information are gained about the object for example its size, height, volume etc.. In total ten features are extracted, which basically establish the input of the classification algorithm.

Feature Subset Selection The computed features may contain redundant information. It is desirable to reduce the size of the feature set to gain robustness in classification performance. Feature subset selection aims at evaluating the effectiveness of individual features or their combination for classification, and selects only the effective ones. This requires an evaluation criterion and a search algorithm. The evaluation criterion evaluates the capacity of the feature subsets to distinguish one class from another or the classification accuracy, while the search algorithm explores the potential solution space. Sequential Forward Selection (SFS) search methods are used as search algorithms to select the feature subset. [6].

Step 3: Classification Method

Step 3 covers the action to be taken in the event of an accident , determined by situation and according to FMVSS 208 LRD. The system has to find out

- if the seat is occupied or not,
- if yes, if the seat is occupied by a FFIS or a RFIS, or
- if the seat is occupied by a small person, the pattern of which corresponds to either a 3 year-old child, a 6 year-old child, or a 5-percentile woman.

A polynomial classifier has been selected for the classification task. Classifiers based on polynomial regression are confirmed techniques [7]. The advantage with this approach is that it makes no assumptions about the underlying statistical distributions and leads, when using the least mean square error optimization criterion, to a closed solution of the optimization problem without iterations.

The discriminate function is given by,

$$d(v) = A^T x(v) \quad (3)$$

where A is a coefficient matrix which is to be optimized using training samples and is given by,

$$A = E\{xx^T\}^{-1} E\{xy^T\} \quad (4)$$

and $x(v)$ is the matrix of polynomials of the input feature vectors [7]. The discriminate function has as many components as there are classes defined to be discriminated. Finally the decision is based on the nearest neighbor principle,

$$Bestmatch = \arg\max_i (d_i(v)) \quad (5)$$

DYNAMIC TRACKING ALGORITHM

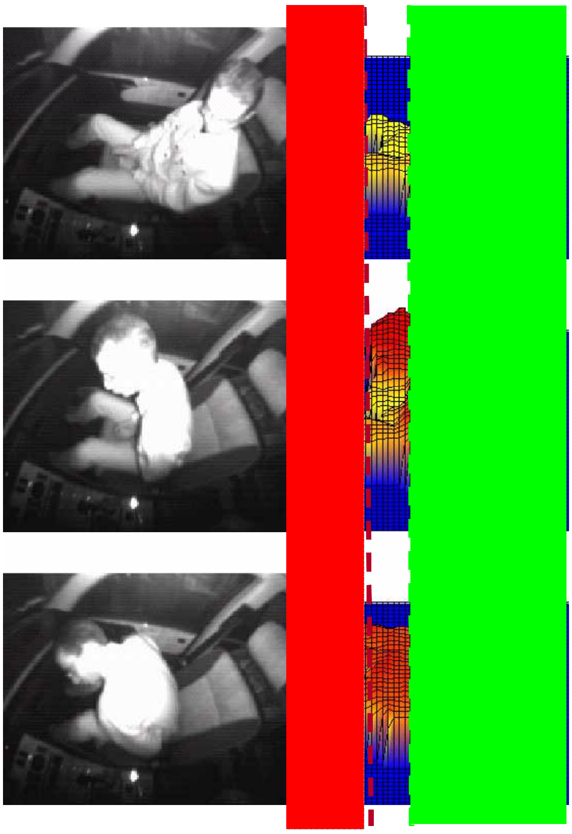

Figure 9: Definition of occupant in position (top image), occupant out of position (middle image) and occupant in critical out of position (bottom image)

The fourth and last step covers the recognition and tracking of the occupant's head position in relation to the dashboard surface. For this purpose, an edge detection and a morphological boarder separation are first carried out for the object of interest. From these results, the shapes of interest (ellipses comparable to a human head) are selected and finally a decision is taken, which of the ellipses detected are in accordance with a human head (and not with similar shapes such as a headrest or a football). The selected shape is then transferred into a Cartesian coordinate system. This data then permits the read out of the actual distance between the head and the place of airbag deployment in an x-, y-, and z-axis (and also to track the head position over a selected period of time).

With a 100Hz system refresh rate of the respective algorithm loop, the occupant's head position is determined and matched into one of three areas: 'in position', 'out of position' and 'critically out of position' (Figure 9). Following completion of this fourth step, all required data is available to take the right decision on how to deploy the airbag (either not at all, with reduced energy, or fully) in line with the Dynamic Automatic Suppression Strategy.

SYSTEM PERFORMANCE EVALUATION

To evaluate the performance of the optical occupant classification system, as developed by IEE, static classification tests were carried out in-house. For this purpose, a verification of the system according the FMVSS 208 requirements was performed. Subsequently the tests were expanded to include a 'misuse test scenario', as developed by IEE. Tests with separate alternating learning and testing sequences were conducted with an empty seat, both RFIS and FFIS, 'boosters', which are used to give older children a higher sitting position, and with five different population types of humans ranging from the 3 year-old child to the 95-percentile man (Figure 10).

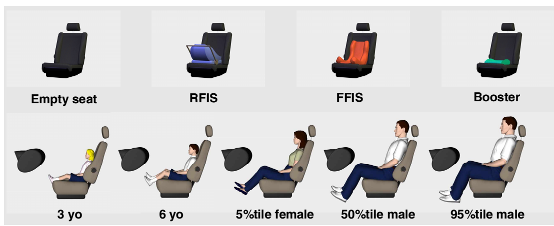

Figure 10: Overview of different occupant types used for static classification

To check the reliability of the test system, a range of different environmental influences were applied (i.e. temperature, vibration, contamination of air and camera lens, reflections and scattered light from different sources) as well as various occupant scenarios (i.e. blankets, reflecting glasses, magazines etc.). On top of that a large variety of torso positions and inclinations of the backrest was compared for the adult occupants.

The results are highly convincing, both for the test series where separate frames were analyzed, and for those with sequences of up to 50 frames (corresponding to a duration of half a second), where a simple filter was applied, significantly improving the results. For the separate frames series, the rate of correctly detected scenarios varies from 99.9% for the FFIS to 92.5% for the adult dummy, and for the sequences this rate varies between 100% (empty seat and FFIS) and 97.8% (adult dummy). The uncertainties in the distinction of persons versus RFIS result from very far forward bending persons, as no history buffer and filtering logic was applied.

%	Estimated Class			
True Class	Empty seat	RFIS	FFIS	P
Empty	97.6	0	0	2.4
RFIS	0	97.9	0	2.1
FFIS	0	0.1	99.9	0
P	0	7.1	0.4	92.5

Figure 11: Summary of classifier performance based on single images (no history), misuse scenarios included

%	Estimated Class			
True Class	Empty seat	RFIS	FFIS	P
Empty	100	0	0	0
RFIS	0	98.2	0	1.8
FFIS	0	0	100	0
P	0	2.2	0	97.8

Figure 12: Summary of classifier performance based on 50 consecutive images, misuse scenarios included (simple filter, no history)

It is to be expected that filtering strategies based on history buffers will of course eliminate misclassification of adults into the child seat category, as false-true criteria will back up the decision robustness of the system

Further tests show the limits of the test procedure, using living persons as test subject:

Distinction between adjacent size classes (e.g. 5-percentile vs. 50-percentile) is possible at a rate of about 90%.

Distinction between 5-percentile and 95-percentile is possible with almost 100% reliability.

A distinction between six year-old children and small adults is difficult to achieve with high confidence, as the normal distribution of the two classes overlap.

Children on a booster are particularly difficult to determine as their stature is close to the one of the 5%tile female.

%	Estimated Class	
True Class	3 - 6 year or smaler	5%tile or larger
3-6 year on booster	75.6	24.4
3-6 year	90.9	9.1
5%tile	7.5	92.5
50%tile	3.6	96.4
95%tile	0.1	99

Figure 13: Summary of classifier performance for different population percentiles

Beyond occupant classification, as described above, the IEE 3D-Camera can also be used for the head-tracker-test, as separate investigations have shown. Tests had been conducted according to the proposed FMVSS 208 S28.4, DASS test procedure (petition submitted in November 04). For this, a working group called “Smart Vision” (TRW, Siemens VDO, Bosch and IEE) had developed a dynamic OOP test tool to certify the performance of dynamic occupant detection systems in vehicles. Three different analyses – vehicle braking tests, sled tests with braking action, and MADYMO modeling – were conducted to determine the appropriate motion for the DASS tester.

Test results show that

- there is a certain vertical movement of the head, but its vertical position does not change significantly during the tests, and

- the maximum average occupant acceleration relative to vehicle interior is around 4.1 m/s^2. This determines (an additional safety factor included) a resulting acceleration of the tool of around 4.1 m/s^2 in the specific test setup.

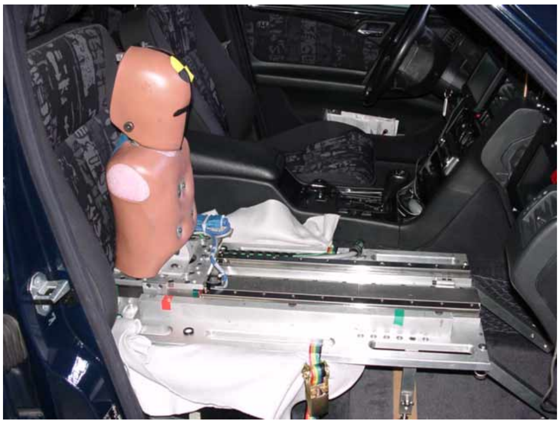

Figure 14: DASS test tool

This led to the definition of the following parameters for the DASS Head Tracker Test:

- Linear motion
- Acceleration: 0 to 1.2 g
- Deceleration: 0 to 3 g

- Velocity: 0.5 to 3.1 m/s
- Dummy height: 546 to 635 mm (adjustable)
- Maximum travel: 525 mm

Figure 15 shows a comparison between the positions of
- the test tool,
- the dummy head as recorded by the 3D MLI system, and
- the dummy head as detected by the Head Tracker software.

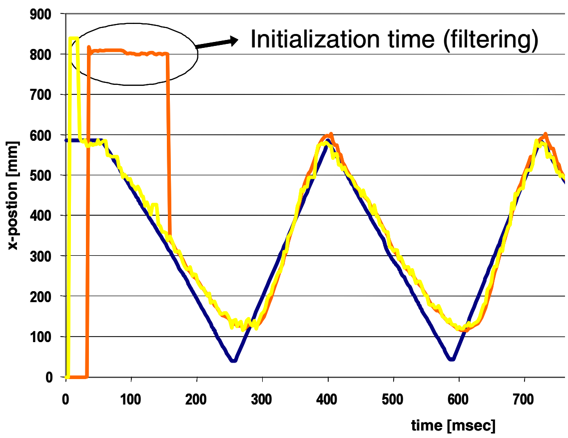

Figure 15: Head tracker performance. Motion of test device (blue); Head position seen by the camera (yellow) vs position of head defined by tracker (orange)

The short initial period of only a few hundred milliseconds, when the traces of tracker and camera deviate, marks the time required by the tracker to verify the correspondence of the identified 'ellipse' and the real object of interest, the head. The virtually perfect coincidence of both traces after this period proves that an optical sensor system, such as the IEE 3D camera, is also applicable for high speed tracking of a moving dummy.

SUMMARY

As the investigations described here prove, the 3D system developed by IEE provides distance data, which allows a highly precise recognition of the position of an object / a passenger in the FOV (field of view) and thus allows the application of LRD and DASS strategies. 3D data is directly available at the output of the sensor, therefore no additional image processing is required.

The test results also show that vision-based sensors will have their place in the automotive passive safety. Camera systems will be used in future in various passive and active safety applications. Stand-alone camera solutions, as well as a combination of different sensing technologies, will be part of the next generation safety strategies.

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Effectiveness Estimation Method for Advanced Driver Assistance System and its Application to Collision Mitigation Brake System

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ABSTRACT

A Collision Mitigation Brake System (CMBS), which is mainly focused on rear-end collisions, was introduced in the Japanese market in June 2003. To make such kinds of advanced driver assistance systems more available in and accepted by society, it is essential to measure their effectiveness in enhancing safety. However, it is difficult to estimate the reduction in the number and severity of accidents quantitatively, because crash data rarely contain enough detail regarding the pre-crash accident scenarios. Such data are very important to predict how well such technologies can work when a collision is impending. In this study, a new approach was developed for technology effectiveness estimation using a simulation model and applying it to CMBS evaluation. The simulation model consists of the accident scenario database, the vehicle model, the driver model, and the environment model. We reconstructed accident scenarios of about 50 cases for rear-end collisions from US National Automotive Sampling System / Crashworthiness Data System data, resulting in time histories of striking and struck vehicles such as velocity, heading angle, trajectory, relative movements, and struck position. The vehicle model includes a radar model, CMBS control logic, and a brake actuator model as well as a conventional vehicle dynamics model. The driver model, which can react to the warnings of CMBS by braking and/or steering, was based on test results using a driving simulator. We first ran the simulations using the vehicle model without CMBS and calibrated the necessary parameters such as delta V with the accident data. Then CMBS was added to the system, and simulations were run repeatedly with some Monte Carlo type variations of variables such as driver's response time and amount of maneuver. Finally we estimated the probability of fatality and other injury indices based on the calculated delta Vs. The results showed that CMBS has substantial potential to reduce or mitigate rear-end collisions.

INTRODUCTION

Research and development of advanced driver assistance systems, which detect environmental conditions and provide necessary help for a driver depending on the situation, is becoming increasingly popular recently. They are expected to be effective in situations of imminent collisions, assisting to avoid or mitigate them. A Collision Mitigation Brake System (CMBS), which is mainly focused on rear-end collisions, was introduced in the Japanese market in June 2003.

To make such kinds of systems more available in and accepted widely by society, it is essential to measure their effectiveness in enhancing safety. However, it is difficult to estimate the reduction in the number and severity of accidents quantitatively, because the pre-crash accident scenarios were not clear in detail.

NHTSA reported analysis of pre-crash scenarios using data from the 2000 National Automotive Sampling System/General Estimates System crash database, presenting a crash taxonomy of pre-crash scenarios and their distribution for all accident types [1]. NHTSA also tried to evaluate the timing of collision alarm with statistical variables based on the taxonomy of rear-end collisions using Monte-Carlo simulation in the report of automotive collision avoidance system field operational test [2].

Such pre-crash scenario taxonomy is the basis, on which future active safety technologies should be considered, and is good for identifying new technology concepts. But, data from statistical accident analysis is not enough for accurate design and evaluation of new technologies, because those systems will operate differently depending on various parameters such as time histories of relative position and velocity between a subject vehicle and other vehicles, driver's maneuver, and so on.

In this study, 50 cases of rear-end collisions were reconstructed one by one using in-depth survey by US National Automotive Sampling System / Crashworthiness Data System (NASS/CDS). Using reconstructed accident data, simulations were carried out, taking variance of drivers' response into account. Then, safety effectiveness of CMBS was estimated.

THE CONCEPT OF THE EFFECTIVENESS ESTIMATION METHOD

Figure 1 shows the concept of the effectiveness estimation method. For this study, 50 rear-end collision cases were randomly sampled from NASS/CDS data during 2000 and 2001, which consist of tow-away crashes. Each case in the NASS database has a weight, which indicates how many accidents (out of all of the accidents in the US) that the case represents. If the weights of all the cases in the database are added together, the result is the total number of tow-away crashes that occurred in that time frame. The sampled set of weighted rear-end collision cases is a representative sample of the population of all rear-end tow-away crashes in the US.

In the next step, the whole set was distributed depending on parameters, which take a driver's response to the warning of CMBS into account. Then, simulation was run with CMBS for each scenario case with selected parameters, and the total number of reduced accidents was calculated.

ACCIDENT RECONSTRUCTION

Accident reconstruction provides position and speed time histories for the reconstructed crash, which a simulation model uses to simulate the crashes with various CMBS-related human behaviors.

First, the sampled NASS/CDS case's accident reconstruction diagram files were imported. Next, the specific vehicles in the case are identified from the text summary of the NASS database and determined vehicle properties.

Using PC-Crash, a commercial software program, the vehicles are placed into position at the point of impact and points of rest, and calculation is iteratively made to estimate various parameters, including the speed of each vehicle at impact, the post-impact steering of each vehicle, and the post-impact braking of each vehicle based on recorded deformations and points of impact.

Then, the pre-impact path that the cars followed is estimated. Any pre-impact driver control (pre-crash braking or acceleration) is input based on the interpretation of the NASS data.

After the reconstruction, output files are

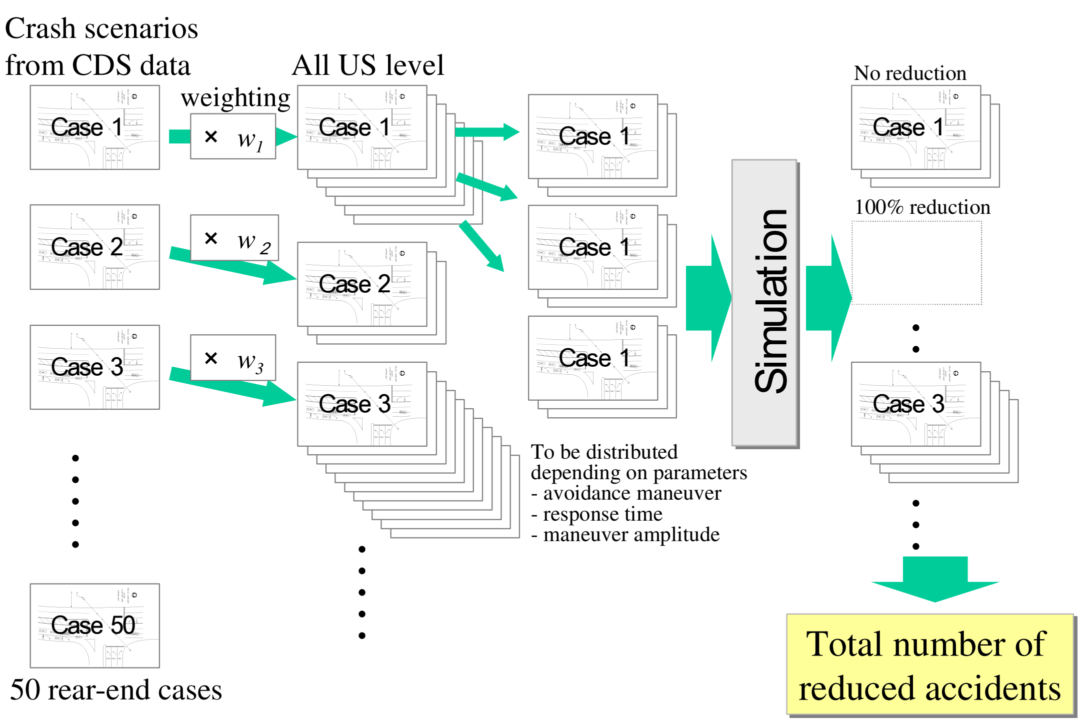

Figure 1. The concept of the effectiveness estimation method.

produced that report the time histories of the crash (i.e., x and y positions, heading angle and forward speed).

After the reconstruction was completed, the cases were broken down into categories of rear-end collision pre-crash scenarios specified by Najm [1], as those scenarios may influence the effectiveness of CMBS. The categories used by Najm were: lead car accelerating, lead car constant speed, lead car decelerating, lead car stopped, and either car changing lanes. However, all of the lead car stopped cases had unknown stop duration. Our reconstructed cases were broken down into similar categories. Since pre-impact stop time was also reconstructed, it was possible to specify the time between the lead vehicle stopping and the case vehicle impacting it. Figure 2 shows the comparison between the distributions of rear-end crash scenarios broken down by lead car speed at the time of impact. The distribution of the reconstructed cases showed good agreement with that of GES data by Najm. The distribution of “stopped for a short time” vs. “stopped for a long time” scenarios are also represented for the distribution of the reconstructed cases.

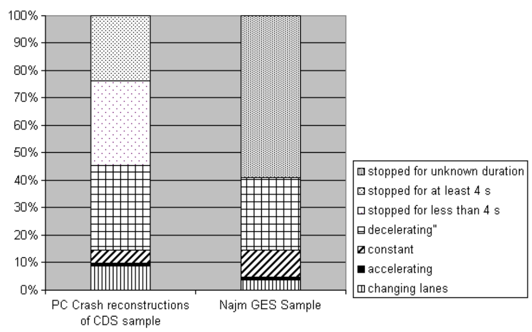

Figure 2. The comparison between the distributions of rear-end crash scenarios.

Collision Mitigation Brake System

Figure 3 shows the system configuration of CMBS [3]. A millimeter wave radar sensor is

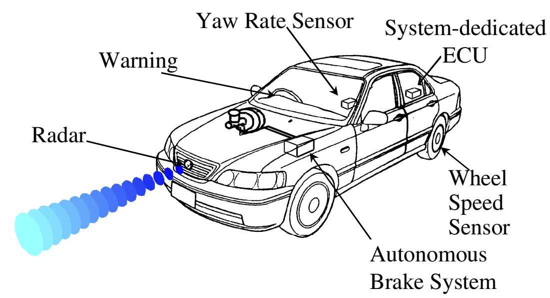

Figure 3. System configuration of CMBS.

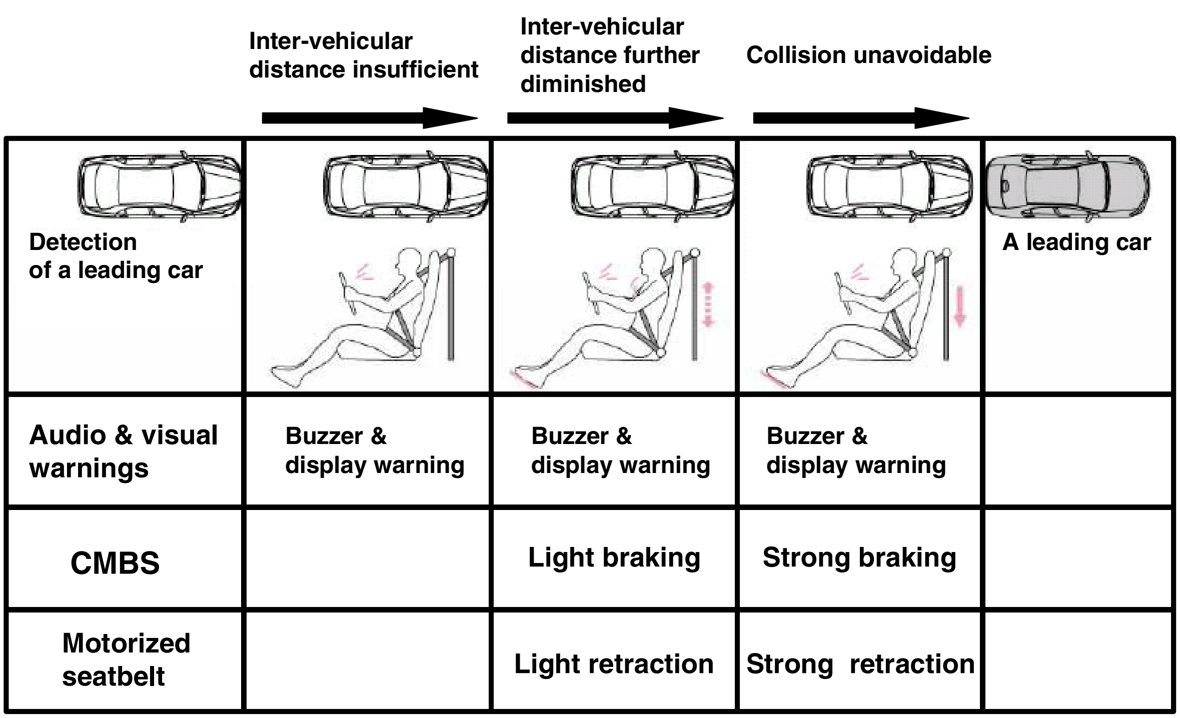

Figure 4. Operation modes of CMBS with motorized seatbelts.

equipped as the sensor for forward obstacle detection.

Figure 4 shows basic operation modes of the system. CMBS operates combination with motorized seatbelts. If the subject vehicle gets close to a leading vehicle and distance becomes short, primary warning occurs by audio and visual warning.

If the subject vehicle approaches closer and the system judges a collision may occur, the system issues tactile warning in addition to audio and visual warning. The motorized pretensioner retracts a driver's seatbelt

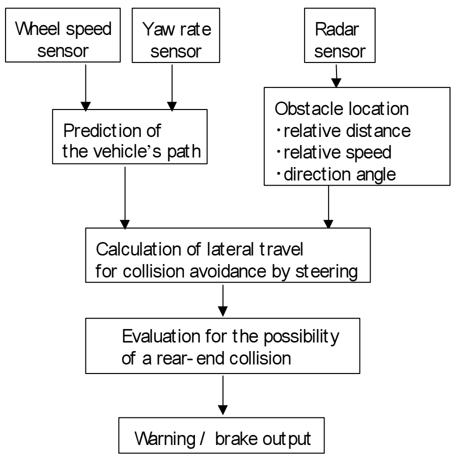

Figure 5. Basic control logic of CMBS.

gently and CMBS activates light braking.

And when the system judges that a collision is unavoidable, the motorized pretensioners retract seatbelts strongly to hold the driver in position, and the system engages strong braking to compensate for a driver's operation delay and insufficient brake pedal force. Thus the system assists a driver effectively and reduces collision velocity.

Figure 5 shows the basic control flow. The system recognizes a leading vehicle by a radar sensor, and the subject vehicle's path is estimated from its dynamics state quantities. Then, the system calculates lateral travel, which is necessary for collision avoidance by steering, and evaluates the possibility of a rear-end crash. When the possibility of a rear-end collision becomes high, the warnings is issued, and if this state continues and avoidance becomes very difficult, emergency braking is carried out.

The model of the CMBS control logic was directly built-in to the simulation model. It was also used in the complementary driving simulator experiments described subsequently.

SIMULATION MODEL

Figure 6 shows the concept of the simulation

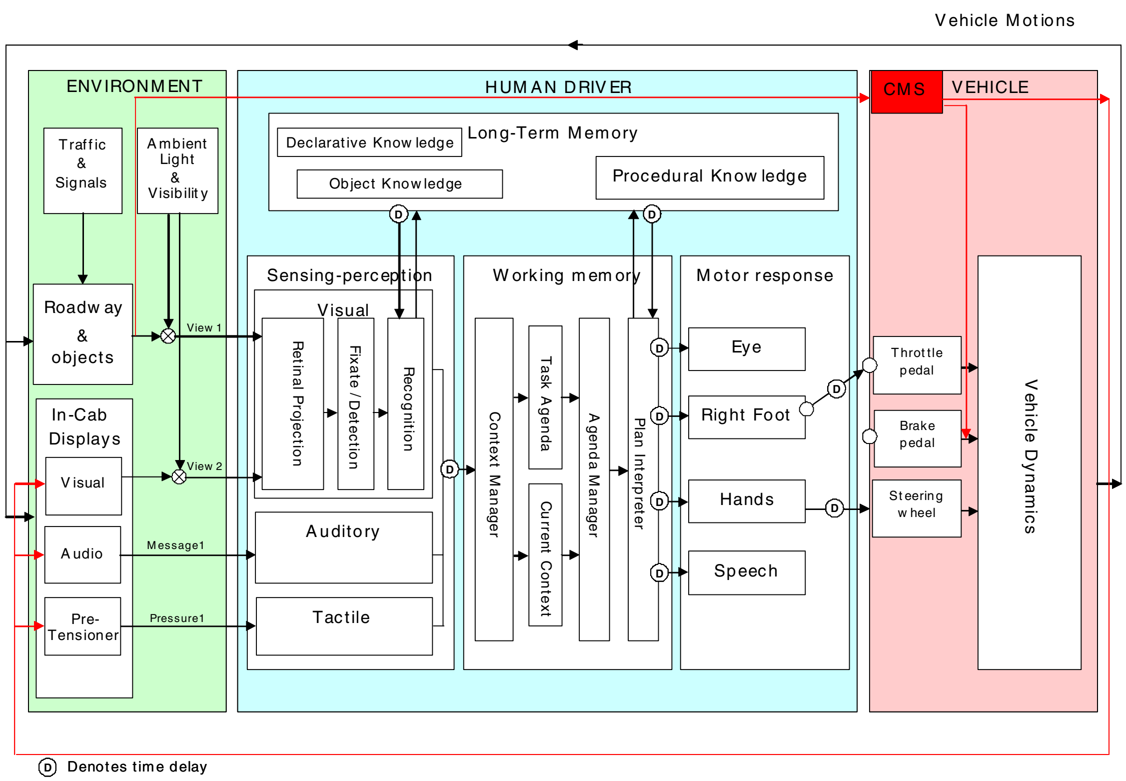

Figure 6. The concept of the simulation model

model, which is structured similar to NASA's MIDAS program [4]. The model has three main components: the environment, the human driver, and the vehicle.

Environment Model

The environment model contains the world outside the driver's vehicle. In this study, the environment contains the driver's intended path and the other vehicle involved in the scenario. The environment also contains the in-cab displays available to the driver; most importantly it contains the visual, audio, and pretensioner warnings.

Driver Model

The human driver model contains four major sub-modules: sensing-perception, working memory, long-term memory, and motor response. The sensing-perception module processes information from the environment into sense-organ primitive form and performs basic processing of the information. The current model has three modules in sensing-perception: look-ahead path prediction, speed sensing and collision detection. Currently, the collision detection module is only sensitive to CMBS warnings, which cause the module to recognize that a collision is imminent. The working memory module performs higher-level processing of information. It maintains a "current context," which is a description of the current state of the world, including such things as level of traffic, weather, lighting conditions, pending events, etc. The "task agenda" is a list of tasks that the driver might want to perform. These tasks are weighted relative to the factors in the current context, creating a vector of weights for the tasks, which specifies the priority for performing each one. Tasks with low priority will not be performed due to limited capacity.

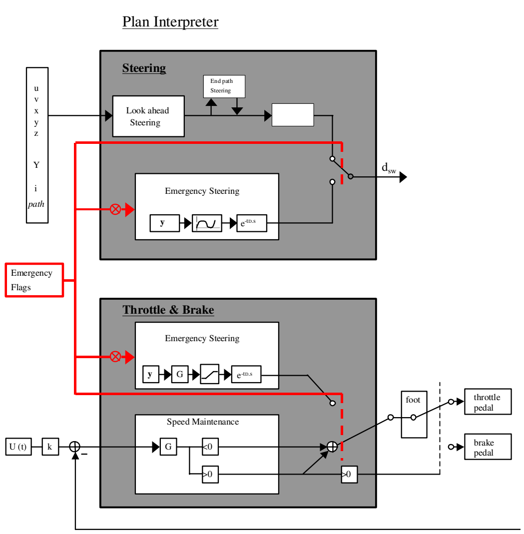

Figure 7. Plan interpreter model

Collision Detection

In the currently implemented driver model, the collision detection model is set to detect collisions only after a CMBS warning occurs. As soon as the CMBS warning sounds, there is a detection/recognition/decision time delay, and then a variable called "emergency flag" is set to "1" in order to indicate that the driver should initiate a collision avoidance response.

Plan Interpreter

The plan interpreter (See Figure 7) is the module that implements the tasks performed by the driver. In the current model, the only tasks performed by the driver are: emergency steering, look-ahead steering, speed maintenance, and emergency braking.

If "emergency flag" is set to "1" by collision detection module, plan interpreter module switches look-ahead steering to emergency steering and/or speed maintenance to emergency braking.

Emergency Steering

The emergency steering module contains a preprogrammed open-loop steering maneuver used to avoid a collision by performing a quick lane-change to the right.

$$\delta = \delta_0 \cdot \sin(0.63 \cdot t) \qquad (1).$$

where δ is wheel steering angle, and δ_0 is amplitude of wheel steering angle.

After one cycle of the steering wheel angle sine wave is complete, δ is set to zero for the remainder of the simulation. The assumed frequency of the sine wave is 0.63 rad/s, and the assumed amplitude of wheel steering angle is 90 deg, based on past experimental data for severe lane change.

Emergency Braking

The emergency braking module contains a preprogrammed open-loop braking acceleration routine used when an emergency situation occurs.

$$\begin{aligned} a_{emergency} &= G \cdot t \quad \text{for } t \le 0.2s \\ &= C \qquad \text{for } t > 0.2s \end{aligned} \qquad (2).$$

where $a_{emergency}$ is emergency braking acceleration, G is the rate of change of the braking function, and *C* is the maximum command acceleration level of the braking function.

<u>Reaction Time</u>

The driving simulator study was performed to come up with a set of reaction times that constitute a representative sample of driver reaction time to the initial CMBS warning. After the screening of the data, 73 test results were acquired. The corresponding response times ranged from 0.32 seconds to 1.64 seconds. The 33rd, 50th, and 67th percentile values were selected from this distribution for purposes of simulation. These three values are 0.52, 0.82, and 1.10 seconds, respectively.

VEHICLE MODEL

The vehicle model contains the dynamics of the subject vehicle based on a mid-size passenger car. The variables modeled include x and y positions, vehicle lateral and longitudinal speeds, yaw rate and heading angle. An autonomous brake function module by CMBS is also included. It gets other vehicles' relative position from environment model and output commands to warning interfaces and a brake actuator.

Total braking deceleration is the sum of a driver's operation and the brake command by CMBS, which is limited by friction between tires and road.

SIMULATION RESULTS

Simulation runs were repeated with a variety of parameters.

One parameter is "Human Reaction Type". It has 4 options for a driver's response to CMBS warning. The first is the baseline simulation, in which there is no CMBS warning and no driver reaction to the collision event (other than his regulation of the speed and lane position time history imported from the accident reconstruction). It is intended to reproduce the accident as it happened, without CMBS. The second option is that CMBS functions and the driver uses emergency braking in response to the CMBS warning. The third option is that CMBS functions and the driver uses emergency steering in response to the CMBS warning. The last option is that CMBS functions and the driver both brakes and steers in emergency situations.

There are also other parameters such as human reaction time and emergency braking amplitude, which allow differences in human driver reactions to be considered.

With combination of those parameters, 22 simulation runs were carried out for each crash scenario. The results were used to estimate technology effectiveness with proper weight for each result, as described later.

Some examples of simulation results are shown in Figure 8 and 9. Figure 8 is a baseline simulation result without CMBS. The subject vehicle's driver failed to decelerate when a leading vehicle started braking and collide with relative velocity of 40 km per hour. Figure 9 shows a simulation result for the same scenario with CMBS. The driver's response is emergency braking. In this case, the subject vehicle succeeded to avoid collision.

Figure 10 shows snapshots of animation which visualize simulation results.

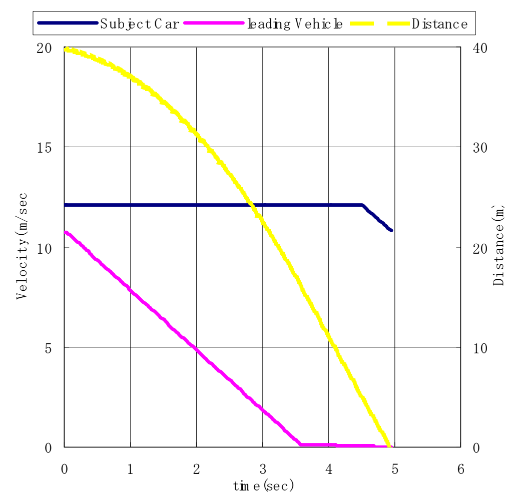

Figure 8. Simulation result of baseline condition without CMBS

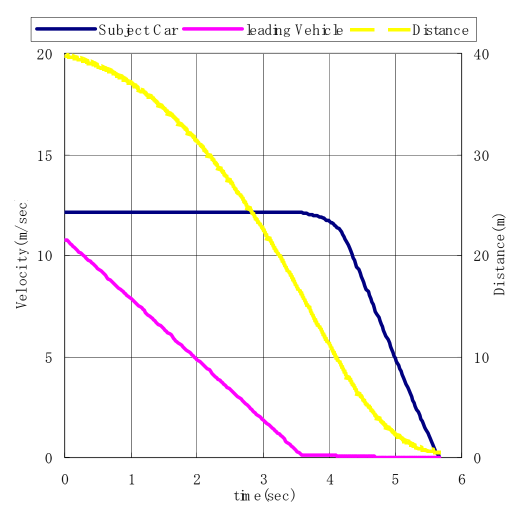

Figure 9. Simulation result with CMBS

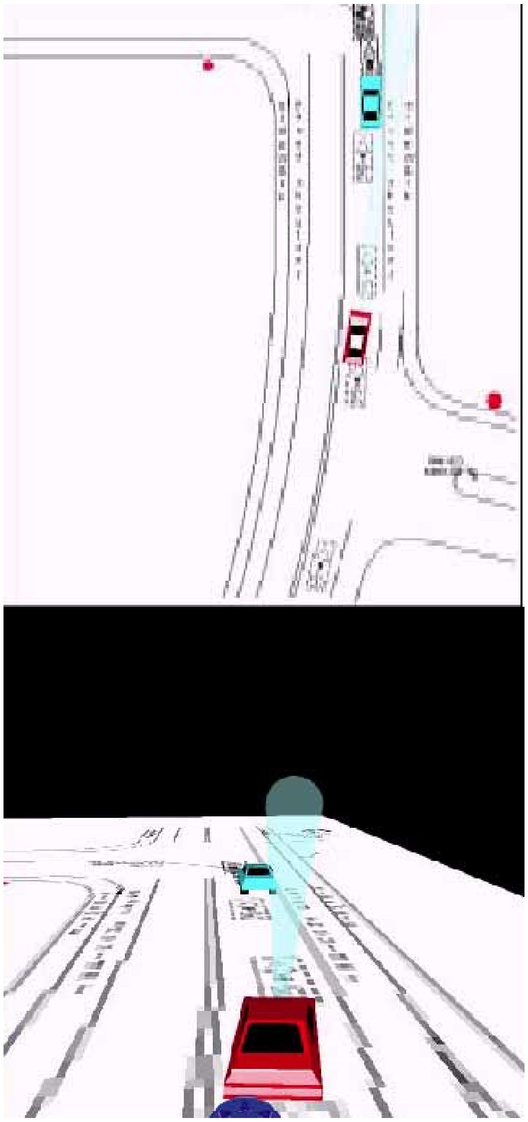

Figure 10. Animation of simulation results

EFFECTIVENESS ESTIMATION

After each simulation run was complete, an output file is produced that contains vehicle characteristics for the collection partners (mass, length, width, center-of-gravity location, etc.) and impact velocities and headings.

Then, a multi-body crash simulation was used to calculate the ΔV of each vehicle, which is the difference between the linear velocity at first impact and the linear velocity when the vehicles first separate. (For the simulations that do not end in an impact, ΔV is zero). In a multi-body crash simulation, equal and opposite contact forces between a hyperellipsoid representing the case vehicle and a hyperellipsoid representing the opposing vehicle are calculated based on the contact force-deflection function, vehicle-to-vehicle (or vehicle-to-object) coefficient of friction, and crush distance. At each time step the contact forces are calculated and then applied to each vehicle. The resulting linear and angular accelerations are calculated based on each vehicle's mass and moments of inertia. These accelerations are then integrated to determine the linear and angular velocities, which are then integrated to determine the linear and angular positions.

After the ΔV's are determined, an estimate of probability of fatality for the simulation is calculated. A model to estimate US driver casualty vs crash ΔV was developed. It was postulated that probability of fatality for the driver of an impacted vehicle is a function of collision ΔV.

The effectiveness of the CMBS can be calculated according to the following equation:

$$Effectiveness(x) = 1 - \frac{\sum_i \sum_j p_j w_i x_{i,j}}{\sum_i w_i x_{i,0}} \qquad (3).$$

$x_{i,j}$ is the casualty value (e.g. probability of fatality) for the *i*th crash scenario and the *j*th driver response due to CMBS.

$x_{i,0}$ is the casualty value for the *i*th crash scenario without CMBS (i.e., baseline run).

p_j is probability of the *j*th driver response. These probabilities are estimated from accident data and driving simulator experiments.

Note that

$$1 = \sum_j p_j \qquad (4).$$

w_i is the *i*th unique case sampling frequency

Note that

$$total\ number\ of\ cases = \sum_i w_i \qquad (5).$$

The driver response probabilities p_j are calculated based on the following assumptions:

- The probability of no driver response is assumed to be 0 based on data from the driving simulator experiments.

- The 0.75, 0.10, 0.15 weightings for brake, steer, and brake plus steer are based on analysis of 1997 to 2002 NASS/CDS data.

- The distributions of brake amplitude and response time are based on driving simulator data.

Based on the results of the simulations and analyses, it is estimated that if CMBS had been installed in all of the vehicles involved in rear-end collisions: there would have been a reduction in overall number of collisions, and ΔV's for many of the unavoided collisions also would have been reduced. There would have been a 38% reduction in the number of collisions that occurred. For our preliminary model of probability of fatality as a function of ΔV, we estimate there would have been a 44% reduction in probability of fatality in these rear-end collisions.

CONCLUSION

A new approach was developed for technology effectiveness estimation using a simulation model of environment, driver, and vehicle. A feature of our method is that it utilizes real accident scenarios as far as possible. It could be useful not only for validation of a new technology, but for detail considerations on its design.

The results that was estimated using this method showed that CMBS has substantial potential to reduce or mitigate rear-end collisions.

There might be still room for improvement in accuracy of estimation. However, the method has shown good possibility to apply to new safety technologies such as advanced driver assistance systems. Our driver model is rather simple for now, as crash causation by human factors is not clear in detail with the data from current NASS/CDS data, which is mainly focused on passive safety issues.

If more detail data on crash causation becomes available in the future, the model could be improved further and applicable more widely and accurately.

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ROADSIDE HAZARD AND BARRIER CRASHWORTHINESS ISSUES CONFRONTING VEHICLE AND BARRIER MANUFACTURES AND GOVERNMENT REGULATORS.

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Paper Number 05-0149

ABSTRACT

Run-off-road crashes into roadside hazards that include impacting rigid objects and roll-over constitute approximately 40% of road fatalities and cross over two car frontal collisions account for around 7% of fatalities in Australia. Considerable onus to protect vehicle occupants during such crashes sits with vehicle manufactures. It is clear from research to date, however, that side impacts into narrow objects beyond impact speeds of 40 km/hr, head-on and large engagement offset crashes at closing speeds of 120 km/hr, and roll-over crashes are presently at the limits of survivability.

One way of protecting occupants in such crashes is to use a roadside or median barrier to safely redirect the vehicle. Road crash barriers can in themselves be hazardous unless designed properly. Errant vehicle redirection should occur so that air bag and seat belt pretensioning systems do not fire and rollover does not occur. Research into roadside barrier crash tests carried out by the Department of Civil Engineering at Monash University over the past decade, has revealed some key crashworthiness characteristics that both vehicle and barrier manufacturers alike need to consider. This paper presents results of crash tests that provide some insight into vehicle-barrier crash pulses, occupant and vehicle kinematics and desirable occupant protection systems related to existing barrier profiles and properties and what are the most suitable vehicle and barrier crashworthiness features essential for safe vehicle redirection. The paper also argues, using some real-world examples, in favour of bringing together road designers and car manufacturers with associated regulatory bodies to emphasise a holistic perspective to enhance occupant protection in road crashes.

INTRODUCTION

One way of safely redirecting an errant vehicle away from a hazard, such as a roadside tree or oncoming traffic, is to use a roadside or median barrier. The most commonly used barriers are made from either concrete and/or steel. In the case of concrete barriers they are usually fixed such that when struck, deformation is small. Hence they are commonly referred to as rigid concrete barriers. Steel tubing can be fixed to the top of concrete barriers to provide extra height in order to prevent vehicles with a high centre of gravity (COG), e.g. trucks, from rolling over the top of them.

Steel barriers can be constructive from guardrail, wire rope and tubular sections. Steel barriers are often used to reduce the severity of the crash because they deform when struck, hence they are often referred to as semi-rigid or flexible barriers systems.

Another form of barrier that is commonly used on roads is the temporary barrier for road works. These can be made again either from concrete or steel and, more recently, are being constructed from plastic.

Ideally, roadside safety barriers when struck by an errant vehicle, should redirect the vehicle away from the hazard within a narrow angle so that it follows the line of the barrier while at the same time does not gyrate, overturn or result in any significant damage to the impacting vehicle, or subject the occupants to life-threatening decelerations. The best way of achieving this is to redirect and/or decelerate the vehicle over a short distance that is well within human tolerance/comfort levels.

When a barrier moves sideways during impact this helps reduce the severity of the crash. This movement sideways is known as the barrier's "working width". The working width for a rigid barrier system is in the range from zero to only a few centimetres. On the other hand, the working width of flexible systems can be as much as three to four metres in the extreme but preferably should be no more than one to two metres.

The main issue for car manufacturers is to understand how flexible systems can affect timing of the air bag triggering. Of particular concern is the issue of an airbag firing late in the impact event when the occupant's head has already moved close to the airbag cover.

The main issue for barrier designers, barrier manufacturers and road authorities is to ensure that when a vehicle strikes the barrier system the airbags do not unnecessarily fire and/or result in a vehicle rollover. Firing of an airbag considerably hinders the driver's recovery process. Similarly rollovers need to be avoided because regulations at this present time do not adequately cover rollover crashes and hence rollover roof strength and seat belt and curtain triggering to prevent ejection.

In regards to temporary barriers, the main issue barrier designers need to be aware of is that the working width of the barrier does not encroach into the work zone where workers or pedestrians could possibly be struck.

To assess the crashworthiness characteristics of barrier systems it is useful to recall how the systems were developed over the past 60 years.

Concrete barriers

Concrete safety barriers are widely used where there is no room to accommodate a working width for a deforming barrier, such as narrow medians, bridge barriers and roadsides where hazardous objects are close to road edges. The other reason such barriers are used is that repair maintenance costs are low when these barriers are struck.

Currently, there are four major types of concrete barriers: the New Jersey concrete barrier, the F-shape concrete barrier, the Single-slope concrete barrier and the Vertical concrete barrier. These concrete barriers are someties referred to as "Safety Shape Barriers" (Sicking, 2004). They have all been crash tested and can be used as roadside barriers, median barriers and bridge barriers. Generally, these concrete barriers when adequately designed and reinforced may all be deemed to meet Test Level 4 of NCHRP Report 350 (Ross, Zimmer and Michie, 1993) at the standard height of 810 mm and meet Test Level 5 when the design height is 1070 mm (AASHTO, 2002). Figure 1 shows the cross section profiles of the New Jersey, the F-shape and the Single-slope median concrete barrier.

The New Jersey barrier is the most widely installed concrete barrier. The F-shape barrier, which is supposedly named on the basis that this geometry was the sixth alternative identified and was labelled with the sixth letter of the alphabet: F, performs better for small vehicles with respect to vehicle roll than the New Jersey barrier, but has not been as widely used. The Single-slope barrier, also called Constant-slope barrier, is the most recent generation in the evolution of concrete barrier systems and is becoming popular because the pavement adjacent to it can be overlaid several times without changing the performance of the barrier (Ray and McGinnis, 1997).

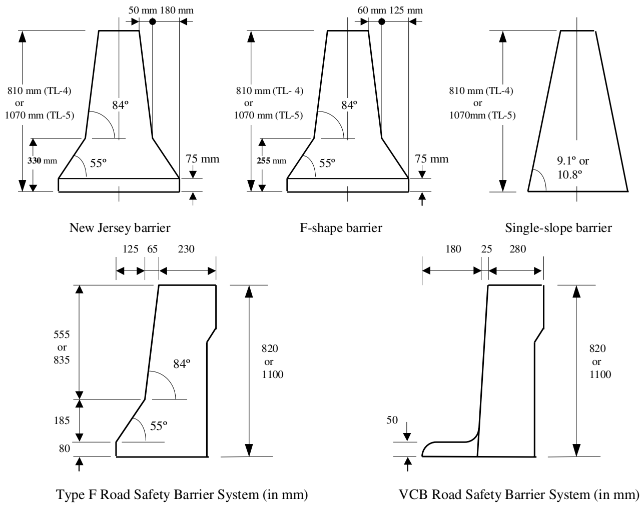

Figure 1 Profiles of more common concrete barriers used in the USA and Australia

In Australia, two types of rigid road safety barrier systems are recommended in AS/NZS 3845: the Concrete Road Safety Barrier Type F and the Vertical Concrete Road Safety Barrier (VCB) (AS/NZS, 1999; 1999). Figure 1 shows the Australian standard Type F and the VCB roadside safety barrier system, which are essentially the same as the USA standard F-shape and the Constant slope concrete barrier respectively.

Concrete barriers were first used in the 1940s in California, USA. The aim was to minimise the number of errant trucks penetrating the barrier and eliminate the need for costly and dangerous barrier maintenance in narrow medians. The widely used New Jersey concrete barrier was tested at the GM proving grounds with the intention of developing a barrier that minimised vehicle damage when struck at a shallow angle. This barrier was first installed in New Jersey in 1955 and was upgraded to the currently used profile in 1959. Apparently no crash tests were carried out in the development of the upgraded New Jersey barrier. Modifications were based on real world accident experience only (Ray and McGinnis, 1997).

As the traffic volume and speed from the early 1950s began to change, concrete bridge barriers were being used to prevent vehicles from penetrating through bridge rails. As a result, the state of California (Beaton, 1956) performed a series of five full-scale crash tests to optimise concrete bridge barrier designs in 1955. Since then, many full-scale crash tests have been carried out in order to develop concrete road or bridge barriers that can prevent penetration of the barrier and redirect a vehicle with as little occupant risk and vehicle damage as possible. As a result, some concrete barriers were proved to have satisfied impact performance such as the F-shape barrier (developed in 1976) and the Single-slope barrier (developed in 1989), whereas some other concrete barriers were demonstrated to have unacceptable impact performance such as the GM-shape concrete barrier (Michie, 1971; Ray and McGinnis, 1997).

In Europe, several types of concrete barriers were developed in the 1960s, such as the German DAV concrete median barrier, the Belgian Trief concrete guardrail, the French Sabla concrete guardrail, the Italian Sergad concrete guardrail and the Italian Vianini concrete median barrier (Michie, 1971). However, most of these concrete barriers were proven to be unsatisfactory after tests were carried out and from real world crash experience. European countries also currently use New Jersey shape for their standard concrete barriers (FEMA, 2000).

Table 1 summarises most of the full-scale crash tests carried out so far on concrete road safety barriers. Basically, these crash tests were carried out to assess the impact performance of a variety of concrete barrier designs. The impact load generated by a car crashing into a concrete barrier can be determined if the barrier is instrumented with load cells. However, such research tests are scarce. Only two research papers written by Neol, Hirsch, Buth and Arnold (1981) and Hellmich (2002) were found in literature by the authors, where full-scale crash tests were specifically performed to investigate the possible impact loads of concrete bridge barriers.

Neol et al. (1981) conducted a series of eight crash tests where two subcompact 817 kg (1800 lb) sedans, two compact 1022 kg (2250 lb) sedans, two full-sized 2043 kg (4500 lb) sedans, one 66-seat 9082 kg (20000 lb) city bus and one two-axle 14531 kg (32000 lb) inter-city bus were used to crash into a vertical concrete wall at a nominal speed of 96.6 km/h (60 mph). The impact angle was between 15 degrees and 24 degrees. The concrete wall was specifically instrumented to measure the magnitude and location of vehicle impact forces. To handle the force spikes observed from the instrumented concrete wall outputs, Neol et al. made some judgements and decided to determine the maximum impact force by using the largest 50 ms average force. The results are summarised in the first eight tests in Table 1. Hellmich (2002) also used a 13 ton bus crash test into an instrumented “Salzburger Klaue” concrete bridge barrier, which is quite similar to the New Jersey barrier, to investigate the impact load level. The peak impact load was recorded as 510 kN for this 70 km/h and 20° test.

The impact load of a vehicle crashing into a concrete barrier can also be determined if the deceleration data at the centre of gravity of the car is recorded during the impact. Nevertheless, as can be seen in Table 1, only several classes of vehicles were selected and tested at a limited number of impact speeds and angles. There is still a need to understand how the impact loads, and hence deceleration forces, are generated and how to calculate them, when different vehicles crash into a concrete barrier at different speeds and angles.

Steel Guardrail barriers

One of the other most commonly used barriers are constructed from steel guardrail or W-beam. Post-and-beam barrier systems can be generally categorised into weak-post-and-beam barrier systems and strong-post-and-beam barrier systems. Weak-post-and-beam barrier systems can be further grouped into weak-post cable barriers, weak-post W-beam barriers and weak-post box beam barriers, whereas strong-post-and-beam barriers can be further divided into strong-post W-beam barriers and strong-post Thrie-beam barriers (Ray and McGinnis, 1997).

Among these post-and-beam barrier systems, the strong-post W-beam barrier is the most common in use today. A typical strong-post W-beam barrier system consists of steel or wood posts that support a W-beam steel rail that is blocked out from the posts with routed timber, steel or recycled plastic spacer blocks (AASHTO, 2002). A variety of posts and blocks for strong-post W-beam barriers are being used in different countries.

In the USA, a wide variety of cross-sections and materials for posts and blocks have been evaluated via numerous full-scale crash tests, such as W150×13.5 steel, W150×16.6 steel, 110×150 mm cold formed channel steel (Charley Post), 150×200 mm rectangular wood, 200×200 mm square wood, 150 mm diameter round wood and 150×200 mm reinforced concrete (Ray and McGinnis, 1997; Plaxico, Ray and Hiranmayee, 2000). The W150×13.5 steel and 150×200 mm rectangular wood posts and blocks are the most common types used, while some of the posts like channel section steel posts and concrete posts have virtually not been used anymore. Figure 1 shows the typical types of strong-post W-beam barrier widely used in the USA (WPI, 2004).

The typical post length is 1830 mm and the post spacing is 1905 mm. Strong-post W-beam barriers using wood or steel posts and wood blocks, as shown in Figure 2, have passed NCHRP Report 350 Test Level 3 crash tests, whereas strong-post W-beam barriers using steel posts and steel blocks (bottom image in Figure 2) have only passed NCHRP Report 350 Test Level 2 crash tests (Ray and McGinnis, 1997; AASHTO, 2002).

Table 1 Summary of full-scale crash tests on concrete safety barriers

Barrier type	Barrier height (mm)	Vehicle mass (kg)	Impact speed (km/h)	Impact angle (degrees)	Maximum impact load or deceleration a_x (g's)	Maximum impact load or deceleration a_y (g's)	Performance comment	Test institute and Year	Ref.
Vertical Concrete Barrier	1070	931	95	15.5	81.9 kN			Texas Transportation Institute (TTI) 1980~ 1981	Neol *et al.* (1981)
		949	94	21.0	93.9 kN				
		1271	94	15.0	82.3 kN				
		1285	90	18.5	97.9 kN				
		2125	85	15.0	194.0 kN		Redirected		
		2152	96	24.0	309.7 kN		Redirected		
		9094 School bus	93	15.0	328.4 kN		Redirected		
		14537 Inter city bus	97	15.0	939.0 kN		Redirected		
Vertical Concrete Parapet	810	892	97.3	21	8.0	14.0	Redirected	TTI 1987~ 1988	Buth *et al.* (1990)
	810	2615 (Pickup)	96.1	20.2	5.7	13.1	Redirected		
	810	8172 Single-unit truck	80.5	14	1.7	4.6	Redirected, rolled 90º		
	1070	22723 Tractor trailer	82.7	16.2	3.3	3.7	Redirected, rolled 90º		Menges *et al.* (1995)
Texas Concrete Median Barrier	810	1910	98	7	8.4	29.2		TTI 1973	Troutbeck (1975)
	810	1910	98	15	7.8	14.0			
	810	1920	90	25	10.3	13.3			
	810	1800	100	25	8.7	16.1			
	810	21770 Tractor trailer van	55	16			<8º Roll		
	810	21770	56	19			<8º Roll		
	810	21770	72	15			<17º Roll		
Concrete Median Barrier	810	9203 School bus	99	15			Rolled over	Dynamic Science Inc. (DSI) 1981	Hirsch (1986)
	810	9075 School bus	97	16			Rolled over		
	810	9080 School bus	93	15			Rolled over	TTI 1984	
	810	18169 Scenic cruiser bus	89	16.2			Redirected	DSI 1981	
	810	18174 Scenic cruiser bus	87	14			Redirected		
Concrete Median Barrier	810	8281 (Truck)	97	15			Rolled over	TTI 1985	Hirsch (1986)
	810	8251 Tractor trailer van	85	15			Mounted	DSI 1981	
	1070	36402 Tractor trailer van	84	15			Rolled over	TTI 1985	
	1070	36688 Tractor trailer van	84	16.5			Redirected	TTI 1984~ 1985	
Concrete parapet	2290	36374 Tractor trailer tank	83	15			Redirected		
Single-Slope Barrier	1070	817	97.7	19.9	6.5	15.3	Redirected	TTI 1989	Beason (1989)
	1070	2043	101.5	26.5	6.4	13.1	Redirected	TTI 1989	

Table 1 (Con't) Summary of full-scale crash tests on concrete safety barriers

Barrier type	Barrier height (mm)	Vehicle mass (kg)	Impact speed (km/h)	Impact angle (degrees)	Maximum impact load or deceleration		Performance comment	Test institute and Year	Ref.
					a_x (g's)	a_y (g's)			
New Jersey Barrier	810	2060	61	7				California Division of Highway 1968~1971	Troutbeck (1975)
	810	2060	105	7					
	810	2060	101	25					
	810	2260	72	7					
	810	2260	103	7		4.8			
	810	2260	106	7		4.8			
	810	1800	82	25					
New Jersey Barrier	810	2052	94.3	16.2			Redirected	TTI 1986	Ray and McGinnis (1997)
	810	1021	94.8	15.5			Redirected	Southwest Research Institute (SwRI) 1976	
	1070	809	96.4	14			Redirected	TTI 1986	
	1070	36402(36000V)	83.8	16.5			Redirected	TTI 1986	
	1070	2000 (Pickup)	101.2	25.6			Redirected	TTI 1995	
	810	1244	81	45			Rolled over, airborne	Monash University 2000	Grzebieta *et al*, (2002)
	810	1244	112	20			Redirected, airborne		
	810	1244	110	20			Redirected, airborne		
New Jersey Bridge Rail	750	13000 (Bus)	70	20	510 kN		Redirected	Ministry of Traffic, Austria 2002	Hellmich (2002)
	810	2599 (Pickup)	92.8	20.6	6.6	7.3	Redirected	TTI 1988	Buth *et al.* (1990).
	810	8172 Single-unit truck	83.0	15.5	3.2	2.5	Redirected		
Ontario Tall Wall	1070	36287 (Tractor trailer)	79.8	15.1			Redirected	TTI 1990	Ray and McGinn (1997)
F-shape Barrier	810	1982	98.8	15.2			Redirected	SwRI 1976	Ray and McGinn (1997)
	810	1021	90.8	14.3			Redirected		
F-shape Bridge Railing	810	893	96.7	21.4	8.0	12.8	Redirected	TTI 1987 ~ 1988	Buth *et al.* (1990).
	810	2624 (Pickup)	105.2	20.4	4.7	13.1	Redirected		
	810	8172 Single-unit truck	83.8	14.8	1.4	3.9	Redirected		
	1070	18414 Scenic cruiser bus	89.6	15.7	1.5	6.5	Redirected		Menges *et al.* (1995)
	1070	22700 (Tractor trailer)	84	14	2.2	4.7	Redirected		
Single-Slope Bridge Rail	810	2076 (2000P)	97.2	25.5	7.3	13.3	Redirected with airborne	TTI 1994	Mak *et al.* (1995)
	810	8172 (8000S)	82.1	10	1.3	2.7	Redirected, rolled 90º	TTI 1994	
	810	8172 (8000S)	82.5	17.9	2.0	5.6	Redirected, rolled 90º	TTI 1994	

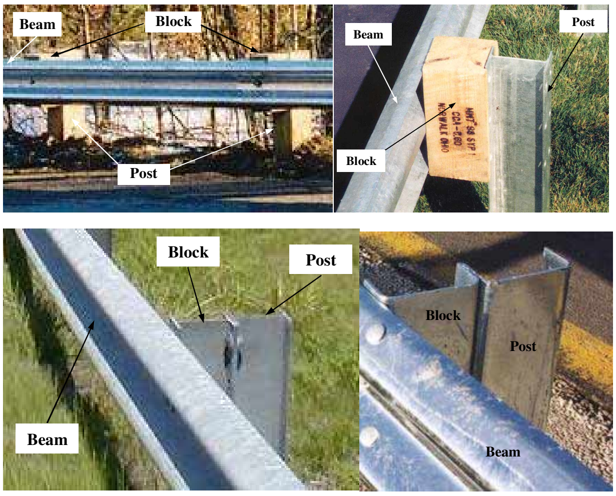

Figure 2 Guardrail barriers used in the US and in Australia

In the Australian standard AS/NZS 3845:1999, only the 110×150 mm channel steel post and block, as shown in Figure 3, are recommended for strong-post W-beam barriers. The standard post spacing is 2000 mm. The post length is 1800 mm. It is stated in the standard that such W-beam barrier systems comply with the requirements of Test Level 3 (Standards Australia, 1999). However, no certification crash tests have been carried out for this system. Strong-post W-beam barriers are widely installed in the states of Victoria, Queensland and South Australia where 6 mm thick 178×76 mm cold rolled channel steel posts and blocks, spaced at 2500 mm are used (Vicroads, 1997; Grzebieta, Zou, Corben, Judd, Kulgren, Tingval and Powell, 2002).

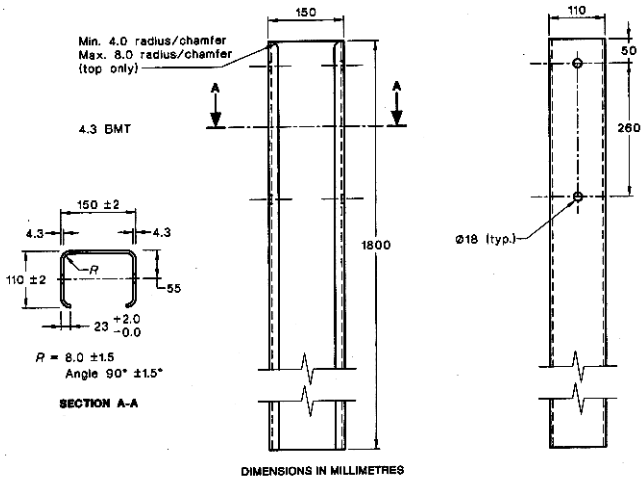

Figure 3 Strong-post W-beam barrier recommended in AS/NZS 3845

In Australia barrier specification can be confusing. AS3845 [3], AS 1742.3 [4] and AS 5100.2 [5] are the standards that specify how permanent and/or temporary barriers are to be designed, used or tested for roadside and bridge barrier systems. However, each state regulatory authority also has its own road design guidelines that further complicate barrier specifications.

In Europe, W-beam barriers are different from those used in the USA and Australia. The W-beam rails are essentially the same, but the posts and blocks are quite different. Barriers should comply with European Standard EN1317-1 & 2. Five millimetres thick 100×50 mm and 4 mm thick 120×55 mm C-shaped steel are used for posts. A variety of blocks are used and mounted in different manners (Fattorini and Fernandez, 2000; Vesenjak and Ren, 2002). The typical post spacing is also 2000 mm.

Wire rope barriers

Another form of barrier that is now beginning to be used widely because of its good crashworthiness features for cars is the wire rope barrier. Two forms have been used in Australia since 1992; the Brifen system and the Flexfence system (VicRoads, 1998). Wire rope barriers are also used in Europe and the US. Figure 4 shows two systems currently used in Australia. Both are made from 4 wire ropes that are maintained in position and are placed under tension.

The key feature of wire rope barriers is that when a vehicle strikes them, the deceleration is low enough during the redirection process that the airbags do not trigger. Hence, such barriers are being referred to as flexible systems.

Figure 4 Left: Brifen system tested at Monash. Right: Flexfence system

Figure 5 Wire-rope underide (after Owen, 2005)

Statistics both in Australia and Sweden are highlighting their excellent crashworthiness characteristics particularly on rural roads and freeways (Larsson et al, 2003) with as much as 90% reduction in fatalities wherever they are installed. However, despite this good record, there are still some contentious issues regarding the use of such systems. The first concerns motorcycle safety which is discussed in another ESV paper (Berg et al, 2005). The second issue concerns vehicles under riding the wire ropes (Figure 5) for various reasons including inadequate rope tension because of poor maintenance and/or installation. The third issue concerns whether such barriers can adequately redirect rigid and articulated trucks. However, this last concern also applies to both W-beam and medium height concrete barriers.

Temporary plastic barriers

Temporary barriers for use in protecting workers in road works are made from concrete, steel and more recently from plastic polymers (Carey and Grzebieta, 2004). Polymer water-filled modules were first seen in Europe as channelling devices during the Tour de France in the 1980's. They were first introduced into Australia in the early 1990's. Later modules soon followed with an increased physical size and a variety of interlocking joining mechanisms. The profiles were generally based on the New Jersey concrete road barrier shape.

Figure 6 Waterfillable Roadliner barriers tested and certified to AS/NZS 3845.

Their lightweight portability became the feature of these systems. Water ballast could be added to the modules to increase mass and the water then dumped when the system needed to be relocated.

The visual appearance of plastic systems gave rise to the perception that when impacted they would redirect errant vehicles in a similar manner to temporary concrete structural barriers. This turned out to be quite misleading and more recently has resulted in fatalities on Australian roads where non-certified units were struck.

In 1988 the French Company Sodirel impacted their system with a 1250 kg vehicle to ER DPS134 and took their product to Canada at the same time as the Matsuta modules from Israel were informally tested in the United States.

Both the US and Canada used NCHRP 350 as the testing benchmark for plastic road barrier systems. Neither of these products could meet the first part of the Level 1 test criteria.

US companies at this time (1995) had designed plastic water ballasted barriers that met level 2 two (2) of the NCHRP350 longitudinal barrier test. Hence, the descriptive term adopted for NCHRP350 compliant systems in Australia became "safety barriers".

The importation cost of plastic "safety barriers" was high as these products were engineered with steel internal frames or external saddles and certified to NCHRP 350. They were thought to be clumsy and extremely expensive compared to the European lightweight modules then appearing in Australia and elsewhere in the world.

In the early nineties all manner of road furniture items were in use in Australia; painted 44 gallon drums, timber barrier boards suspended between steel trestles, lengths of guardrail bolted to steel stakes and drums, etc. Contractors fabricated home brew devices from any materials at hand and were delighted when plastic barrier like units made their way into the hire company's inventories.

These new devices could be set up in a myriad of configurations and had stanchion apertures as well as water filling holes from which various fences and signage could be suspended. In fact, these devices became the universal fixit for contractors. Certainly they were highly visible from long distances, commanded the attention of drivers and were perceived to be safety devices.

For a long period there was no challenge to these devices because Australian State road authorities initially ignored their deployment. After numerous complaints directives were issued by regulators advising where safety barriers should be used and requiring the marking of non-compliant units with the instructions "NOT TO BE USED AS A SAFETY BARRIER". Advice was also issued to manufacturers that such units must meet the NCHRP350 traffic device test 70/71 if they were to be used to channel traffic. These directives only now are slowly being enforced.

In 1999 Standards Australia published AS/NZS 3845 "Road safety barrier systems". The committee implementing this standard when examining the issue of plastic water filled safety barriers added an additional Level 0 (820 kg vehicle at 50 km/hr and at 20º and 1600 kg vehicle impacting at 50 km/hr at 25º) to the test Matrix with the intention of setting a minimum credential requirement for all plastic barriers at roadwork sites.

CRASH TESTS

Monash Crash Test Series

A series of small car crash tests into roadside barriers were carried out by the Department of Civil Engineering, Monash University with Swedish and Australian sponsors at a decommissioned airforce base at Laverton near Melbourne in Victoria, Australia. Wire-rope, W-beam, Concrete median barriers and a Pipe-fence system were tested.

The testing included development of a remote control system, vehicle preparation and data logging. High-speed cinematography was carried out by Autoliv Australia.

A Toyota Echo was chosen as the test vehicle. The crashworthiness of this vehicle was at the time of testing ranked as the 2nd best in the world for a small car according to NCAP (New Car Assessment Program) tests. Two crash tests were carried out (80 km/hr at an impact angle of 45º and 110 km/hr at 20º) as indicated in Table 1.

A general description of the car setup, remote control system, data acquisition system, dummies and barrier test layout and general overview of the test outcomes including the crash pulses (see also Figure 19) are provided in other earlier papers (Corben et al, 2000, Ydenius et al, 2001, Grzebieta et al, 2002). What is highlighted here are some of the outcomes that are relevant to improving the crashworthiness of vehicles and barriers for designers and manufactures.

Rigid concrete barrier

What is most evident from the crash tests is that the pretensioners and airbags will more than likely fire and the vehicle undergoes significant damage to steering when the vehicle strikes the barrier. This will be the case for any crash into any type of rigid concrete barrier be it a Jersey, F shape, Constant slope barrier or vertical barrier, where impact speed exceeds around 60 km/hr and the impact angle is equal to or greater than 20º.

Impact forces can now be predicted with reasonable accuracy and hence average decelerations can be obtained for designers of both barriers and airbag systems so long as the crush characteristics of the vehicle are known (Jiang, Grzebieta & Zhao, 2004).

Jersey and F shape barriers will launch vehicles into the air and more than likely result in a vehicle rollover if struck at larger angles. Figure 7 shows the small car (Table 1) impacting the barrier at 80 km/hr at 45º. The crash was not survivable with large intrusion into the vehicle cabin and roof crush as shown in Figure 8. Figure 9 shows how the vehicle launches in the air at 110 km/hr at 20º impact angle. The dummy's head is thrown towards the side window and the passenger's head strikes the shoulder of the driver. The dummy kinematics is a combination of a frontal offset crash and a near side impact crash for the passenger and a far side impact for the passenger. Side air curtains would provide benefit in such crashes but a frontal airbag firing would hinder recovery.

Whilst there is a higher risk of rollover with the Jersey barrier than with the F shape barrier, Sicking has pointed out at a recent NCHRP 350 meeting (2004), the risk of rollover for these barriers is around 2.3 times greater for both barrier types than for a vertical barrier. Figure 10 shows how a pick up rolls over when hitting F-shape temporary and rigid barriers.

Car manufacturers need to consider how best to protect occupants in such crashes. Barrier manufacturers need to consider Sicking's (2004) proposal of manufacturing vertical wall barriers.

The main issue with rollover is that presently there are no suitable design rules that protect vehicle occupants in rollover crash anywhere in the world. FMVS216 has been shown to provide inadequate protection by Friedman and Nash (2001). This issue is further discussed in the section dealing with wire rope barriers.

Guardrail barrier

The guardrail test with the vehicle striking the barrier at 110 km/hr at 20º resulted in a low deceleration crash. The airbag did not fire and the vehicle was brought safely to rest in a controlled manner. The barrier dissipates energy by movement of the posts in the soil sideways. The blocks shown in Figure 2 help keep the vehicle's tire from interacting with the posts and possibly cause the vehicle to roll over. However, research work presently being carried out to determine equations for predicting working width, impact loads and the minimum post spacing required that ensures smooth redirection (Jiang, Grzebieta & Zhao, July 2004), has revealed that posts that are concreted into the pavement as shown in Figure 11 will cause the impacting vehicle to rollover. This practise of concreting the posts is common and highlights a problem of systems being installed by contractors that have little understanding of how such barrier systems redirect vehicles.

An interesting result was obtained with respect to the 80 km/hr at 45º impact test into the guardrail system. The vehicle "pocketed" into the barrier rather than being redirected. The front right wheel also under-rode the barrier and was torn from the vehicle during rebound as shown in Figure 12. What was revealed was the barrier was incorrectly installed by the contractor in that it was missing end

Figure 7 Impact of Echo into New Jersey barrier at 80 km/hr and 45º.

Figure 8 External and internal crush deformation for 80 km/hr at 45º impact into concrete barrier.

Figure 9 Impact at 110 km/hr at 20º.

Figure 10 Top: F shape moveable, Chevy C-20 at 99.4 km/hr and 26.4º Bottom: F shape fixed, Chevy ¾ ton at 99.8 km/hr @ 25.3º (after Sicking, 2004).

Figure 11 Guard rail barriers. Left: posts move in soil. Right: post set in concrete.

cables that provide further tensioning of the guardrail. Nevertheless it was felt that this would not have significantly altered the test outcome. The major issue was that the tyre under-rode the barrier. Hence barrier height is important and variation in wheel diameters needs to be considered by both vehicle and barrier manufacturers.

Whilst the crash was survivable it did fire the airbag. Moreover the firing of the airbag occurred when the head was already close to the steering wheel as shown in Figure 13. Details of the trigger timing for both the seat belts and airbags are published elsewhere (Grzebieta and Zou, 2001, Grzebieta et al, 2002). It is also worth noting that the head was guided towards the A-pillar both by inertia and by the airbag. Impact of the head with the airbag is similar to an out-of-position occupant situation.

Figure 12 Pocketing and under-ride into guardrail barrier – 80 km/hr at 45º.

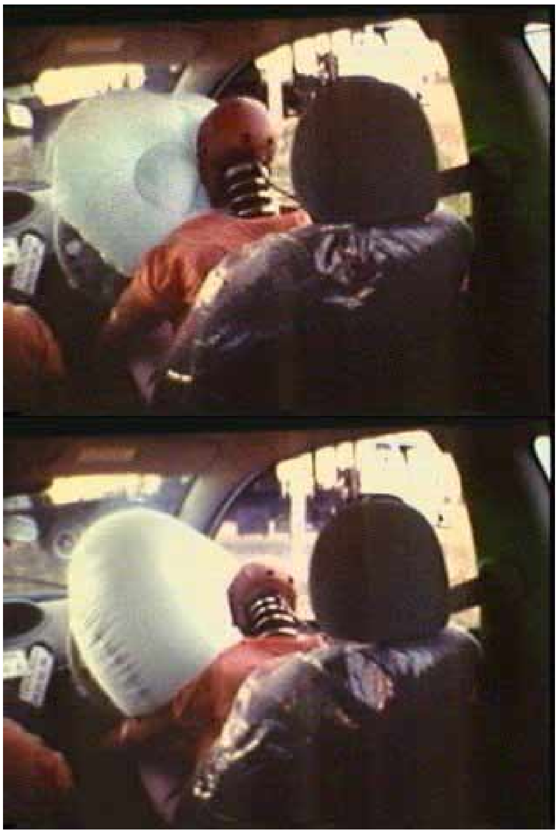

Figure 13 Top: airbag not fully inflated. Bottom: at full inflation.

Wirerope barrier

In the impact with the wire rope barrier at 110 km/hr at 20º the vehicle rolled over. The cause of the rollover was considered to be due to the shortness of the wire rope barrier which was tensioned to specification. Hence care needs to be taken in ensuring wire rope barriers are not only of adequate length but also set up exactly in the configuration as they were tested and certified.

An interesting outcome from the rollover crash was the on board image of the roof crushing onto the dummy head as shown in Figure 14. This high speed film captured the moment when the neck of the

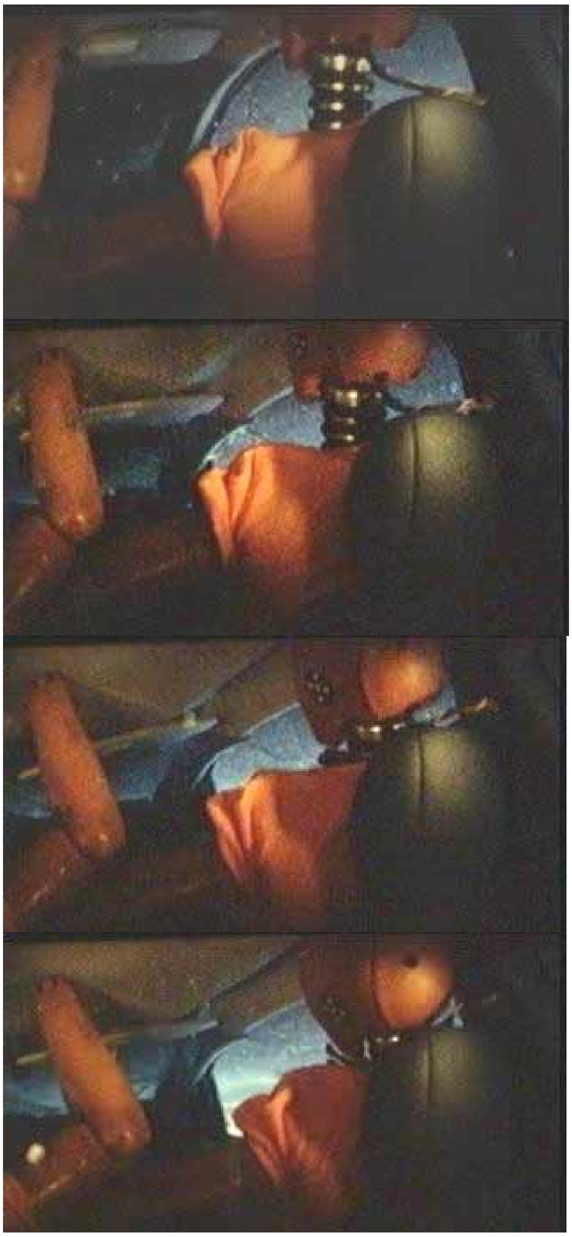

Figure 14 Roof crush in rollover compresses neck.

Hybrid III dummy is loaded and deforms into an S shape providing further good evidence of how roof crush in a rollover event can lead to either a fatality or serious neck injury where paraplegia or quadriplegia would occur. Rechnitzer et al in their study of serious neck injuries in rollover crashes pointed to the issue of roof crush as the main contributor to such injuries in 1998. The vehicle deformation shown in Figure 15 from both the Monash crash test and the vehicle shown in their paper, illustrating how an Australian football celebrity died in a rollover crash, are notably similar.

<u>Temporary water filled barriers</u>

A second series of crash tests were carried out at Monash University during development of roadside temporary barriers. Figure 16 shows a small compact car striking a water filled plastic barrier at 50 km/hr at 20º that replicates the Jersey Barrier shape and is commonly used as a delineator. The vehicle rolls on its side during redirection. In another crash a sedan vehicle of 1600 kg mass was made to strike a similar shape water filled barrier from a different manufacturer at 50 km/hr and at 25º. The vehicle climbed over the top of the barrier and down onto the road on the other side of the barrier line at the same angle it was travelling towards the barrier line. In other words, it was as if the barrier line did not exist, and the vehicle was not redirected.

The barriers shown in Figure 16 were redesigned to those shown in Figure 6. These barriers passed the Level 0 test as detailed previously.

The barriers were further redeveloped to those shown in Figure 20. A guardrail was attached to the front of the barrier in order to provide bending capacity and resistance to barrier perforation. A sub compact vehicle, a 2002 Daihatsu Cuore was chosen so that the compliance mass of 816 kg specified in

Figure 15 Top: Damaged profile of vehicle from the Monash Series wire rope crash test. Middle and bottom: Similar crush profile and injury mechanism presented by Rechnitzer et al (1998).

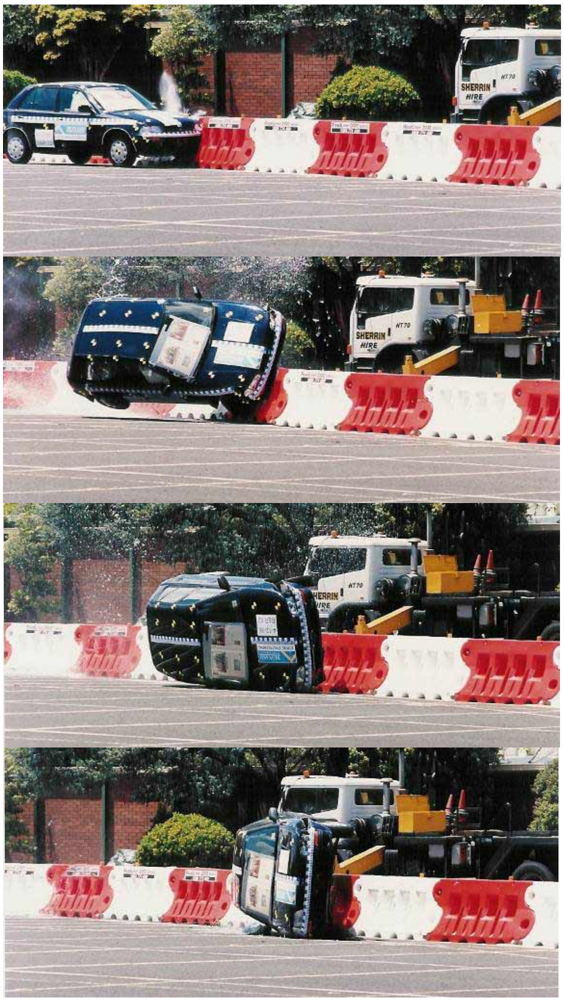

Figure 16 Small car impact into plastic delineator barrier.

NCHRP 350 could be met. Finding a sub compact vehicle that is light enough to meet this requirement is very difficult. Hence the more recent changes to vehicle masses proposed in updates to NCHRP 350. Most common compact vehicles weigh in at around 1000kg kerb mass.

Vehicles of this light mass usually have a short front end. This leads to climbing of the vehicle's struck side because there is insufficient crush distance between the front wheels and the bumper bar and the axle distance is short. It is for this reason the Ford Festiva with its longer front end/bonnet was used to certify most recent US barriers despite being an old outdated vehicle that in reality long ceased to represent the modern US compact car fleet.

Another issue with the smaller sub compact car is that the front bumper, radiator, lights and mudguard (fender) is much softer than the engine rail. The vehicle is fitted with an airbag to comply with frontal offset crash standards. Figure 17 shows the results of the Level 2 Daihatsu impact at 70 km/hr at 20º. However the stiffer engine rail acts like a spear perforating the barrier as shown in Figure 18. The guardrail helps restrict the intrusion and snagging to some degree. The tyre under-rides the barrier, tearing the wheel in a manner somewhat similar to the crash test shown in Figure 12. Again this highlights the need for both barrier manufacturers as well as vehicle manufactures to be aware that smaller diameter wheels can lead to inappropriate snagging problems where guardrail terminals are used.

The deceleration during impact in the Daihatsu crash test (Figure 17) was low enough that the airbag did not trigger. Whilst the engine rail tore the plastic wall the vehicle continued sliding along the barrier line where the average deceleration was around 7 g's.

Figure 17 NCHRP 350 Level 2 (70 km/hr at 20º) barrier crash test involving a Daihatsu car.

Figure 18 Tears in barriers caused by engine rail spearing through plastic.

Figure 20 shows the 2000 kg vehicle impact test at 25º. In this instance the vehicle did not snag. Nor did an engine rail protrude. The barrier redirected the vehicle along the barrier line so that a wave formed in front of the barrier and the vehicle was brought to a controlled slow stop. This is how barriers should ideally react. The airbags did not deploy and the vehicle could be driven away. Again the flexibility of the barrier system resulted in a redirection that did not lift or overtly damage the vehicle and hence would place any occupants at risk.

The vehicle crash pulses from the Level 2 barrier tests are compared to the vehicle crash pulses from the earlier Monash series tests in Figure 19. The crash pulse for the small vehicle (Figure 17) was equivalent in severity to striking a ductile W-beam barrier and for the 2000 kg vehicle the deceleration was even lower.

REAL WORLD EXAMPLES AND CONCLUSIONS

Figure 21 shows a small selection of roadside hazards that typify the problems encountered in regards to road design that the authors have noted and that persist despite available crash test evidence for many years that when vehicles strike such hazards the risk of a fatality or serious injury is high. The pictures are as follows; Frame A: Perth

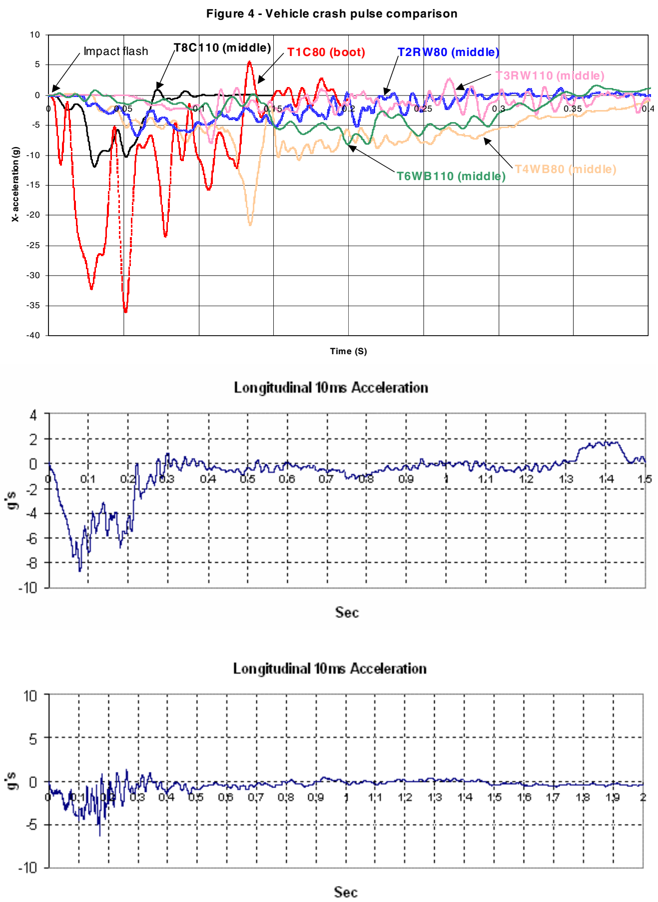

Figure 19 Vehicle crash pulses from Monash test series: (top graph) where C=concrete (Figure 7), WB=W-Beam (Figure 12), W=wire rope (Figure 4 & Figure 15) and speed is 80 or 100 km/hr (see Grzebieta et al 2002 for details); and from water filled Level 2 barrier tests (middle graph is small car in Figure 17, bottom graph is pickup truck in Figure 20)

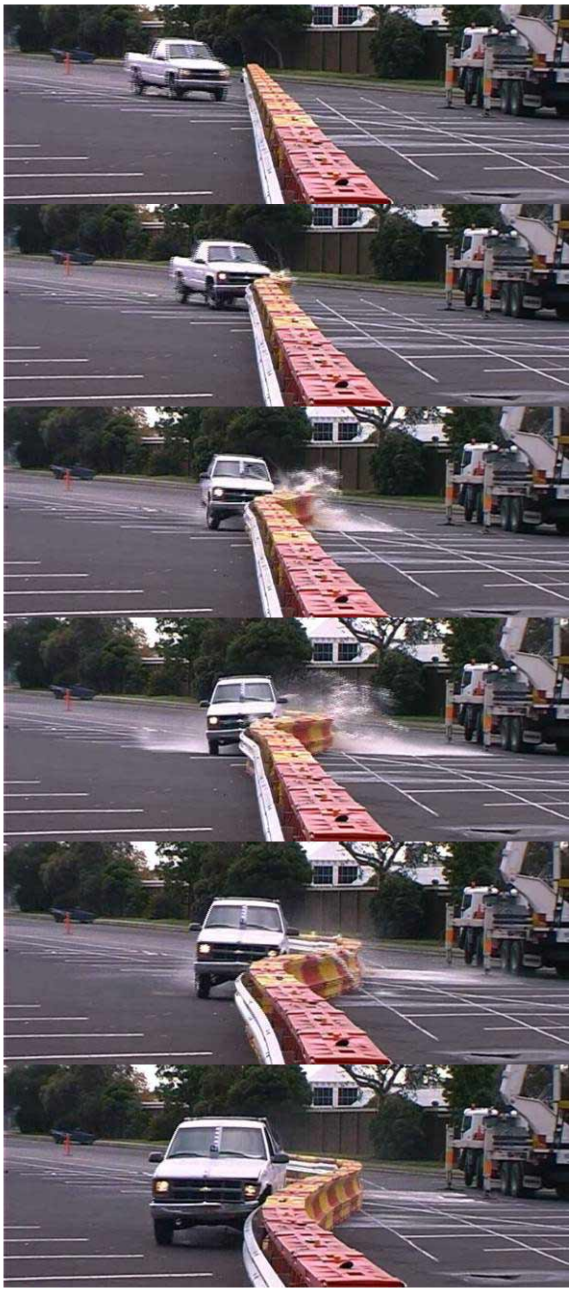

Figure 20 Crash test of 2000 kg US pickup truck impacting barrier at 70 km/hr at 25º.

freeway, B: Melbourne 100 km/hr new freeway, C: Melbourne exit ramp from new freeway, D: Melbourne concrete F shape barrier on 100 km/hr new freeway where wheel imprints are visible, E bridge pier in 100 km/hr zone in Wellington New Zealand with 70 km/hr speed limit zone placed 50 meters past the pier. What is of particular concern is the proliferation of hazards on completely new freeways where a large number of road safety audits have already been carried out.

These selected examples and the crash tests described above demonstrate that road and vehicle engineers must begin to work together such that information regarding vehicle crash behaviour

Figure 21 Real world lethal roadside hazards in Australia and New Zealand.

flows freely between the two disciplines. Such an initiative has already started in Australia with the formation of the Australasian College of Road Safety and the Australian Automobile Association's "SaferRoads" program (see www.acrs.org.au & http://www.aaa.asn.au/saferroads/ & ACRS 2004 Year book). It is clear that government authorities responsible for road safety such as NHTSA and FHWA and similar bodies in other countries can no longer work as separate entities if the road toll is to be dramatically reduced over the next decade.

Another issue critical to further reducing road trauma in different countries is increasing funding to investigate the crashworthiness of roadside barriers via fully instrumented crashes. Whilst considerable resources are available to study instrumented car crashes, the same magnitude of resources are not available to determine how best to design roadside barriers. This is particularly so in relation to trucks impacting barriers. Only a few crash tests of large trucks impacting barriers have been carried out and yet millions of these vehicles transporting goods travel the roads of the world intermixing with cars.

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USE OF THE CRASH PREVENTION BOUNDARY METHODOLOGY TO DESCRIBE THE PERFORMANCE OF ADAPTIVE CRUISE CONTROL SYSTEMS

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ABSTRACT

This paper presents a preliminary exploration of approaches to using experimental data for estimating the safety impact of advanced technology systems. The Crash Prevention Boundary (CPB) methodology is the basis for these new approaches. The CPB is an analytical technique to distinguish between driver performance that prevents a crash and performance that results in a crash. In this paper the CPB concept is used to describe the performance of an Adaptive Cruise Control (ACC) systems. Data from the Automotive Collision Avoidance System (ACAS) field operational test of an ACC system is used. This study explores a method to rate safety performance of ACC systems in two situations; where the host vehicle is overtaking a slower moving vehicle and where the host is following a lead-vehicle that is decelerating.

The paper presents an empirically based discussion of new computational procedures that can lead to improved estimates of the safety impact of driver assistance systems. The purpose of this paper is not to do a complete analysis of results from this test; but rather, to use a convenience-sample as a means of exploring new approaches to analyzing the data. The paper compares existing descriptions of safety boundaries with new approaches that are based on the CPB concept. Based on the ACC, it appears that these new approaches have the potential of improving the utility of such data for estimation of the safety impact of driver assistance systems.

INTRODUCTION

As advanced technology systems have an impact on crash prevention, it will be necessary to develop new analysis tools to help assess the safety impact of the systems. The crash prevention boundary (CPB) methodology is one such technique. This paper uses adaptive cruise control (ACC) system as an example of how the CPB methodology can be used.

The underlying principle behind the CPB concept is that drivers make choices each time they are presented with a situation that may lead to a crash; e.g. catching up to a slower moving vehicle. This choice includes when to take action and how aggressive the action should be; e.g. when to brake and how hard to brake. The consequence of these choices is that in each case the driver either does or does not avoid a crash.

The CPB methodology provides a means of describing the minimum performance that will avoid a crash in each specific situation. The CPB methodology also provides a quantitative means of describing the closeness to a crash that results from a specific performance choice. This closeness, called the Estimated Closest Approach (ECA) can be used to describe an individual driver's performance, or it can be used in the aggregate to describe changes in driver performance, that results from introduction of a driver assistance system, or other type of system that interacts with the driver.

This paper uses a convenience-sample of driving performance from a recently completed field operational test (FOT). The FOT used vehicles that were equipped with a rear-end crash warning system in combination with an adaptive cruise control (ACC) system. The purpose of this paper is not to do a complete analysis of results from this test; but rather, to use this convenience-sample as a means of exploring new approaches to analyzing the data. A complete analysis will be performed by the Volpe National Transportation Systems Center; and results will be published later this year.

This paper is divided into four additional sections. The first section briefly discusses the background, including the concept of the CPB and its role in understanding driver performance in situations that have the potential of evolving into a crash, the computational procedures for reducing experimental data, and a short description of adaptive cruise control systems and the data used in this study. The second section discusses analysis of data; for a subset of data where a following-vehicle overtakes a slower moving lead-vehicle and for a subset of data involving decelerating lead-vehicles. The third section presents several safety contexts for the analysis, including new techniques that are part of the CPB methodology and application of the results to assessment of safety benefits. A fourth, and final, section summarizes the material in the paper.

BACKGROUND

Crash Prevention Boundary

The Crash Prevention Boundary (CPB) methodology is an analytical technique to distinguish between driver performance that prevents a crash and driver performance that does not prevent a crash. The foundation of the method – first introduced by Burgett and Miller [3] – is the premise that, for the purpose of understanding driver crash prevention performance, vehicle braking may be described by a constant deceleration profile.

A CPB is an analytical means of describing driver performance in situations that might result in a crash. Figures 1 and 2 are examples, respectively, of CPB curves for situations where the lead-vehicle is traveling at a constant velocity and the lead-vehicle is decelerating. In Figure 1, the driver's performance is described by the time-to-collision (TTC) when effective braking begins and the level of braking. The CPB curve range rate separates this two-dimensional description of driver performance into regions that prevent crashes (to the right of the curve) and regions where driver performance does not prevent a crash (to the left of the curve).

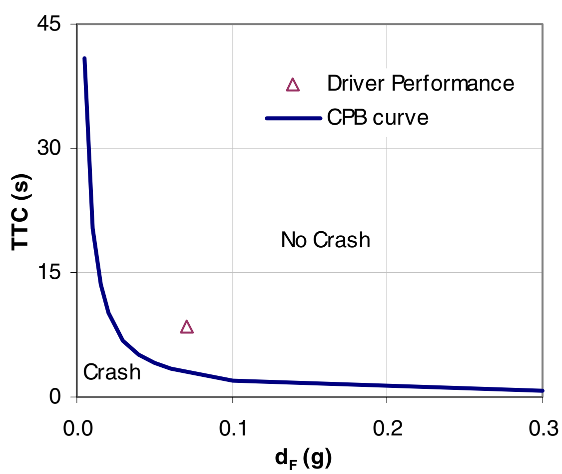

Figure 1. Example Of A Crash Prevention Boundary, Lead-vehicle At Constant Velocity.

In the example shown in Figure 2, the CPB curve corresponds to a situation with initial conditions of : both vehicles traveling at 29m/s, with a distance between them (range) of 55.4 m and the lead-vehicle decelerating at 0.4g. The crash prevention performance of the following-vehicle is described by the two parameters; the time at which effective following-vehicle braking begins and the level of braking that the driver chooses. As is described in more detail later in this paper, this parametric description of driver performance is obtained by calculating a "best-fit" approximation of the braking profile of the following driver during the event.

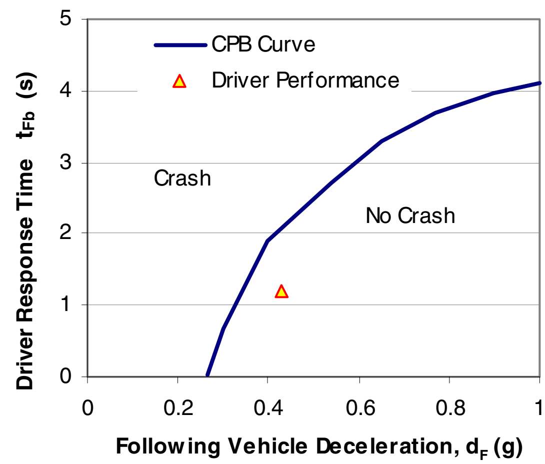

Figure 2. Example Of A Crash Prevention Boundary, Lead-vehicle Decelerating.

An extension of the CPB methodology is to estimate how close a driver might have come to a collision during the event. It can be shown that the value of closest approach of the two vehicles that would have occurred if the driver had applied the "best-fit" level of deceleration throughout the event called the estimated closest approach (ECA) is directly related to the closeness of the values of this pair of parameters to the CPB curve.

Computation Of Empirical Data

Characterization of an ACC braking event is based on the principle of minimization of an measure of error between experimental response data and approximations based on assumed descriptions of the response [2, 4]. The assumed description consists of the starting time for deceleration of both the lead-vehicle and the following-vehicle as well as the level of deceleration for each. Both decelerations are assumed to be constant for the duration that they are applied by the driver. The error measure consists of the following summation of differences between experimental and approximations of speed of both vehicles and range between them.

$$\sum_{t=0}^{t=s}\left(\frac{\left(V_F^{approx}-V_F^{test}\right)^2}{V_F^{test}}+\frac{\left(V_L^{approx}-V_L^{test}\right)^2}{V_L^{test}}+\frac{\left(R^{approx}-R^{test}\right)^2}{\left(R^{test}\right)^3}\right)$$

.

Resulting velocities and displacement that result from the deceleration profiles that minimize this error measure are used for the analysis described in this paper.

Figure 3 is an example showing the deceleration trajectories of an Intelligent Cruise Control (ICC) [7] decelerating event. Deceleration in ICC was achieved by down shifting rather than braking. In this example the lead-vehicle is traveling at a constant velocity. d_F^{test} and d_L^{test} denote actual test deceleration trajectories for the following and the lead-vehicle respectively. Also seen in the plot are the respective best-fit decelerations, which minimize the error measure.

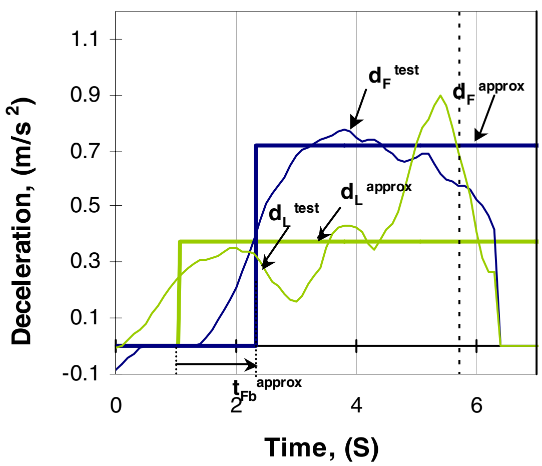

Figure 3. Deceleration Of Lead And Following Vehicle, Experiment And Best-Fit.

A comparison of the trajectory of range vs. range-rate of the experimental and its corresponding approximate trajectory is shown in Figure 4. This figure also introduces the concept of estimated closest approach (ECA). This is the closest distance the following vehicle would approach the lead-vehicle, based on the best-fit deceleration profiles.

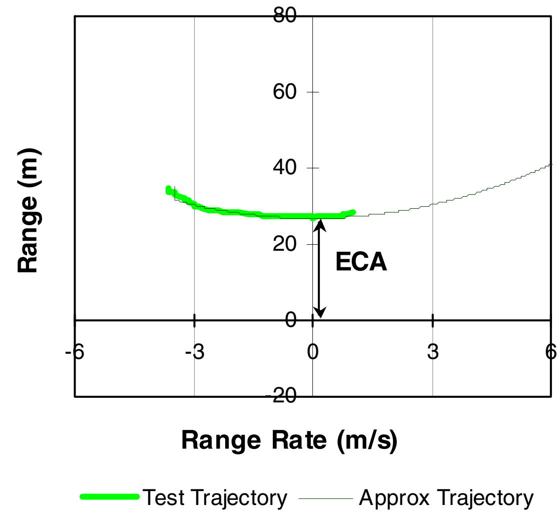

Figure 4. Experimental And Approximate trajectories in Range/Range-rate coordinates.

Description Of ACC System And Data

The ACC subsystem is a complete control system that uses on board radar to detect objects in front of the vehicle, and provide throttle and brake control to maintain a safe distance to the vehicle ahead. When active, the ACC has two modes, maintain the set speed and maintain the selected headway. In maintaining headway, the system is capable of slowing the vehicle to the speed of lead-vehicle that is traveling slower than the set speed

The Field Operation Test (FOT) of the Automotive Collision Avoidance System (ACAS) had the following features [1].

- Ten ACC equipped 2002 Buick LeSabres.
- Participants use vehicles as personal vehicle for 4 weeks unsupervised and unrestricted.
- 96 total participants.
- Participants grouped in 20-30, 40-50,and 60-70 age groups and split by gender.
- Over 500 data channels were recorded.
- 137,000 miles driven by the subjects during the FOT.

Operational description of ACAS ACC system;

- Headway, range from 1 to 2 second with 0.2-second increment.
- Maximum deceleration level of 0.3g.
- ACC does not react to stationary objects

In order to understand the ACC brake process, a 2 second span of ACC brake action is essential. Hence only data sets with 2 seconds or more of ACC braking are considered. Data one second before and after ACC braking was examined to understand the dynamics that lead to ACC braking.

Convenience sample

Driving data from the 10 drivers in the convenience sample included ACC initiated brake control in 670 events. The ACC brake control event time span range varied from a few tenths of a second to six or seven seconds. Of these, only 130 events were used in the analysis. The rest either had a short time span of ACC brake (less than 2 seconds), were involved a cut-in situation, or were involved in a lead-vehicle acceleration situation.

ANALYSIS OF DATA

Overtaking at Constant Speed Subset

This section discusses analysis of the data for cases where the subject vehicle, i.e. the host vehicle of the ACC system, is catching up to a slower moving vehicle. At some point the ACC system recognizes the disparity in speed and chooses to decelerate the host vehicle to the speed of the lead-vehicle. This idealized process is described graphically in Figure 5. The diagram shows the path, in range/range-rate coordinates, of motion between the two vehicles as the following vehicle overtakes the lead-vehicle. At some point (denoted by the letter A) the ACC system in the following (host) vehicle chooses to reduce speed to match that of the lead-vehicle. The host vehicle then decelerates to a zero range-rate and begins to follow the lead-vehicle at a fixed distance. The headway setting that the driver of the host vehicle has selected and the speed of the lead-vehicle determine the value of the fixed-distance.

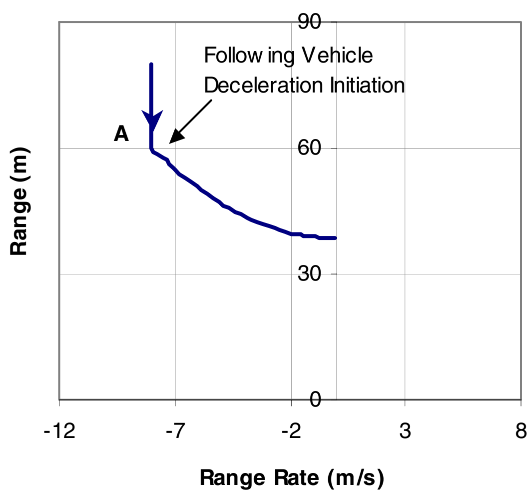

Figure 5. Range / Range-rate Plot Of An Ideal ACC Braking When Lead-vehicle Is Traveling At Constant Speed.

In practice, the ACC system performs as a closed-loop control system. The control algorithm, as shown in Figure 6 [7], initiates deceleration or acceleration as a function of the values of range and range-rate relative to an idealized path shown by the diagonal line through the final value of range. The slope of this line and the allowable smallest value of range are design parameters of the control system. In practice, the path of motion in the range/range-rate coordinates is a spiral as shown in Figure 6.

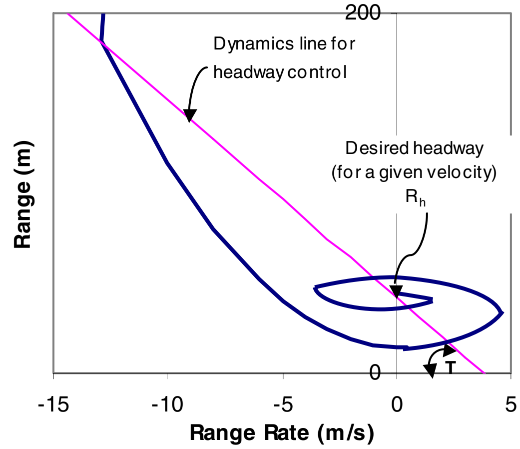

Figure 6. ACC Overtaking A Slower Vehicle

A well-designed ACC system should be able to manage most situations where one vehicle overtakes a slower moving vehicle. Thus, it is expected that the data from this FOT would reflect a safe and comfortable reaction to these situations. This intuitive expectation is confirmed by the following discussion of ACC response in overtaking situations.

There are many studies in the literature of how to describe various levels of safety. In this paper, two recent approaches are used and discussed, keeping in mind that the purpose of this paper is to develop procedures more than it is to do a thorough analysis of safety impact. One approach describes regions of the range/range-rate space by the level of safety that those regions represent [5].

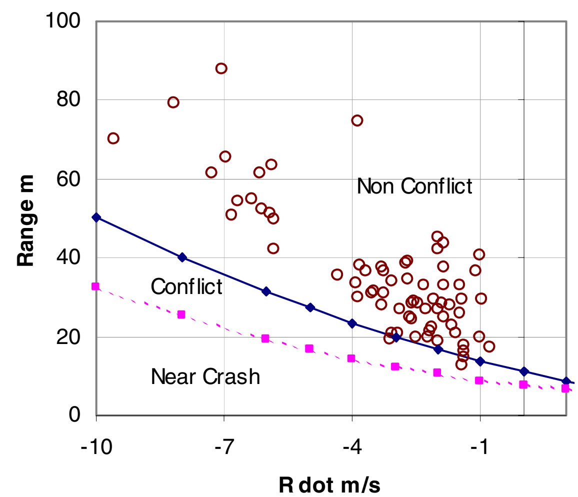

Figure 7. Braking Response At Constant Speed Scenarios.

Figure 7 shows curves that describe the estimated level of risk. An event with initial braking conditions that are above the top curve is considered to be a "non-conflict", an event with initial braking conditions between the two curves is considered to be a "conflict", and an event with initial braking conditions below the bottom curve is considered to be near-crashes. Data for the conditions when the following vehicle ACC begins to brake (t_{Fb} Figure-3) are overlaid on these curves. As expected, most of the ACC braking scenarios are in the "non-conflict" region, with a few in the "conflict" region. None of them are in the "near-crash" region.

The second approach uses driver attributes to subdivide the normalized (lead vehicle speed) range/range-rate space into safety-relevant subsets [7]. This classification scheme quantifies driving styles at highway speeds. One of these driving styles is "fast and close". An event with initial braking conditions in the highlighted area reflect a close and/or fast driving style. An overlay of the ACC data shows that the performance of the ACC does not coincide with driver performance that would be considered close and fast.

These two approaches have a common feature that they characterize the safety of response by the conditions that exist at the beginning of the action to resolve an impending conflict.

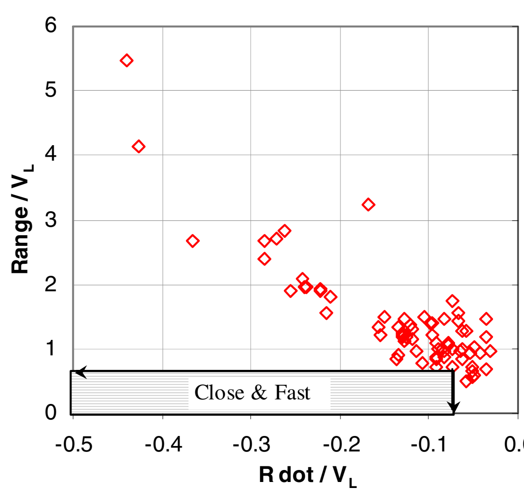

Figure 8. Driving Style Boundaries, ACC Data

The two approaches in the discussion above are complemented by two approaches that make use of the Crash Prevention Boundary (CPB) concept. The advantage of the CPB approach is that it is tied directly to the response to a pending conflict rather than being limited to the conditions that exist at the beginning of the response. The first of these CPB approaches uses the distribution of Estimated Closest Approach as the means of assessing the level of safety . The frequency and cumulative distribution for the ACC data is shown in Figure 9. These distributions can be compared with baseline driving to provide a measure of the level safety of the ACC system. Baseline data have not yet been analyzed and the ACC data is only a convenience sample. Therefore the comparison of distributions cannot be made at this time.

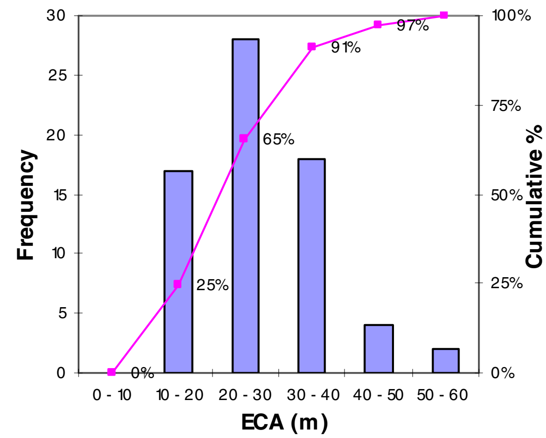

Figure 9. Distribution of Estimated Closest Approach (ECA).

The second approach combines ECA and estimated level of braking (d_F) as the means of assessing the level of safety. the values of these two parameters for the ACC data are presented in Figure 10. The logic behind this approach is that either a high level of deceleration or a close approach to the lead vehicle is indicative of a less safe condition than if both of them were smaller. This hypothesis has not been studied, so no threshold values exist at this time, although ECA=10 m and d_F =0.3g are shown for demonstration of the approach only.

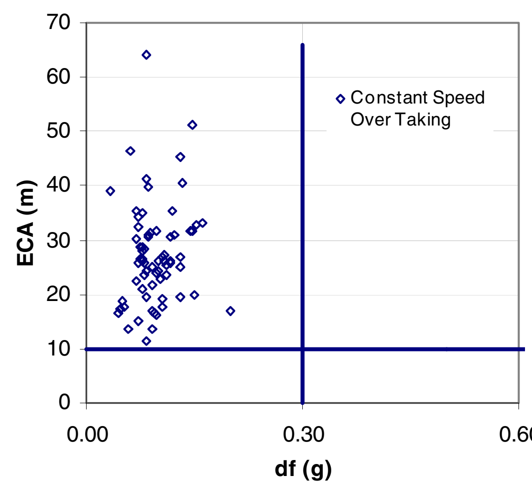

Figure 10. Estimated Closest Approach Vs Level Of Deceleration By The Following Vehicle.

Decelerating Lead-vehicle Subset

This section analyzes the data for cases where the subject vehicle, i.e. the host vehicle of the ACC system, is initially following another vehicle when the lead-vehicle begins to brake. When the ACC system recognizes the lead-vehicle deceleration it commands an appropriate deceleration by the host vehicle. A graphical depiction of an idealized example is shown in Figure 11.

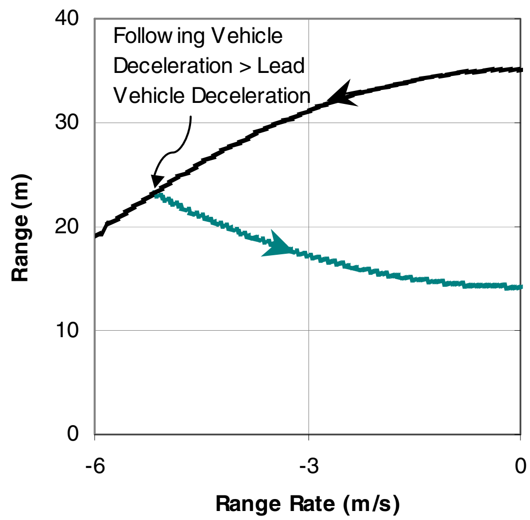

Figure 11. Range / Range-rate Plot Of Ideal ACC Braking When Lead-vehicle Is Braking.

The diagram shows the path, in range/range-rate coordinates, of motion between the two vehicles as the lead-vehicle begins to decelerate which causes a negative range-rate and consequent reduction in range. As the host vehicle begins to decelerate, the range-rate becomes less negative and the two vehicles eventually resume travel at the equal speeds. In practice, the closed-loop control of the ACC system performs similarly to its performance in overtaking a slower vehicle, as described above.

One feature of ACC system design is that there is limited deceleration authority. Thus, if the lead-vehicle deceleration is larger than that authority, it will not be possible for the ACC system to completely manage the situation and the driver will have to intervene. Drivers may also intervene if they are not comfortable with the levels of range and range-rate created by the ACC. Thus, it is expected that the data from this FOT would reflect a safe and comfortable reaction to most lead-vehicle situations and that there would be driver intervention in a limited number of cases. This intuitive expectation is confirmed by the following analysis of ACC response in the lead-vehicle deceleration situations experienced in this convenience sample of the FOT.

The two approaches to characterizing the level of safety that were discussed in the preceding section are also applicable to lead-vehicle deceleration situations. Figure 12 describes regions of the range/range-rate space by the level of safety that those regions represent [6]. An event with initial braking conditions that are above the top curve is considered to be a "non-conflict", an event with initial braking conditions between the two curves is considered to be a "conflict", and an event with initial braking conditions below the bottom curve is considered to be near-crashes. Data for the conditions when the following vehicle ACC begins to brake (t_{Fb} Figure-3) are overlaid on these curves. As expected, most of the ACC braking scenarios are in the "non-conflict" region, with a few in the "conflict" region. None of them are in the "near-crash" region

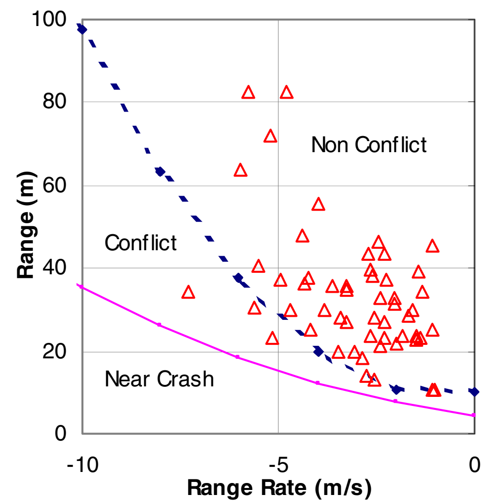

Figure 12. Braking Response In Decelerating Lead-vehicle

The second approach shown in Figure 13 uses driver attributes to subdivide the normalized (lead vehicle speed) range/range-rate space into safety-relevant subsets [7]. This classification scheme quantifies driving styles at highway speeds. One of these driving styles is " close". A event with initial barking conditions in the highlighted reflect a close fast driving style. An overlay of the ACC data shows that the performance of the ACC in most of the cases does not coincide with driver performance that would be considered close. On thorough examination of the ACC cases that were in the close region reviled revealed that they were either a cut in or a lane change, which resulted in required deceleration levels greater than the ACC threshold of 0.3g.

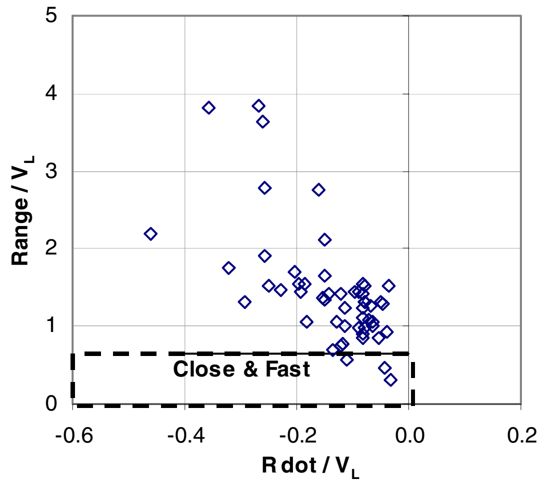

Figure 13. Driving Style Boundaries, ACC Data

Similarly, the two methods of analyzing data using the CPB methods are discussed, the first uses the distribution of Estimated Closest Approach as the means of assessing the level of safety and the second approach considers both the Estimated Closest Approach and the level of braking as the means of assessing the level of safety, these are shown in Figures 14 and 15.

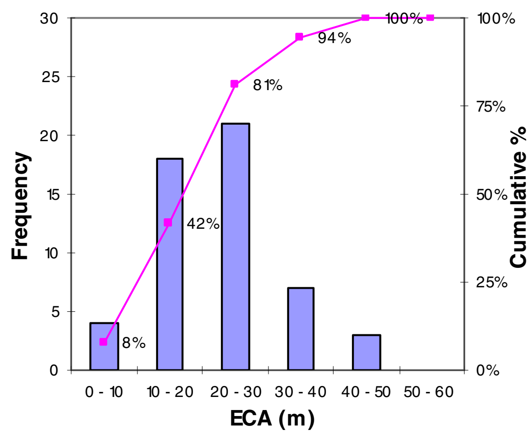

Figure 14. Distribution Of Estimated Closest Approach (ECA).

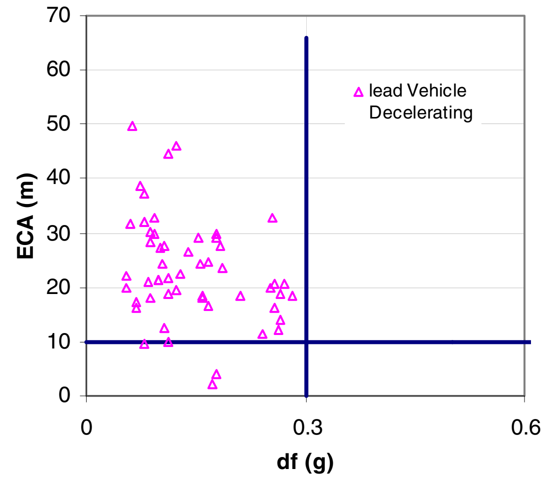

Figure15 Estimated Closest Approach Vs Level Of Deceleration Of The Following Vehicle.

A comparison of Figures 14 and 15 with corresponding figures for the overtaking situations shows that the ACC system allows smaller values of ECA and uses higher levels of deceleration than it did for the overtaking cases. However, there is no indication that performance of the ACC system is not adequate or is unsafe for the levels of lead-vehicle decelerations that were experienced in this set of data.

APPLICATIONS AND ASSESSMENT OF BENEFITS

This section pulls together the data analysis and safety concepts from the preceding sections. The underlying purpose for analyses such as those discussed in this paper is the assessment of the safety impact of driver assistance systems. Many of these same approaches can also be used to address the safety impact of technologies that produce distraction or excessive driver inattention. A standard expression that incorporates all of the elements for producing a quantitative assessment of safety impact is the following equation [8]

$$B = N_{wo} \times \sum_i P_{wo}(S_i \mid C) \times [1 - \frac{P_w(C \mid S_i) \times P_w(S_i)}{P_{wo}(C \mid S_i) \times P_{wo}(S_i)}]$$

In this expression, the subscript i corresponds to unique situations and the ratio of $P_w(C|S_i)$ to $P_{wo}(C|S_i)$ is termed the prevention ratio. It describes the relative likelihood of a crash in a specific situation with and without the driver assistance system. Thus, estimation of this ratio is a key step in making an assessment of safety. The following discussion proposes one approach to obtaining an estimate of this ratio.

It was seen in the preceding sections that the distribution of Estimated Closest Approach provides a quantitative description of the safety performance of a system. In this paper the system is the ACC that was used in the FOT. In the preceding sections, the performance was subdivided into two conditions, overtaking at constant speed and reacting to deceleration of a lead-vehicle. The cumulative distributions of ECA for both types of event are shown in Figure 16.

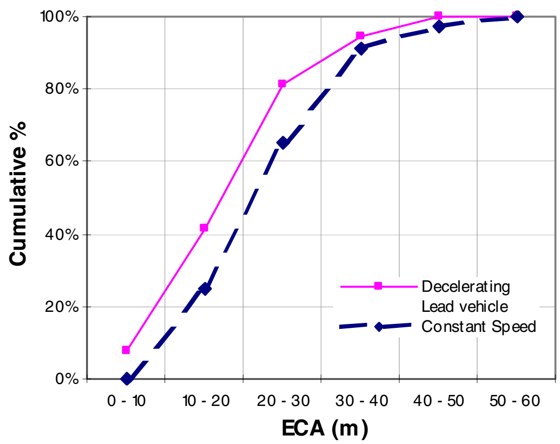

Figure 16. Comparison Of Cumulative Distribution Of ECA For Two Types Of Events.

One way to characterize the relative position of the two distributions is to use the value of ECA for a specific percentile for the distribution. For example, if 25 percentile is used, the corresponding values of ECA are 9 m and 14 m, respectively for the decelerating lead-vehicle and overtaking conditions. These values of ECA can then be used as surrogates in the calculation of prevention ratios. It should be noted that the corresponding distributions for driver performance without the assistance of the ACC are not available, so calculation of prevention ratios is not possible at this time. It should also be noted that this use of values of ECA is hypothetical and has not been tested or verified.

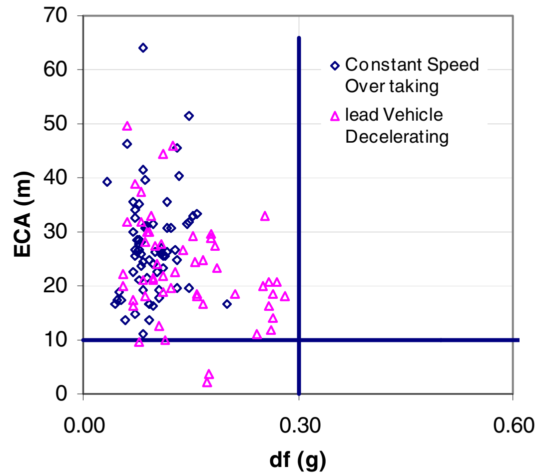

Figure 17. Summary Of ECA And d_f Data.

A variation on this approach is the recognition that if short values are combined with high levels of host vehicle deceleration, it is a good indication that the situation resulted in a near-crash. This recognition can be quantified by separating system response data into the four quadrants shown in Figure 17. If appropriate values are assigned to the edges of the quadrants, e.g. 0.3 g and 10 meters, the percentage of responses that fall in the lower right quadrant is an indication of the level of safety of the driving experience. In this case, the values in the lower right quadrant for baseline and assisted conditions would be used to compute the prevention ratio.

SUMMARY

This paper has presented an empirically based discussion of new computational procedures that can lead to improved estimates of the safety impact of driver assistance systems. An Adaptive Cruise Control system that was tested in a field operational test is the basis for the discussion. The purpose of this paper is not to do a complete analysis of results from this test; but rather, to use a convenience-sample as a means of exploring new approaches to analyzing the data. The paper compares existing descriptions of safety boundaries with new approaches that are based on the Crash Prevention Boundary concept. Based on the data from use of adaptive control system it appears that these new approaches have the potential of improving the utility of such data for estimation of the safety impact of driver assistance systems.

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SAFETY EVALUATION OF LANE CHANGE COLLISION AVOIDANCE SYSTEMS USING THE NATIONAL ADVANCED DRIVING SIMULATOR

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ABSTRACT

This paper reports on the status of the evaluation of several lane change collision avoidance systems (CAS) types using the National Advanced Driving Simulator (NADS). The goal of this evaluation is to examine driver behavior with a variety of lane change CAS to determine what leads to the safest driver behavior, and to investigate if the use of a lane change CAS with only a proximity warning system (i.e., blind spot detector) provides sufficient warning to drivers. The study begins with a comprehensive review of literature in this area. Then, simulator test scenarios are developed for the NADS to examine and compare five lane change CAS types, namely a representative commercially available proximity warning system, the TRW proximity only CAS, the TRW comprehensive system, a nonplanar mirror on the left (driver's) side of the vehicle, and a baseline with standard passenger vehicle mirrors. The test scenarios are based on Sen, Smith, and Najm [1] lane change crash data analysis. Preliminary results on the driver's acceptance of the lane change CAS and decision to use CAS information in making lane change decisions are presented. This research is still in progress and is planned to be completed in mid 2005.

INTRODUCTION

Lane change collision avoidance systems (CAS) are designed to prevent crashes in lane change maneuvers by alerting the driver to hazards in the adjacent lanes of traffic. From previous studies, it has been determined that many crashes during a lane change occur when drivers are unaware of hazards around their vehicle. A CAS can detect surrounding vehicles that are in zones on the sides and behind the vehicle and notify the driver through the use of a warning signal such as an auditory message or a visual symbol in the side or rear view mirrors. Lane change crashes account for approximately 5 percent of the total of all reported crashes in the General Estimates System (GES) data. To the extent that a CAS helps drivers avoid unsafe lane changes, it has the potential to reduce crashes.

The Space and Electronics Group of TRW has developed a CAS consisting of two detection and warning subsystems [2]. The first subsystem, a proximity warning subsystem, detects vehicles in a defined proximity zone on the side of the vehicle including the region referred to as the blind spot. The second subsystem, the fast approach subsystem, detects vehicles further behind the vehicle than the proximity zone that are at high closing speeds approaching the proximity zone.

LANE CHANGE CAS

Five types of lane change CAS were tested: 1) TRW proximity only system, 2) TRW proximity and fast approach system, 3) commercially available proximity warning system, 4) nonplanar mirror (left side), and 5) baseline (standard left and right side mirror).

TRW Proximity Only System

The first lane change CAS is TRW's Space and Electronics Group proximity-warning subsystem that detects vehicles in a defined proximity zone on the side of the vehicle including the region referred to as the blind spot. The proximity zone, also known as the keep-out zone, is adjacent to and 30 feet behind the vehicle [3]. The system does not warn drivers about stationary objects but does monitor vehicles in the blind spot. A red triangle appears right in the field of view in the rearview and side-view mirrors when another vehicle is in a vehicle's path (see Figure 1). This CAS has been designed to warn drivers about vehicles not in the mirror, i.e., in the blind spot. The red triangle has been also used in the Buick XP2000 concept car [4]. The display associated with this system simulation in NADS is presented in Figure 2 for driver's side mirror and Figure 3 for the passenger side mirror.

Figure 1. TRW view from driver's seat of warning icons in and next to mirrors [2].

Figure 2. View from driver's seat of TRW CAS simulation in NADS.

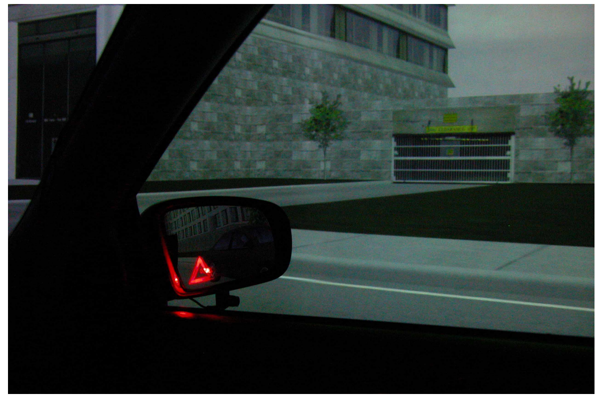

Figure 3. View from driver's seat of passenger's side mirror of TRW CAS simulation in NADS.

TRW Proximity and Fast Approach System

TRW also developed a fast approach subsystem, which detects vehicles further behind the vehicle than the proximity zone that are at high closing speeds approaching the proximity zone. Specifically, this system has a three second time to arrival into the proximity zone for fast approaching vehicles [3]. This second TRW system comes packaged with the proximity warning system in an integrated package. This CAS has been designed to overcome driver's inability to accurately perceive closing times. This system has a maximum relative velocity detection limit of 50 km/h (31.07 mph).

Limited Proximity Warning System

The third lane change CAS tested is a limited proximity warning system (LPWS). The LPWS system is mounted on the side mirrors and flashes when it detects an obstacle in the blind spot (see Figure 4 for both versions 1 and 2). The detection fields of view are arranged so that the tires of the vehicle in the blind spots are detected (see Figure 5). This typically covers an area approximately 3.5 to 4.2 m (12 to 14 ft.) to the side and up to 7.6 m (25 ft.) back from the external side view mirrors. The LPWS uses signal to noise processing methodologies of two sensors to measure the same field of view at two points in time. The system is operational when the vehicle is traveling at 20 or more mph. LPWS's sensor enables the detection of an object that is stationary or moving relative to the sensor but moving with respect to the background (or road surface). It can detect over one or more lane widths and back from the side view mirrors 8 to 20 meters (24 to 66 ft.) or further (using different lenses). It detects other vehicles with relative velocities of 0 to 64 km/h (40 mph). Over 10,000 units have already been sold. The display automatically adjusts to lighting conditions and works in all weather. This CAS has been designed to warn drivers about vehicles that are close but not in the mirrors (like the TRW Proximity Only System), vehicles with high closing speeds (like the TRW Proximity and Fast Approach System), and potential hazards not seen (such as stationary objects in the adjacent lane). The LPWS warns of a vehicle entering the blind spot under the following circumstances: 1) the participant automobile overtaking another automobile, 2) another automobile entering from the rear of the blind spot in the adjacent lane, and 3) another automobile entering laterally from the second lane over. These algorithms have been included in the NADS simulation. The display associated with this system simulation in NADS is presented in Figure 6. The triangular symbol is lit when it is unsafe to change lanes.

Figure 4. LPWS side mirror display [showing version 1 (top) and version 2 (bottom)].

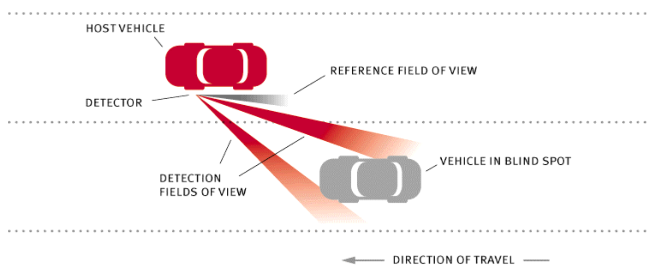

Figure 5. LPWS blind spot detection (note: warnings are provided for blind spots on both sides of the test vehicle).

Figure 6. View from driver's seat of LPWS CAS simulation in NADS (same as TRW systems).

NonPlanar Left-Side Mirror

A fourth lane change CAS is a nonplanar mirror attached to the left side of the vehicle. The fields of view for both the right and left side mirrors are those illustrated in Figure 7. The implementation in NADS is presented in Figure 8. A spherical convex mirror with 1400 mm (55.1 in) radius of curvature on the passenger side has been used in this study. The radius of curvature is the common radius [5]. This is the low-cost proposed solution for blind spot collisions. Performance can be compared against the baseline to determine safety benefit and against the CAS to determine cost effectiveness.

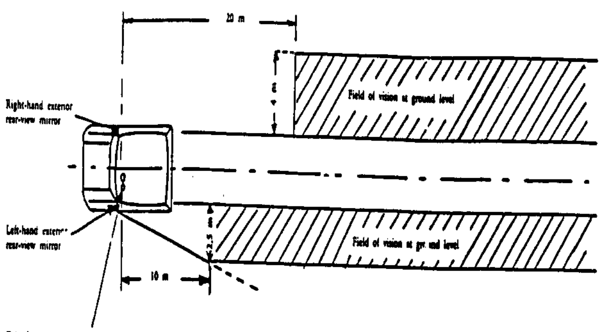

Figure 7. Required field of view main exterior rearview mirrors [5].

Figure 8. View from driver's seat of convex mirror in NADS.

Baseline (Standard Side Mirrors)

This is the baseline against which the performance of all the lane change CASs are being compared. This is critical in determining the benefit of each CAS. The baseline is standard U.S. vehicle mirrors: planar on the driver's side, and a standard convex passenger side mirror.

SIMULATED LANE CHANGE CONDITIONS

The lane change scenarios occur on nonjunction segments of roadway without traffic control with 50 mph speed limits. The status of the blind spot, the actions of the lead vehicle(s), and the direction of lane change defined the lane change scenarios. All three blind spot conditions have been combined with both sets of lead vehicle actions (described in the next section) and both left and right lane changes.

Blind Spot Status

There are three possible conditions of the blind spot. In the first, there is no vehicle in the blind spot. In the second, there is a vehicle in the blind spot and it is traveling at the same speed as the test vehicle. In the third, there is a fast approaching vehicle in the blind spot and it is traveling at speed 30 mph (48 km/h) greater speed than the test vehicle. It is timed to be in conflict with the test vehicle during the lane change. This third condition for the blind spot status occurs only in the last trial. This limitation has been imposed in keeping with estimates for the frequency of occurrence of fast approach vehicles since no on road or simulator data are available for actual driver behavior. These estimates are based on naturalistic driving data collected in Virginia by Olsen and Lee. Specifically, naturalistic lane change data were reviewed [6,7] to see how many cases fit the fast approach criteria. Their data included 8,677 lane changes (including some that were full passing maneuvers). They chose 500 lane changes for in-depth review. The 500 chosen for further analysis included all of the more severe and urgent cases (the fast approach criteria would definitely have been classified as a severe case and thus all cases fitting these criteria would have been included in the 500 lane changes analyses). There were 16 drivers who drove the instrumented vehicles for 20 days each (10 days in the sedan and 10 days in the Sport Utility Vehicle (SUV)). These drivers logged almost 25,000 miles in the course of the study. Drivers commuted in interstates and US highways in southwest Virginia (commutes of at least 40 km (25 mi.) each way). In the 500 cases, there was only one case in which a vehicle was approaching at >30 mph in the adjacent lane during the lane change (so this means 1 out of 8,776 lane changes). Olsen and Lee were unable to distinguish cases in which a driver was just considering making a lane change, checked the side mirror, saw a fast approaching vehicle, and decided to wait. For all of the lane changes, there was at least some lateral movement observed. Related data are available in reference [2]. These authors collected passing speed data from highway driving in Southern California.

In a recent study, Smith, Glassco, Chang, and Cohen [8] tested metrics defining last-second lane-change characteristics against data collected on a closed course, on the road, and in a simulator. The closed course data were collected as part of the Crash Avoidance Metrics Partnership (CAMP) between General Motors and Ford. The scenarios are more fully described in reference [9]. Drivers approached a stopped lead vehicle, a lead vehicle moving at a constant slower speed, or followed a decelerating lead vehicle. They were asked to either pass the lead vehicle "at the last second they normally would to go around a target representing a vehicle in the adjacent lane" or "at the last second they possibly could to avoid colliding with the target".

The above data were used to design simulation scenarios. In addition, the closing speed has been pre-tested to ensure that the drivers are able to perceive that the vehicle is indeed closing and not staying at the same distance. Also, on-road pre-testing has identified that high profile vehicles in the rear of the test vehicle can occlude the view of the fast approaching vehicle. Therefore, no trucks, busses, or SUVs have been included in the simulated traffic.

Simulated Lead Vehicle Actions

There are two sets of lead vehicle actions as summarized below.

Lead Vehicle Braking

The vehicle ahead in the same lane as the test vehicle slows to a distance 50% of the CAMP drivers selected as the hard steering distance to a stopped vehicle. Pre-testing was used to determine the timing to ensure that the stimulus for initiating a lane change is similar across.

Uncovered Slower Lead Vehicle

The vehicle ahead in the same lane as the subject vehicle makes a lane change to the adjacent lane and reveals (uncovers to the driver's view ahead) a slower lead vehicle when the test vehicle is at the distance 50% of the CAMP drivers selected as the hard steering distance to a slower moving vehicle (driver at 60 mph and slower lead vehicle at 30 mph). Again, pre-testing was used to determine the timing to ensure that the stimulus for initiating a lane change in the simulator is as similar to collected test data as possible.

Several outcomes to these lead vehicle actions are possible. In the event that the participant comes to a stop, traffic in the adjacent lane continues to flow by until the lane is cleared. In this case, the participant was asked by the researcher to go around the vehicle in front when the lane clears. If the participant does not change lanes, the slowing/stopped vehicle turns off the roadway. In the event that the participant waits for the lane to clear, the vehicle in the participant's blind spot moves past the participant thereby clearing the lane and enabling the participant to complete the lane change.

Lane Change Direction

The direction of the lane change is based on the participant making successful left and right lane changes in response to the lead vehicle actions. Participants are given instructions to change lanes when forced by traffic conditions and to stay in the new lane until forced again by traffic. Lane changes have been in either the right or the left direction. The active lane-change CASs provide similar warnings for either direction. The test convex mirror is mounted only on the left side. The baseline has standard U.S. vehicle mirrors: planar on the driver's side, and a standard convex passenger side mirror.

EXPERIMENTAL DESIGN

The experiment is a split plot (i.e., combination between and within subject design). The between subjects independent variables are age and CAS. There are two levels of age based on crash data and the NHTSA Research Goals: 16-21 years old, and > 65 years old. Subjects must have valid driver's licenses and were all recruited from the vicinity of Iowa City or Cedar Rapids, Iowa. All must meet NADS medical requirements. Subjects are paid $10 per hour for their participation. In addition, all subjects were selected for visual acuity, color vision, and contrast detection in the normal range. This criterion is based on work by Johnston, Cole, Jacobs, and Gibson [10]. There are four CAS systems to be compared to the baseline: TRW proximity (TRW), TRW proximity and fast approach (TRWF), LPWS, and convex mirror. There are 4 participants per age by CAS condition. Each participant has driven baseline and one of the four CASs. The within subjects variables have been trial, blind spot status, lead vehicle actions, and lane change direction.

Trial 1 is a baseline and is used for comparison against the four remaining trials of CAS (trials 2-5). All other independent variables (e.g., where forcing events occur) will be random with equal occurrences across subjects. To decrease predictability of events, each trial will begin at a different point in the driving database.

The remaining trials vary from 2 through 5 for the four CAS systems to be evaluated. Blind spot status is no vehicle in the blind spot (no), vehicle in the blind spot moving at the same speed as the test vehicle (same), or vehicle in the blind spot moving at 30 mph greater speed than the test vehicle (fast). Since this last blind spot condition occurs in less than 10% of lane changes (engineering estimate since no on-road crash data are available for this specific case), the fast approach vehicle is a threat only during this last trial (trial 5). Lead vehicle actions include lead vehicle brakes (brakes) and slow lead vehicle uncovered (uncovered). Lane change direction is left or right.

NADS

The NADS is located at the University of Iowa's Oakdale Campus. It consists of a 24-foot dome in which an entire car, SUV, or truck cab can be mounted. All participants use the same vehicle, a passenger automobile (Chevrolet Malibu). The vehicle cabs are equipped electronically and mechanically using instrumentation specific to their make and model. At the same time, the motion system, on which the dome is mounted, provides 400 square meters of horizontal and longitudinal travel and ±330 degrees of rotation. The driver feels acceleration, braking, and steering cues as if he or she were actually driving a real vehicle. Each of the three front projectors has a resolution of 1600 x 1200; the five rear projectors 1024 x 768. The edge blending between projectors is 5 degrees horizontal. To enhance the resolution of the side and rear view mirrors, a 63-inch plasma panel has been mounted on the rear bumper to provide higher resolution images to the driver side, rear, and passenger side mirrors. The panel resolution is 1366 x 768.

DATA COLLECTION SOURCES, TIMING, REDUCTION, AND "QUICK LOOK" VERIFICATION

There are four data collection sources: lane change characteristics and crash severity and pre-crash behavior from the NADS digital data, video, eye tracking over –60 to +170 degrees field of view with accuracy of one degree and 30 Hz update rate, and interview and questionnaire data. All digital data have been recorded at 120 or 240 Hz. Video is at 60 Hz. These sampling frequencies are based on previous driving simulator research.

PRELIMINARY RESULTS

Sample driver responses to lane change scenarios are presented in Figures 9 through 15. On the plots of the steering wheel angle, a vertical dashed line indicates a lane change left (line points upward) or right (line points downward). A solid line indicates a crash occurred. One of the most common responses to the events is the driver braking in response to the action of the lead vehicle. Figure 9 illustrates a typical driver response to a braking lead vehicle. As can be seen from the figure, the participant applies the brake at a moderate level, thus allowing the vehicle in the blind spot to drive past and then changes lanes once the right lane is clear. Figure 10 illustrates a typical response to an uncovered slower moving lead vehicle. As can be seen in the figure, the driver applies the brakes slightly to slow down, and changes lanes once the adjacent lane is clear.

Another typical response to the event would be for the driver to slow down without changing lanes. This type of response was more common for an uncovered slow moving vehicle than for a braking lead vehicle. A typical response of this type is illustrated in Figure 11.

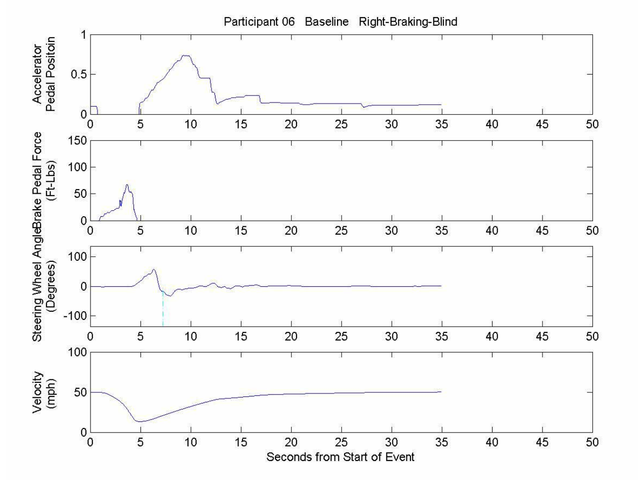

Figure 9. Driver response to a braking lead vehicle in the form of braking followed by a slow speed lane change to the right.

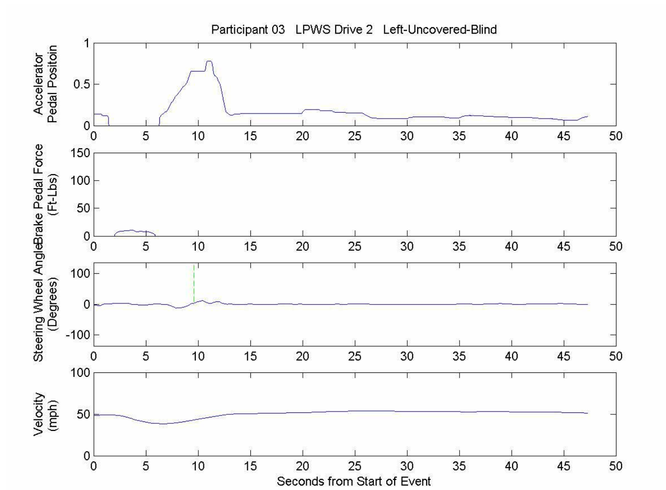

Figure 10. Driver response to an uncovered slow moving lead vehicle in the form of slight braking followed by a lane change to the left.

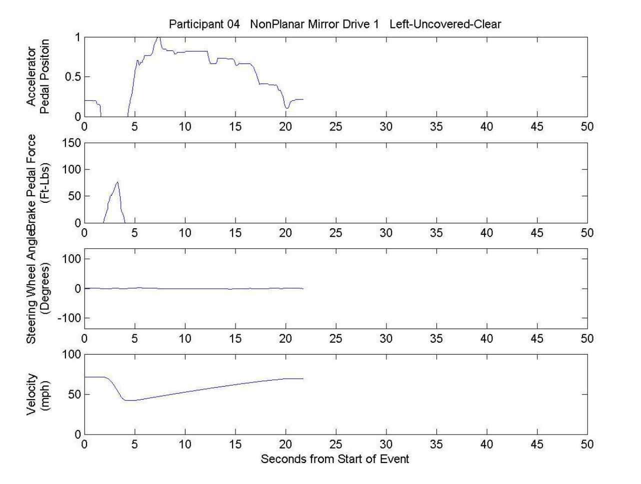

Figure 11. Driver response to an uncovered slow moving lead vehicle in the form of braking without changing lanes.

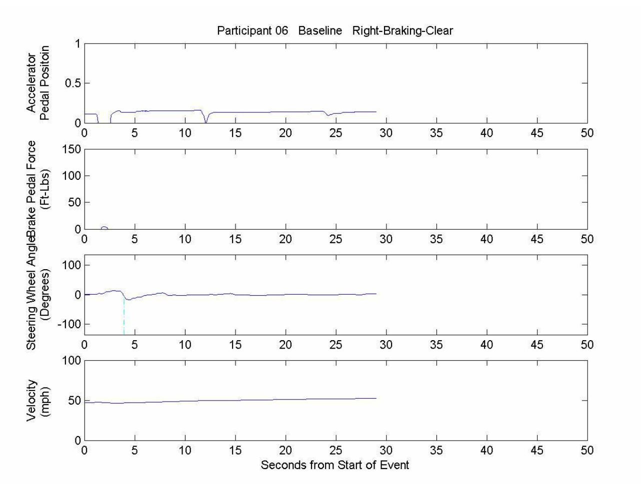

Figure 12. Driver response to a braking lead vehicle in the form of changing lanes to the right without slowing.

Although slowing in response to the actions of the lead vehicle was a common response, not all participants responded in that manner. Some participants would change lanes at speed without slowing down. Figures 12 and 13 illustrate lane changes to the right and left, respectively, without any application of the brakes by the driver.

Another response, although even less common, was that the driver would make multiple lane changes during the event. Figure 14 provides an example of this type of response. As can be seen in the figure, in this case the participant changed lanes to the right without slowing and then changed lanes back to the left after negotiating around the braking lead vehicle.

Another outcome was a collision with the vehicle in the adjacent lane. Figure 15 illustrates a typical situation where the driver changes lanes to avoid colliding with the lead vehicle, but does not see the vehicle in the blind spot. As a result the participant cuts off the driver and a collision results.

At the time of publication of this paper, data collection has been completed only for participants in the age group ≤ 21. Therefore the results presented

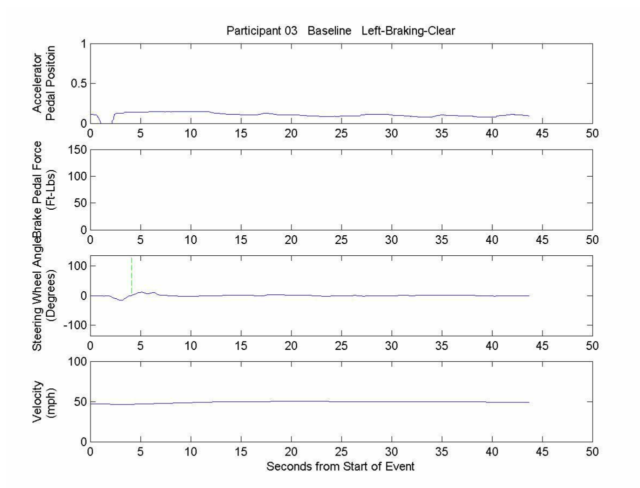

Figure 13. Driver response to a braking lead vehicle in the form of changing lanes to the left without slowing.

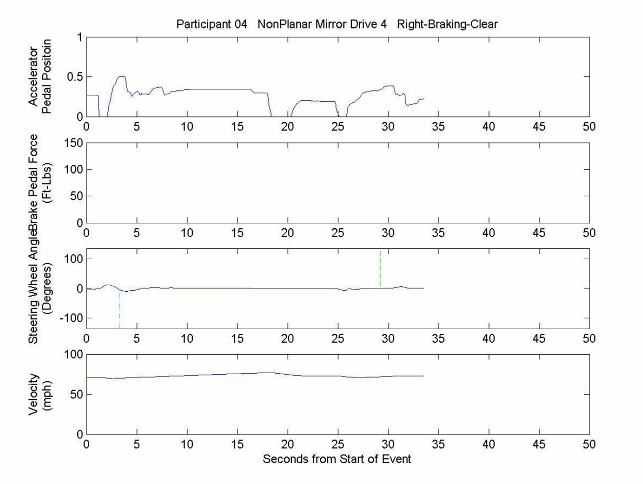

Figure 14. Driver response to a braking lead vehicle in the form of changing lanes to the right and then back to the left without slowing.

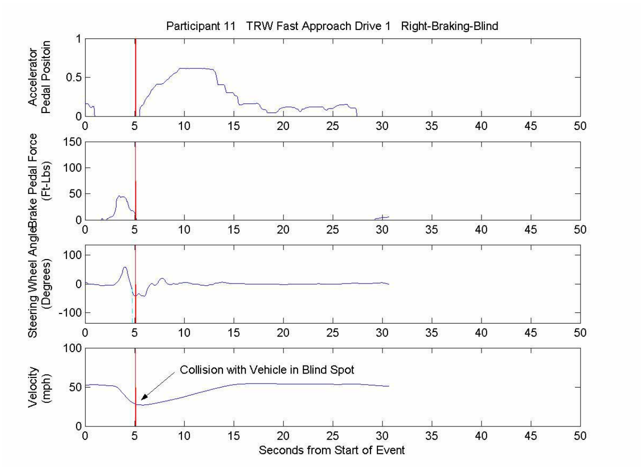

Figure 15. Driver collides with vehicle in blind spot while responding to a braking lead vehicle.

here are preliminary and will be expanded to include the > 65 age category in the final report of this study.

CONCLUSIONS

From the preliminary results presented here, drivers in this study with an age of ≤ 21 when confronted with either a lead vehicle braking or an uncovered slower lead vehicle scenario, had one of two typical responses: 1) braking followed by a lane change or, 2) driver changes lanes by entering into the gap between vehicles in the adjacent lane and crashes into another vehicle. The first outcome was the more common and this result was not expected for drivers in this age group. The outcome that resulted in a crash was rare and occurred as a consequence of the driver changing lanes to avoid colliding with the lead vehicle, but did not see (or notice) the vehicle in the blind spot.

Additional analysis needs to be conducted to establish the limitations to their effectiveness and whether drivers will heed their warnings. A complete analysis will be presented in the final report at the completion of this study.

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DEVELOPMENT OF A PRE-CRASH SYSTEM USING THE VEHIL TEST FACILITY

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ABSTRACT

Pre-crash systems (PCSs) use environment and vehicle dynamics sensors to improve the effectiveness of passive safety devices by activating them before a collision occurs. The autonomous character of these intelligent vehicle systems, required to anticipate dangerous traffic situations, as well as the combination of new hardware and software technologies make the design extremely complex.

This paper presents an evaluation of a PCS using the VEhicle Hardware-In-the-Loop (VEHIL) test facility. The prototype system utilizes a long-range forward-looking, installed for adaptive cruise control systems, for activation of a reversible belt retractor. The VEHIL laboratory enables testing of intelligent vehicle systems in a hardware-in-the-loop environment, where only the relative motion between host and target vehicle is reproduced. The accuracy of VEHIL test setup made sensor validation and control system testing much easier and more flexible. It appeared to be useful for fine-tuning sensor post-processing algorithms, path prediction algorithms, and activation times.

In addition, the radar system is modeled with the PRESCAN simulation tool, which enables simulation of environment sensors in a virtual environment. The simulated sensor output can be used for development of sensor post-processing, sensor fusion and control algorithms. Also other design aspects like sensor positioning and overall system architecture can be considered.

INTRODUCTION

In the US, the number of all, injury and fatal crashes has remained somewhat constant over the last decades, as shown in Figure 1. However, when looking at the number of accidents per miles traveled, the number has been decreasing, as shown in Figure 2. This is primarily due to improvements in passive safety, such as seat belts and airbags.

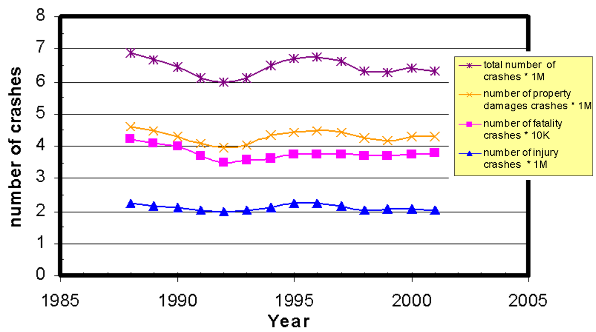

Figure 1. Absolute accident statistics [NHTSA, 2002].

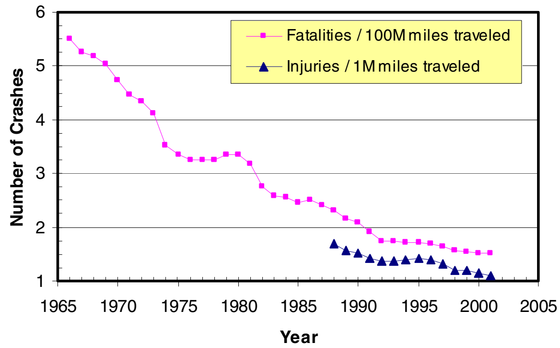

Figure 2. Accident statistics per mile traveled [NHTSA, 2002].

Nowadays, the recent trend in the safety community is to integrate both active and passive safety so further reduction can be achieved. Examples of active safety are vehicle control systems that use environment sensors like radar to improve the driving comfort and traffic safety by assisting the driver in recognizing and reacting to dangerous traffic situations. The effectiveness of *passive* safety restraints can be increased by using the time between initial recognition of an imminent crash and the actual impact to tune the restraint systems and position the occupants.

This potential for improving occupant safety has stimulated research on so-called pre-crash systems (PCSs) [Alessandretti, 2002] [Moritz, 2000] [Tokoro, 2003], and its recent market introduction [Honda, 2003], [Schöneburg, 2003]. A PCS is a system that uses environment sensors, vehicle dynamics sensors, and electronic control functions to mitigate the crash severity by deploying passive and/or active safety measures *before* a collision occurs.

The development of a PCS is a critical process, because of the necessary high reliability of the system. Failure or inappropriate activation of an automatic safety system simply cannot be tolerated. Therefore, automatic deployment of a belt pre-tensioner should be executed if, and only if, a crash is imminent and unavoidable. Using sensor data on the path of the obstacle and the estimated time-to-collision, it can be predicted with a certain probability if a collision is imminent, and that a collision cannot be avoided anymore by either braking or steering.

Due to the high reliability requirements, a PCS needs to be thoroughly tested. A PCS test is however very safety-critical, since an actual collision is necessary to reproduce the operating conditions. Obviously, because of the inherent safety risks and prototype costs, pre-crash conditions are instead reproduced using critical near-collision road tests or crash tests with foam dummy vehicles [Sala, 2003]. However, these tests are often characterized by trial and error, not reproducible, and difficult to analyze, thus time-consuming and costly. Simulations are an alternative, but currently lack the possibilities for testing the complete system with full integration of the operating conditions, high level sensor characteristics, vehicle dynamics and complex traffic scenarios.

An efficient methodology and new tools are therefore required for evaluation of the performance and reliability of a PCS. This paper presents a series of evaluation tests of a PCS using the VEhicle-Hardware-In-the-Loop (VEHIL) test facility. This laboratory allows for testing of advanced driver assistance systems in a hardware-in-the-loop environment, where only the relative motion between host and target vehicle is reproduced.

The paper starts with a description of the PCS. Next, results of an accident study are provided. This study was performed to define test scenarios for the evaluation of the system. After a short introduction into the VEHIL facility the test set-up for the PCS is presented. The added value of VEHIL in the development process of the PCS is illustrated with test results. In addition, the PCS is modeled with the PRESCAN simulation tool to evaluate the PCS in a virtual environment. Finally, conclusions are presented.

PRE-CRASH SYSTEM

The prototype system used during the evaluation process was representative of first-generation pre-crash systems that have recently been offered as optional content on series production vehicles. Such systems typically utilize the pre-existing long-range, forward-looking radar (FLR) or laser sensors that are installed for adaptive cruise control or distance-keeping driver convenience systems to provide additional safety functions. The particular FLR used for this testing was the most-recent version of a product that Delphi has had in production since 1999. Some relevant performance specifications are noted in Table 1 below, along with an accompanying picture in Figure 3.

Table 1.
Forward-looking radar spec

Parameter	ACC-2 Specification
Range Coverage	1 – 150 m (for 10m^2 RCS)
Range Resolution	2 m (80 cm range bin)
Range Accuracy	2 m
Range Rate Coverage	-230 to +115 km/h
Range Rate Accuracy	± 1.8 km/h
Azimuth Coverage	15°
Azimuth Accuracy	±0.3°
Track Outputs	no classification; angular extent available
Tracking Data	15 targets
Acquisition Time	< 0.3 s
Cycle Time	100 ms
Sensor Size	(140 x 70 x 100) mm
Frequency	76 GHz

Figure 3. FLR module.

The prototype sensing system consists of a long-range radar with embedded pre-crash threat assessment algorithms working in conjunction with a laptop computer. As the radar detects and tracks objects within its zone-of-coverage, real-time target data is transmitted over the CAN bus to the laptop for data collection and display purposes. The CAN bus is also used to transmit the output decisions for driver warning and actuation commands for the motorized seat belt retractors and autonomous braking functions. A picture of the system configuration is shown in Figure 4.

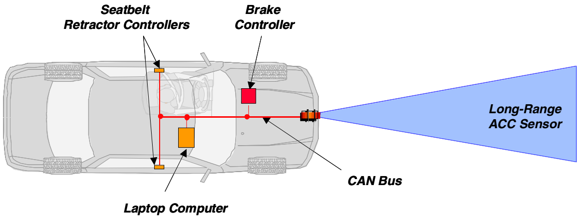

Figure 4. Pre-crash prototype system configuration.

The FLR within the PCS is responsible for converting real-world objects in front of the vehicle into radar targets and tracking those targets over time, including the range, range rate, azimuth angle, and other target attributes. The threat assessment algorithms must determine the threat level posed by each object and decide if and when a collision is imminent. For the purposes of this study, a triggering time for the motorized seat belt retractors was chosen to be at 500 ms before impact under all true collision scenarios. Of course, driver warnings are given significantly earlier than that. However, autonomously triggering seat belt countermeasures or brakes prior to that time increases the opportunities for false triggering in the event that the driver of either the host or target vehicle, or both, could evasively steers to avoid the impact. These tradeoffs in algorithm performance are typically different for each vehicle manufacturer based on their customer preferences. This conversion of real-world scenes to pre-crash threat assessment is depicted in Figure 5.

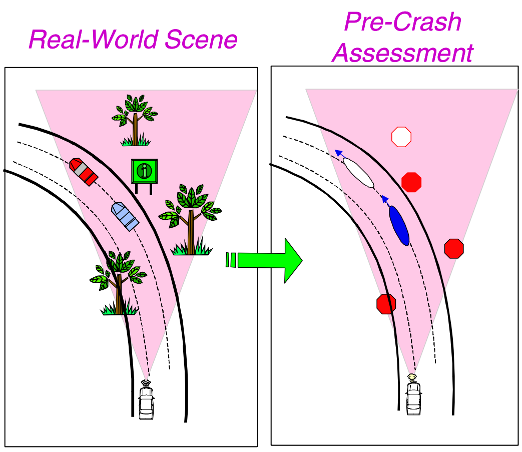

Figure 5. Pre-crash scenario assessment.

ACCIDENT STUDIES AND DEFINITION OF TEST SCENARIOS

The definition of the VEHIL test matrix started with an assessment of the field relevance of accident scenarios.

The field data were obtained from the 2000 General Estimates System (GES). Data for the GES comes from a nationally representative sample of US police reported motor vehicle crashes of all types, from minor to fatal.

Each year, 6.4 millions accidents take place on US roads. For this first evaluation in VEHIL only accidents involving two vehicles were analyzed. Those comprise of rear-ends, avoidance maneuver with roadway departure, opposite direction collisions, sideswipe collisions and intersecting path accidents. Figure 6 shows these accident scenarios found in the GES database.

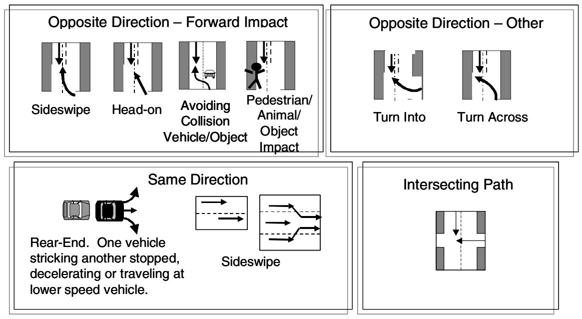

Figure 6. Relevant accident scenarios for PCS.

Rear-end: Of the 6.4 millions accidents, 1,710,639 were rear-ends, accounting for 27% of all accidents. Of those, (a) 1,370,239 accidents occurred when 2 vehicles are traveling in the same lane, where the critical event consisted of the front vehicle was traveling at a lower speed, and (b) 128,049 accidents occurred when 2 vehicles are traveling in the same direction but where one vehicle encroached into the other lane. These number exclude loss of control, vehicle failure, and accidents where an animal/object or pedestrian were avoided and resulted in a rear-end collision.

Avoidance maneuver: In the data, there were 1,454,581 accidents that occurred off roadway. Of those, 354,053 were due to avoidance maneuver or hitting a parked vehicle.

Sideswipe: 9% or 570,123 accidents resulted due to side-swipe collisions. Of those, 30,315 accidents occurred when 2 vehicles are traveling in the same lane, where the critical event consisted of the front vehicle was traveling at a lower speed.

Opposite Direction: There were 142,678 accidents that took place where 2 vehicles were traveling in opposing direction. Accidents that involved vehicle failure or loss of control were excluded.

Intersecting Paths: There were 1,575,413 accidents that involved 2 vehicles that were proceeding straight ahead and as a result, collided with each other.

As indicated the accidents were selected based on the relevancy of a first evaluation using VEHIL that included two vehicle accidents only. The selected accidents accounted for about 60% of all accidents.

INTRODUCTION TO VEHIL

The VEhicle Hardware-In-the-Loop (VEHIL) concept makes it possible to conduct experiments with full-scale intelligent vehicles in a laboratory, where only the *relative* motions between the test vehicle and obstacles are reproduced. This indoor test facility eliminates weather influences and provides a relative world that reduces the necessary space and vehicle speed considerably, resulting in a safe and adaptable testing environment. Testing with a full-scale vehicle, possibly treated as a 'black box', allows the possibility to test the real behavior of a complete system, with real phenomena such as noise and faults in the sensor data.

The Vehicle Under Test (VUT) is mounted on a chassis dynamometer and placed in an emulated environment consisting of mobile robots. Each robot, a so-called 'moving base' (MB), see Figure 7, emulates the motion of a specific road user relative to the VUT [Ploeg, 2002]. On the basis of real vehicle data of the VUT (measured by the chassis dynamometer since the vehicle itself is treated as a 'black box'), the Multi-Agent Real-time Simulator (MARS) calculates the relative motions and sends position commands to the MBs. In this way, the MBs adapt their positions according to the traffic scenario.

The VUT that is equipped with environment sensors will track the MBs as it would do with real road users when driving on a road. The pre-crash controller might activate safety actions such as active braking, and in an actual traffic situation the vehicle would decelerate. In the VEHIL facility, the corresponding braking forces are measured by the chassis dynamometer and converted into a predicted path of the intelligent vehicle. The MARS calculates the corresponding relative positions and the MBs adjust their relative positions accordingly. Figure 8 gives an overview of the working principle. The absolute equivalent of the emulated relative scenario can also be visualized on a computer. VEHIL is located in Helmond, the Netherlands, and is operational since November 2003 as an independent test facility.

TESTING A PRE-CRASH SYSTEM IN VEHIL

Experimental set-up

To overcome the difficulties of testing a PCS on a test track, VEHIL can provide an alternative approach. During the experiment the MB follows a crash trajectory, such that it is recognized by the sensor as a potential obstacle. When the controller estimates that a collision is imminent and unavoidable (taking conventional vehicle dynamics into account), it activates safety measures. However, an actual collision is avoided, because the MB can achieve a much higher lateral acceleration than a normal passenger car. It can therefore make an evasive maneuver at the last moment, while still triggering activation of the PCS, as illustrated in Figure 9.

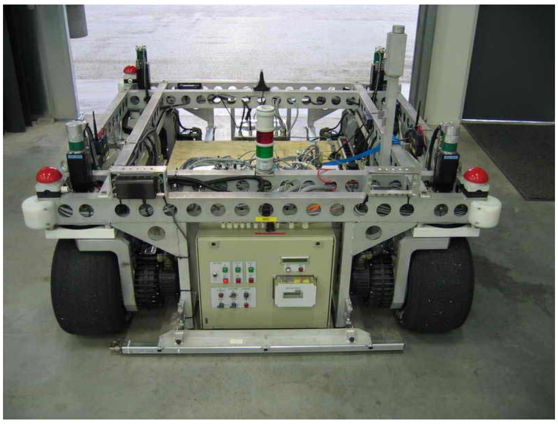

Figure 7. Moving Base.

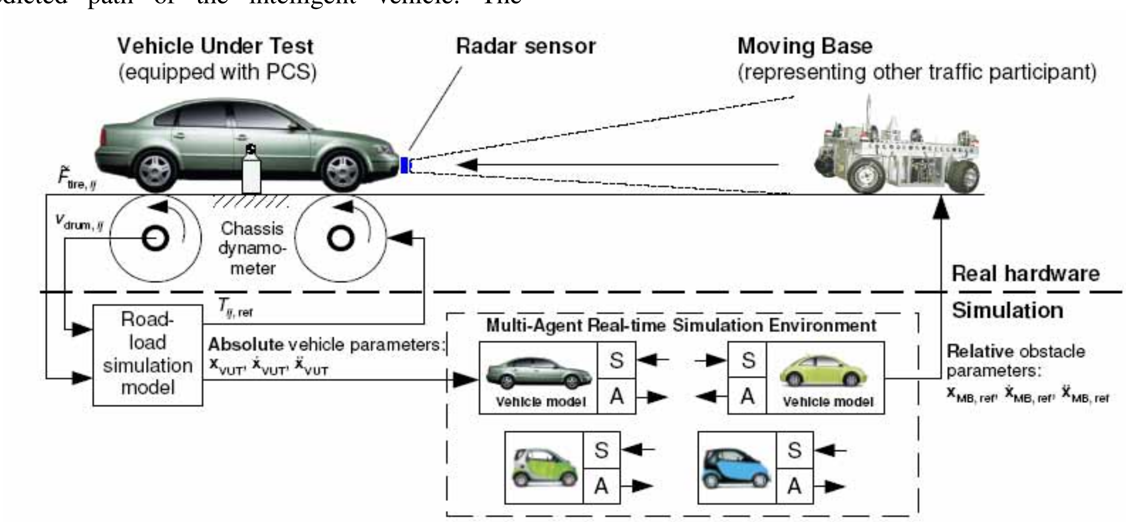

Figure 8. Working principle of VEHIL [Gietelink, 2004].

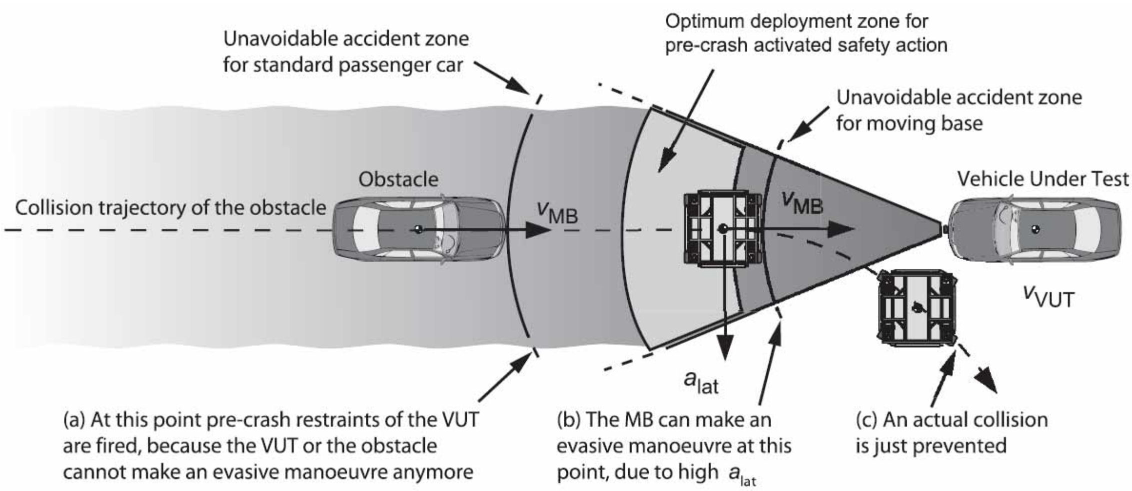

Figure 9. Pre-crash test for a head-on collision scenario in VEHIL.

These safety-critical experiments can be performed with relative speeds up to 50 km/h and closing distances up to 50 cm. At 50 km/h the lateral acceleration of 13 m/s^2 allows the MB to approach the VUT up to a time-to-collision of 120 ms without causing a real collision. In this way, it is possible to evaluate a PCS in a realistic, but non-destructive way. These VEHIL experiments are always performed open loop, since the test is finished at the moment the test vehicle responds, and there is no effect of vehicle actions on the relative motion.

The PCS obtains pre-crash information with a radar sensor. The vehicle is equipped with a reversible belt pre-tensioner that is tested with both a crash dummy and a human driver, as shown in Figure 10. Two different positions were evaluated:

- Leaning forward about 15° (Position-1) with and without 100 mm slack in the shoulder belt.
- Leaning forward about 30° (Position-2) with and without 100 mm slack in the shoulder belt.

The experimental setup for the scenarios as identified in the accident study (see Figure 6) basically consists of three different test types, illustrated in Figure 12 on the next page:

(a) The target vehicle (the MB) drives towards the host vehicle equipped with the sensor (the VUT).

(b) The target vehicle (the MB) is equipped with the sensor and drives towards the host vehicle (the VUT).

(c) One MB is equipped with the sensor and drives towards another MB. Both MBs can drive at a velocity of up to 50 km/h, ensuring a closing velocity of 100 km/h. During these scenarios the sensor is mounted on the Moving Base, as shown in Figure 11.

For each scenario different permutations of the scenario parameters were used to test the system exhaustively. Head-on collisions with full or partial overlap, near-misses or complete misses were simulated at different speeds. Also the approach was varied: pure longitudinal, under an angle or on a curve.

Figure 10. Experimental set-up of a pre-crash test.

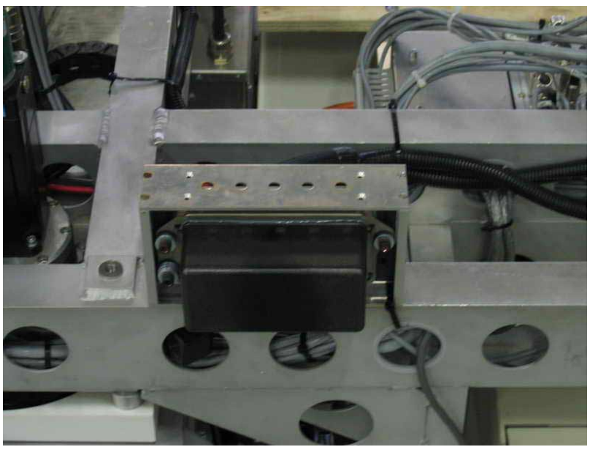

Figure 11. Sensor mounted on the Moving Base.

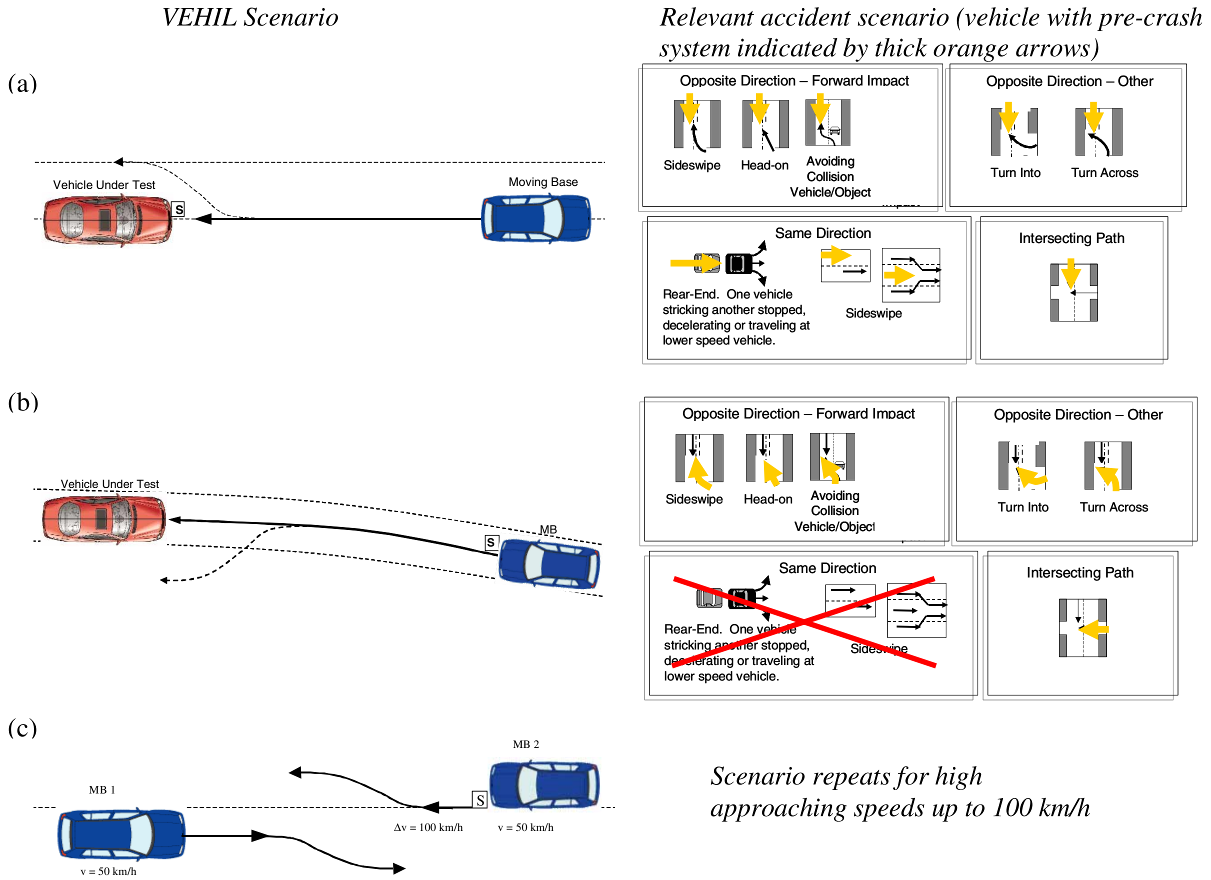

Figure 12. Pre-crash scenarios considered in the VEHIL tests: (a) target vehicle approaches host vehicle; (b) host vehicle approaches target vehicle; (c) two moving bases (one host and one target vehicle) drive towards each other up to a collision velocity of 100 km/h. Related accident scenarios indicated in right column.

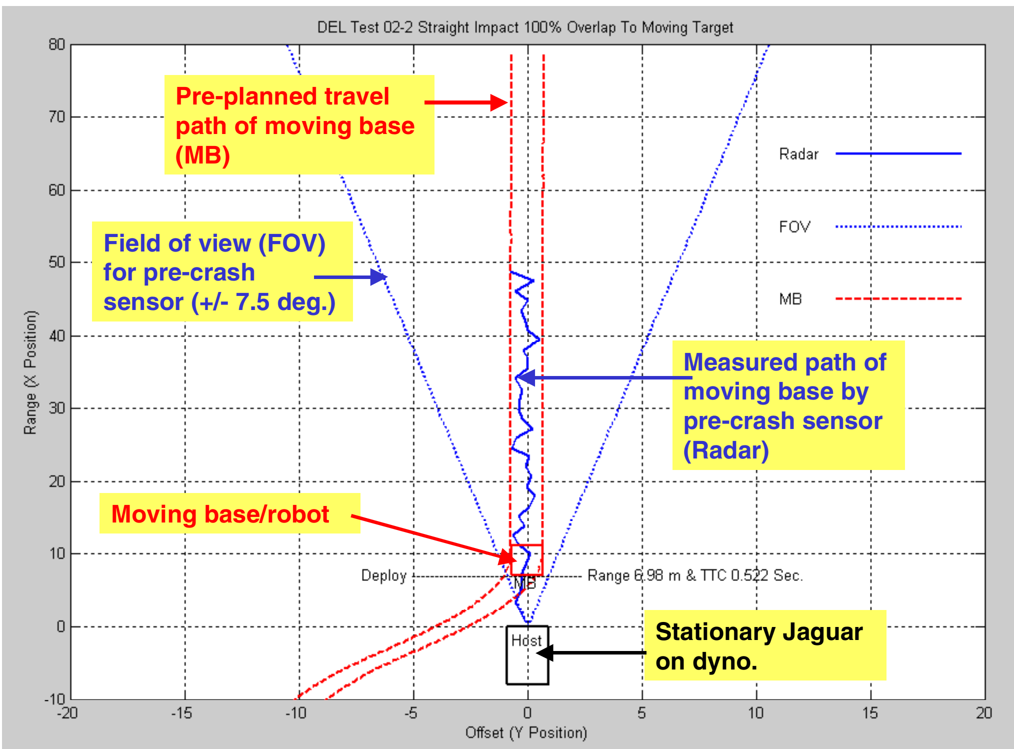

Figure 13. Test result rear-end scenario.

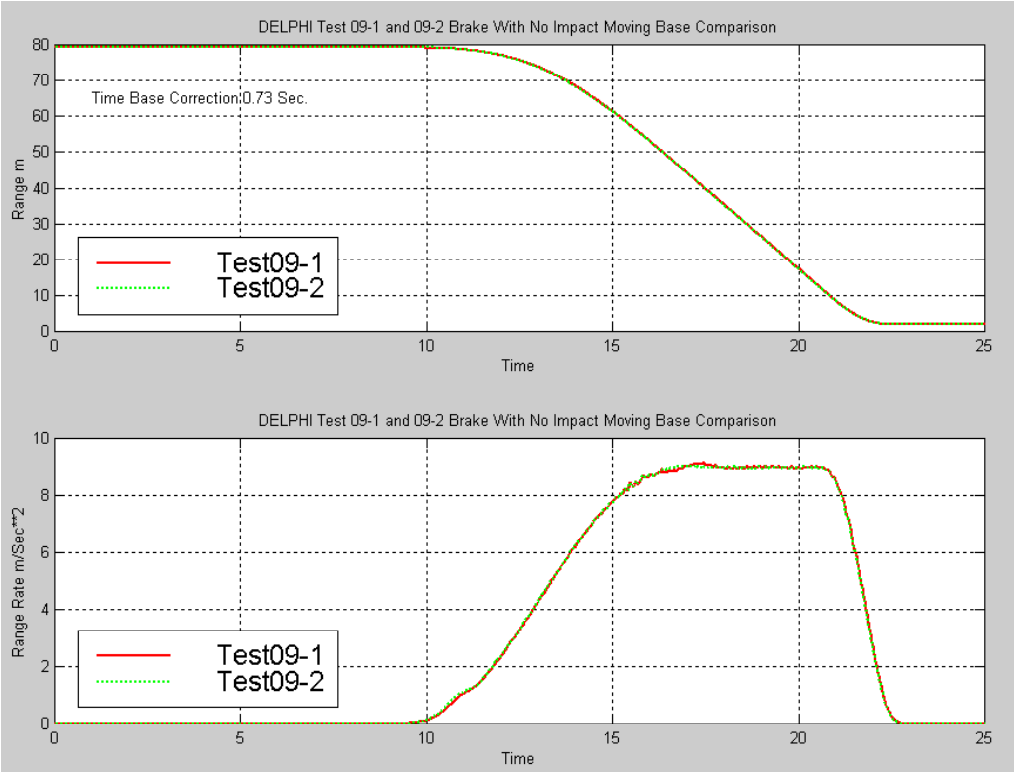

Figure 14. Comparison of test repeats.

Analysis of test results

In total 74 pre-crash tests were executed. Figure 13 shows the test results for a rear-end collision scenario at a relative speed of 50 km/h. During the tests it was verified that with a time-to-collision threshold at 500 ms the driver can be fully retracted from its forward position to an optimal crash position. This was true for both 15 and the 30 degrees position. Here it has to be noted though that the occupants do not undergo any deceleration due to braking. This may increase the required time for full retraction. Other test results indicated that a pre-crash brake assist function applied 1 s before the collision, a reduction in crash velocity of at least 5 m/s can be reached. This velocity reduction corresponds to a 40% reduction in the kinetic energy that has to be dissipated during this particular crash scenario. The PCS can therefore obtain a significant reduction in injury values [Lemmen, 2004].

Figure 14 shows results of a repeated test. It can be seen that scenarios are reproduced very accurately. The MB has a very high positioning accuracy of 10 cm. The maximum position error between two repeats is 3 cm. This enables to evaluate the effects of parameter tuning in between test runs. The repeatability and accuracy of the test setup made sensor validation and control system testing much easier and more flexible. It appeared to be useful for fine-tuning sensor post-processing algorithms, path prediction algorithms, and activation times. This was especially true for the tests that included severe braking. When performed with drivers, these tests are lacking accuracy and are difficult to repeat. For such conditions it is difficult to separate sensor noise introduced by the braking action from inaccuracy in the measurements. The detailed VEHIL measurements allowed to identify the sensor noise. This information is used to update the sensor algorithms, resulting in an improved performance under severe braking conditions.

Because of the high accuracy, repeatability and fast response, ground truth data can be compared very well to test results, in order to easily evaluate timing and sensor issues. An example of comparison of the radar and laser sensor data with the real 'ground truth' data is shown in Figures 15a and 15b, respectively. From this follows that the radar has a good performance with a dynamic accuracy of around 1.5 m. The dynamic accuracy of the range rate measurement is around 1 m/s. The range (rate) measurement is more accurate for scenarios with lower dynamic maneuvers. The laser system (not used for the PCS algorithm but available in the vehicle for testing) has slightly worse dynamic performance.

After fine tuning of the system it appeared that the system passed all tests, activating the belt system only when required and well in time. For further evaluation of the system drive tests are needed to check the performance under real world conditions.

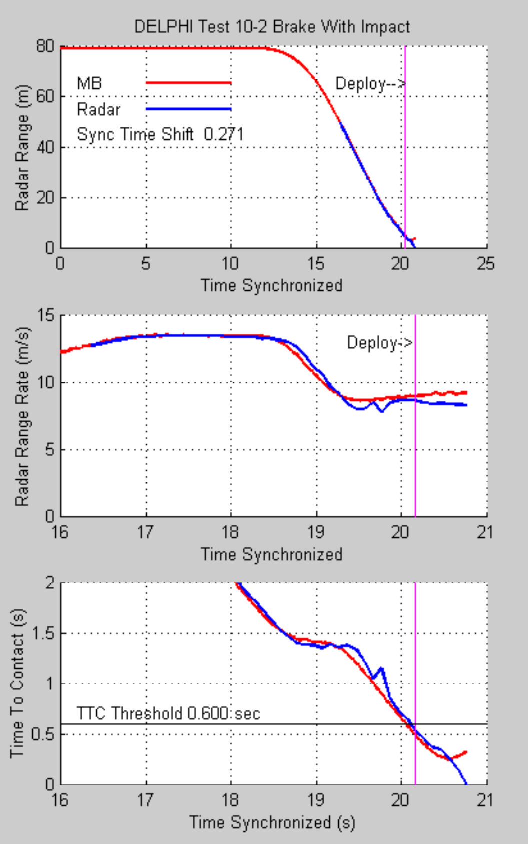

Figure 15a. Comparison of radar data to 'ground truth' data.

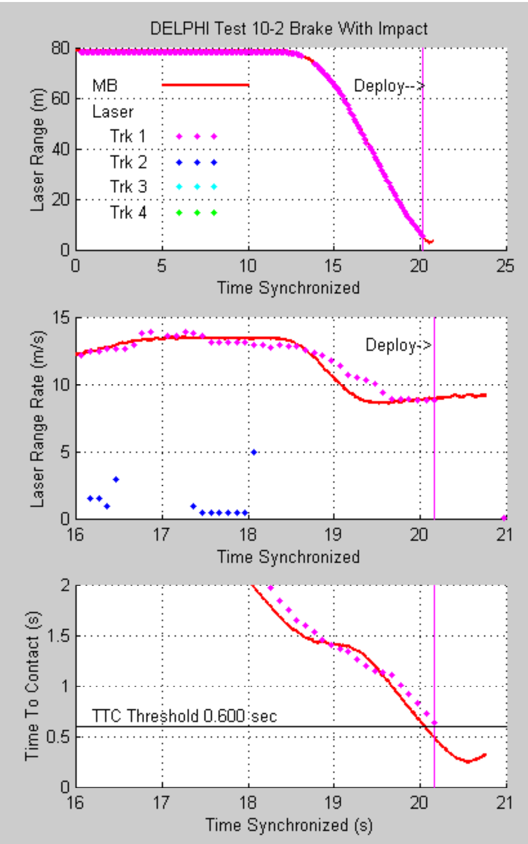

Figure 15b. Comparison of laser data to 'ground truth' data.

NUMERICAL SIMULATIONS

In addition to the VEHIL tests a numerical simulation model of the PCS is being developed to perform further system analysis. The model is developed in the PRESCAN (PRE-crash SCenario ANalyzer). In PRESCAN real world scenarios can be modeled in a virtual environment to simulate environment sensors. Figure 16 gives an example for a laser scanner. The simulated sensor output can be used for development and evaluation of the system, i.e.:

- assessment of different sensor types;
- assessment of sensor positioning;
- prototyping of sensor post-processing algorithms;
- prototyping of data fusion algorithms;
- prototyping of control/decision algorithms; and
- definition of the overall system architecture.

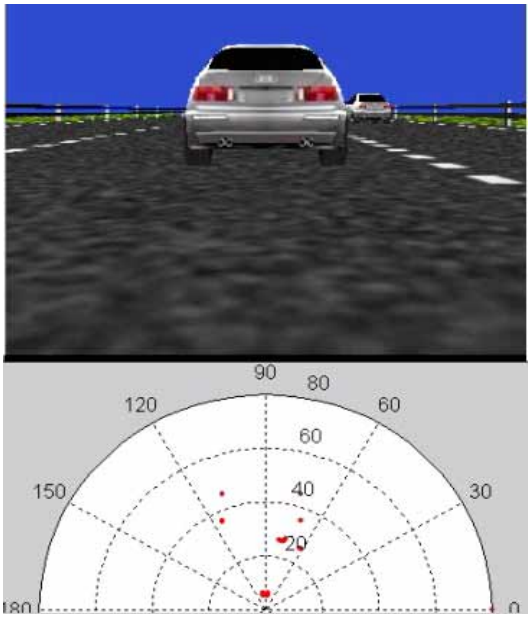

Figure 16. Laser scanner model: view from sensor position and sensor output.

Simulation models are constructed from a library set that contains scenarios, sensor models, infrastructural elements, relevant obstacles and vehicle models. The sensor library currently provides models for FMCW radars [Thean, 2004], stereo camera [Sunyoto, 2004] and laser. Models of different detail and complexity are provided for different phases of the design process. On a first level, basic functional models are provided that give deterministic information on the position, velocity, and shape of objects. These models can be extended with effects that represent noise and errors in a basic way. The specific effects that deteriorate the sensor performance can be obtained from VEHIL tests. Finally, dedicated physical sensor models are provided for detailed simulations. These physical models are hardware specific.

For the radar model targets are modeled using a small plate approximation, meaning that the object is divided into sub-regions that each has a specific radar cross section. Each sub-region is dealt with as a single flat plate with a given orientation. The radar model calculates the vector sum of the reflected waves from all objects in the field of view. The summation keeps track of signal phases. As a result interference effects are accounted for.

The PCS considered in this study uses mechanically scanned frequency modulated radar. This device was modeled in PRESCAN. To this end the existing radar model [Thean, 2004] was adjusted to emulate the hardware radar and sensor data processing algorithms were implemented. Amongst others these included algorithms for amplitude weight and IQ balance, Fast Fourier Transformation, detection thresholding and range-rate determination.

Figure 17 provides a simulation result of the reflection of the moving base. The intensity of reflected signals is plotted for the different beams of the radar as function of the range. In this first simulation a single radar cross section was assigned to the moving base. Variations in intensity of the MB occur due to the fact that adjacent beams are in a different phase of the frequency modulation.

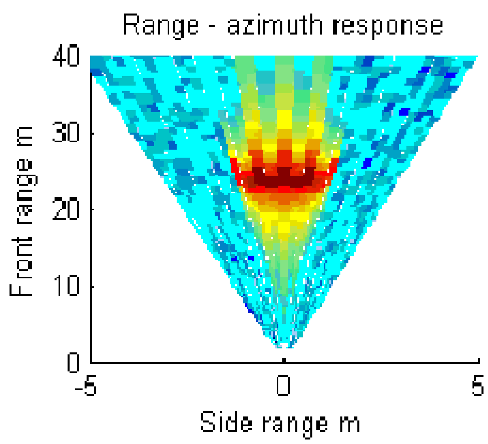

Figure 17. Radar sensor model: view from sensor position and sensor output.

The simulated radar output is processed using the implemented data processing algorithms. Figure 18 compares the resulting range estimations for a given test scenario with the actual VEHIL data. Note that experimental data are available only for ranges below 50 m. It can be seen that simulated data correlate quite well with experimental data. Although this high level validation provides confidence in the model, further work is needed to develop a more detailed radar model of the moving base. Once such a model is available a wide range of scenarios can be evaluated using PRESCAN to further fine tune the system and consider real world conditions.

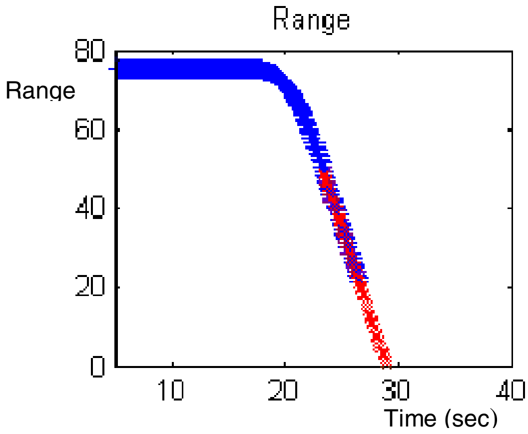

Figure 18. Comparison of simulated (blue) and real range (red) of MB.

CONCLUSIONS

An evaluation of a pre-crash system (PCS) using the VEhicle Hardware-In-the-Loop (VEHIL) test facility was presented. The prototype PCS uses a long-range forward-looking radar sensor installed for adaptive cruise control. To provide additional safety functions the sensor is linked to motorized belt retractors in the front seats. For this study the trigger time of the seat belt retractors was chosen to be at 500 ms.

A total set of 74 pre-crash scenarios was run in VEHIL, representing rear-end impacts, avoidance maneuvers with roadway departure, opposite direction collisions, sideswipe collisions and intersecting path accidents. The test scenarios were based on field data obtained from the 2000 General Estimation System (GES). The considered scenarios accounted for about 60% of all accidents in the GES.

The repeatability and accuracy of the VEHIL test setup allowed for fine-tuning of the sensor post-processing algorithms, path prediction algorithms, and activation times. This was especially true for the tests that included severe braking where accurate measurements are required to identify sensor noise due to braking.

After fine tuning of the system it appeared that the system passed all tests, activating the belt system only when required and well in time.

For further evaluation of the system drive tests are needed to check the performance in real world conditions. These activities can be supported using a detailed simulation model of the radar sensor that is currently under development. The model is based on VEHIL test data.

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ESC AS A BASELINE FOR ACTIVE SAFETY

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Paper Number 05-0332

ABSTRACT

Electronic Stability Control (ESC) systems were first introduced in the mid 1990's. This technology is proving itself by preventing crashes and saving lives each day. Several studies from Europe and Japan have shown significant reductions in serious crashes and fatalities when vehicles are equipped with ESC. Results of recent studies in the U.S. now confirm these gains also apply on the U. S. highways.

Now that ESC is in place on many vehicles, this technology has become a baseline for expansion of Active Safety functions to further reduce crashes. These systems add sensors and actuators to ESC to anticipate crashes and integrate other vehicle safety systems to further protect the vehicle occupants. This Active – Passive Integration Approach will enter the market in the next few years and promises another major step in reducing traffic crashes and the tragedies that result.

INTRODUCTION

Traditional vehicle safety systems have largely been passive and focused on occupant protection. Smart Automobiles will work proactively to help avoid potentially fatal vehicle crashes from occurring. The future belongs to innovative driver-assistance technology. These systems will impact active vehicle safety and make our highways safer. Helping to drive this shift is the leveling-off of safety gains over the last decade.

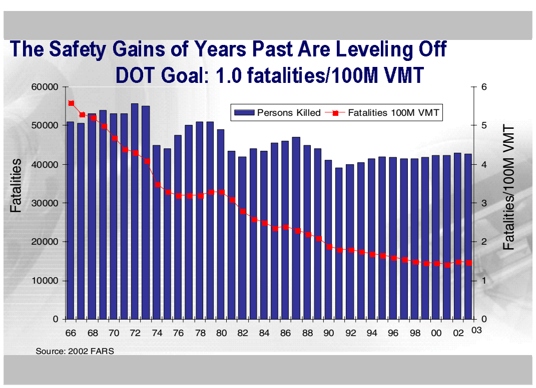

Figure 1

Overall, the number of crashes in the U.S. has remained relatively unchanged over the past two decades, at just over 6 million per year according to NHTSA data. With accident metrics at a plateau, the time is right for new, technology-based systems to enter the market with new solutions to old problems. Using ESC as a base, Continental is adding ever-smarter systems and capability to vehicles, eventually leading to a "Total Safety System."

Tomorrow's automobile will have "anticipatory" qualities that enable it to provide operating recommendations and active support to the driver. It will do this by monitoring the ambient traffic situation, and recognizing upcoming circumstances that require responsive action, and where desired, taking that action. This revolution is being made possible by the great leaps in microelectronics capability and functionality – accompanied by the decline in prices of semiconductor technology. Consequently, automotive applications have been expanding in great technological leaps.

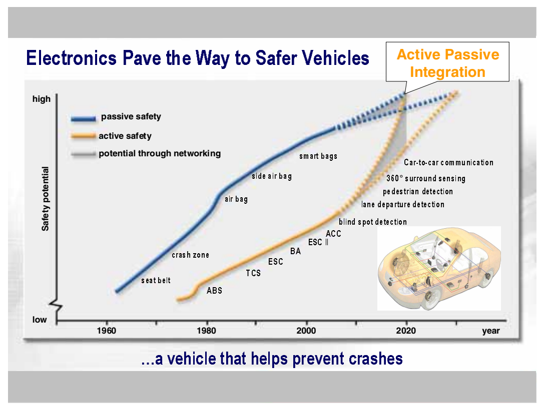

Figure 2

Figure 2 shows the progress of both passive safety systems such as seat belts and air bags, and active systems such as ABS, ESC and ACC.

DISCUSSION

Electronic Stability Control

Electronic Stability Control systems were first introduced by Mercedes in the mid 1990's. Since that time, ESC applications in Europe have increased to some 35 percent of new cars sold. In Japan, the application rate is about 15 percent. In the US, the adoption of this safety technology has been much slower, with 10 percent of new cars sold in 2004 equipped with ESC.

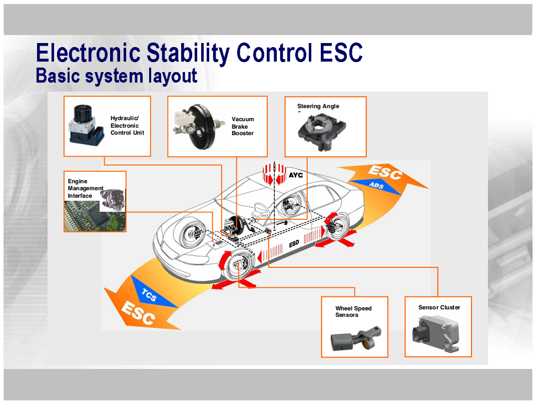

Figure 3

This technology uses sensors to measure each of the wheel speeds, the steering wheel angle, the vehicle yaw rate and lateral acceleration. The system calculates the driver's desired path and the actual vehicle motion and applies the brakes, individually, to correct for differences.

Studies in Japan and Europe have shown significant reductions in crashes and fatalities when ESC was installed on vehicles. Recent studies in the U. S. now confirm these results on U. S. highways. A National Highway Transportation Safety Administration (NHTSA) study last fall indicated a reduction of 30 percent in fatal crashes for passenger cars equipped with ESC and 63 percent for SUVs equipped with ESC. The Insurance Institute for Highway Safety (IIHS) released a study that showed similar findings, with a reduction of 41 percent in single- vehicle crashes and concluded that more than 7000 lives could be saved each year in the U. S. if all passenger vehicles were equipped with ESC.

Partly as a result of these studies, several automobile manufacturers have increased the applications and announced that future models will offer ESC as standard equipment. We estimate that 50 percent of new vehicles will be equipped with ESC by 2008.

Adaptive Cruise Control

Adaptive Cruise Control (ACC) provides a real-world example of technology integration serving to accelerate this timeline. ACC is available on cars today. Both radar-based and infrared-based systems are in use. ACC uses sensors to monitor and maintain a set speed and distance to the vehicle in front. Should traffic in front slow, the ACC-equipped vehicle will automatically reduce speed to maintain a safe distance. When traffic resumes speed, the vehicle will re-accelerate to the speed at which it was previously set.

The next generation of ACC will feature a full-speed-range function to provide even more driving convenience through the use of a special, closing velocity sensor. These ACC systems can slow a vehicle to a standstill, and not just to 30 kph as with current systems. After coming to a standstill, these new systems will also detect any movement by traffic ahead, and notify the driver. An important safety benefit of these ACC systems is that they prevent tailgating, which is a factor in many rear-end collisions, which account for 29 percent of light vehicle crashes, according to the U.S. Department of Transportation.

Even more important may be the integration with ESC to provide the functions of the APIA project.

Tomorrow's Technologies Will Drive Enhanced Active Safety

This next technological leap forward will feature the cross-linking of today's many, varied, and largely stand-alone chassis control units. Additional and enhanced functionality will be achieved, not so much by adding extra hardware or control equipment, but instead by connecting existing equipment electronically, adding software and having the various pieces of networked equipment communicate with each other. In effect, the car will have electronic reflexes, with each step enabling the next. Referring back to Figure 2, as the active and passive systems are integrated, additional safety potential is achieved.

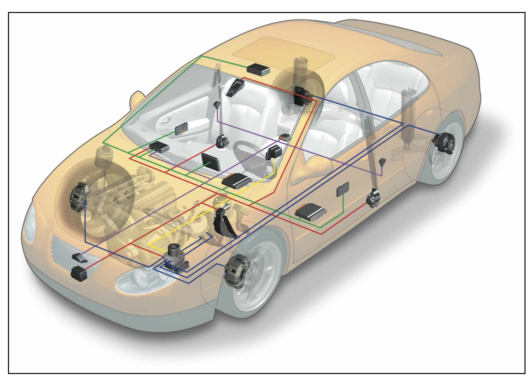
Figure 4

Active Passive Integration Approach (APIA)

Continental is working aggressively on these developments in a project called the APIA, and also known as the "Total Safety" project. APIA points the way to a vehicle that helps avoid accidents and prevents injuries. This is achieved by integrating the sensors and controls of the ESC with environmental sensors, to network active and passive vehicle safety systems. Forward sensors from the Active Cruise Control monitor the distance and closing velocity of a vehicle in front. A safety control module determines the probability of an accident for the current traffic situation. When necessary, the module initiates a staged hazard response designed to protect the occupants and other road users. The goal is to incorporate proactive vehicle intervention technology to prevent accidents from happening. A prototype of this vehicle has been built and demonstrates the potential to avoid or minimize the effect of rear-end crashes. When an APIA vehicle closes on another car too quickly, the APIA car senses the closing velocity and makes needed adjustments. First there is a distance warning, then feedback from the gas pedal – and the driver brakes, avoiding a collision.

In a more aggressive scenario, should an APIA vehicle close even faster, more functionality would be activated. The distance warning would come on again, as would the gas pedal feedback. Then, the brake system would pre-charge, the sunroof and windows would automatically close, and the seatbelt pre-tensioner would activate.

With yet a more aggressive scenario, and the APIA vehicle closing even more quickly making a crash imminent, in addition to the gas pedal, brake system, sunroof/window and seatbelt responses; the airbags would be readied for deployment and the seats would readjust to place occupants in safer positions for the impending crash.

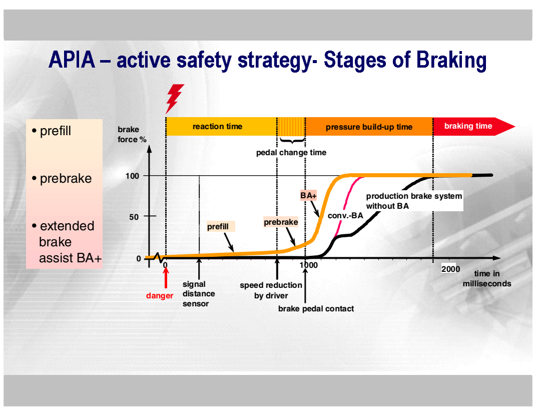

Figure 5

Figure 5 illustrates the improved braking function of the APIA vehicle. When the APIA vehicle anticipates the need for braking, it pre-charges the brake system. When needed, the system will apply the brakes at 0.3g to slow the vehicle. If the driver quickly moves his or her foot from the throttle to the brake, brake assist is activated and full braking is applied.

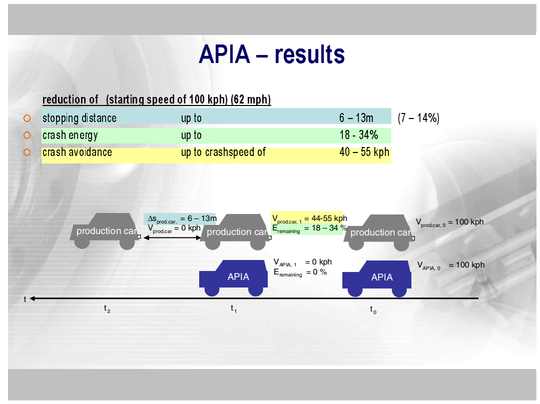

Figure 6

Figure 6 shows an example result of this functionality. Note that when the APIA car is stopped, the production car is still traveling at 44 – 55 kp/h.

Long term, the objective is to develop a comprehensive vehicle assistance system that will provide drivers with the best possible information and support under all conditions and minimize injuries if a crash does occur. The APIA system reflects Continental's basic safety philosophy. Motor vehicle safety is made up of three components: avoidance, control and protection.
Avoidance, in this concept is provided by technology or system features that can keep a driver from getting into trouble in the first place. Control, is the next objective and is provided by the integrated safety systems in the event trouble begins. Finally, protection of vehicle occupants is automatically provided when the traffic situation has continued to escalate and sensors detect that a collision is imminent.

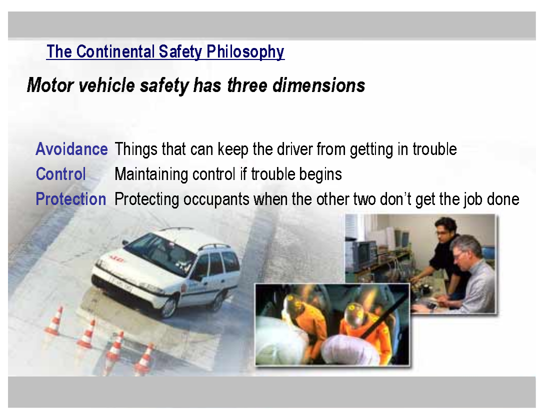

Figure 7

Driver-Assistance Systems of the Future

Technology that is on the road today cannot prevent accidents caused by a driver taking no response, or an inappropriate response to an emergency traffic situation. However, in the relatively near future, automobiles will have anticipatory capabilities that will allow systems to make appropriate recommendations for vehicle occupant safety. They will also provide active driver support.

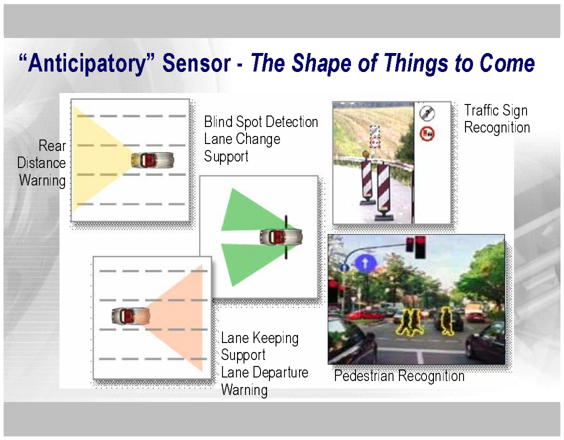

Figure 8

The following safety equipment reflects the state of current thinking and points to important capabilities under development:

Electronic Stability Control II or ESCII is the next generation of the ESC systems widely available on a number of vehicles today. ESCII builds upon the capability of sensors already in use to provide enhanced functionality, responsiveness and safety. An active steering capability is integrated with traditional ESC functions that include: anti-lock brake system (ABS), electronic brake force distribution (EBD), traction control systems (TCS), and active yaw control (AYC.) Together, the networked handling system enhances the stabilizing effect of ECS by enabling controlled, direct, automatic steering corrections in emergency situations.

Lane Departure Warning (LDW) is an assistance technology that is expected to make a significant impact on crash avoidance. NHTSA studies show that 55 percent of fatal crashes in the U.S. are caused by unintentional lane departure resulting from a variety of things including driver distraction and inattention. LDW uses cameras to identify lanes and a vehicle's position in relation to lane markings, as well as following vehicles and parallel traffic. If a vehicle drifts from its lane, the system will warn the driver. Additional sensors can be added to these systems that further enhance functionality by providing another aspect of safety in poor visibility and detecting obstacles, or other hazards are in the vicinity. As LDW capability becomes networked with other systems such as ACC and Navigation, total system responsiveness and flexibility will be enhanced.

Traffic Sign Recognition is a technology solution that aids compliance to situations where changing speed limits and ambiguous or unclear road signs are encountered during the course of travel. Some of the systems under development use digitally-broadcast traffic sign information from vehicle navigation systems. Vehicle navigation information is continually updated by service providers and this source would provide comprehensive coverage corresponding to virtually all mapped areas. Other systems being developed will receive data from radio transmitters installed on traffic signs. Still other, camera-based systems will "read" the signs. These systems will display information indicating the start and end points of speed limits on a multi-functional display inside the cockpit. The ACC system can also be programmed to maintain the vehicle speed to that posted. Integration with ESC will allow appropriate braking to maintain a set speed.

Perception of Vehicle Surroundings combines all of a vehicle's sensor information to create a complete, 360 degree model of its immediate vicinity. The sensor data is processed and then used to create a real-time depiction of the surroundings in a way that identifies any risks such as people, obstacles or traffic entering the lane.

CONCLUSIONS

We are in the midst of a revolution in smart vehicle technologies. Tomorrow's automobile will have "anticipatory" qualities that enable it to provide operating recommendations and active support to the driver. It will do this by monitoring the ambient traffic situation, and recognizing upcoming circumstances that require responsive action, and where desired, taking that action. This revolution is being made possible by the great leaps in microelectronics capability and functionality – accompanied by the decline in prices of semiconductor technology. Consequently, automotive applications have been expanding in great technological leaps

The vehicle systems discussed here represent a natural evolution of enhanced, technology-driven capabilities readily available to the broader motoring public in the very near future. Their development is being driven in large part by the safety concerns of regulatory agencies and enabled by the incredible leaps in technology we read about daily. Acceptance by the public will largely be driven by perception of need and cost. Long term success will be determined by these systems' effectiveness and reliability.

Disregarding uncertainties, the fact remains that traffic safety has reached a plateau, and technology is providing the means to dramatically improve it. This inexorable march of technology will only continue. As systems we envision today become commonplace, new concepts in traffic management will couple with advances in areas such as artificial intelligence and pattern recognition, causing today's visionary systems to be viewed in the much same light as we consider seatbelts today.

DETERMINATION OF LANE CHANGE MANEUVERS USING NATURALISTIC DRIVING DATA

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Paper Number 05-0337

ABSTRACT

Heavy truck on board yaw rate recordings are used to discriminate between different driving maneuvers and motions such as turning a curve, changing lanes, or wandering in a road lane. Such discrimination is important for trucks using a front end radar as a sensor for adaptive cruise control and collision warning systems. Turns can cause radar returns from objects outside the roadway or confuse the adaptive cruise control operation. A methodology for determination of a maneuver is derived and then applied to driving data. Correlation of the results is validated by the use of video data. The method has been found to be approximately 80% accurate in identification of the truck maneuver.

INTRODUCTION

The Yaw Rate signal was recorded in the use of a fleet of commercial truck vehicles for a period of two years in a field operational test (FOT). The original intent of recording yaw rate was to determine truck lane change maneuvers. It was hypothesized that a lane change maneuver would generate a Yaw Rate signal that approximates a noisy sine wave as the vehicle moves from the current lane to an adjacent lane. The amplitude and frequency of the yaw rate signal determines the exact nature of the maneuver in that it could be a vehicle turn, multiple lane change, a single lane change, or just small variations within the same lane. In this regard the yaw rate signal for a lane changes and curves differs from that of a signal where the vehicle is wandering within the same lane. It was found that the sinusoidal pattern was indeed reflected in the recorded FOT data mixed in with noise and signal variations due to roadway changes, truck vibration, and driver differences. These factors were all dealt with to define an algorithm that reliably determined the occurrence of a lane change. Development of the algorithm was validated using video data to ascertain the maneuver for a given yaw rate pattern.

BACKGROUND

For short time periods of a few seconds, a simplified model of a vehicle trajectory may be used to determine lateral movement vs. steering input.

The recorded yaw rate $\dot{\gamma}$ may be described by the equation:

$$\dot{\gamma} = K \cdot \sin\alpha$$

Where K is a constant and α is the vehicle steering angle. The yaw angle at any time point, i, may be determined by the following equation,

$$\gamma_i(t) = \sum_{i=1}^{n} \dot{\gamma}_i \Delta t$$

Where Δt is the time increment between any two successive time points. The respective components of the horizontal (x) and longitudinal (y) velocity are expressed as follows.

$$Vx = V\sin\gamma$$

$$Vy = V\cos\gamma$$

This allows the computation of the horizontal and longitudinal displacement equations.

$$Dx(i) = Vx(i)\Delta t + Dx(i-1)$$

$$Dy(i) = Vy(i)\Delta t + Dy(i-1)$$

From the above equations $Dx(i)$ is the current horizontal position of the vehicle at any arbitrary time.

METHODOLOGY

In general, a single sinusoidal signal is sought out of the entire Yaw Rate trace and one cycle of this signal must be of sufficient amplitude, polarity, and duration to represent a lane change as described in the following paragraphs. An algorithm was developed to compute horizontal position from the recorded data. This computation required several steps to remove noise and determine the nature of the signal as follows.

Bias Removal

It turned out that the raw recorded Yaw Rate signal had a bias added to it such that the expected sinusoidal function is not centered around zero for one cycle for a lane change. The bias was therefore removed as part of the post-processing procedure by computing the median value of Yaw Rate followed by subtraction of the median value from every Yaw Rate time point, which in net effect produces a Yaw Rate signal with zero median value. The source of the removed bias is not well known; but ideally should not exist at all. Therefore, it is removed.

Threshold of the Yaw Rate Signal

Due to ambient noise, the algorithm requires that the value of Yaw Rate at each time point exceed the threshold of 0.05 degrees per second. If the threshold is exceeded, the value is retained otherwise the signal is given the value of zero. This is done for all time points from beginning to end of the trace.

Sine Wave First Half Cycle Determination

It was necessary to determine if the yaw rate signal approximated a sine wave. This was done by estimating the period of the sine wave. The potential sine wave pattern was examined to see if a first half cycle occurred within the Yaw Rate signal trace. To do this, both the period and the amplitude of candidate sine waves are examined. If a half cycle sine wave is found, then following that, the total cycle of the sine wave must be found. If a half cycle sine wave is not found, then it is determined that no lane change occurred; but some other maneuver is still possible. Figure 1 shows an idealized example of signals and computations of horizontal position. Figure 2 shows an example of the difference in horizontal displacement for a lane change at different speeds with a yaw rate period of 2 seconds.

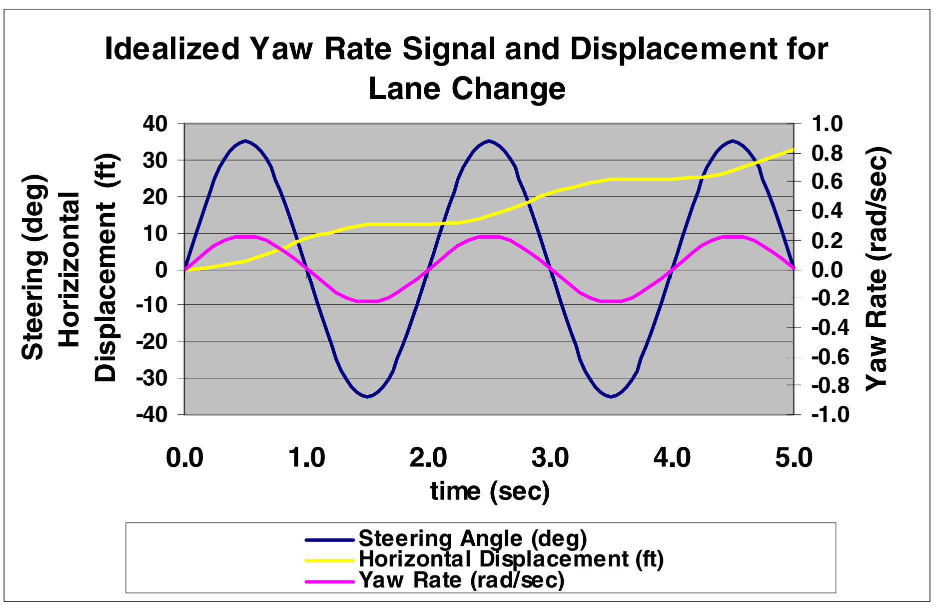

Figure 1. Example of Displacement Due to Lane Change

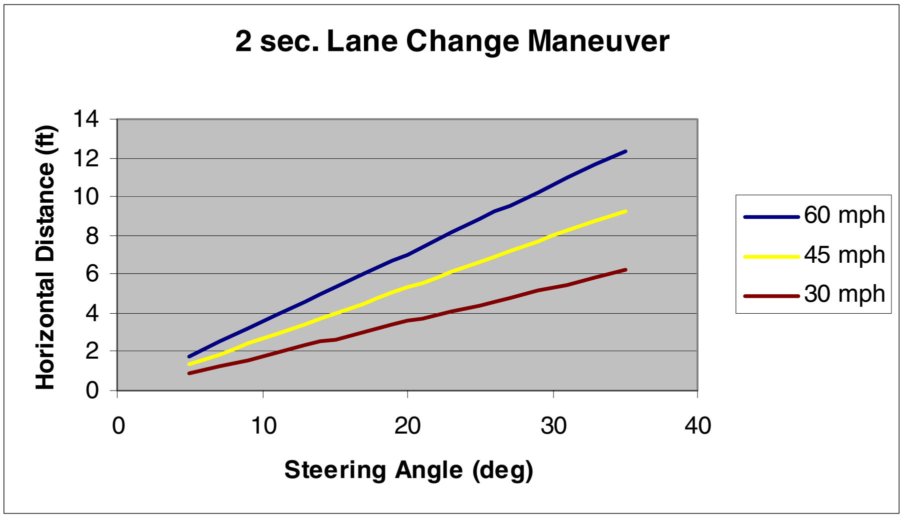

Figure 2. Effect of Vehicle Speed on Horizontal Distance

To ascertain the existence of a first half cycle sine wave, all of the zero crossings of the Yaw Rate signal are isolated. Next, a time threshold is used to see if two successive zero crossings have a period of greater than 1.83 seconds. This period was determined based on the time required for the truck to make a lane change and for that lane change to be reflected in the yaw rate signal. Any two zero crossings with a lesser time span are not considered as being a valid part of a sinusoid that could be used to determine lane change. Such a signal could be the result of merely wandering within the same lane. Any zero crossings equal to or greater than the threshold represent a valid half cycle sine wave. Thus, half of the sine wave is potentially determined. Recognition of a total sine wave, however, is required to detect a lane change.

<u>Total Time Span of Sine Wave</u>

If a valid first half cycle sine wave is found , then the total time span for the sine wave must be determined. In order for a lane change to be recognized, three successive zero crossings for the sine wave are determined as was previously done. All three zero crossings must all be within a time period of 12 seconds; otherwise a maneuver such as turning a curve would be implied.

Thus, the third successive zero crossing determines the end point of the sinusoid. To find this point, small amplitude variations around the second zero crossing are ignored until a zero crossing close to the period of the first half cycle is found. The amplitudes of both half cycles should be close to the same magnitude. In finding this third zero crossing, the period of the sine wave is now known. If this test is failed, then it is determined that no lane change occurred.

<u>Sine Wave Amplitudes</u>

This check is made to see if the amplitudes of the two half cycles are of opposite sign. The first half cycle must be followed by a half cycle of the opposite sign in amplitude. When the Yaw Rate first half cycle is positive, the lane change is from the left lane to the right lane; and if the first half cycle of the signal is negative, the lane change is from the right lane to a left lane. If the amplitudes of both half cycles are not of the opposite sign, then the Yaw Rate does not represent a lane change.

<u>Wandering In Lane</u>

A final check is made to see if the amplitudes are less than 0.5 degrees per second which represents normal “Wandering in the Lane” (WIL) rather than a lane change.

Thus, the algorithm must test to find a sinusoid that meets the other criteria. If a sinusoid fails any one of those tests, it is then subjected to a WIL test; and failing that is deemed not to be a lane change. The four decisions that can result from the algorithm are no lane change, lane change from right to left, lane change for left to right, or wandering in the lane.

SUMMARY

It can be seen that horizontal displacement that results from steering action is reflected in both the amplitude and the frequency of the yaw rate signal. If the yaw rate amplitude is below the noise threshold, horizontal displacement cannot be computed. Yaw rate amplitude much less than that produced by a steering angle of 30 degrees but at the same frequency as a true lane change results in some wandering within the same lane. Yaw rate frequency much lower than that required for a lane change but at a similar amplitude as a lane change amounts to negotiation of a curve. In a curve maneuver, the driver is keeping the steering wheel in some angular position for a longer period without returning it to home resulting in a very low frequency sinusoid. The resultant horizontal displacement of these three effects may be observed in Figures 1 and 3 thru 5.

PERFORMANCE RESULTS

A limited number of video clips were available for verification of the algorithm results. From 105 usable videos, the lane change algorithm had a detection reliability of 80 per cent as shown in Figure 6 below. This reliability rate was deemed reasonable and used for further analysis of driving data from the FOT.

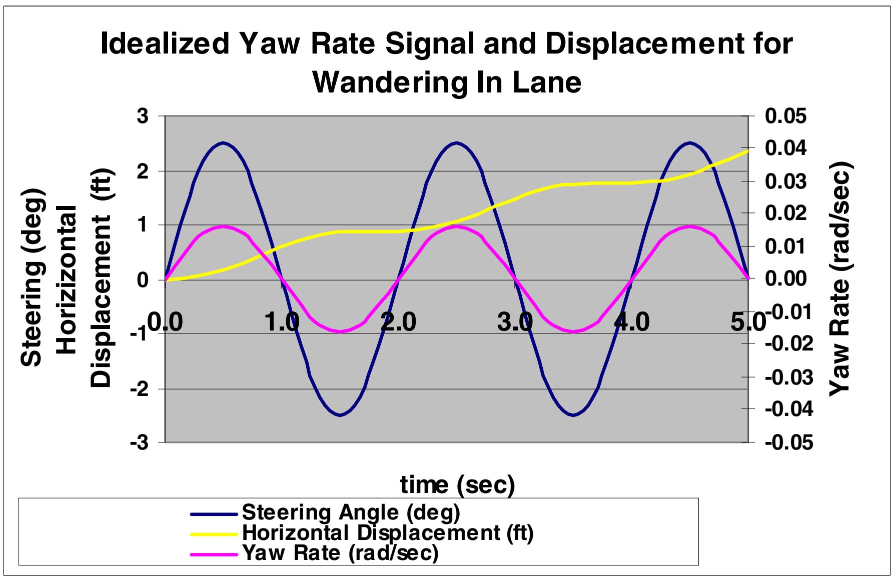

Figure 3. Wandering In Lane Functions

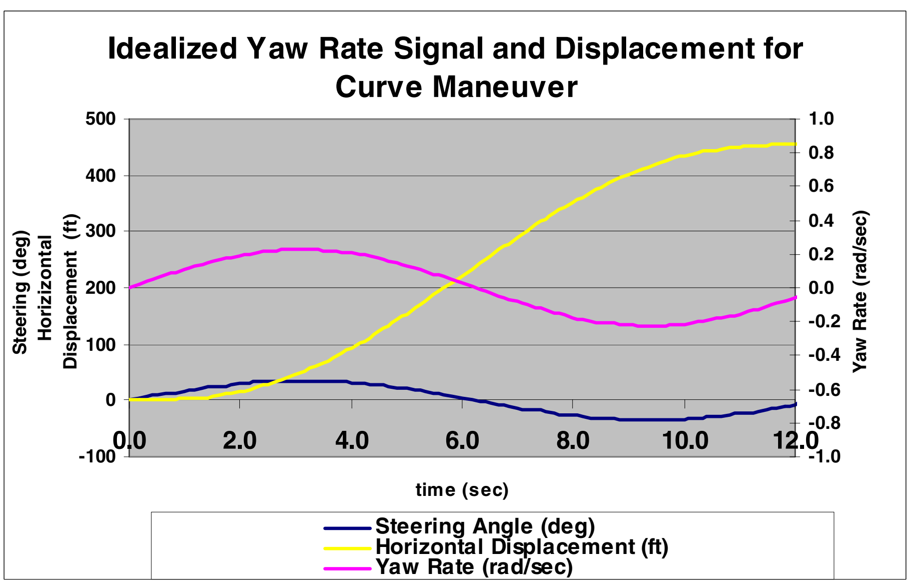

Figure 4. Curve Functions

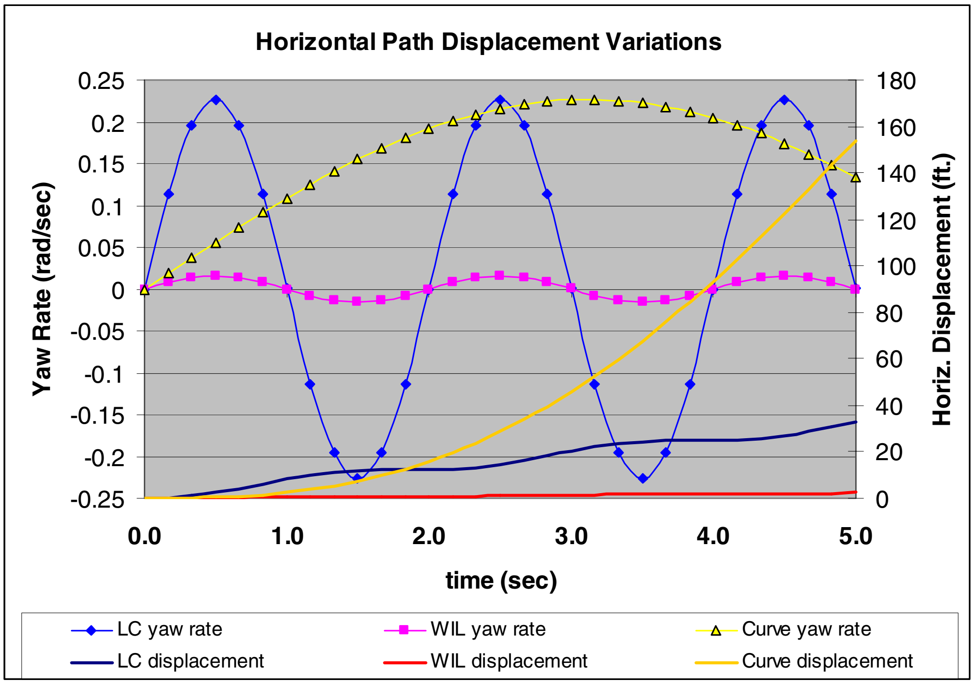

Figure 5. Summary Displacements vs. Yaw Rate Signals

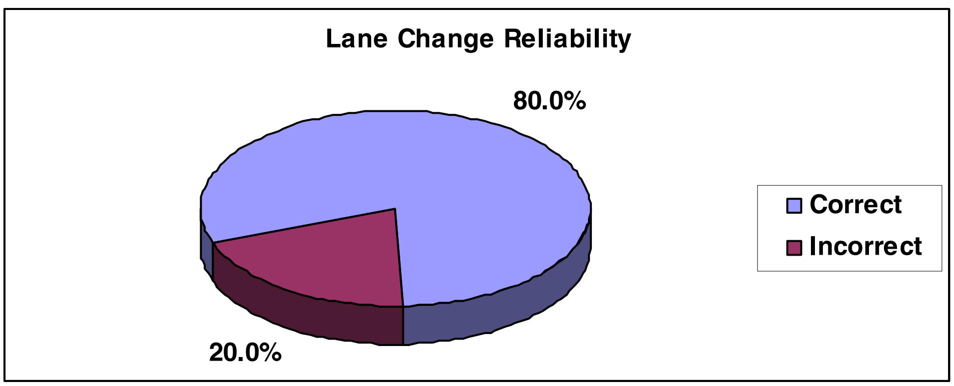

Figure 6. Lane Change Algorithm Performance

EVALUATING ONE SCREEN/ ONE CONTROL MULTIFUNCTION DEVICES IN VEHICLES

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ABSTRACT

Multifunction in-vehicle information systems are becoming increasingly prevalent in cars. These systems typically use a centrally located display and a single control device to carry out a variety of operations including navigation, communications, entertainment, and climate control. Advantages of these systems include: conservation of dashboard space, improved styling, function integration and flexible configuration of functions. The aim of this research was to investigate potential disadvantages of these systems. Given the quantity and complexity of the information these systems provide and the attention required to operate these devices, there is concern that they may be overly difficult and distracting to use while driving. Two 2004 European luxury vehicles containing multifunctional information systems were used in this study. Both systems consisted of a center-mounted LCD screen and a console-mounted primary control knob. A combination of human factors assessment techniques were used to assess the systems: 1) expert evaluations: the Transportation Research Laboratory (TRL) Checklist and heuristic evaluations, 2) user testing and 3) the occlusion test. Six human factors experts performed the expert evaluations and 12 drivers participated in the user testing and occlusion testing. Results from the expert ratings provided a detailed account of problems. Specifically, the information display format in System A helped drivers maintain a correct representation of system status and provided immediate feedback. System B, in contrast, was less successful in terms of providing informative menu labels, appropriate feedback and navigation aids. The number of tasks successfully completed was assessed for the two systems. An average of 82% passed the performance goal in System A, and only an average of 38% in System B. Although these issues are important to the design of any consumer product, they are critical to the operation of in-vehicle systems as they could impair driver performance and increase crash risk.

INTRODUCTION

In order to add more functionality into cars without increasing dashboard clutter, manufacturers are developing one control/one display information systems. These information systems integrate multiple functionalities, such as climate, navigation, entertainment and communication, and can be accessed via a single control. This space saving results in benefits such as more freedom for options and styling that enhances aesthetic and market appeal. Whereas the older style of interfaces generated distraction by requiring drivers to use multiple knobs and buttons, these newer systems may contribute to cognitive distraction by requiring drivers to remember what mode they are in. To access information that was once a button press away, drivers must now navigate through multiple hierarchical menu structures. Research is needed to evaluate how the use of these systems impacts driver safety.

At present, multifunctional systems are being introduced into cars without any standard criteria for their design. There are also no standard methods for assessing their ease of use and safety of operation while driving. To ensure that unsafe devices are not added to cars, appropriate assessment methods are required. The ultimate goal would be an assessment procedure that would eventually become the basis for an objective performance standard.

In the present study, we evaluated the effectiveness of both usability and safety assessment methods. The assessments were made using: (1) two version of expert evaluations, (2) user testing, and (3) occlusion testing.
We were specifically interested in the methods' sensitivity to different tasks and different interfaces.

Expert Evaluations

Expert evaluations are performed by human factors and vehicle safety specialists who test how well a system meets a set of safety and usability design guidelines. These guidelines are based on requirements such as standards for physical sizing, location of controls, labelling and display of information, as well best practices for "look and feel" and functionality of interfaces. For each identified problem, experts give a severity rating to guide re-engineering priorities and provide solutions. Examples of expert evaluations include the Transportation Research Laboratory (TRL) checklist (Stevens et al., 1999) and Heuristic Evaluations (Nielsen, 1994).

TRL Checklist The TRL checklist is a structured evaluation tool in checklist format for assessing the safety related features of an in-vehicle information system. It was developed based on accepted existing codes of practice and emerging international standards and has much in common with the European Statement of Principles. It is a low cost assessment technique that only requires a pen and an in-vehicle information system. Following the checklist assessment, assessors complete a final report detailing both the good and bad features of the system's design. Systems recognised as having major safety concerns or numerous minor safety concerns are considered to be less safe than systems that are rated as having fewer or less serious safety concerns.

Heuristic Evaluation Heuristics, or "rules of thumb", are general principles used to guide design decisions. A Heuristic Evaluation (HE) consists of having evaluators examine a user interface, usually in the context of typical user tasks, to generate a list of problems and associated heuristic violations (Nielsen, 1994). The purpose of this method is to identify problems that could hinder the ease of use of the system. Nielsen's 1994 list of 10 heuristics provides the best developed set of user interface principles for use when critiquing a system. This set of principles is based on a principal components analysis of the usability problems found in a number of studies of various user interfaces. Nielsen suggests that 3 to 5 evaluators usually result in approximately 75% of the overall usability problems being discovered. Heuristic evaluations were first developed to evaluate website interfaces but have been applied in many other domains such as in the evaluation of in-vehicle devices. Both types of expert evaluations (i.e., TRL checklist and HEs) are inexpensive and can be performed quickly and easily. As such, they offer a valuable front-end design evaluation tool for the automotive sector. Although expert evaluations highlight specific instances of problems, their usefulness lies in their ability to yield a high-level indication of weak aspects of an application that need further scrutiny. Expert evaluations are often combined with other assessment methods such as user testing. Specifically, once experts have identified types of problems, user testing can be performed on features that are most critical and relevant to tasks likely to be performed on these systems.

User Testing

In User Testing evaluations, participants interact with an interface while being observed by an experimenter. Specifically, users are asked to perform a given task and speak aloud as they interact with the system. The experimenter notes the mistakes that the user makes as well as the "play by play" verbal feedback given by the user. Videotaping the session ensures that no important information is lost and also provides a compelling video record of the specific problems encountered by the user. In contrast to the qualitative and subjective expert evaluation methods discussed thus far in this paper, a user test is an objective performance measure that aims to test a product or system against a predetermined set of high-level usability goals such as efficiency, effectiveness, and satisfaction. Usability testing was applied in the present study to verify that problems indicated by the two expert evaluation methods result in actual problems for target users. The tasks chosen for the user testing were a set of common difficult in-vehicle tasks (i.e., set address and point of interest).

Occlusion Testing

The probablility of a crash has been shown to increase as a function of increasing visual demands imposed by in-vehicle systems (Wierwille & Tijerina, 1998). Measuring "eyes-off-road" time by having people drive while interacting with an in-vehicle device can be dangerous and difficult. The occlusion method was developed as an indirect measure (i.e., no driving required) of visual demand of an in-vehicle task (ISO, 2004). Participants perform in-vehicle tasks while wearing occlusion goggles that intermittently block their view of the in-vehicle device. The occlusion interval simulates drivers having to take their eyes off the display to look back at the road while still being able to manually operate the in-vehicle system. The vision interval is 1.5 seconds and the occlusion interval is 2.0 seconds. During the occlusion interval, the in-vehicle displays and controls are not visible but operation of the controls is still permitted. The occlusion testing technique differentiates in-vehicle tasks that require more or less sustained visual attention to complete a task successfully. The key measure of sustained visual attention is the Total Shutter Open Time (TSOT) which is calculated by multiplying the number of vision intervals (i.e., shutters open) needed to complete the task by the 1.5 seconds vision interval. Tasks that can be completed in a few brief glances (i.e., shorter TSOT) are considered to be less visually distracting than tasks that require a greater number of glances (i.e., longer TSOT). Presently, there are no agreed upon specific performance criteria although these issues are being examined in an ISO draft work item. The Japanese Automobile Manufacturers Association (JAMA), however, has recently provided guidelines recommending a maximum TSOT of 7.5 s when a system is bench tested using the occlusion method.

METHODOLOGY- EXPERT EVALUATIONS

Evaluators

Six usability experts, working in pairs, performed 3 evaluations using the Transportation Research Laboratory (TRL) checklist and 3 heuristic evaluations. Three experts had background and experience in automotive human factors. The remaining three experts had combined backgrounds and experience in cognitive psychology, human-computer interaction and systems engineering. Because the three evaluators with expertise in automotive human factors were familiar with both multifunctional devices, they were each paired with one of the other three evaluators. Specifically, the combinations of expertise were as follows: pair #1- automotive human factors/cognitive psychology, pair #2- automotive human factors/human-computer interaction and, pair #3- automotive human factors/systems engineering. The evaluator familiar with the systems was able to acquaint the other evaluator with the system and describe the typical task scenarios in which the interface is used. The same pair of evaluators assessed System A and B separately.

Apparatus

Two European luxury vehicles (model year 2004) containing multifunctional information systems (System A and System B) were used in the evaluations. Both multifunctional information systems consisted of a centre-mounted Liquid Crystal Display (LCD) screen and a console-mounted main control knob that worked as the system's primary control. Both vehicles were stationary during testing.

Procedure

Each team of evaluators began the evaluation with an introduction to the system provided by the evaluator most familiar with the system. After the explanation of the nature and purpose of the functions included in the multifunctional systems, the team proceeded with their systematic evaluation of the interface.

Materials

TRL Checklist The TRL checklist used in the present study was developed by the Transport Research Laboratory for the UK Department for Transport. Prior to commencing the evaluation of the multifunctional interfaces, evaluators read the comprehensive instructions and detailed guidelines contained in the user manual that accompanies the TRL checklist. This manual contains supportive information providing: (1) an explanation about the application of the checklist, (2) the rationale for the questions contained in the checklist, (3) a list of technical references and abbreviation, and (4) a glossary of terms. Evaluators completed the 3 separate parts of the TRL checklist: (1) assessment scenario, (2) in-depth assessment, and (3) assessment summary.

Heuristic Evaluation The checklist guiding the evaluation contained 10 heuristics (see Nielsen 1994 for a review) that have been shown to cover the majority of usability problems users might encounter. The list functions as a reminder to the evaluator of potential problem categories. An example of one such heuristic "navigation" refers to the presence or absence of suitable navigation tools, presented in appropriate places, and leading to application areas that are consistent with the users' expectations. The evaluators worked through a set of typical tasks identifying problems and their associated heuristic violations as these occurred.The result is a list of problems and their corresponding severity. The process can be taken a step further in that solutions can be proposed.

RESULTS- EXPERT EVALUATIONS

TRL Checklist

Results from the TRL checklist provided a detailed account of potential problems. Specifically, experts predicted that the way information was displayed in system A would help drivers maintain a correct representation of system status and provide immediate feedback. Conversely, experts predicted that System B placed inadequate emphasis on issues such as use of informative labels, appropriate feedback and navigation aids. Although these issues are important to the design of any system, they are critical to the operation of in-vehicle systems as they could impair driver performance by increasing the demands on the driver.

The greatest difference between the two systems, based on how they scored on the TRL checklist, was that visual information presentation was better for System A than for System B. The larger number of menus and menu layers on System B increased its complexity relative to System A. Experts judged that System B's design would make it more difficult for users to see where they were in the system, how they got there, and how to get back to the starting point. Experts also rated System B as being more difficult to return to the start or escape from a dead end. This problem was due to the inconsistency in the return and escape options. In sum, experts concluded that it would be more difficult to navigate System B's interface than System A's interface. The TRL checklist states that systems that are more difficult to navigate will require more visual interaction time. This hypothesis was tested during the occlusion testing, the results of which are discussed below.

Heuristic Evaluation

As shown in Table 1, the total number of problems identified for System A was 35 and the total number of problems identified for System B was 51. Some problems identified violated more than one heuristic resulting in the number of violations exceeded the number of problems.

Both systems had a large number of heuristic violations given that these heuristics cover fairly basic requirements. From Table 1, we can see that there were more heuristic violations in System B than in System A which suggests that System B is less easy to use than System A.

Table 1
Number of Violations by Heuristic and System

Heuristic	System A	System B
1. Visibility of system status	11	17
2. Match between system and the real world	10	26
3. Recognition rather than recall	3	6
4. Consistency and standards	12	18
5. User control and freedom	9	7
6. Flexibility and efficiency	0	6
7. Aesthetics and minimalist design	5	9
8. Error prevention	6	6
9. Help users recognize, diagnose, and recover from errors	0	0
10. Help and documentation	3	4
Total	**59**	**99**

The number and nature of heuristic violations give a global overview of problems. This overview is regarded as a first step in usability evaluation in which areas of concern are identified to guide further, more detailed usability evaluations and to highlight specific issues to be exposed in subsequent user testing. For example, System B's interface appeared to suffer from a lack of match between system and the real world. This finding signals a need to review all words, symbols, actions and concepts to ensure that they are familiar to users (rather than system-specific engineering terms) and to test the effect of one or two instances of the problem on user performance. Furthermore, the design of the interface's navigation should reflect the order in which users will most likely perform tasks. System B's interface also appeared lack of standardization and consistency. This finding signals that users may be confused as to whether different words, icons and actions mean the same thing in different situations. It is prefreable to follow a conventional platform when designing an interface.

Experts predicted that terminology would be a problem for locating and interpreting information on System B due to the observation that headings and sub-headings were often difficult to understand and the information contained under many of these headings might not meet users' expectations. In this way, the heuristic evaluation serves as a guide for deeper subsequent probing to ensure identification and removal of all instances of a given problem type.

In sum, results from the Heuristic Evaluation were consistent with findings from the TRL checklist. In both cases experts found more usability and safety isues with System B's interface than System A's interface. Once experts identified the potential usability and safety problems perceived to exist in these systems, user testing was conducted to determine the degree to which the problems impede the typical user's' ability to complete specific tasks.

METHODOLOGY- USER TESTING

Participants

Twelve participants (11 males and 1 female) took part in the user testing. The participants ranged in age from 25 to 57 years with a mean age of 40. All were experienced drivers with normal or corrected to normal vision.

Materials

The same vehicles and multifunctional devices used for expert evaluations were used for the user testing. Both vehicles were stationary at all times.

Procedure

Participants sat in the drivers seat of the stationary vehicle. An experimenter seated in the front passenger seat administered the tasks to the participants. The experimenter seated in the back of the vehicle video- recorded the session. Participants were first familiarized with how the multifunctional information system functioned and given a few minutes to review the system. The goal was to assess how easy it is for drivers to locate and interpret specific information in the system. They performed four tasks which were developed based on the features that are most critical and relevant to tasks likely to be performed on these systems. Specifically, the experimenter asked participants to perform the following tasks:

- Task 1- Set address as destination: Participants were given an Ottawa address and asked to enter the street name and street number into the navigation system as the destination.
- Task 2 - Manually tune radio station and store it: Participants were given a specific radio frequency and asked to manually search for and select it.
- Task 3 - Set point of interest as destination: Participants were given a specific place of interest (e.g., restaurant, hotel) in other cities (i.e., different from Ottawa) and were asked to search for that place of interest within the navigation system and input it as the destination.
- Task 4 **-** Adjust audio setting: Participants were asked to adjust different "Treble/Bass" or "Balance/Fader" settings.

Each participant attempted the four tasks three times for a total of 12 tasks using each of the systems. Task order and system used was counterbalanced across participants. Participants were asked to speak out loud about their actions as they performed each task. Individual sessions lasted up to one hour.

Measures

The number of tasks completed successfully was the usability metric applied to all tasks. For a task to be completed successfully, users had to complete it making a maximum of two errors. If users made more than two errors, or they were unable to find the information, it was considered a failure.

RESULTS- USER TESTING

Of the 4 main tasks, an average of 82% of participants passed the performance goal in System A, and only an average of 38% in System B. The following table shows a summary of the results.

- 8/12 drivers using System A, and 6/12 drivers using System B were able to set an address as their destination point.
- 9/12 drivers using System A, and 6/12 drivers using System B were able to manually tune the radio station and store it.
- 10/12 drivers using System A, and 1/12 drivers using System B were able to set a point of interest as their destination.

- 12/12 driver using System A, and 5/12 drivers using System B were able to adjust the audio to a given setting.

These are indicated as percentages in Table 2. The results from the user testing support the experts prediction that System B was more difficult to use than System A. For system B, the major usability issue was that participants didn't know what menu or sub-menu labels to look under to find the desired information. This result is also consistent with the finding from the Heuristic Evaluation that terminology appeared to be a problem for locating and interpreting information on System B.

Table 2.
Percentage Completion by Task and System

Tasks	System A	System B
Set Address as Destination	67%	50%
Manually Tune Radio	75%	50%
Set Point of Interest as Destination	83%	8%
Adjust Audio	100%	42%
Average	***82%***	***38%***

To a large extent, the success of any information system, such as an Intelligent Vehicle Information System (IVIS), will depend on its usability or ability to be easily understood and conveniently employed by a user. Another important factor to consider when evaluating these devices is their safety performance. To assess whether these systems differ in the safety they provide to users, a user testing employing the occlusion procedure was performed. If results from the user testing suggest that System B is less safe than System A in terms of the amount of visual resources needed to perform the tasks, it will be more compelling for designers to take more care and effort to improve the systems.

METHODOLOGY- OCCLUSION TESTING

Participants

The same 12 participants that participated in the user testing took part in the occlusion testing.

Apparatus and Tasks

Liquid crystal shuttering spectacles were used to intermittently block the participant's vision (Translucent Technologies Inc. Toronto). The goggles were programmed such that the vision interval, with shutter open, was 1.5 seconds (within the suggested maximum time tolerance for having eyes off the road; Zwahlen et al., 1988) and the occlusion interval, with shutter closed, was 2.0 seconds. The same vehicles and tasks used for expert evaluations and user testing were used for the occlusion testing.

Procedure

During the experimental task trials, participants sat in the driver seat of the stationary vehicle. An experimenter seated in the front passenger seat administered the tasks to the participants. The experimenter seated in the back of the vehicle recorded task completion times. Sessions were conducted during daylight hours.

Participants were familiar with the multifunctional in-vehicle devices from the previous user testing session. They were given three occlusion warm up tasks involving the climate control system to familiarize themselves with the goggles and viewing conditions. Participants were then presented with the experimental conditions where they performed 12 tasks (3 repetitions of the 4 tasks) while wearing the occlusion goggles. The lenses on the goggles alternated from clear to opaque at intervals of 1.5 seconds and 2 seconds respectively until task completion. Participants also performed the 12 tasks with the lenses open. Performance was timed for each task. System order, task order and occlusion order were counterbalanced across participants.

Before each task began, the goggles remained open while participants viewed instructions printed on a flash card. Participants were asked to signal that they had read and understood the instructions by saying 'OK', and then were asked to complete the requested task to the best of their ability using the system. The task ended when the participant had completed the task or when five minutes had elapsed (whichever came first).

The dependent variable of interest was the Total Shutter Open Time (TSOT), the total time that vision is not occluded when using the occlusion procedure. TSOT is the sum of vision intervals required to complete a given task (ISO, 2004) and is a surrogate for total eyes-off-road time.

RESULTS- OCCLUSION TESTING

A 4 x 2 analysis of variance (ANOVA), with repeated measures on both factors (i.e., 4 task type; set address vs. tune radio vs. set point of interest vs. adjust audio and 2 devices; System A vs. System B) was conducted to test for differences in mean Total Task Time in the unoccluded condition (TTT_{unocc}). A significant interaction of task type and device type was observed [F (3,33) = 30.02, $p < 0.001$]. Post hoc pairwise comparisons using Fisher's LSD test revealed that for the "Set address as destination" task, the mean total task time was significantly higher when participants used System B (mean = 78.26sec.) than when they used System A (mean = 54.66 sec.). Similarly, for the "Set point of interest" task, the mean total task time was significantly higher when participants used System B (mean = 95.42 sec.) than when they used System A (mean = 48.22 sec.) (see Figure 1). These results suggest that the components involved in the "Set address as destination" and the "Set point of interest" tasks may be unsafe and require further scrutiny.

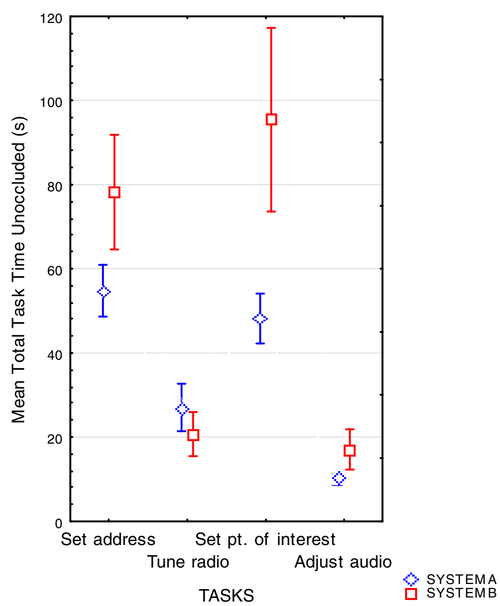

Figure 1. Mean Total Task Time without Occlusion by Task and System.

Results for the Total Shutter Open Time (TSOT) were similar to results for the total task time (TTT_{unocc}). Specifically, a 4 x 2 analysis of variance (ANOVA) with repeated measures on both factors (i.e., 4 tasks; set address vs. tune radio vs. set point of interest vs. adjust audio and 2 devices; System A vs. System B) was conducted to test for differences in mean Total Shutter Open Time (TSOT). A significant interaction between task type and device type was observed [F (3,33) = 34.15, $p < 0.001$]. Post hoc pairwise comparisons using Fisher's LSD test revealed that for the "Set address as destination" task, the mean total shutter open time was significantly higher when participants used System B (mean = 58.67 sec) than when they used System A (mean = 46.79 sec). Similarly, for the "Set point of interest as destination" task, the mean total shutter open time was significantly higher when participants used System B (mean = 78.53 sec.) than when they used System A (mean = 35.93sec). These task times are quite long. To ensure safe operation of multifunctional information systems, complex operations such as setting an address or point of interest as a destination should be restricted by only being accessed when the vehicle is not in motion.

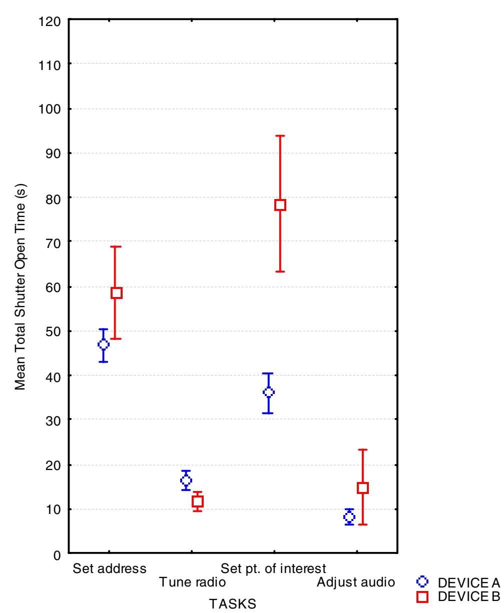

Figure 2. Mean Total Shutter Open Time by Task and System.

In sum, results for TTT_{unocc} and TSOT show that the occlusion procedure was able to discriminate between the demands of the two different interfaces. Thus, the power of the occlusion procedure as a method for evaluating visual demands of in-car information systems is supported. These results also support the TRL statement that the system most difficult to navigate (i.e., System B) would also require the most visual interaction time (TSOT System B sig. > TSOT System A). Further, a safety requirement for display-based in-vehicle systems is that the information must be quickly readable and understandable (Baumann et al. 2004). Results indicate that System A satisfied the latter requirement more so than System B, suggesting that System A is safer than System B. It is interesting to note that based on the JAMA guidelines for TSOT, none of these tasks would be considered safe or acceptable because they exceed their 7.5 seconds TSOT criteria.

GENERAL DISCUSSION

Expert evaluations of the two multifunctional devices yielded a global overview of their associated problems and were valuable in identifying the number and nature of usability and safety violations. Specifically, System B showed more usability and safety violations than System A. This finding demonstrates the value of expert evaluations in discriminating the number of basic usability and safety problems between two multifunctional displays. The increased number of usability violations found in System B, relative to System A, was consistent with the subsequent user testing results which indicated that users had more difficulty performing tasks on System B than on system A. Thus, user testing contributed to the assessment process by validating assumptions from expert evaluations. Finally, the occlusion procedure proved to be a useful method for evaluating safety, by assessing the visual processing demands of the multifunctional displays. The results in terms of total task time (TTT_{unocc}) and total shutter open time (TSOT) clearly showed that System A was superior to System B for the two more complex tasks (i.e., “Set address as destination” and “Set point of interest” tasks).

The present findings provide an important perspective on the different roles of assessment methods in the evaluation of multifunctional in-vehicle interfaces. Expert evaluations and user testing of System A and System B accurately predicted superior safety performance of System A over System B. Given the latter and the fact that expert evaluations and user testing are cost effective and can be applied quickly, proper evaluation chronology should first conduct expert evaluations and user testing and then more defined tests such as occlusion testing. Thus, to have the most impact on the usability of a system, expert evaluations and user testing should be incorporated into the early phases of the development process and continue as iterative testing during the remainder of the development process. Most developers acknowledge the value of usability testing, but many still view it as a hindrance to a timely and orderly product development process. The results from the present study suggest that these fears are justified when a usability evaluation serves only as a final checkpoint before the product is released to the public.

Given the number and seriousness of the problems found with the readily available systems evaluated in this study, one is lead to wonder why the developers did not catch these problems given that these techniques are simple and cost effective to implement.

Researchers have suggested that methods to evaluate safety and usability of multifunctional interfaces in cars are needed early on in the design process (Bullinger & Dangelmaier, 2003; Nowakowski et al., 2003). The results of the present research support this view and demonstrate that expert evaluations, user testing and occlusion testing provide a good combination of methods for assessing usability and safety of multifunctional information systems.

CONCLUSION

While safety should be at the forefront of system design and evaluation, user requirements also need to be met. It is imperative that a balance is reached between safety and user requirements. There is a need to understand how drivers use functions and services provide by multifunctional systems. The input of human factors specialists early in the development would help ensure user requirements are examined and met so that IVIS s may even decrease driver workload if user needs are matched in a way that is compatible with the primary task of driving. Together, the expert evaluations (i.e., TRL checklist and heuristic evaluation), the user testing and the occlusion testing results can help designers identify the areas and seriousness of both usability and safety issues.

Although System A showed less usability and safety problems than System B, it is surprising and disappointing that both systems rated poorly on these safety and usability evaluations. There is clearly a need to incorporate usability and safety assessment methodologies in the development of in-vehicle devices. If such methods are being used, then a better process is needed to place more importance on this information and to assure that problems are acknowledged, assigned and tracked until they have been resolved. Once evaluations become an integral part of the system development process, the end result is a safe and easy to use system.

More research is needed to validate and refine assessment methods. Specifically, assessment methods would benefit from criterion values for acceptable driver distraction. Thus, the next step will be to define some criteria on which to set performance limits for unsafe tasks.

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NHTSA's RESEARCH PROGRAM ON WIRELESS PHONE DRIVER INTERFACE EFFECTS

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ABSTRACT

Studies have shown that wireless phone use while driving contributes to crashes [1]. To address this phenomenon the U.S. Department of Transportation's National Highway Traffic Safety Administration (NHTSA) designed research to assess the impact of wireless phone use on driving behavior and performance. This research focused on the examination of the effects of interface type (i.e., hand-held versus hands-free) on driving performance. Unconstrained, on-road research examined drivers' wireless phone use in a real-world setting. Research using the National Advanced Driving Simulator (NADS) examined the effects of wireless phone use on driving performance in a controlled environment.

Research findings highlighted the impact of wireless phones on driving performance and behavior. The results of the on-road study indicated that phone use alters drivers' attention, as evidenced by changes in patterns of eye glance behavior. However, the variability of driving conditions observed in this study hindered the identification of specific patterns of degraded driving behavior. Although hands-free interfaces allow drivers to steer using both hands, in practice drivers were observed to steer using two hands quite infrequently during routine driving as well as during hands-free phone use. In the more controlled laboratory study, we found that phone use degraded driving performance, including measures of vehicle control and car following. There were also differences between interfaces. Specifically, hand-held phone interfaces were shown to interfere with steering and lane position variability more than hands-free interfaces, however the hand-held interface was associated with faster dialing times and fewer dialing errors than the hands-free interfaces.

INTRODUCTION

Studies have shown that use of wireless phones while driving contributes to crashes [1]. The crash-related effects of wireless phone use while driving is a controversial issue, and has been under public scrutiny in recent years. Across the United States and in other countries, numerous efforts are underway to pass legislation that allows only hands-free wireless phone use while driving. This move is based on the assumption that any technology that reduces the visual-manual demands of wireless phone use must be safer, since the driver can keep both hands on the wheel and both eyes on the road when using a hands-free system.

To gain insight as to how phone use might be impacting crash rates, the U.S. Department of Transportation's National Highway Traffic Safety Administration (NHTSA) performed research to assess the extent and nature of the impact of wireless phone use on driving performance. NHTSA's research used instrumented vehicles for on-road testing and the National Advanced Driving Simulator (NADS). The on-road research examined drivers' wireless phone use in a more naturalistic setting. The NADS research allowed the study of drivers' actions while using wireless phones in a tightly controlled environment. Through these research programs, the effects of interface type and phone task (i.e., dialing answering, conversing) on driving performance and eye glance behavior were examined.

This paper describes the types of research performed to examine driver distraction due to wireless phone use with different interfaces while driving. This paper also discusses drivers' preferences regarding phone interfaces and compares them to objective phone use data.

ON-ROAD WIRELESS PHONE STUDY

This research examined the effects of wireless phone interface type on driving performance and wireless phone usage behavior. Naturalistic (an observational method involving no specified route or commanded tasks), on-road data collection with instrumented vehicles was conducted to examine patterns of drivers' use of wireless phones as a function of phone interface type (i.e., hand-held vs. hands-free) under real-world conditions. Specifically, driver eye glance activity, driver-vehicle performance measures, and wireless phone use were examined. This comparative analysis examined the response measures to better understand how wireless phones change the driver's behavior and performance.

The objectives of this research were: 1) to assess the effects of wireless phone use while driving on driving performance as a function of wireless phone interface type (i.e., hand-held, hands-free headset, and hands-free with voice dialing), and 2) to observe patterns of phone use while driving including the frequency and duration of phone use. Additionally, the study sought to examine the types of driving situations associated with phone use. More specifically, this research was intended to identify differences in driving performance during hand-held wireless phone use versus during hands-free phone use.

Method

The experimental design for this study was a one within, one between mixed factor design. The within-subjects (i.e., repeated) measure in this study was type of in-vehicle wireless phone. The three wireless phone interface conditions were: hand-held (manual phone dialing and talking), hands-free headset (manual dialing, hands-free conversation), and hands-free with voice dialing (AutoPC voice controlled dialing, hands-free conversation). The between-subjects factor was frequency of wireless phone use (self-reported: moderate or frequent) while driving. Gender was balanced across experimental conditions.

The vehicles were programmed to record vehicle control inputs (steering, brake activity) and driving performance measures (headway, lane position). Dependent variables relating to vehicle motion and operation included lane position, number of lane exceedences, longitudinal acceleration (g), number of steering reversals, degree of throttle application, time headway (ft), and vehicle speed (mph). Video cameras were unobtrusively installed in the test vehicle to capture driver eye glance behavior during each phone conversation as well as during baseline episodes. Video data were reduced to obtain eye glance information including glance location, glance duration, and glance frequency. Phone call information including number of calls, dialing duration, conversation duration, and traffic density surrounding the vehicle during phone use were also obtained from video data.

Procedure

Ten participants drove an instrumented vehicle unaccompanied on public roads for a total of six weeks. Since only six test vehicles were available for use, the data were collected in two, 6-week phases. Participants drove for two weeks with each of three types of wireless phones: hand-held, hands-free headset, and hands-free with voice dialing. Participants were instructed that the study sought to assess a state-of-the-art data acquisition system and also gather drivers' opinions about new in-vehicle technologies. At the beginning of their 6-week phase, participants were instructed in the use of the in-vehicle computer system. This system provided phone, phone book, radio control, and other functions. Every two weeks, the phone interface configuration was altered and participants were instructed on the use of the wireless phone interface that would be present in the vehicle for that period. Drivers were instructed that they were free to use the wireless phone provided to them (rather than their own personal phone) and the test vehicle in their normal, daily routine. Thus, the test vehicles were to take the place of participants' normal vehicles during the course of their participation in the study.

Observation over a period of time during normal, unrestricted driving provided the gathering of naturalistic driving data with a minimum of experimental artifacts. This method also provided insights into frequency of use, duration of use (e.g., conversation), and driving situations during use as a function of the technology. However, this unrestricted driving led to highly variable driving conditions that complicated data analysis.

Results

The following is only a brief summary of the results from this study. The complete results are documented in [2].

Drivers in this study engaged in 2.25 calls per hour (7 calls per 100 miles) on average. The average call (conversation) duration was 2.4 minutes (SD =3.5 min.). Calls were involved in 5-9 percent of driving time observed, depending on the phone interface.

One important question this research sought to answer was whether drivers would make more calls and longer calls with a hands-free phone than with a hand-held phone due to presumed increased ease of use. Drivers in this study did not make more calls or longer calls with hands-free wireless phones than with hand-held wireless phones. In fact, the hand-held wireless phone interface used in this study was associated with more calls and calls of longer duration. This could be attributable to increased familiarity with hand-held phones, as well as poor performance of the voice recognition system used for the hands-free with voice dialing interface. Anecdotal evidence based on video data suggests that some drivers had considerable difficulty in voice dialing using the hands-free with voice dialing wireless phone interface supported by an in-vehicle computer (AutoPC). More than half of calls made in the hands-free with voice dialing condition were dialed manually. Drivers ignored instructions to use hands-free (voice) dialing, suggesting drivers found voice dialing difficult to use. The hand-held wireless phone was associated with shorter dialing periods.

Drivers engaged in fewer wireless phone calls when driving in conditions of high traffic density, particularly when using the hands-free phone interfaces. Ninety-two percent of calls were made when there were less than 10 vehicles present in the vicinity of the participant's vehicle. Seventy-five percent of calls were conducted in the presence of five or fewer surrounding vehicles. The mean number of surrounding vehicles was highest during hand-held calls (4.5 vehicles) and lowest during hands-free with voice dialing calls (3.2 vehicles), suggesting drivers may have felt more comfortable engaging in calls using the hand-held phone interface.

Significant trends that would distinguish the effects on driving performance of hands-free wireless phone use from hand-held wireless phone use were not found. However, some interesting findings were obtained relating to glance behavior during wireless phone use:

--Drivers spent proportionately less time looking at the roadway ahead while dialing (40-50%), relative to baseline driving (70%). Hands-free dialing was associated with a modest increase in the percentage of time spent looking at the forward roadway (50%), relative to manual dialing (40%). Hands-free dialing thus allowed drivers to recover approximately one-third of the 30% decrement in time spent looking at the forward roadway associated with hand-held dialing.

-- During phone conversation, drivers made fewer glances of longer duration relative to baseline driving, suggesting a decrease in situational awareness while engaged in phone conversation. Drivers spent almost 90% of the time during phone conversation looking straight ahead when using the hand-held interface, versus approximately 77% for the hands-free interface and 70% during baseline driving.

-- For conversations of 2 minutes or longer, the percentage of time spent looking at the forward roadway increased across successive 30-second segments. At the same time, the percentage of time looking inside the vehicle decreased, as did the percentage of time spent looking left and right. The results suggest that drivers gradually became less attentive to the immediate driving situation as the phone call continued.

-- During baseline driving, participants steered with both hands for 13.4% of the time. The corresponding percentages for hands-free conversation were 13-16% versus less than 1% for hand-held conversations. Thus, while hand-free phone use allows drivers to keep their hands on the wheel, the present results suggest that they most often choose to drive with less than two hands on the wheel.

It is unclear whether the difference in time spent driving with two hands on the steering wheel between hand-held and hands-free of approximately 12 percent relates to a significant difference in drivers' ability to operate the vehicle safely. However, statements arguing that "hands-free lets you keep your hands on the wheel" appear less significant when considering the finding of this study that drivers may only be steering with two hands 13 percent of the time when not using the phone.

Conclusions from This Study

In summary, while some differences were found between phone interfaces for dialing duration and conversation durations, significant differences in driving performance were not found for the specific measures examined. Significant differences in driving performance during conversation versus driving performance during baseline driving were also not distinguishable based on data collected in this study. However, the robustness of eye glance data provided useful information regarding drivers' glance behavior during conversations and how this glance behavior can change as the conversation progresses in time. While drivers were observed steering with two hands on the wheel 12 percent more during hands-free conversation than during hand-held conversation, it is unclear whether this difference relates to a substantial difference in drivers' ability to safely operate the vehicle.

Given that the analyses reported here demonstrated the large amount of variability in driving conditions and based on the fact that many studies have shown performance degradation due to conversation generally, the absence of such effects in this study suggest that the experiment might not have the sensitivity necessary to detect differences in driving performance due to the interface conditions. While the lack of control of driving conditions is inherent in naturalistic studies, this type of research allows for observation of behaviors which drivers might be less inclined to exhibit in a more controlled setting.

EXAMINATION OF THE DISTRACTION EFFECTS OF WIRELESS PHONE INTERFACES USING NADS – FREEWAY STUDY

This research investigated the effects of wireless phone use on driving performance and behavior. The study had two primary objectives: (1) to assess the distraction potential associated with the use of wireless phones while driving, and (2) to determine whether distraction potential was related to the specific phone interface used. In particular, the experiment addressed the question of whether hands-free operation substantively affected the distraction potential associated with wireless phone use while driving. In addition, the experiment investigated whether voice-activated dialing affected the distraction potential associated with using a phone while driving. The secondary objective was to determine whether the distraction potential associated with phone use varies with driver age.

This research was conducted by NHTSA using the National Advanced Driving Simulator (NADS) in collaboration with NADS staff at the University of Iowa. The experiment was one of the first to use the NADS' capabilities for developing complex driving scenarios.

Method

Fifty-four subjects drove a freeway route scenario on the NADS with each of three different wireless phone interface types: hand-held, hands-free headset, and hands-free speaker kit with voice dialing. Phone conversations consisted of a verbal interactive task involving judging whether sentences made sense and later recalling words from each sentence.

Each driver completed a single session of participation in which the same scenario route was driven three times, once per phone interface. The order of presentation of interface conditions was varied systematically. Each traversal of the route involved one incoming and one outgoing call, for which the presentation order was balanced.

The route consisted of a four-lane divided freeway with a 65-mph speed limit with traffic present. The route generally consisted of four straight segments of nearly equal length joined by right-side interchanges requiring exiting and merging behavior. The treatment drives were approximately 15 minutes in length and required participants to drive three segments of the divided freeway route. The route segments corresponded, respectively, to the incoming phone call, outgoing phone call, and baseline (no call) periods. Each route segment involved a series of interactions between the driver and the scenario vehicles (i.e., events). Events included a sudden lead-vehicle cut-in, sudden braking by the lead vehicle, a car following event, and a merge. Each traversal of the route was associated with a different order of events. The intention of the scenario design was to overlap the events with the 3.5-minute conversation task periods. Each participant also experienced a brief final event involving a more critical lead vehicle-braking event.

A more through description of the methodology used for this study is contained in [3].

Results

The following is only a brief summary of the results from this study. The complete results are documented in [4] and [5].

Results showed that the simulated phone conversations used in this experiment impaired aspects of driving performance. The car-following events provided the strongest demonstration of performance impairment effects due to phone conversation. Phone conversation was associated with increased delay in responding to lead-vehicle speed changes, which indicates significant cognitive impairment due to phone conversation. Steering entropy (error) was also found to increase during phone conversation in car-following events, reflecting an increase in high-frequency steering corrections. Phone use was associated with elevated steering reversal rates during car following, which reflect the increased workload associated with the combination of car following and phone conversation.

The results provided some support for the hypothesis that hand-held phone use would degrade driving performance more than the hands-free interface conditions during car-following events. Specifically, steering entropy was highest in the hand-held condition. In addition, lane position variability was greater in the hand-held condition than in the other interface conditions, also presumably reflecting the physical conflict. These two results presumably reflect the physical conflict between holding the phone and steering, both of which require use of the hands. However, the interpretation of these results was complicated by the overall finding that phone use generally was associated with decreased lane position variability during car-following events, which suggests improved lane tracking performance while drivers were engaged in phone conversation.

The results for steering holds, which represent periods of steering inactivity and are assumed to reflect increasing neglect of steering due to the demands of other tasks, were contrary to predictions, reflecting better performance during the simulated phone conversation. Specifically, the baseline condition was associated with higher steering hold rates than the hands-free or hand-held conditions. Finally, the observed decrease in modulus (gain) during car following indicates more conservative responses when drivers were engaged in conversation, and may be interpreted as an attempt to compensate for the increased demands of car following and phone conversation.

Beyond the car-following events, there was only modest evidence consistent with predictions of performance impairment due to phone conversation. Neither the lead-vehicle braking nor lead-vehicle cut-in events exhibited the predicted slowing in accelerator release and brake response times. The merge event provided one piece of evidence of impairment due to phone use. Specifically, while engaged in the phone conversation task, drivers devoted less visual attention to planning for an upcoming merge event. They made fewer glances toward the traffic stream and spent proportionately less total time looking in that direction relative to the baseline condition. This suggests that drivers diverted attentional resources from merge planning to manage the phone conversation task.

Results suggested that the drivers may have compensated for phone conversation by increasing their time headways, but at the same time, they were likely to have diverted attention away from speed monitoring, which led, unintentionally to increased average speeds.

There were modest differences between interface conditions during conversation for the other events. First, there was some evidence that the hand-held interface interfered with steering and lane control, as would be expected since both tasks require use of the hands. Second, there was some evidence that the hands-free speaker kit interface was associated with faster speeds, relative to the other interfaces. In particular, speeds for the hands-free speaker kit interface were fastest at the beginning of the cut-in events and also at the end of the merge events. Hands-free speaker kit calls were associated with more slowing at the very beginning of the merge and more increase in speed at the end of the merge. One interpretation is that while engaged in hands-free speaker kit calls, drivers felt safer and thus paid less attention to speed control.

Differences among interfaces conditions were stronger for dialing and answering than those associated with conversation. Specifically, the hand-held interface was associated with consistently faster dialing times and fewer dialing errors (i.e. repeated attempts) than the other interface conditions. Voice dialing times exceeded hand-held dialing times by 84 percent for hands-free speaker kit and by 51 percent for hands-free headset. The hands-free speaker kit interface was associated with significantly faster answering and hang-up (call termination) times than the other interfaces.

Several differences among age groups were found. Young drivers were more aggressive in their car following, as reflected by higher modulus scores. Older drivers exhibited more steering reversals during car following, indicative of higher workload for this group. Drivers in the middle age group were faster than younger drivers at the beginning of the LV cut-in event. In the merge event, relative to the other age groups, older drivers made proportionately more glances leftward before the merge event and spent more time looking left to plan the merge. Older drivers also maintained greater following distances than younger drivers.

Analysis of the final event scenario revealed significant differences for some dependent measures. Hypothesized effects related to phone interface were complicated by significant interactions between phone interface and age. For first response to the final brake event, participants in the hand-held condition responded significantly faster than those in the hands-free and no-phone conditions, contrary to hypothesis. These results appear to agree with results of the previously mentioned on-road study [2] that showed that drivers looked forward more with hand-held than with hands-free.

Although participants rated the hand-held interface to be most difficult to use, this interface was associated with the fewest dialing errors (in terms of the number of attempts per dialing trial). Participants' feelings that the hand-held interface was the most difficult to use were also not supported by dialing time results, which showed that the hand-held interface was associated with significantly faster dialing times than the other two interfaces for all three age groups. Shorter dialing times for the hand-held interface may be attributable to participants' prior experience with hand-held wireless phones, which was approximately 6 years on average. However, it should be noted that the length of time required to perform voice digit dialing depends on the interface being used. This study used the Sprint PCS Voice Command system, since it was assumed that a system-based voice-dialing interface would be more likely to have better voice recognition capability than phone-based voice dialing. Some newer phone designs feature integrated voice digit dialing capability that may allow shorter dialing times. Use of voice "tags" for dialing may also afford shorter dialing times; however, voice digit dialing was chosen for implementation in this study since it provided the most direct comparison between manual and voice dialing.

Conversation task performance did not differ as a function of phone interface. Age was the only examined variable significantly related to phone task performance, with younger individuals performing better than older individuals.

Conclusions from This Study

Based on the preceding results, it was concluded that:

1. Phone use while driving degraded driving performance particularly during car following. The simulated phone conversation was associated with a significant delay in responding to lead vehicle speed changes. Phone conversation also degraded vehicle control, as reflected by increased steering error and an increase in one measure of driver workload. Drivers spent less time planning for merge events while engaged in the phone task.

2. Overall, there were modest differences among interface conditions during the conversation task. The hand-held phone interfered with steering and lane position more than the hands-free interfaces.

3. Differences among interface conditions were strongest for dialing and answering. Specifically, the hand-held interface was associated with fastest dialing times and fewest dialing errors. Drivers rated this interface most difficult to use while driving.

4. Neither older nor younger drivers exhibited consistently worse performance due to simulated phone conversation.

EXAMINATION OF THE DISTRACTION EFFECTS OF WIRELESS PHONE INTERFACES USING NADS –ARTERIAL

NHTSA also conducted research to investigate the effects of wireless phone use on driving performance and behavior in an urban arterial driving environment. The urban arterial environment represented required a more active style of driving and employed a more dynamic visual scene.

The main objective of the research was to collect information useful in the assessment of 1) the distraction potential of wireless phone use while driving, and 2) the difference in distraction caused by the use of a hands-free phone interface versus that associated with use of a hand-held interface. Of particular interest was whether using hand-held phone interfaces (e.g., dialing, answering, conversation) while driving degrades driving performance more than does hands-free wireless phones. In addition, the research addressed the question of whether younger and/or older drivers exhibit worse driving performance during wireless phone task components than middle-aged drivers. Lastly, the research examined whether drivers glance away from the forward roadway more when using a hands-free phone interface than they did when using a wireless phone in a hand-held configuration.

Method

Fifty-four participants drove an urban arterial driving scenario on the NADS with each of three difference wireless phone interface types. Like the freeway study, phone conversations consisted of performance of a verbal interactive task involving judging whether sentences made sense and later recalling words from each sentence.

Each participant completed a single session in which the same basic route was driven three times, once with each phone interface. The order of presentation of phone interface conditions was varied systematically. Each traversal of the route involved one incoming call, one outgoing call, and a baseline period, as well as a unique order of scenario events. The order of presentation of incoming and outgoing calls was balanced.

The route consisted of four-lane undivided arterial roadway with a 45-mph speed limit and other traffic. The route was approximately 15 minutes in length and generally consisted of three segments of equal length. Each segment corresponded to an incoming call, outgoing call, or baseline driving period.

Each segment contained a “between towns” section and an “in town” section. Between town sections were characterized by mild, alternating curves. A visual target detection task was presented during between town sections in which participants had to press the vehicle’s horn button when they spotted a pedestrian wearing a shirt with an “I” on it amongst a number of other similarly dressed pedestrians. In town sections consisted of straight portion of roadway lined with buildings and some vehicles. During in town sections, events were presented including incursions, occasional static vehicles blocking the participant’s travel lane, and changing traffic signals that required drivers to respond to avoid a collision or running a red light.

Dependent measures used to characterize driving performance included reaction time in response to discrete events (i.e., conflict events and traffic lights), as well as reaction time and accuracy of responses for the visual target task. Phone task performance measures included dialing time, number for dialing errors, answering time, and the number of correct judgments and recalled terms for the conversation task. Participants also completed a post-drive questionnaire used to report perceived difficulty of driving and phone tasks, as well as preferences regarding phone interfaces and related features.

Status

Data analysis for this study is scheduled for completion in Spring 2005. Analyses are focused on assessing the impact of phone use on individual measures of driving performance. Analyses will highlight the degree to which phone use affects a driver’s ability to respond to conflict events and objects in their visual environment.

SUMMARY

NHTSA has conducted on-road and NADS studies to examine the effects of wireless phone use on driving performance and behavior.

On-road testing showed that using a wireless phone while driving altered drivers’ eye glance behavior. Although hands-free interfaces allow drivers to steer using both hands, in practice drivers were observed to steer using two hands quite infrequently.

NADS testing showed that phone use while driving degraded driving performance and vehicle control. Differences in phone task performance among interface conditions were determined to be strongest for dialing and answering. Specifically, the hand-held interface was associated with fastest dialing times and fewest dialing errors. Drivers rated this interface most difficult to use while driving. While hand-held phone interfaces were shown to interfere with steering and lane position more than the hands-free interfaces, the hand-held interface tested was associated with fastest dialing times and fewest dialing errors.

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NHTSA'S NATIONAL ADVANCED DRIVING SIMULATOR RESEARCH PROGRAM

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ABSTRACT

Since its completion, the National Advanced Driving Simulator (NADS) has been used for a variety of NHTSA research projects. NHTSA-sponsored research using the NADS has spanned a variety of topics including driver distraction, drivers' responses to vehicle component failures, and the effects of alcohol impairment on driving performance. The validity of the NADS has also been verified empirically. The NADS provides the computational capabilities and fidelity necessary to create complex driving situations with varying task demands with high repeatability. The use of the NADS also allows the inclusion of conflict situations that cannot safely be created in on-road experiments. NHTSA research utilizes these unique capabilities of NADS to address questions that cannot be addressed with on-road or test-track experimentation. This paper highlights NADS capabilities through descriptions of NHTSA research programs.

INTRODUCTION

Historically, a number of methods have been available for use in studying driver behavior and performance including: (1) observation of real world, "naturalistic," driving, (2) testing with instrumented vehicles on public roads, (3) testing with instrumented vehicles on test tracks, (4) low fidelity driving simulators, and (5) a variety of in-laboratory tests. However, frequently these methods do not have the capability to test drivers in safety critical situations with a high degree of realism. Test repeatability is also difficult to achieve with non-simulator methods, particularly in complex driving scenarios.

Thus, to improve NHTSA's ability to perform driver behavior and performance testing, the Agency decided in 1992 to build a high fidelity driving simulator in the U. S. – the National Advanced Driving Simulator (NADS). Such a simulator would benefit industry and academia as well as NHTSA. Therefore, following a site selection competition, the NADS was built by a partnership between NHTSA and the University of Iowa. The NADS became operational in January 2002.

OBJECTIVE

The objective of this paper is to outline the capabilities of the NADS and provide a description of the research programs that NHTSA has undertaken to date. The description of each research program will highlight the capabilities of NADS that were necessary to perform that particular program.

BASIC DESCRIPTION OF THE NADS

Reference [1] contains a comprehensive description of the NADS. The following brief description of NADS was excerpted from Reference [2] with minor modifications to accommodate changes since Reference [2] was written and improve clarity.

NADS is physically located on the University of Iowa's Oakdale Research Park in Iowa City, IA. It consists of a large dome in which entire cars and the cabs of heavy trucks and buses can be mounted. The dome is mounted on a six degree of freedom hexapod that is mounted on the large excursion motion base. The large excursion motion base provides 20 meters of both lateral and longitudinal travel and ∀330 degrees of yaw rotation. The resulting effect is that drivers feels acceleration, braking, and steering cues as if they were actually in a real vehicle. This greatly reduces the incidence of simulator sickness compared to simulators that have less motion capability.

The Motion System provides a combination of translational and angular motion that uses nine degrees of freedom to mimic scaled vehicle motion. The Motion System is coordinated with the Control Feel System (described below) to provide the driver with realistic motion and haptic cuing during normal driving and pre-crash scenarios. A "washout" filter is used so that the Motion System can correctly represent the specific forces and angular rates associated with vehicle motions for the full range of driving maneuvers.

Four additional actuators, one at each wheel of the vehicle, provide vertical vibrations. This simulates the feel of a real road. Without these actuators, driving on NADS would feel like driving on ice.

The Visual System provides the driver with a realistic field-of-view in all directions (including rearview mirror images). The driving scene is three-dimensional, photo-realistic, and correlated with other sensory stimuli. The Visual System database includes highway traffic control devices (signs, signals, and delineation), three-dimensional objects that vehicles encounter (animals, guardrails, pillars, etc.), high density, multiple lane traffic interacting with the driver's vehicle, common intersection types (freeway interchanges, overpasses, bridge structures, tunnels, railroad crossings, etc.), and roadway weather.

The Cab System holds the driver (participant) and the experimenter during testing. NADS has four vehicle "cabs" that can be used for testing: a Chevrolet Malibu (passenger car), a Ford Taurus (passenger car), a Jeep Cherokee (sport utility vehicle), and a Freightliner Century (heavy truck-tractor). For the passenger car and sport utility vehicle cabs, the entire vehicle is mounted inside the NADS dome. For the heavy truck-tractor, only a portion of the actual vehicle (the actual vehicle's cab) is present inside the dome. All vehicle cabs are equipped electronically and mechanically with the correct steering wheel, brake and throttle pedals (the Freightliner also has a clutch pedal), transmission lever, ancillary controls, entertainment system, air conditioning, gauges, and warning lights for their make and model.

The Control Feel System provides realistic steering wheel, brake, throttle, and clutch pedal, and transmission lever reactions in response to driver inputs, vehicle motions, and road/tire interactions. The Control Feel System is capable of power steering, power brakes, antilock brake systems (ABS), cruise control, and automatic and manual transmissions with different numbers of gears. The control feel cuing feedback has high bandwidth and no discernable delay or distortion associated with driver control actions or vehicle dynamics.

The Auditory System provides motion-correlated, three-dimensional, realistic sound sources coordinated with the driving situation. The Auditory System also generates vibrations to simulate vehicle/roadway interactions. The auditory database includes sounds emanating from the subject vehicle during operation, from other traffic, and from contact with three-dimensional objects that the subject vehicle may contact (traffic cones, orange barrels, etc.) This database also contains sounds and vibrations generated by driving on various types of roadways in a variety of weather conditions and from encountering joints, potholes, etc. on the road.

The Vehicle Dynamics System computes vehicle motions in response to driver control inputs, tire/road surface interactions, and the aerodynamic forces acting on the subject vehicle. Vehicle responses are computed for commanding the Motion, Visual, Cab, Control feel, and Auditory Systems. The NADSdyna vehicle dynamics simulation currently used by the NADS is a multi-body, high degree of freedom simulation based on the University of Iowa's Real-Time Recursive Dynamics code. Subsystem models are included to realistically emulate each vehicle's tires, brakes, ABS, steering, powertrain, and aerodynamics. NADSdyna models are available for a 1998 Chevrolet Malibu, a 2003 Ford Expedition, a 1994 Ford Taurus, a 1997 Jeep Cherokee, a 2002 Oldsmobile Intrigue, and a 1992 White-GMC heavy truck-tractor with a 53 foot long, 1992 Fruehauf van trailer. Hardware-in-the-loop modeling has been used to realistically emulate electronic stability control for two vehicles: the 2003 Ford Expedition and the 2002 Oldsmobile Intrigue.

NADSdyna has been extensively validated [3 through 14]. It can accurately predict vehicle motions during normal driving conditions, non-linear maneuvering, and during limit performance maneuvering such as might be encountered during extreme crash avoidance conditions (including spinout and incipient rollover).

PAST AND CURRENT NADS RESEARCH

The National Advanced Driving Simulator (NADS) has been used for a variety of NHTSA research projects. The types of research performed by NHTSA using the NADS have spanned a variety of topics, such as driver distraction, drivers' responses to vehicle component failures, the effects of alcohol impairment on driving performance, and the validity of the NADS. This paper contains summaries of all completed or in progress NADS projects that were directly run by NHTSA. Projects are listed in chronological order according to when the experimental data collection was performed. For the project mentioned here, the first three projects have been completed, the next two have completed data collection and final reports are currently being prepared, while the data are currently being collected for the last two projects.

Investigation of Driver Reactions to Tread Separation Scenarios Study

The first NHTSA study performed on the NADS was an investigation of driver reactions to tread separation scenarios. This study is fully documented in the NHTSA technical report "Investigation of Driver Reactions to Tread Separation Scenarios in the National Advanced Driving Simulator (NADS)," [2]. The following description of this study and its results is excerpted from [2] with minor modifications to improve clarity.

This research was performed to assess drivers' responses to simulated tire failures, specifically tread separations. The objective of this research was to evaluate the effects of the following independent variables on drivers' responses and the likelihood of control loss following simulated tread separation on one of the rear tires of a simulated sport utility vehicle traveling at high speed:

1. Vehicle understeer gradient
2. Prior knowledge of an imminent tire failure
3. Instructions on how to respond to a tire failure
4. Driver age
5. Location of tire that failed (left rear or right rear)

One hundred and eight participants each experienced two tire failures while driving on a straight, divided highway at approximately 75 mph with light surrounding traffic. Drivers were assigned to a single simulated vehicle condition having one of three understeer gradients. They experienced both simulated tire failures in that same vehicle. Vehicles with different understeer gradients are referred to as Vehicles 1-3. Vehicle 1 had an understeer gradient of approximately 4.7 deg/g with four non-failed tires. Vehicles 2 and 3 were modified from Vehicle 1 so that the resulting understeer gradients were 3.4 and 2.4 deg/g, respectively. Following tread separation for the left rear tire, the understeer gradients resulting from a right turn of these vehicles changed to 1.10, 0.09, and –1.17 deg/g, respectively.

The first tire failure presented was unexpected. Drivers were given no information about the possibility of tire failure; rather, they were told that they were evaluating the realism of the simulator. The second tire failure was expected, although drivers were given different amounts of information. Half of the participants were given specific instructions on how to respond following the second tire failure, while half were told only that one or more tire failures would likely occur.

Decreasing vehicle understeer gradient was strongly associated with the likelihood of control loss following both the unexpected and expected tire failures. Overall, the proportion of trials resulting in loss of vehicle control increased from 10 percent (Vehicle 1) to 35 percent (Vehicle 2) to 68 percent (Vehicle 3). Knowledge of the imminent tread separation reduced the overall probability of control loss from 55 percent to 20 percent. Drivers of Vehicle 3 were still much more likely to sustain a loss of vehicle control following the expected tread separation than were drivers of Vehicle 1 (39 percent loss of control versus 3 percent) and twice as likely to sustain loss of vehicle control following the expected tread separation than were drivers of Vehicle 2 (39 percent loss of control versus 19 percent).

Differences associated with vehicle understeer conditions observed in this study were large and consistent, independent of driver expectations, and varied only slightly across driver age groups. Thus it is fair to conclude that in the event of a complete rear-tire detread, the increased difficulty in vehicle handling and the associated increased likelihood of loss of vehicle control with decreasing vehicle understeer gradient generalize to real-world driving. However, it is also important to note that the model used in this study for the tire detreading event is a worst-case scenario (an extremely rapid, complete loss of tread giving the driver only minimal time to react while the detreading is actually occurring prior to the degradation of the tire's frictional capabilities).

This study was performed on the NADS for several reasons. Most importantly, NADS allows testing of the effects of tire tread separations at high speed (75 mph) to be performed without risk of injury to participants. Test track testing involving vehicle subsystem failures and resulting in limit maneuvers is too dangerous to be performed by members of the general public. In addition, tread separations could be performed repeatably in the NADS, something that is very hard to achieve on the test track. Another reason for using NADS was NADSdyna, can accurately predict vehicle motions up to the limits of vehicle performance, including loss of control. Finally, NADSdyna's tire parameters could be configured with minimal effort to permit accurate modeling of the forces and moments generated by a tire that had completely lost its tread.

Low Speed Turn NADS Validation Study

Low speed right-angle turns (of the type encountered at intersections) have traditionally been a problem for lower fidelity driving simulators. Difficulty in providing adequate motion cues to the driver and in low speed tire modeling have made this situation beyond the capabilities of many driving simulators. Due to its large excursion motion base (particularly its ∀330 degrees of yaw rotation) and because the NADSdyna tire model has been specially formulated to be able to provide accurate tire forces and moments at speeds down to 0.0 mph (an even when the vehicle is in reverse), the NADS was expected to be able to simulate low speed right-angle turns with sufficient validity to allow drivers to maintain precise control. However, initial use of the NADS demonstrated that there were still problems in accurately simulating these turns. Therefore, a small study was performed to determine the reasons for the remaining low speed turn problems.

For this study, a simulated urban street network was developed. Ten participants drove a designated route containing a total of six right-angle turns at intersections, three to the right and three to the left. Two of these turns, one to the right and one to the left, were made at intersections with stop signs so that the vehicle came to a complete stop prior to making the turn. For the other four turns, the drivers drove through the turns at whatever speed seemed natural to them. This speed was always very low, never exceeding 15 mph.

Comparison data were obtained by having a subset of the test participants perform right-angle turns at simulated intersections on the Transportation Research Center, Inc.'s Vehicle Dynamics Area (VDA). Participants drove the same vehicle that was simulated on the NADS. This research found that the handwheel steering angle of drivers on the NADS was overshooting the values observed during testing on the VDA. Drivers then had to take corrective steering actions to achieve their desired course. The reason for the handwheel steering angle overshoot was determined to be the lack of visual delay compensation on the NADS. (Due to hardware limitations, the NADS Visual System displays a visual scene that lags the actual visual scene by approximately 100 milliseconds.) A visual delay compensation subsystem was then added to NADS. This visual delay compensation system is documented in [15].

Additional NADS testing was performed following the addition of the visual delay compensation system. Figure 1 shows handwheel steering angle versus distance traveled before and after the addition of visual delay compensation. The reduction in steering overshoot is apparent. Figure 2 is close up of the handwheel steering angle versus distance traveled at one right-angle turn. While the NADS without visual delay compensation had no steering overshoot for this turn, as Figure 2 shows there was a substantial amount of unrealistic steering oscillation. This testing showed that the driver steering, vehicle yaw rate, and vehicle trajectory on NADS during a low-speed, right angle turn was now very realistic.

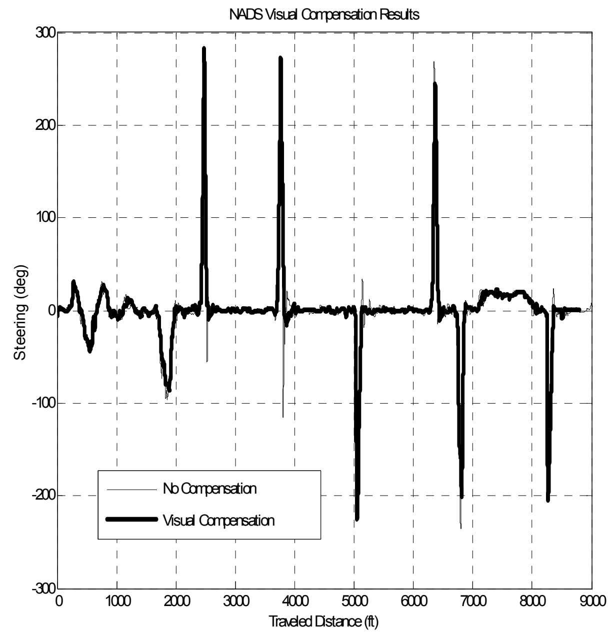

Figure 1. Handwheel steering angle versus distance traveled for a typical low speed turn test.

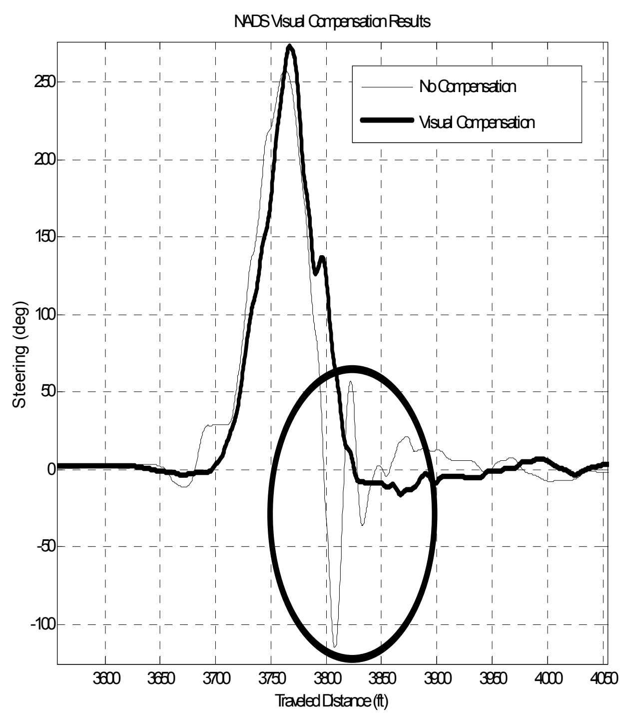

Figure 2. Close up of handwheel steering angle versus distance traveled during one typical right-angle turn.

Examination of the Distraction Effects of Wireless Phone Interfaces Using NADS – Freeway Study

In recent years, studies have shown that use of wireless phones while driving contributes to crashes. Numerous efforts are under way to pass legislation that makes it illegal to use hand-held wireless phones while driving. The assumption behind this move is that any technology that reduces the visual-manual demands of wireless telecommunications must be safer, since the driver can keep both hands on the wheel and both eyes on the road. However, research has not supported this assumption.

This study investigated the effects of wireless phone use on driving performance and behavior. The study had two primary objectives: (1) to assess the distraction potential associated with the use of wireless phones while driving, and (2) to determine whether distraction potential was related to the specific phone interface used. In particular, the experiment addressed the question of whether Hands-Free operation substantively affected the distraction potential associated with wireless phone use while driving. In addition, the experiment investigated whether voice-activated dialing affected distraction potential while driving. The secondary objective was to determine whether the distraction potential associated with phone use varies with driver age.

This study was performed on the NADS for two main reasons. First, NADS allows drivers to be subjected to potentially dangerous driving events (vehicles cutting-in close to the subject vehicle, lead vehicle braking, merging) while talking on the wireless phone. While these events do occur during real world driving, they happen so infrequently that studying them during actual (naturalistic) driving is almost impossible. Second, NADS provides the experimental control to allow a specific driving scenario to be repeatably presented to multiple subjects. This repeatability allows more sophisticated analyses of data to be performed than is the case for public road driving. Further more, liability issues would arise if a researcher directed a participant of an on-road study to perform a task and a crash resulted.

The procedure involved 54 participants driving a freeway route scenario on the NADS with each of three different wireless phone interface types: Hand-Held, Hands-Free with headset, and Hands-Free speaker kit with voice dialing. Phone conversations consisted of performance of a verbal interactive task involving judging whether sentences made sense and later recalling words from each sentence.

Each participant completed a single session lasting 3 hours. The participant drove the same scenario route three times, once for each phone interface. The order of presentation of phone interface conditions was randomized. Each traversal of the route involved one incoming and one outgoing call. The order of presentation of incoming and outgoing calls was balanced.

The route consisted of a four-lane divided freeway with a 65-mph speed limit with traffic present. The route generally consisted of four straight segments of nearly equal length joined by right-side interchanges requiring exiting and merging behavior. The treatment drives were approximately 15 minutes in length and required participants to drive three segments of the divided freeway route. The route segments corresponded, respectively, to the incoming phone call, outgoing phone call, and baseline (no call) periods. Each route segment involved a series of interactions between the driver and the scenario vehicles (i.e., events). Events included a sudden lead-vehicle cut-in (LV cut-in), sudden braking by the lead vehicle (LV brake), a car following event, and a merge. Each traversal of the route was associated with a different order of events. The intention of the scenario design was to overlap the events with the 3.5-minute conversation task periods. Each participant also experienced a brief final event driving involving a more critical lead vehicle-braking event.

Results showed that wireless phone use impaired aspects of driving performance. In particular:

1. Phone use while driving degraded driving performance, particularly during car following. The simulated phone conversation was associated with a significant delay in responding to lead vehicle speed changes. Phone conversation also degraded vehicle control, as reflected by increased steering error and increased one measure of driver workload. Drivers spent less time planning for merge events while engaged in the phone task.
2. Overall, there were modest differences among interface conditions during the conversation task. The hand-held phone interfered with steering and lane position more than the hands-free interfaces.
4. Neither older nor younger drivers exhibited consistently worse performance due to simulated phone conversation.
5. Analysis of the final event scenario revealed significant differences for some dependent measures. Hypothesized effects related to phone interface were complicated by significant interactions between phone interface and age. For first response to the final brake event, participants in the hand-held condition responded significantly faster than those in the hands-free and no-phone conditions, contrary to hypothesis. These results appear to agree with results of the previously mentioned on-road study [16] that

showed that drivers looked forward more with hand-held than with hands-free.

Results also showed that the wireless phone task performance differed as a function of phone interface. More specifically:

1. Although participants rated the Hand-Held interface to be most difficult to use, this interface was associated with the fewest dialing errors (in terms of the number of attempts per dialing trial).
2. Participants' feelings that the Hand-Held interface was the most difficult to use were also not supported by dialing time results, which showed that the Hand-Held interface was associated with significantly faster dialing times than the other two interfaces for all three age groups. Shorter dialing times for the Hand-Held interface may be attributable to participants' prior experience with Hand-Held wireless phones, which was approximately 6 years on average. However, it should be noted that the length of time required to perform voice digit dialing depends on the interface being used. Voice digit dialing was chosen for implementation in this study since it provided the most direct comparison between manual and voice dialing.
3. Conversation task performance did not differ as a function of phone interface.
4. Age was the only examined variable significantly related to phone task performance, with younger individuals performing better than older individuals.

This study is fully documented in two NHTSA technical reports, "Examination of the Distraction Effects of Wireless Phone Interfaces Using the National Advanced Driving Simulator – Preliminary Report on Freeway Pilot Study," [17] and "Examination of the Distraction Effects of Wireless Phone Interfaces Using the National Advanced Driving Simulator - Final Report on a Freeway Study," [18] and one Human Factors and Ergonomics Society Paper, "Hand-Held or Hands-Free? The Effects of Wireless Phone Interface Type on Phone Task Performance and Driver Preference" [19]. Most of the preceding description of this study and its results was excerpted from [18] with minor modifications to provide additional information and improve clarity.

Examination of the Distraction Effects of Wireless Phone Interfaces Using NADS – Arterial Study

NHTSA also conducted research to investigate the effects of wireless phone use on driving performance and behavior in an urban arterial driving environment. The urban arterial environment required a more active style of driving and employed a more dynamic visual scene.

The main objective of the research was to collect information useful in the assessment of 1) the distraction potential of wireless phone use while driving, and 2) the difference in distraction caused by the use of a hands-free wireless phone interface versus that associated with use of a hand-held interface. Of particular interest was whether using hand-held wireless phone interfaces (e.g., dialing, answering, conversation) while driving degrades driving performance more than does hands-free wireless phones. In addition, the research addressed the question of whether younger and/or older drivers exhibit worse driving performance during wireless phone task components than middle-aged drivers. Lastly, the research examined whether drivers glance away from the forward roadway more when using a hands-free wireless phone interface than they did when using a wireless phone in a hand-held configuration.

Fifty-four participants drove an urban arterial driving scenario on the NADS with each of three different wireless phone interface types. Like the freeway study, phone conversations consisted of performance of a verbal interactive task involving judging whether sentences made sense and later recalling words from each sentence.

Each participant completed a single session, in which the same basic route was driven three times, once with each phone interface. The order of presentation of phone interface conditions was varied systematically. Each traversal of the route involved one incoming call, one outgoing call, and a baseline period, as well as a unique order of scenario events. The order of presentation of incoming and outgoing calls was balanced.

The route consisted of four-lane undivided arterial roadway with a 45-mph speed limit and other traffic. The route required approximately 15 minutes to drive and consisted of three segments of equal length. Each segment corresponded to an incoming call, outgoing call, or baseline driving period.

Each segment contained a "between towns" section and an "in town" section. Between-town sections were characterized by mild, alternating curves. A visual target detection task was presented during between town sections in which participants had to press the vehicle's horn button when they spotted a pedestrian wearing a shirt with an "I" on it amongst a number of other similarly dressed pedestrians. In-town sections consisted of straight portion of roadway lined with buildings and vehicles. During in town sections, events were presented including incursions, occasional static vehicles blocking the participant's travel lane, and changing traffic signals that required drivers to respond to avoid a collision or running a red light.

Dependent measures used to characterize driving performance included reaction time in response to discrete events (i.e., conflict events and traffic lights), as well as reaction time and accuracy of responses for the visual target task. Phone task performance measures included dialing time, number for dialing errors, answering time, and the number of correct judgments and recalled terms for the conversation task. Participants also completed a post-drive questionnaire used to report perceived difficulty of driving and phone tasks, as well as preferences regarding phone interfaces and related features.

Data analysis is currently underway for this study. Analyses are focused on assessing the impact of phone use on individual measures of driving performance. Analyses will highlight the degree to which phone use affects a driver's ability to respond to conflict events and objects in their visual environment. The anticipated time frame for release of a final report on this study is mid-2005.

The Urban Arterial Wireless Phone Interface Study was performed on the NADS for the same two main reasons as was the Freeway Wireless Phone Interface Study: ability to subject drivers to potentially dangerous driving events while talking on the wireless phone, to be able to tell the participant when to use the phone without risk of liability issues, and to have repeatable driving conditions.

Older Driver NADS Validation Study

Older drivers are a group of special interest and concern for NHTSA. Due to the aging of America, there is expected to be a substantial increase in the number of older drivers. According to the United States Census Bureau, by the year 2020 "about 50 million Americans will be aged 65 or older – roughly one-fifth of the driving-age population." [20]

In preparation for the initiation of an older driver research program on the NADS, NHTSA is conducting a preliminary investigation comparing older driver behavior and performance on the NADS with that on similar public roads. For the planned, upcoming, NHTSA older driver research, it is essential that older driver behavior and performance in the NADS be comparable to that which is observable in real vehicles on real roads.

Validation studies comparing driver behavior and performance in the NADS to that while driving on public roads have, to date, only been conducted for a very limited number of driving situations. The assumption made by researchers is that because the NADS simulates the vehicle and its visual and kinesthetic environment with high fidelity, driving performance and behavior on the NADS must be similar to that of drivers on similar public roads.

Because older drivers generally tend to be less familiar with and less receptive to technology, researchers are concerned that their behavior and performance in the NADS may not be comparable with that seen on public roads.

The specific objectives for this program are:

1. To demonstrate that driving performance and behavior on the NADS is, in general, comparable to driving performance and behavior on public roads for all ages of drivers.
2. To determine whether there are any older driver specific problems in driving on the NADS.

The fundamental paradigm for this research was for test participants to drive an instrumented vehicle over a designated course on public roads and through a test track course (the "Actual Road" drive). Either immediately before or just after the Actual Road drive, participants drove the NADS through a simulated version of the same course (the "NADS" drive). Data collected during the Actual Road and the NADS drives were then compared. The following independent variables were examined:

1. Participant age. Three age groups were used 35–55, 60–70, and 75+. Gender was balanced for each age group.
2. Test vehicle (NADS or instrumented vehicle). To permit within-subjects testing, NHTSA's Vehicle Research and Test Center sent a suitably instrumented Chevrolet Malibu to Iowa where participants drove it on public roads and through a test track course.
3. Driving situation. Driving situations included freeway driving, straight and curved two-lane road driving with a speed limit of 25 and 55 mph, right-angle turns with and without stop signs, approaching/leaving a traffic light, driving through a simulated construction zone, and driving through a handling course delineated by traffic cones.
4. Run repetition. To check consistency of driver behavior and performance, a limited number of test participants drove the course, both on the NADS and on public roads/test track, once per day for five days (not necessarily consecutive).

The test matrix for the main test was a double test matrix. The first matrix involved twelve participants in each of the three age categories performing all driving situations in both the simulator and on the public road/test track. The second matrix involved a subset (four) of the same twelve performing the same driving situations another four times for both the simulator and public road/test track

Data analysis and report writing for this study is currently in progress. The anticipated time frame for release of a final report on this study is mid-2005.

Impairment Due to Various BAC Levels Study

NHTSA estimates that in 2000, alcohol was involved in 40 percent of fatal crashes as well as in eight percent of all crashes and that about three of every 10 Americans will be involved in an alcohol-related crash at some time during their lives. Much of the information available about the impact of alcohol on safety is from collision statistics where someone has been injured or killed. This data frequently does not tell investigators what led to the crash. Thus, to investigate the degree of impairment associated with particular blood alcohol concentrations (BAC) NHTSA is conducting a research program using the NADS. This work will examine the effects of alcohol in situations that are over-represented for alcohol-related crashes. This data can be used to develop countermeasures to reduce the frequency and severity of alcohol related crashes. The key advantage of using the NADS for this research is its high fidelity and the ability to examine the effects of alcohol on driving performance in a safe setting.

Efforts to date for this project have focused on sensitivity testing. Sensitivity testing examines whether or not a given driving scenario is sensitive to the effects of alcohol. This information is vital for the development of efficient driving scenarios that will be used for majority of the testing.

Following sensitivity testing, testing will be conducted to examine impairment associated with various levels of BAC, ranging from 0.02 to 0.08 in 0.02 increments. The 'no alcohol use' case (BAC of 0.00) will also be tested. Other independent variables will include driver age (younger, middle, older) and different drinking practices (heavy drinker, light drinker). Dependent variables will include a full set of vehicle control variables along with driver reaction times to various events.

In future testing, drivers will experience variations in environmental conditions and roadway situations such as denser traffic and roadway types and will be given realistic in-vehicle tasks such as talking on a cell phone, eating, drinking, or changing a CD while driving at various BAC levels. Since NHTSA estimates the rate of alcohol involvement in fatal crashes is more than three times as high at night as during the day, testing will examine how time of day influences the degree to which the BAC level degrades driving performance.

Electronic Stability Control Effectiveness Study

In late 2004, NHTSA began a research program to investigate the potential benefits of Electronic Stability Control (ESC) systems from the perspective of how drivers utilize such as system. This research seeks to assess how drivers use ESC and how ESC affects drivers' ability to avoid crashes. In addition, this research will allow the examination of drivers' reactions to ESC activation on the NADS.

Electronic stability control (ESC) is an electronic, active-safety system designed to help the driver maintain vehicle control under adverse conditions. ESC uses sensors to detect when the motion of the vehicle differs from what the drivers inputs suggest is desired and applies the brakes at individual wheels to correct the vehicle's motion. Recent crash data studies from Germany and Japan have shown significant crash reductions with ESC systems. NHTSA has an interest in assessing this technology to determine whether these benefits might also be attainable in the U.S. NHTSA is currently conducting a comprehensive program of ESC hardware and performance testing. Using instrumented vehicles, maneuvers that may be sensitive to ESC intervention are being run with and without ESC on a test track to identify differences in stability as a function of ESC presence or absence. While ESC may show benefits in hardware testing, NHTSA is interested in examining the extent to which average drivers can take advantage of ESC. Since the largest benefit of ESC is achievable on low coefficient of friction surfaces and curves, placing average drivers in this type of roadway environment is of great interest.

NHTSA is currently developing plans to use NADS to examine how ESC affects average drivers' ability to avoid crashes. This research will assist NHTSA in understanding for which situations (i.e., event type and pavement conditions), drivers (age), and vehicle types ESC is most helpful. Use of NADS will allow drivers to be put into crash-imminent situations with no danger of injury. Research results are hoped to provide insight as to what characteristics of operation equate to a "good ESC system." Lastly, this research will allow the examination of drivers' reactions to ESC activation on the NADS. Experimentation for this research will occur in mid-2005. Data analysis and report writing for this study is currently in progress. The anticipated time frame for release of a final report on this study is early 2006.

SUMMARY

Since it became operational in January 2002, NHTSA researchers have used the NADS to study a diverse collection of research topics. Topics studied include driver distraction, drivers' interactions with vehicle subsystems and their responses to subsystem failures, the effects of alcohol-related impairment on driving performance, and the validity of the NADS.

The NADS provides the computational capabilities and fidelity necessary to create complex driving situations with varying task demands with high repeatability. The use of the NADS also allows the inclusion of conflict situations that cannot safely be created in on-road experiments. NHTSA research utilizes these unique capabilities of NADS to address questions that cannot be addressed with on-road or test-track experimentation.

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THE EFFECT OF PHYSICAL WORKLOADS ON DRIVING PERFORMANCE

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ABSTRACT

Besides primary driving task, we used to have additional actions, for example, operating some buttons and looking for something. Such secondary actions have been the major cause of accidents. Using a driving simulator the effect of the physical workloads on driving performance was examined for two traffic situations. From the experimental results, the driving performance was influenced by the body movements caused by the physical workloads and the effects were verified by computational driving model in the case of the emergency avoidance.

INTRODUCTION

A wide range of driver support system has been proposed and a number of operations for these devices are increased[1][2][3]. Besides primary driving task, we used to have various actions, for example, we operate some buttons and look for something. These actions are necessary for drivers to drive comfortably in everyday life. However maneuverability will become narrow by these body movements. There are several researches that quantified the manipulability of the steering influenced by traffic situation and the sitting posture[4][5]. In this research, we refer to such secondary body movements as physical workloads. We investigate effect of the physical workloads on driving performance.

The physical workloads are classified by a distance from normal driving position to the target and the operational strategy for reaching. The targets are hazard switch, something on the passenger’s seat and dash board as examples. The strategies can be classified into three categories as follows: i) stretching one's hand to the target after looking at the target, ii) glancing at the target without changing hand’s position, iii) stretching one's hand to the target without looking at the target. There are nine physical workloads as combination of three targets and three strategies in this paper.

First of all, driver model with the physical workload is derived in order to investigate the effect of the physical workload on driving performance. Secondly, in experimental I, we measure a lane keeping ability while curved road running with the physical workloads using driving simulator. In order to quantify the physical workload causing the car deviation from the center line, body movements are measured by a motion capture system to evaluate the grade of the physical workloads. Moreover eye movements of drivers are also measured. In experimental II, we evaluate the avoidance ability using steering with the physical workloads in the emergency situation. Finally, we try to explain the results of experiment II by the proposed driver model.

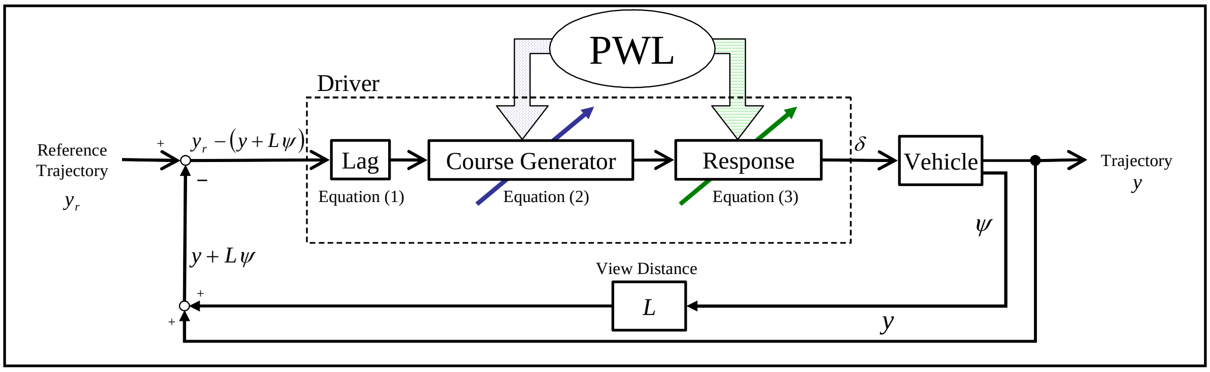


Figure 1. Driver Model with Physical Workloads.

DRIVER MODEL CONSIDERING PHYSYCAL WORKLOADS

The driver model consists of a course generator, response, and a dead time (see Figure 1). The course generator is first order lead element to foresee and estimate the car position. The response is first order lag element to drive the car considering body position. They are defined as following equations.

$$G_{Lag} = e^{-\tau s}, \tag{1}$$

$$G_{eye} = 1 + T_{eye} s, \tag{2}$$

$$G_{body} = \frac{k_{body}}{1 + T_{body} s}, \tag{3}$$

$$\frac{\delta}{y_r - (y + L\psi)} = k_{body} \frac{1 + T_{eye} s}{1 + T_{body} s} e^{-\tau s}, \tag{4}$$

where τ is a dead time. The variables T_{eye} and T_{body} denote time constant for the course generator and the response, respectively. The variables k_{eye} and k_{body} means a gain for the response. As the whole, we adopt a driver-vehicle model that keeps a distance between the target lateral position and estimated lateral position to the minimum (see Figure 1 and 2). The equation (4) denotes the driver-vehicle model. The physical workloads that are looking aside and body movement cause lack of visual information and decrease in manipulability of the steering wheel, respectively. Thus we suppose that these workloads change the parameters of lead and lag elements, respectively.

In the physical workloads, there are various tasks that driver stretches one's arm to the targets. The manipulability becomes narrow by reaching ones arm. The targets of the physical workloads are classified by distance from the normal driving position to the target (see Figure 3) ;

a) Hazard Switch
b) A Something on the Passenger's Seat
c) Dash Board

On the other hand, there are three strategies on the physical workloads while driving;

i) Eyes and Body : Stretching one's hand to the target with looking at the target.
ii) Eyes Only : Glancing at the target without stretching one's hand to the target.
iii) Body Only : Stretching one's hand to the target without looking.

In the experimental I, there are nine physical workloads tasks as combination of three targets and three strategies.

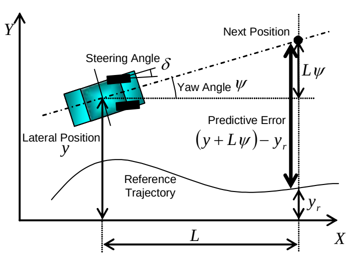


Figure 2. Predictive Control.

a) Hazard Switch

b) Passenger's Seat

c) Dash Board

Figure 3. Targets of Physical Workloads.

EXPERIMENT OF LANE KEEPING

Experimental Procedure

We measure a lane keeping ability while curved road running with the physical workloads using a driving simulator (see Figure 4). The experimental course in the simulator is a curve with the radius of 300 [m], because the car deviation of lateral position is longer in the curve than in the straight. Subjects drive along the counterclockwise curve at 60 [km/h]. In order to quantify the physical workload causing the car deviation from the center line, body movements are measured by a motion capture

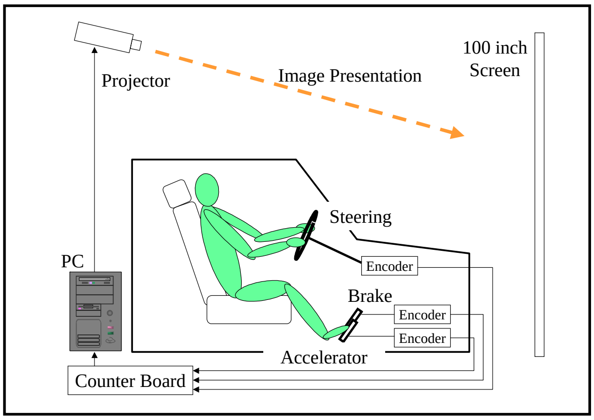


Figure 4. Experimental Setup.

system. Measured seven points are chin, both shoulders, elbows, and wrists. Eye movements of drivers are also measured.

The physical workloads in the experiments are nine kinds of tasks as shown above. In more detail, the strategy i) Eyes and Body is a repetition of stretching one's hand to the target after looking at the target at one's discretion. The strategy ii) Eyes Only is a repetition of looking at the target at one's discretion. The strategy iii) is a repetition of stretching one's hand to the target looking forward.

The seven points of the body, eye movements, and the deviation of car lateral position are measured for 30 minutes. Five subjects of 20 to 23 years old are employed. Every task is measured twice. The subjects have enough practice to measure the driving performance.

As the estimation, three indices are defined as below. The car deviation index *D*, the eye movement index *E*, and the body movement index *B* are defined as following equations;

$$D = \sqrt{\frac{\sum_{i=1}^{n}\left(d_i - d^*\right)^2}{n}}, \tag{5}$$

$$E = \sqrt{\left(\frac{\sum_{i=1}^{n}\left(\theta_{x_i} - \theta_x^*\right)}{n}\right)^2 + \left(\frac{\sum_{i=1}^{n}\left(\theta_{y_i} - \theta_y^*\right)}{n}\right)^2}, \tag{6}$$

$$B = \sqrt{\left(\frac{\sum_{i=1}^{n}\left(x_i^B - x_*^B\right)}{n}\right)^2 + \left(\frac{\sum_{i=1}^{n}\left(y_i^B - y_*^B\right)}{n}\right)^2 + \left(\frac{\sum_{i=1}^{n}\left(z_i^B - z_*^B\right)}{n}\right)^2}, \tag{7}$$

where n is sampling number measured at 30 [Hz]. The variables d_i, θ_{xi}, θ_{yi}, $x^B{}_i$, $y^B{}_i$, and $z^B{}_i$ denote deviation of car lateral position, horizontal and vertical eye directional angles, and positions of measured points by the motion capture in Cartesian coordinates at the *i*-th sampling, respectively. Every asterisked variable means standard value at the normal driving posture.

Experimental Results

Figure 5 (a) shows the correlation between the car deviation index *D* and the eye movement index *E*. There are less correlation between *B* and *D* for strategy i) and ii). This means that the eye movements do not influence on the car deviation so much.

Figure 5 (b) and (c) show the correlation between the car deviation index *D* and the body movement index *B* for the right and left wrist, respectively. There are high correlation between *D* and *E* for the strategy iii) Body Only. The correlation ratio between B and D of the left wrist is higher than that of the right wrist for the strategy iii). This means

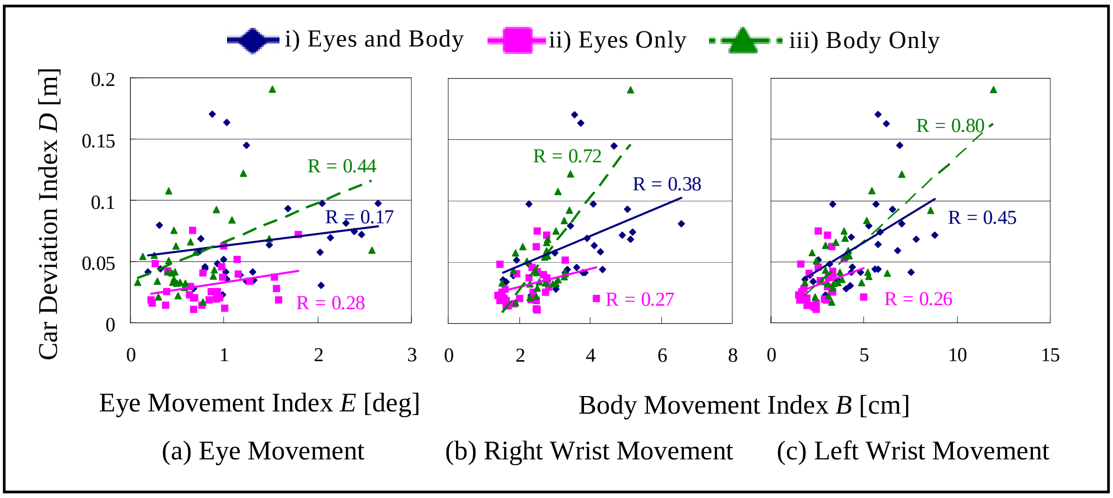


Figure 5. Relationship between Car Deviation and Eye Movement, Body Movement.

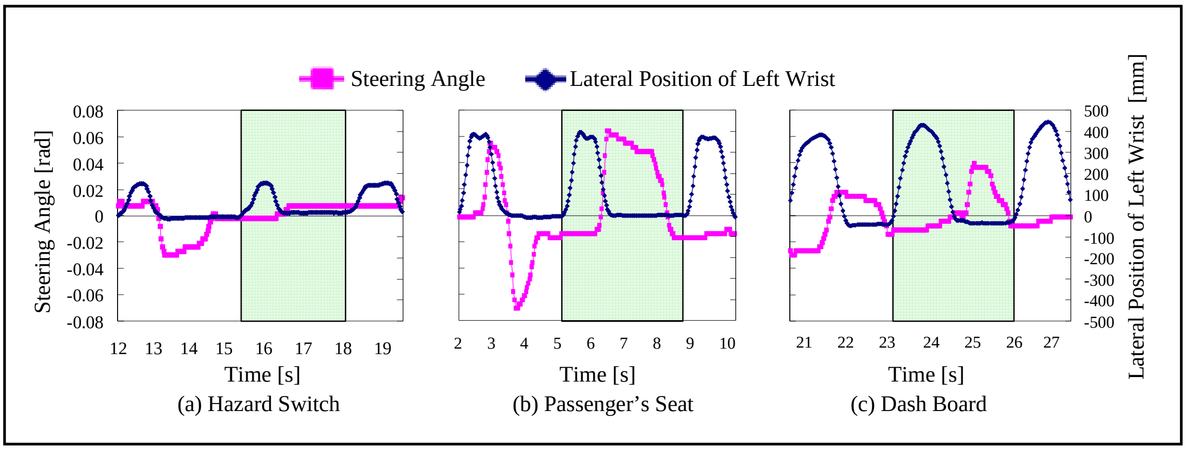


Figure 6. Time History of Left Wrist Position and Steering Angle.

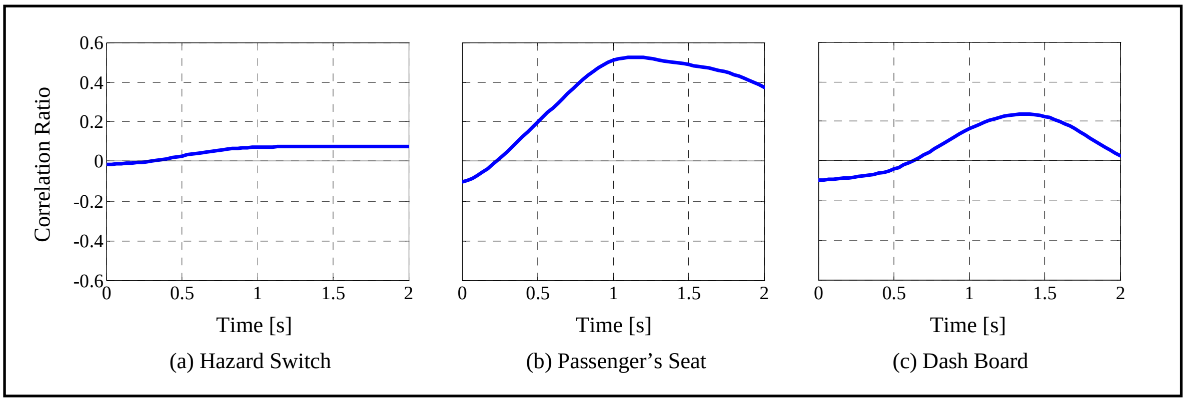


Figure 7. Cross Correlation between Left Wrist Position and Steering Angle.

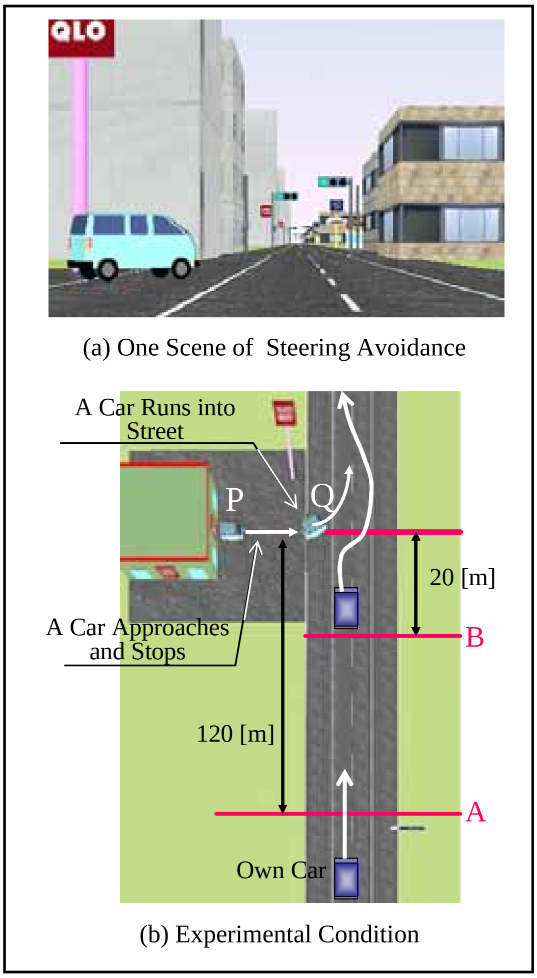
that the left wrist movement according to the physical workloads influences the car lateral deviation. There are not high correlations between *D* and *B* for other body movement indices of the point.

Moreover in order to clarify the relationship between the body movements and the steering wheel angle, we investigate the cross correlation among them. Figure 6 shows the time history of the steering angle and the left wrist position for each strategy, respectively. Figure 7 shows the cross correlation of the steering wheel against the left wrist position for net area in Figure 6, respectively. In the every figure in Figure 6, the positive value represents right direction for the steering angle and the distance from the steering wheel to the left wrist, respectively. In Figure 6 (a), there is no correlation between them for the target a) Hazard Switch. In the situation of the target b) Passenger's Seat, there is a tendency that the subject steers for modification when start to returning one's left hand to the steering wheel. The timing of the adjusting steering is later in the task of the target c) than in the task of the target b). Accordingly, it is understood that the manipulability has changed by the distance from the left hand to the steering wheel position.

EXPERIMENT OF STEERING AVOIDANCE

Experimental Procedure

In this section, we evaluate the avoidance ability using steering with the physical workloads. The situation is supposed the urgent case of sudden car emergency from left side of the straight street (see Figure 8 (a)). The long straight street includes six crosses. There is a car that may run into the street at the center of the short straight street among the crosses. One car among five cars runs into the road. As shown in Figure 8 (b), when own car runs through the line A, a car approaches from Point P and stop beside the street (Point Q). A car runs into the street suddenly at one of the every five P-Q line at random when own car runs through line B. The distance from line B and line P-Q is 20 [m]. Own car runs at constant 60 [km/h]. Driver can avoid only by the steering toward to coming lane. The targets of physical workloads are same as previous experiments. The physical workload strategy is supposed as one condition of iii) Body Only. Six subjects of 20 to 23 years old are employed.



(a) One Scene of Steering Avoidance

(b) Experimental Condition

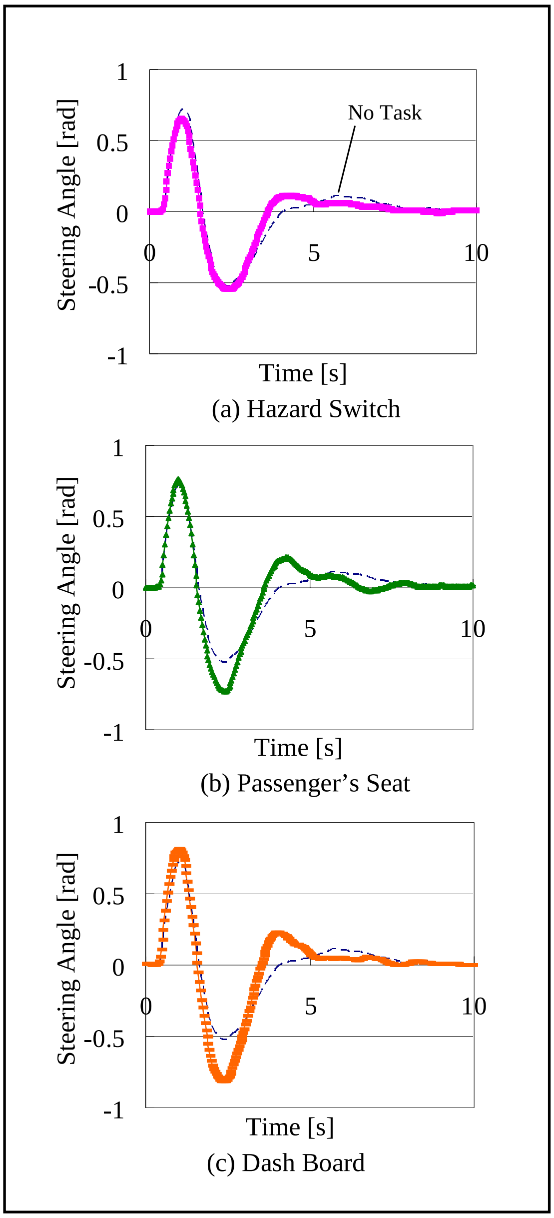
Figure 8. Outline of Steering Avoidance.

Experimental Results

Figure 9 shows the time series of averaging steering angles, after own car runs through line B. As a comparison, the series of No Task is illustrated in the figure. When a car runs into the street, drivers steer to the right for the avoidance. From the figures, there are overshoots of the steering angle after the avoidance compared with the case of No Task. The amount of overshoots becomes larger in order of the strategy i), ii), iii). This means that the maneuverability of the steering wheel becomes narrower according to the grade of the physical workloads.

Verification by the Driver Model

We verified the results of the avoidance experiments by the driver-vehicle model. Supposing the variables τ and T_{eye} in the equation (4) are constant, the variables of time constant and lag elements of every physical workload of targets are determined by the phase of a peak of cross correlation figures. The input trajectory is approximated by a sine curve. Figure 10 shows the simulation's results. According to the distance from the target to the steering wheel, the adjusting amount of steering wheel after the avoidance was increased. These tendencies coincide with the experimental results of the emergency avoidance.



(a) Hazard Switch

(b) Passenger's Seat

(c) Dash Board

Figure 9. Steering Angle in Emergency Avoidance Compared with No Task.

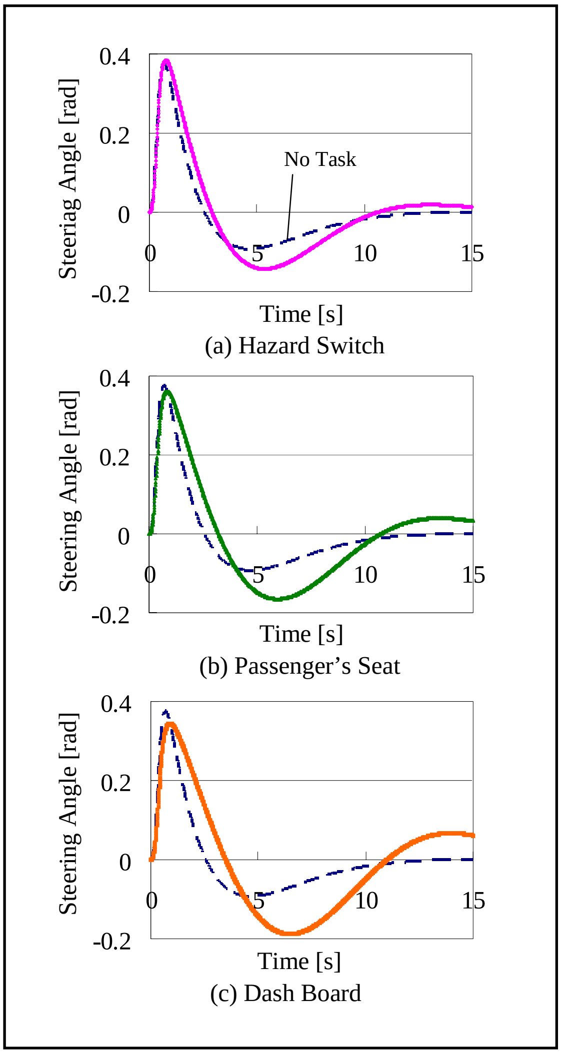


Figure 10. Simulated Steering Angle in Emergency Avoidance Compared with No Task.

CONCLUSIONS

Using a driving simulator the effect of the physical workloads on driving performance was examined for two traffic situations. We constructed the driver-vehicle model with the physical workloads. Second, to investigate the decline of the maneuverability of the steering wheel with the physical workloads, we carried out the experiments of the lane keeping and the emergency avoidance. The conclusions of this paper are as follows:

(1) The driver model was consisted of the course generator and the body response according to the physical workloads. The course generator is first order lead element to foresee and estimate the car position. The characteristic of the body response is modeled by first order lag element considering to the specific target.

(2) As the results of lane keeping experiment, there are high correlations between the car deviation index and the body movement index of the left wrist position. Moreover it is clarified that the adjusting steering had been later than the movement of the left wrist, in order of the target a) Hazard Switch, b) Passenger's Seat, c) Dash Board.

(3) Experimental results of emergency avoidance, it is clarified that there are the overshoots of the steering angle after the avoidance.

(4) We studied the steering angles by the simulation, according to the delay of the steering angles against the left wrist movements as mentioned above (2). As the results, there are the overshoots of the steering angles after the avoidance coincident with the experimental results.

As a future work, we will study the more suitable model parameters based on the experiments with much more subjects and confirm the feasibility of their approach.

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EEVC WG19 ACTIVITIES ON PRIMARY AND SECONDARY SAFETY INTERACTION

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Paper Number 05-0462

ABSTRACT

The European Enhanced Vehicle Committee (EEVC) established a new Working Group (WG19) in December 2001, to carry out a study on primary and secondary safety interaction. During the first phase (until 2004), the study was performed under the following terms of reference: overview of existing and future techniques, effect of these techniques on priorities for injury prevention and effect of these techniques on existing regulations.

The achievements obtained after the first phase of work is summarized hereafter:

The conceptual framework of primary and secondary safety interaction was defined and established within the new concept of integral vehicle safety and taking into account existing safety models. It was also established priorities regarding situations and systems in which the group will center its activities in the future: adaptive occupant protective systems, intelligent break system and pedestrian protection.

WG19 performed an analysis of the European accident databases including the EACS database. The analysis revealed the lack of data related with the instants straight before the impact that fully satisfied the requirements of the WG19.

WG19 developed an inventory, of existing and future possible systems, that are of interest for precrash issues. Moreover, a methodology was set up to evaluate the potential effects of selected systems on reducing injuries.

WG19 identified a number of directives and regulations related with the subject covered by the working group; finding out the needs of suggesting modifications for some of them or establishing new ones.

Finally, WG19 established also priorities for its future activities; the focus will be on adaptive occupant protective systems, intelligent braking systems and pedestrian protection implicated in the pre-crash phase.

The objective of this paper is to show in more details the results of the first phase of work and to inform about the objectives of the WG19 for the next three years period.

INTRODUCTION

While primary safety systems focus on providing assistance to the driver in normal driving and in crash scenarios, secondary safety aims to lessen the consequences of the accident. Today’s conception of vehicle safety has blurred the boundary between primary and secondary safety. The extended use of electronic systems in vehicles is foreseen to enable primary and secondary safety interaction, leading to the Integrated Safety concept.

Future safety systems will permit the evaluation, in real time, of the scenario as defined by the vehicle itself, its passengers and the environment, and eventually identify an “unavoidable accident” phase, presetting all safety systems for optimal actuation in crash.

In this context, different conceptual frameworks for integrated vehicle safety have been established, including different traffic scenario phases. The ACEA safety model proposes five phases: (1) Normal driving, (2) Danger, (3) Crash unavoidable, (4) In crash, and (5) Post crash. Other safety models are also available as the Delphi safety model, Mercedes Benz safety model, Autoliv, and TNO models.

WG19 employs the terms “primary” and “secondary” safety instead of the traditional “active” and “passive”. The main reason is that many actual systems do not fit into the classical definitions, proving to provide both active and passive safety.

The main objective of WG19, at the first stage of its work, was to structure the field of interaction between primary and secondary safety. In this line, three terms of reference for the group were defined: (1) Overview of existing and future techniques, (2) Effect of these techniques on accident injuries, and (3) Analysis of these techniques within the existing regulatory context. This paper provides an overview on the main activities of the EEVC WG19.

DEFINITION

The interaction between primary and secondary safety, in vehicles, is the process whereby using information provided by systems which sense the vehicle environment (outside and/or inside) co-ordinated actions are performed by the vehicle control and protection systems. These actions are performed during the pre-collision and collision phases with the aim of decreasing or eliminating injuries to vehicle occupants, or to vulnerable road users. This concept is restricted to situations where a collision has become unavoidable.

Vehicles are involved in a large variety of collisions. Considering the state-of-the-art technology and real world accident data, Primary Secondary Safety Interaction Systems (PSSIS, detailed definition follows) have more immediate relevance to some of them. Vehicles of types M1 and N1 present the highest relevance regarding frontal and frontal/side collisions against other vehicles, vulnerable road users and other obstacles. Primary and Secondary Safety Interaction includes:

1. ADAS (Advanced Driver Assistance Systems) designed to lessen the severity of the collision by means of reducing the impact velocity, varying the location of impact (e.g. side to front) for the vehicle to which the system is fitted or the relative orientation of the path of the vehicles involved.

2. Structural or geometrical adjustments (e.g. extendable bumpers, automatic elevation of the vehicle to fulfil compatibility requirements, raising the bonnet to protect pedestrians…) and devices, other than restraint system such as knee bolsters, moving steering column, automatically closing sunroof, activating external airbags etc…

3. Optimized actions developed by the restraint systems, such as seatbelt pre-tensioners, seat conditioning and airbag deployment depending on the type of crash and collision severity, occupant characteristics and other factors.

STATE OF THE ART OF THE SYSTEMS POTENTIALLY INVOLVED IN PRIMARY AND SECONDARY SAFETY INTERACTION (PSSI)

Following, a summary overview of the electronic systems with which cars are currently equipped or will be equipped in the future is introduced. EEVC WG19 experts have focused on devices that could be used in phase 2 and/or 3 of the ACEA safety model described before. In general, all these systems are available for passenger cars or could be in the near future, but not necessarily for commercial vehicles at this time. For the selected systems, some information will be presented.

The table below provides a non exhaustive selection of safety systems, representative of the safety principles described below. For each selected system, the following information is given:

- **Column 1:** "Year of implementation" for light vehicles. Usually the date of introduction for heavy vehicles will be later.
- **Following columns:** Actions of the systems directed to incrementing safety.

Feature	Year of introduction	Decrease the speed	Prepare vehicle to the impact	prepare occupants to the impact	optimise the impact angle	Alert the driver
ABS - 4 channel & EBD	2000	X				
Active Camber Variation	2005	X			X	
Active Knee Restraints Deployable Knee Bolster	2002		X			
Active Roll Control	2000		X		X	
Active Roll Mitigation	2001		X		X	
Active Roll Stabilization	2001		X		X	
Active Safety - Pedestrian Avoidance	n/a	X	X			
Active Safety - Pedestrian Warning	n/a					X
Active Steering Wheel	2005		X		X	
Adaptive Airbag Inflator	2003			X		
Adaptive Cruise Control (ACC) with Forward Collision Warning (FCW)	2000	X				X
Adaptive Cruise Control (ACC) with Reduced Stopping Distance (RSD)	2005	X				X
Brake Assist (BA)	2000	X				
Brake Assist with Forward Collision Warning	2003	X				
Collision Avoidance Systems	2006	X			X	
Collision Mitigation by Braking (CMbB)	n/a	X			X	X
Compatibility - Bumper Airbag	2005		X			
Compatibility - Nose Dipping	2004		X			
Cornering Brake Control (CBC)	2000	X			X	
Deployable Bonnet Pedestrian Contact Sensor	2004		X			
Deployable Bonnet Pre-Crash Sensing	2006		X			
Deployable Head Restraints	2001		X	X		
Dynamic Traction Control	2002				X	
Electric Active Steering (EAS) Active Front Steering (AFS)	2003				X	
Electrical Belt Pretensioner	2001		X	X		
Electronic Stability Program (ESP)	2000	X			X	
Electronic Stability Program	2001	X			X	
ESP - Under steer Control Logic (UCL)	2002				X	
Forward Collision Warning (FCW)	2000					X
Forward Collision Warning with Threat Assist HM	2006					X
Intersection Collision Warning	n/a					X
Lane Change Aid (LCA)	2002					X
Pre-Brake Light Signalling	2004	(X)				X
Pre-Crash Body Structure Adaptation	2005		X			
Pre-Crash Braking	2001	X				
Pre-Crash Interior Re-configuration	2002		X	X		
Pre-Crash Restraints Deployment	2003		X	X		
Pre-Crash Sensing (PCS) Closing Velocity (CV) Sensing	2003			X		
Pre-Crash Vehicle Compatibility	2004		X			
Rollover Prevention - Non-active	2000		X			
Rollover Protection - Convertible	2002		X			
Rollover Protection - Convertible	2004		X			

Table 1. Selection of safety systems.

The presented devices are based on one or more principles to increment vehicle safety; the main guidelines are as follows:

1. Decrease of the speed immediately before impact: This decreases the energy involved in the accident: $E=f(V^2)$.
2. Preparation of vehicle for impact. In the majority of the cases, the systems pre-arm the actuators. There exist two kinds of pre-arming: reversible or non-reversible.
3. Preparation of occupants for the impact. This is a consequence of the preparation of the car for the impact.
4. Optimization of the impact angle of the vehicle.
5. Some cases were identified in which a direct link to injury reduction was not found. In these cases, the warnings must immediately direct the driver to evaluate and react to threats with sufficient time to react in order to avoid or mitigate a potential crash. Audible, visible, and possibly haptic cues will be employed.

ACCIDENT DATA ANALYSIS

The database of the European Accident Causation Survey (EACS) was analyzed with regard to potential effects of (Advanced) Driver Assistance Systems ((A)DAS) on traffic safety. In contrast to most other available accident databases, the EACS database was created to allow in-depth analyses of accident causation.

From 1996 to the end of the project in 2001, a total of 1904 accidents with at least one person injured and at least one vehicle less than 3.5 tons involved were documented. 67% of these accident reports were provided by the German consortium members, mainly by DEKRA.

The EACS database is based on an accident form, constituted by specific, vehicle, passenger, driver and auxiliary forms which may include photographic and other documentation. Resulting from this structure, a complete characterization of each accident is available.

Unfortunately, EACS database also presents some particular aspects which require special treatment in statistical analysis, and at the time of evaluating results. Due to the fact that it only considers accidents with injured people and a certain category of vehicle involved, the database is not representative of all accidents. It should be also noticed that most cases have been documented by DEKRA (Germany), thus biasing the representativeness at a European scale. Further, some forms are partially incomplete due to severe injury or death of the drivers or passengers involved. Finally, the different data sources (nine teams coming from six countries) also imply a certain degree of comparability problems.

Effects of DAS on Safety

In a first approximation, the effects of several DAS on driving safety were analysed by direct comparison between the vehicles equipped with (A)DAS and those not. Such a direct approach was not applicable for the majority of (A)DAS, because the proportion of vehicles in the database equipped with them is too small for reliable statistical comparisons.

Out of the direct approach of data analysis arises no evidence that accident severity is correlated with a 'Cruise Control' or with a navigation system. On the other hand, a tendency of vehicles equipped with ABS to be involved in more severe accidents was found, but only if the data were analysed at a European level and if the criteria were measures of injury severity. No such effect was found if only the data from DEKRA were analysed or if the criterion was a technical measure (Delta V). Therefore, it is concluded that this effect is dependent on national differences or on differences in the accident documentation by the different organisations.

For the complete EACS data as well as for the DEKRA data, it was found that vehicles equipped with ABS had a higher engine capacity than non-equipped vehicles, reflecting the fact that in the majority of cases, DAS are installed in high class vehicles at first. The analysis of the accident data showed that the frequency of different types of impact does not differ between the vehicles equipped and those not equipped with ABS. Furthermore, no clear difference between them was found with regard to the driver behaviour aimed at avoiding the crash, although the drivers of ABS vehicles tended to combine braking and steering sequentially prior to the collision more often than drivers of vehicles without ABS.

Accident Causation

In a second step, the EACS data were analysed with respect to accident causation, in order to make predictions about potential benefits from the implementation of special (A)DAS. Firstly, accidents were classified by categories representing accident type.

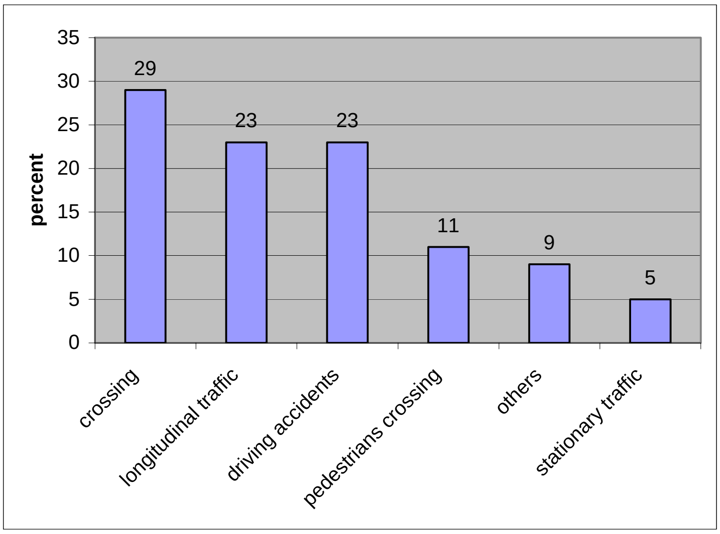

Figure 1. Accidents classified by accident type.

Categories are as follows:

- **Crossing:** Accidents in connection with direction changes and/or at crossings.
- **Longitudinal traffic:** With traffic in the same or the opposite direction.
- **Driving accidents:** Accidents due to driving errors, not caused by conflicts with other vehicles or persons.
- **Pedestrian Crossing.**
- **Stationary traffic:** For example, parked cars.

Following this classification, and based on extensive review of the database, the experts who documented EACS judged which, among 89 possibilities, were the main accident causes. The conclusions can be observed in this graphic:

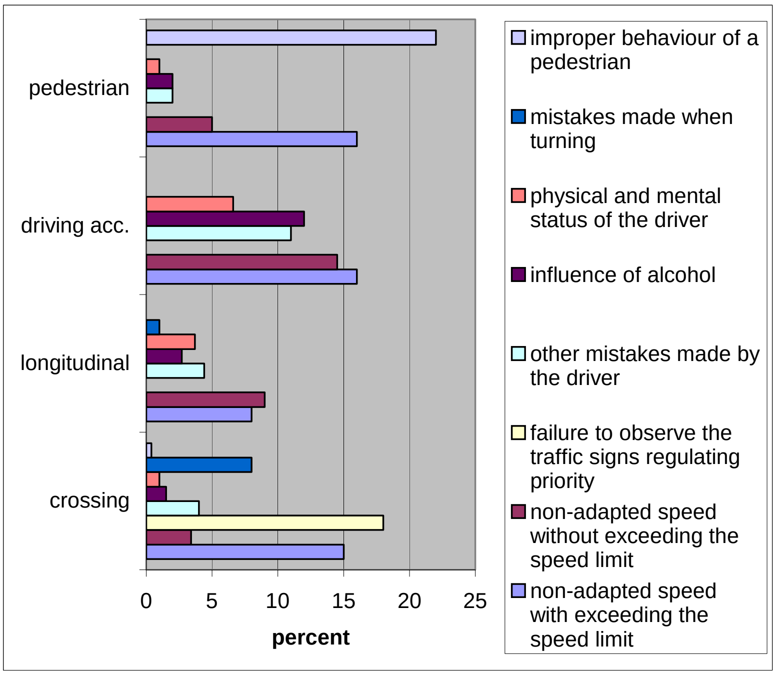

Figure 2. Experts' judgement of main accident causes.

It is shown that the most frequent accident types are accidents at crossings or involving direction changes (29% of all accidents), caused by 'failure to observe traffic signs regulating priority'. A further analysis was carried out, in order to evaluate the influence of environmental conditions on the accidents.

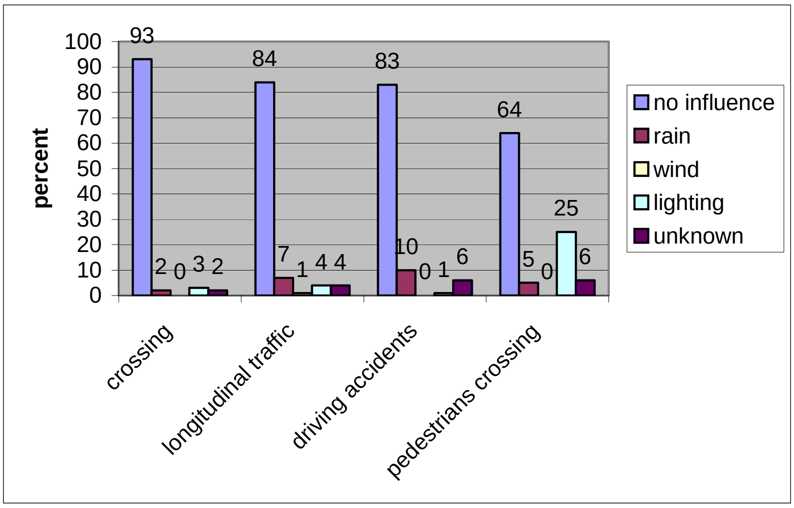

Figure 3. Experts' judgement of the influence of environmental conditions for four accident types.

From these results it can be concluded that at least some drivers would benefit from support, e.g. in detecting traffic signs, in these complex traffic situations. Older drivers could be expected to benefit especially from such a support because this driver group is especially prone to be involved in accidents at crossings. It was recommended that further research should clarify which specific aspects of the complex traffic situation at crossings are actually causing problems to the drivers.

In contrast to older drivers, the younger drivers are involved in an above number of driving accidents (23% of all accidents). This accident group is most frequently related with accidents involving inappropriate speed, either exceeding the legal speed limit or not. Therefore, the risk of driving accidents might be reduced by supporting the driver (especially younger drivers) in choosing the appropriate speed. However, alcohol is identified as the main accident cause in 12% of driving accidents. This phenomenon can be considered to be mainly due to motivational factors, out of the direct scope of action of (A)DAS.

23% of the accidents of the EACS database were classified as accidents with longitudinal traffic. For this type of accident, no prominent cause could be identified, but it is remarkable that in 16% of these accidents the drivers stated that they had not tried to avoid the crash because they were either too surprised or because they did not perceive any danger. Another 10% of the drivers were not able to describe their evasive actions. ADAS warning of approaching hazards, e.g. of accidents on the road, or of a traffic jam, could eventually provide more time to the driver to react appropriately.

Accidents involving pedestrians crossing the road happen more often during darkness than other accident types. Therefore, improving the detection and/or the visibility of pedestrians could help to prevent accidents of this nature. Although this kind of accident is not the most frequent one (11% of all accidents), it is particularly important, because the injuries of pedestrians are much more severe on average than those of vehicle occupants.

POTENTIAL EFFECTS OF SELECTED DAS ON ACCIDENTS

In the following, systems that are of special interest with regard to frontal and pedestrian impacts will be examined. These systems will then be described with respect to their functionality and the operation of different derivatives, and a generic system will be defined. For each of the selected systems, those accident conditions where the system is supposed to have no benefit will be excluded and afterwards, the relevant parameters for a database analysis to estimate the potential safety benefit of the DAS will be defined.

For one selected system, a suitable database and methodology to determine its effectiveness will be chosen. Finally, a study of potential effectiveness will be carried out.

Systems of special interest

For further analysis the following systems were selected:

- Pre-Crash Braking using Forward Collision Warning
- Brake Assist
- Deployable Bonnet with Pre-Crash Sensor
- Pre-Crash Sensing with Electronic Belt Pre-tensioner

Description of selected systems

Because the systems chosen by the experts for further analysis are still in the development phase, there are currently no derivatives to be described and accordingly, no need to define generic systems.

Pre-Crash Braking using Forward Collision Warning

Using data from a Forward Collision Warning, full brake force is applied if an obstacle is detected in front of the vehicle within a 10 meter range and speed is such that a crash is inevitable. A Collision Mitigation System will make an autonomous brake application in case that a collision with another vehicle is unavoidable. The function can also include a panic brake assist program that intervenes if the driver has applied an insufficient level of braking force.

Brake Assist

The brake assist function helps the driver to fully exploit the braking potential of his vehicle. The brake pedal operation is monitored and analyzed in real time in order to detect an emergency braking situation. If the pressure applied by the driver on the pedal is not sufficient for maximum braking force, the system automatically amplifies braking pressure until the pedal is released.

Deployable Bonnet with Pre-Crash Sensor

Microwave pre-crash sensors or other systems can detect pedestrians before the impact and safety devices like the deployable bonnet can be started in advance, thus reducing pedestrian injuries. To improve pedestrian head impact protection, pyrotechnic devices lift the bonnet at the rear edge.

Pre-Crash Sensing with Electronic Belt Pretensioner

If a safety critical situation is anticipated, the belt pretensioners are activated to increase the protection of the vehicle occupants. Electronic belt pretensioners can be reversible, i.e. they can be reset such that they do not need to be replaced after activation.

Relevant accident conditions

The four selected systems are mainly active in the Pre-Crash Phase of the ACEA safety model. Furthermore, all these systems are relevant especially for frontal and/or pedestrian impacts. Nevertheless, there are also some differences among them concerning the context of actuation:

- **Pre-Crash Braking using Forward Collision Warning:** Frontal collisions.

- **Brake Assist:** Mainly effective for frontal collisions. All accidents where the driver did not brake must be excluded. Friction coefficient $\mu > 0,5$.

- **Deployable Bonnet with Pre-Crash Sensor:** Collisions with vulnerable road users (pedestrians and two-wheelers). Impact velocity < 60 km/h (Otherwise, the body will not hit the bonnet but the windscreen.) Frontal collisions.

- **Pre-Crash Sensing with Electronic Belt Pretensioner:** Mainly frontal collisions and roll-over. Seatbelt use is presumed.

Relevant parameters for a database analysis

In order to estimate the potential safety effect of the systems described before, it is necessary to analyse in-depth databases. The more detailed the database, the more precise the estimation. It should be representative to allow for an extrapolation on national statistics. The following parameters should be included:

- Impact type
- Impact velocity
- Type of injury
- Severity of injury
- Collision object
- Driver reaction.

Extremely severe accidents should be excluded from the study as it can be assumed that no system would be of a remarkable benefit in such accidents, and they would therefore introduce biasing in statistical results.

Effectiveness study for one selected system

Taking into account the considerations made above, the method for a study of the potential effectiveness for the brake assist system will be described.

The GIDAS database ('German In-Depth Accident Study') was employed. Although the primary focus of this database is on secondary safety, it contains detailed information about accident causation.

Determination of the Dataset

The first step consisted in determining the relevant dataset for the analysis. For 1991-2003, the GIDAS database contains 1091 accidents with injured pedestrians. These cases are divided according to the AIS classification of injuries (Abbreviated Injury Scale – 1998 Revision): 535 cases with minor injuries (MAIS 1), 498 cases with serious injuries (MAIS 2-4) and 58 cases with very serious injuries (MAIS 5-6). From these accidents, only those where pedestrians were hit by a car with frontal impact were selected (Table 22). In total, the dataset for calculation contained 702 cases.

Table 2.
Number of relevant accidents in the GIDAS database; years 1991-2003; with the following variables known: MAIS, collision speed > 3 km/h, kind of vehicle, weight of vehicle, impact direction

MAIS	1	2-4	5-6	Total
Accidents with injured pedestrians	535	498	58	1077
+ collision with a car	475	448	35	958
+ frontal impact	336	335	31	702

Computation of injury risk functions

On the basis of the selected dataset, the relationship between collision speed and AIS injury severity were analysed and injury risk functions were computed. Such an analysis shows that the probability for a pedestrian to fall into category MAIS 5+ significantly increases at collision speeds higher than 40-50 km/h (Bamberg & Zellmer, 1994).

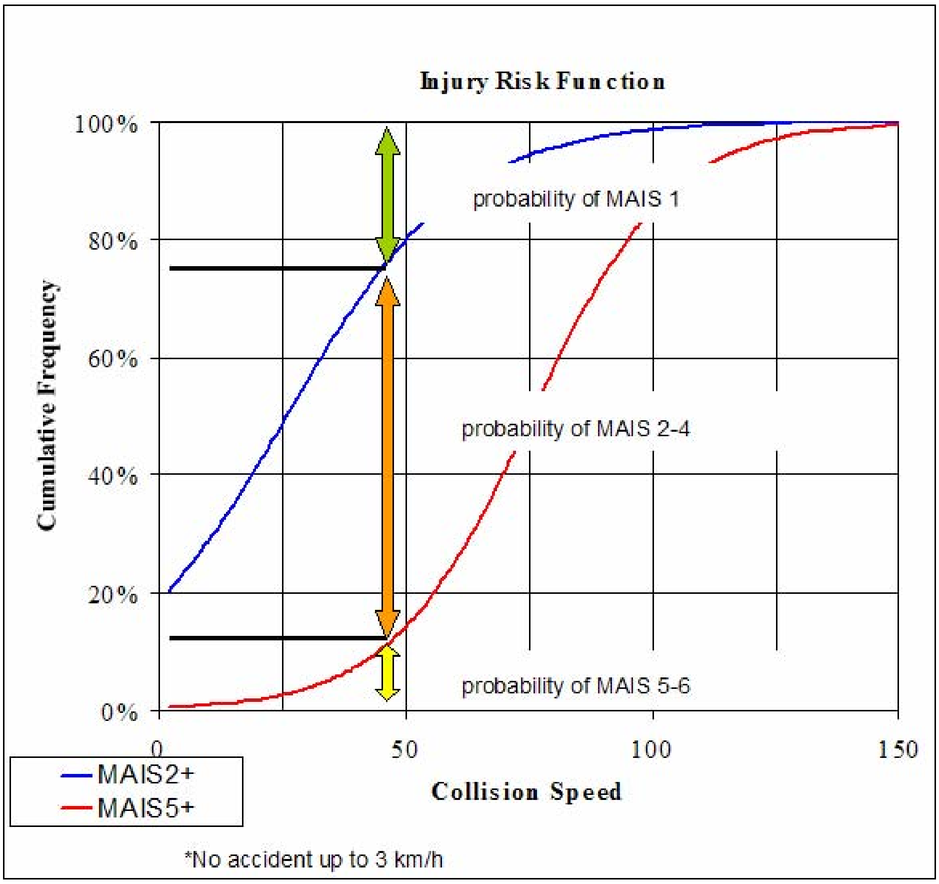

Figure 4. Schematic representation of injury risk functions.

Case-by-case analysis of the safety effects

The computation of the potential safety effect of brake assist is subject to the following assumptions:

1. That a brake assist would have reduced the collision speed in those of the selected accidents where the driver had braked with a deceleration of at least 6 m/s^2.
2. That in these cases, the available adhesion would have provided for a minimum braking deceleration rate of 8.6 m/s^2, i.e. the accidents took place on clean, smooth, dry high friction surfaces.
3. The hypothetical collision speed is deduced taking into account the measured braking distance (distance from the beginning of the braking to the point of collision, taken from the GIDAS data that was based upon wheel slip evidence at the scene).

Whilst brake assist helps to optimise the efficiency of braking in case of an emergency braking, it should be noted that there are no measures in the GIDAS database that allow for a direct judgement whether a brake assist would have been activated in the respective case.

The resulting hypothetical shift in collision speed leads to a reduction of the probability to be severely or fatally injured as shown in the injury risk functions. This computation was made for each single accident and the resulting values of reduction averaged. This procedure yields an estimation of the safety benefit of the brake assist expressed as the average reduction of the probability for a pedestrian to be severely or fatally injured in case of a frontal collision with a car.

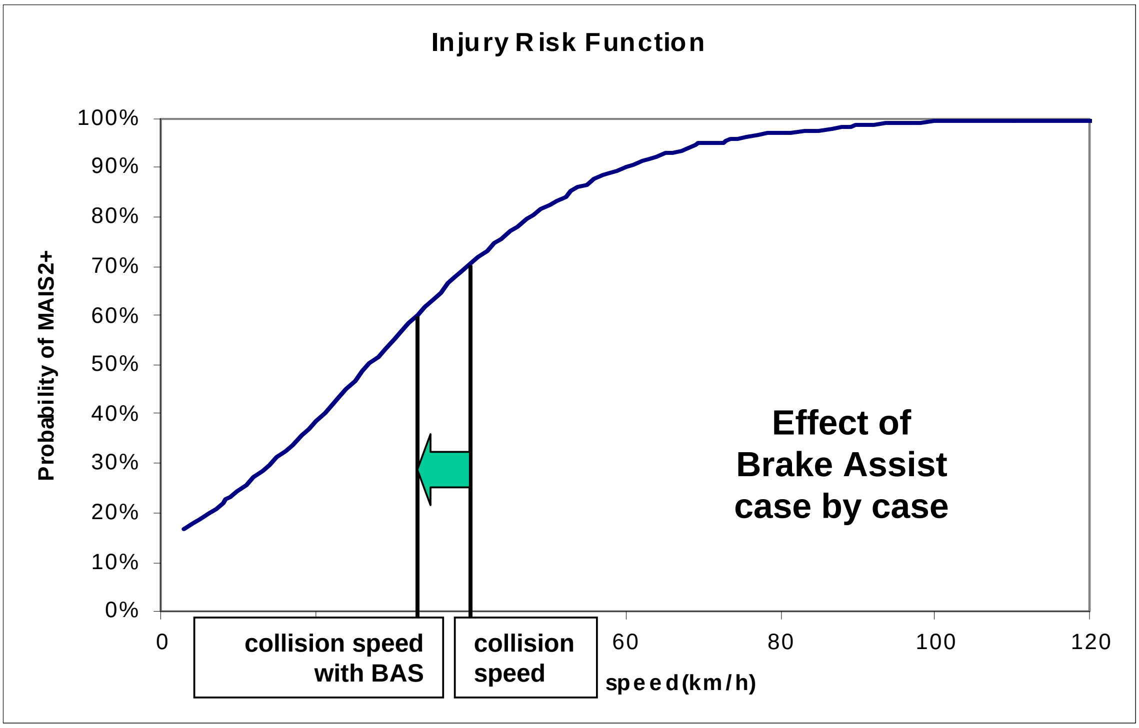

Figure 5. Schematic representation of the effect of the Brake Assist.

Assets and drawbacks of the speed-shift method

The method of a case-by-case analysis of the shift in collision speed to estimate the safety effects of a DAS is very complex and time consuming. Furthermore, specific data are necessary. With regard to the example of the brake assist, collision speed, braking distance, maximum deceleration and injury severity of the pedestrian must be known for each accident. This implies that data from an in-depth accident database are required.

On the other hand, such an analysis as described above has several advantages compared to more generic estimations. Because the safety effect of the brake assist is computed for each relevant accident on the basis of data from accident reconstruction, this allows for a more precise estimation, provided that the accident database is sufficiently representative.

The calculated benefit in this study addresses MAIS 2+ class injuries. The savings are the differences between the predicted numbers of casualties affected by implementation of safety measures and the casualties in the current, real context. The effectiveness of safety measures is referred to all pedestrian accidents.

The results show that BAS has the potential to influence the MAIS class. In the GIDAS dataset, 56 cases (7.9%) out of 702 could completely avoid collision by the implementation of a BAS (BAS collision speed = 0). The injury reducing effect on MAIS 2+ injured pedestrian results in 81 cases (11.5%).

Potential Effects of DAS on Reducing Injuries

In the past, achievements in increasing secondary safety of passenger cars to better protect occupants and vulnerable road users have been remarkable. Whilst further passive safety measures are still possible, it is widely regarded that advanced systems have much to contribute.

Especially with respect to vulnerable road users, physical laws might limit the effect of secondary safety measures. At the same time, the latest developments in electronic and sensor technology promise a successful contribution of primary safety systems. Several of these have already been introduced, and the positive effect in reducing road traffic fatalities have recently been proven – ESP is such an example. The result of this study indicates that also vulnerable road users will have a benefit from such systems.

The previous analysis for a brake assist system (BAS) suggests that primary safety systems could reduce the consequences of pedestrian accidents, as well as offering additional benefit in other accident situations. In this line, it is expected that the importance of primary safety will further increase with technical progress in future.

REGULATION

A number of directives relevant to the work of EEVC WG19 were identified on the basis of the following criteria: *The directive should include injury assessment (protection) and/or parameters operational in the unavoidable crash phase with a potential influence on crash severity*. The parameters were defined as the factors related to vehicle dynamics, to environment and/or to human factors.

A summary on the aspects which can result in non compliance with existing directives or in need of new regulation are listed below:

- Ease the introduction of near field sensors technology (frequency allocation issues were identified by the SARA group).
- Lack of generic guidelines for the evaluation of safety devices triggered before the impact (need of new methodologies for safety evaluation)
- Automatic steering is not defined
- ESP systems were defined as relevant safety systems for WG19 to consider, but are not included in current legislation
- The definition of crash alarm confidence level is not clear while it has a direct impact on safety aspects. This issue has to be tackled by the legislation.

CONCLUSIONS

The boundaries between primary and secondary safety no longer exist. It is observed that further developments for increasing vehicle safety create an overlapping zone. This contributes to a new concept called integrated safety in vehicles.

Despite slight dissimilarities, all actual safety models agree on the existence of an overlapping zone that involves the instants before the impact and extend throughout the collision, in which new safety actions emerge designed to decrease the severity of the collision and offer improved protection to the occupants and other road users.

The interaction between primary and secondary safety in vehicles is the process whereby, using information provided by systems which sense vehicle environment (outside or/and inside), co-ordinated actions are performed by the vehicle control and protection systems. These actions are performed during the pre-collision and collision phases with the aim of decreasing or eliminating injuries to vehicle occupants, or to vulnerable road users. This concept is restricted to the situation of unavoidable collision.

Vehicles are involved in a large variety of collisions. Considering the state-of-the-art technology and real world accident data, Primary Secondary Safety Interaction Systems (PSSIS) have more immediate relevance to some of them.

Several EU countries delivered accident data cases to establish the EACS database aiming to improve the knowledge of accident causation and potential effects of DAS/ADAS on road traffic safety. The analysis showed that there is insufficient (in quantity and/or quality) data to fully satisfy the requirements of the EEVC WG19. The specific problems are:

- Lack of data related to the above-mentioned overlapped zone.
- Not all existing databases are representative for Europe. Some of them are not even representative for a single country.

Several safety systems and mechanisms included within the scope covered by WG19 have been found. Some systems are already available in current production vehicles and others will be introduced in the near future. Nevertheless, in the field of action of our group, these electronic systems work in a very short period of time (less than a second) before a crash. When restricted to the unavoidable accident phase, the driver would not have time to react or understand what is happening. However, where these systems may also operate in the avoidable accident phase (BAS for example) human machine interface issues (HMI) need to also be considered.

EEVC WG19 explored one approach to evaluating the effectiveness of primary safety systems that operate in the unavoidable accident zone. The effect of Brake Assist Systems (BAS) with regard to fatal and serious pedestrian accidents was calculated as an example case study. This methodology could be applied to provisionally assess safety benefits of some other systems. Others might require a different method and/or database.

Generic methodologies for the assessment of Integrated Vehicle Safety Systems operating in the unavoidable accident phase should be developed in order to find out the acceptable confidence levels for false or missing alarms. The possibility of using virtual testing for the evaluation of systems in different weather and other environmental conditions should be investigated.

FUTURE WORK

The results described here have led to WG19 making recommendations to the EEVC for future research guidelines, treating the following topics:

- Adaptive, occupant protection systems
- Intelligent braking systems
- Pedestrian protection
- Frontal collisions
- Vehicle sensorisation:
  - Sensors to detect features outside of the vehicle.
  - Sensors to acquire dynamic variables of the vehicle.
  - Sensors to determine occupant characteristics.

In this context, there exist several methodological aspects to be developed. Firstly, more experience of the application of the assessment techniques for complex electronic systems, as prescribed in UN ECE Regulations, needs to be gained. In particular it is necessary to establish whether these techniques adequately enable analysis of PSSIS according to dependability criteria. Equally, the construction of techniques and methodologies to evaluate the performance and effectiveness of PSSIS are considered necessary for future regulatory development, as well as for industrial (commercial) deployment of PSSIS.

Different knowledge gaps have been identified which need to be investigated in order to establish a sound knowledge corpus which would eventually permit the development of practical criteria and future methodologies.

The future development of PSSIS as well as their real effectiveness on safety depend largely on their acceptance by the user. On the other hand, if these systems are to be required by regulation it will be necessary to carry out an in-depth cost/benefit analysis.

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