# LOGICAL MEDIATION STRUCTURES FOR TOYOTA'S DRIVER SUPPORT SYSTEMS

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## ABSTRACT

The driver support system (DSS) computer is an important part of systems such as adaptive cruise control (ACC), pre-collision system (PCS), and lane-keeping assist (LKA).
The DSS computer receives information from peripheral sensors such as the forward radar, forward camera, and driver-monitoring camera, and transmits requests to controllers such as the engine, brakes, steering computer, and combination meter.
DSS such as those listed above use the peripheral sensors in common and are also activated simultaneously, which makes it necessary to consider coordination among the systems.
For example, if a part becomes inoperable, each system that uses the part reverts to a default condition and the condition of each system is shown on the combination meter.
In such a case, the combination meter must not flash or show other such undesirable conditions.
Therefore the behavior of these systems must be fully taken into consideration and guidelines for mediation constructed in terms of ergonomics.
As a result, three aspects of design for mediation must be reviewed: diagnostic design, control design, and human-machine interface (HMI) design. These are all important for effective coordination among these systems.

## INTRODUCTION

Various advanced systems that further enhance the driving experience have been developed over the years.
Adaptive cruise control (ACC) systems that use laser radar to control the vehicle-vehicle distance for driving speeds over 40 km/h were introduced in 1997 to reduce driver pedal operation workload (these systems are referred to as AC- below). Subsequently, in 2004, an ACC system was released capable of control in lower speed ranges below 30 km/h. This was further developed and released in 2006 as ACC with a full-speed range (AC+) capable of control from higher speed cruising to start/stop driving in congestion.
In Europe, cruise control systems with speed limiters (CSL) have been on the market since 2006 to meet the requirements imposed by speed limit regulations.
The first pre-collision system (PCS) was commercialized in February 2003. This system used forward millimeter wave radar (F-MMW) to help detect vehicles or obstacles in front of the vehicle and controlled the pre-collision seat belt (PSB) and pre-collision brake assist (PBA) system just prior to a collision to reduce damage.
In August 2003, the pre-collision brake (PB) and adaptive variable suspension (AVS) were added to the PCS. AVS switches to sport mode to reduce nosedive caused by emergency braking.
In 2004, an improved PB system was introduced that fuses the detection results of F-MMW and a forward camera (F-CAM) (fusion processing).
In 2005, the pre-collision alert brake (PAB) system that uses a driver-monitoring camera (DMC) was added. This system warns the driver of an imminent collision and regulates brake operation when the driver is judged not to be looking straight ahead.
Moreover, an advanced PCS was introduced in 2006 with additional variable gear ratio suspension (VGRS) and rear PCS. This vehicle has a forward stereo camera that detects pedestrians and the positions of objects in more detail. In rear PCS, the pre-collision hazard lights (PHL) are flashed to warn the driver of a vehicle approaching from behind, and the pre-collision headrests (PHR) are automatically moved forward to reduce the risk of whiplash injury.
In 2008, PAB was further developed by the introduction of a function capable of detecting the driver's eye opening angle that indicates drowsiness.
In 2009, two forward millimeter wave radars (L/R-F-MMW) were added to detect vehicles approaching from the front diagonally. This system quickens the response to the side airbags (PSA).
Figure 1 shows the functions of the PCS described above.
The lane keeping assist (LKA) system was commercialized in 2004 to reduce the driver's steering workload. When it detects the possibility of lane departure, the LKA system warns the driver and controls the electric power steering (EPS) actuators to produce inward steering torque for a short period of time (this is referred to as lane departure alert (LDA)).
When ACC is in operation, the LKA system controls the EPS actuators to assist the driver to keep the vehicle in the center of the lane (lane keeping (LK)).

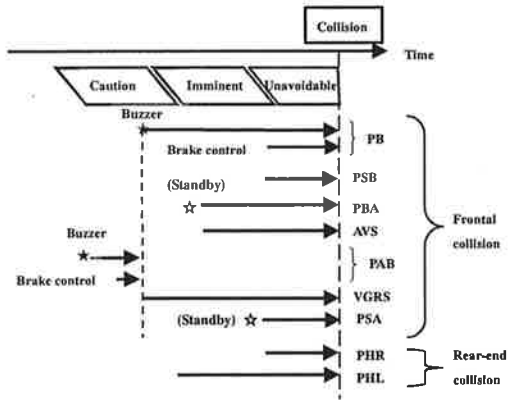



**Figure 1. PCS operation timing.**

As mentioned above, the functions of the ACC, PCS, and LKA systems have developed through the use of radars and cameras.
The main computer used to control these systems is called the driver support system (DSS) computer. This paper describes the configuration of the electronic control unit (ECU) and the logical structures for mediation control of Toyota's DSS.

## 1. DSS Configuration

As shown in Figure 2, the main categories of parts in these systems are sensors, computers, and actuators. ACC can be classified as either AC- or AC+.
AC- uses a forward radar and maintains an appropriate vehicle-to-vehicle headway time at a selected cruising speed over 40 km/h. In contrast, AC+ uses a forward radar and a forward camera to control the vehicle from higher speed cruising to stop/start driving.
There are two types of PCS system: one for frontal collisions and one for rear-end collisions.
The former system uses F-MMW, F-CAM, and DMC. It controls the PSB system, engine, brakes, AVS system, a warning buzzer, VGRS system, and the PAS system in accordance with the possibility of collision.
The latter system uses the rear millimeter wave radar (R-MMW). It controls the PHL system, the PHR system and PAS system.
The LKA system also uses the forward camera. It controls the EPS to assist the driver keep the vehicle in the center of the lane.

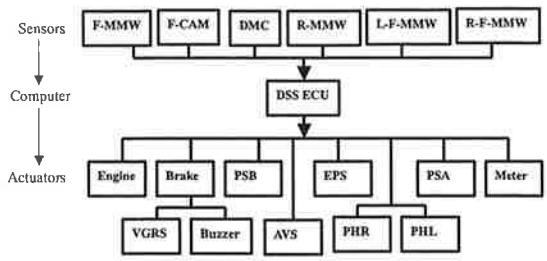



**Figure 2. Information flow of DSS.**

Figure 3 shows the configuration of the parts used for these DSS.

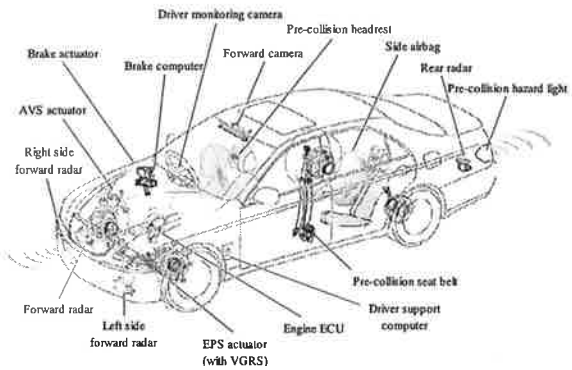



**Figure 3. Configuration of parts.**

## 2. DSS ECU Configuration

As computerized control technology has improved greatly in recent years, the number of computers and the scale of software have also multiplied rapidly. In response, it is necessary to efficiently integrate these computers. The trend also applies to the DSS ECU.
Figure 4 shows the trend for volume. The present volume of the ECU is about 60% of the distance control computer that was introduced for the first time in 1997 for AC-.

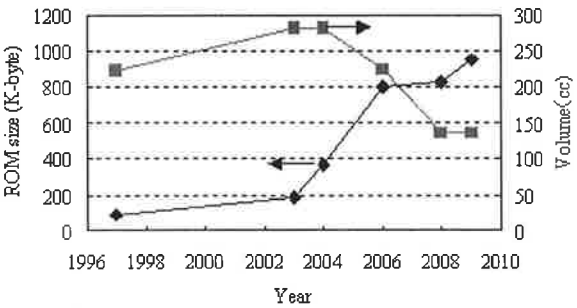
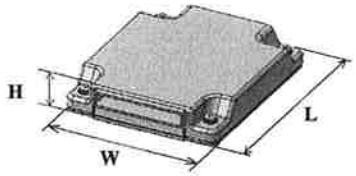



**Figure 4. Trends for ECU volume and ROM.**

Figure 4 also shows the trend for the software scale. The software scale has increased due to the addition of the PCS and LKA systems. The present scale is about eight times larger than the initial ECU.

Therefore, by a simple calculation, the software density has grown by about 13 times (=8/0.6). Figure 5 shows the present DSS ECU.




**L: 100**
**W: 80**
**H: 17**

**Figure 5. DSS ECU.**

As the scale of software increases, a recent trend has been to standardize software to improve quality and reduce development costs.
In Japan, the non-profit organization Japan Automotive Software Platform and Architecture (JASPAR) was set up in 2004. This group cooperates with Europe's standardizing group, Automotive Open System Architecture (AUTOSAR).
Following this trend, the DSS ECU adopted the same standardized software platform as that for brake and engine computers.
Figure 6 shows the software structure of the DSS ECU. Data is transmitted between among the modules by the distribution component (DIS). The order of operation is as follows.
Input transaction (SCOM, IOD) → Pre-transaction (Pre-T) (AFW) → Main transaction (APL, AFW) → Post-transaction (Post-T) (AFW) → Output transaction (SCOM)
Pre-T consists of input Pre-T, diagnostic Pre-T, sensor fusion. Post-T indicates output mediation.
The order of the APL transactions is as follows, in accordance with the priority order of control.
PCS→ACC→LKA
ACC/PCS/LKA and output mediation, which are classified as either control or diagnostics, and the order of each transaction is as follows.
Diagnostic → Control

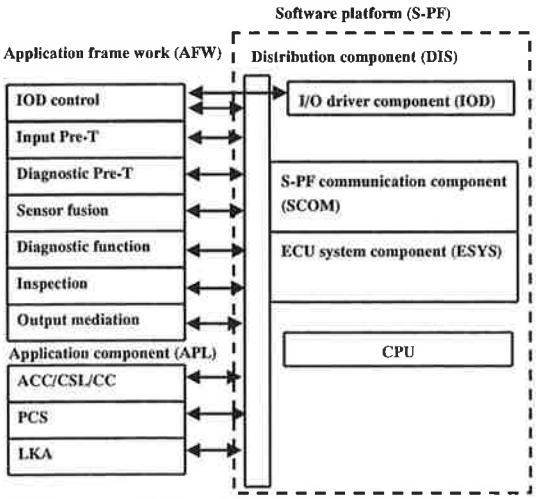



**Figure 6. Software structure of DSS ECU**

**3. Guideline of Coordination**
Figure 7 shows the correlation among DSS.

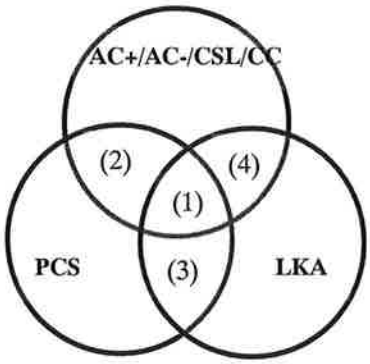



**Figure 7. Coordination among DSS.**

If a part used by these systems in common becomes inoperative, each system that uses the part reverts to a default condition and the condition of each system is shown on the combination meter for the driver.
In this case, it is more appropriate to inform the driver of this information considering the priority order of the systems. On the other hand, when there are no parts used in common, only the system using the inoperative part transits to the above-mentioned condition. For example, as the parts used in the rear PCS and PAB systems are not associated with ACC or LKA, there is little need to consider their coordination.
This guideline also applies to the control of these systems.
When the PB system is activated in a situation where the DSS judges that a collision is unavoidable, ACC and LKA are automatically canceled and the driver is informed of this state via the combination meter.
Therefore, the behavior of these systems has to be fully taken into consideration and guidelines for mediation must be constructed in terms of ergonomics.
The three types of coordination (fail-safe, control, and HMI) among these systems are reviewed as follows.

**(1) Fail-Safe** - The ACC, PCS, and LKA systems share sensors and actuators. If a part becomes inoperative or a system judges that control is inappropriate, the concerned system stops the control and reverts the vehicle to a normal driving state.
The following terms need to be considered in this case.

a) The concerned system has two types of behavior: whether its diagnostic state is displayed on the combination meter or not
b) There are four combinations of coordination among these systems, as shown in Figure 7.
c) Cruise control systems (AC+, AC-, CSL, and CC) are controlled separately and not simultaneously.

Therefore, 32 variations (=2×4×4) must be fully

taken into consideration.

**(2) Control** - Similarly, the priority order of control among these systems must be decided in advance.

This priority order is defined as PCS>ACC>LKA.

Examples of this prioritization are as follows.

When the brake control of PB is activated, ACC and LKA are automatically canceled.

If ACC is canceled due to the forward radar detecting that the grille is obscured by snow, LK is also automatically canceled.

Moreover, system behavior must be decided when systems other than DSS are activated.

For example, when vehicle stability control (VSC) is activated in the event of skidding, ACC and LKA are automatically canceled.

**(3) HMI** - HMI coordination is related to the combination meter, head up display (HUD), and buzzer.

The most important consideration for HMI coordination is the design of the display on the combination meter since a flashing display may annoy the driver.

As the HUD display includes items that are also shown on the meter, this section describes only meter coordination.

HMI coordination design for the combination meter is reviewed as follows.

DSS-related meters generally have a multi-information area. This area conveys messages to the driver in accordance with the priority order. The messages are largely divided into those related to diagnostics and those related to the vehicle's condition.

The former basically has the priority over the latter.

The former types of message pop up in the area the instant that a problem with the system occurs, and are displayed cyclically instead of other messages when the display request continues. Warnings for the PB system have a high priority and are included in this group.

The latter types of message pop up in the area the instant that the vehicle condition changes but are not shown again without manual operation or a further change in condition. Displays related to the outside temperature, fuel-efficiency, and the DSS are included in this group.

The DSS is indicated in the display and the design for each system generally overlaps those of other systems.

The display guidelines are as follows when multiple systems are designed to be displayed in the same area.

1. DSS must be classified into three categories: cruise control systems, the steering support system (LKA), and the collision mitigation system (PCS). Cruise control systems consist of AC+, AC-, CSL and CC systems, which are exclusive of each other.
2. The combinations of these three categories that need to be displayed must be listed.
3. If the systems are designed so that overlap occurs, the priority order must be decided. First, the mediation within the DSS ECU must be considered. Once that is completed, the mediation within the combination meter must also be considered.

   An example of mediation within the DSS ECU is as follows.

   When a vehicle with active ACC is too close to a vehicle ahead, the ACC display will blink to alert the driver.

   On the other hand, if there is an imminent risk of collision, the PCS display will blink.

   Therefore the overlapping alert of ACC and PCS are designed carefully and the priority order is set to ACC alert > PCS alert and the output request of for a PCS alert from the DSS ECU to the meter must be OFF when the ACC alert is ON.

   An example of mediation within the combination meter is as follows.

   When a vehicle with an active CSL system is cruising over the selected speed limit, the CSL alert display will revert to black and white.

   In this case, when a PCS alert is issued, the priority order of the combination meter is set to PCS alert > CSL alert.

   This is because Toyota has two kinds of drive power control systems, and the CSL output computer may be different from the PCS output computer.

   Therefore the combination meter needs to perform mediation in terms of the difficulty of mediation within the DSS ECU and the shared software of the meter.
4. When blinking requests overlap each other, synchronization must be performed within the combination meter.
5. There are two kinds of meter display: monochromatic and color. Therefore, suitable designs for each display must be reviewed as means of notifying the driver.

HMI coordination design for the buzzer is reviewed as follows.

DSS share the buzzer of the brake computer. The computer that requests an ACC alert to the brake computer differs depending on the two kinds of drive power control systems. The VSC and hill assist control (HAC) systems also share this buzzer.

Therefore the brake computer must mediate requests from the ACC, PCS, LKA, VSC, and HAC systems.

## 4. Fail-Safe Design

The ACC, PCS, and LKA systems share the forward radar and camera as sensors and the buzzer as an actuator.

Therefore, the behavior of inoperative sensors or the actuator is divided into four cases, as shown in Tables

1a to d.
When the forward radar is inoperative, system behavior is as follows.
The ACC and PCS systems revert to the default condition and their diagnostic state is displayed because the forward radar is used as a major sensor in these systems (a). In contrast, the diagnostic state of the LKA system is not displayed and only LK is automatically cancelled because LKA uses the forward radar as an auxiliary sensor (c).
When the forward camera is inoperative, system behavior is as follows.
Although AC+ uses the forward camera, AC-, CC, and CSL do not. The diagnostic state of AC+ is displayed and the system is automatically cancelled (a). No display is made for AC-, CC, or CSL and these systems remain activated (d).
The diagnostic state of the PCS system is displayed as it uses the forward camera to provide auxiliary data. However, it remains activated by using the forward radar only (b).
The diagnostic state of the LKA system is displayed, and it reverts to the default condition as it uses the forward camera as a major sensor (a).

**Table 1.**
**Display combinations of diagnostics and control**

| | | Control of system | |
|---|---|---|---|
| | | Cancellation | Continuation |
| Diagnostics display | With | (a) | (b) |
| | Without | (c) | (d) |

Coordination among the DSS has four combinations, as shown in Figure 7.
Of these DSS, the AC+, AC-, CC, and CSL cruise control systems all use different parts.
As an example, AC+ and AC- use the buzzer and yaw rate sensor, but CC and CSL do not. AC+ uses the forward camera, but AC- does not.
Therefore cases (1), (2), and (4) in Figure 7 must be divided between the four kinds of cruise control systems.
Table 2 shows the result of behavior (a) and (c) above as examples.
The priority order for notifying the driver of system cancellation due to behavior (a) only is
ACC>LKA>PCS. (4-1)
As the state of the PCS system is not displayed on the meter during normal driving conditions, the priority of PCS is lower relative to the other systems.
The time used to determine whether these systems are inoperative is set to a common fixed time. When the buzzer used by these systems becomes inoperative as shown in "Fail BUZZ" in Table 2, the output mediation for DSS diagnostics determines the priority order and the DSS ECU sends diagnostic messages in sequence to the meter with a time lag by CAN communication. Therefore, the meter displays each message in turn in the order of priority.

**Table 2.**
**Fail-safe matrix (excerpt)**

| | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| (a) only | AC+<br>AC-<br>CC<br>Ncom B-ECU<br>Ncom Y-SEN<br>Fail BUZZ<br>Ncom F-CAM<br>Fail F-CAM | AC+/AC-<br>CC<br>Ncom E-ECU<br>Fail E-ECU<br>Ncom S-SEN | AC+/AC-<br>Fail Y-SEN | AC+/AC-/CC<br>Fail STP<br>Ncom B-ECU |
| (a)+(c) | AC+<br>AC-<br>Ncom F-MMW<br>Fail F-MMW<br>F-CAM overheat | None | None | AC+/AC-<br>Dirty F-MMW<br>Wiper operation |

Note 1) Forward radar (F-MMW), Forward camera (F-CAM), Brake ECU (B-ECU), Engine ECU (E-ECU) Yaw rate sensor (Y-SEN), Steering sensor (S-SEN), Buzzer circuit (BUZZ), Stop switch (STP)
Note 2) Ncom A means lost communication with A
Note 3) Fail B means B malfunction

Figures 8 and 9 show system behavior when this condition occurs.
Figure 8 (a) shows the displays for ACC under normal cruising. The vehicle-to-vehicle distance can be set in three ways: long, medium, short. A vehicle ahead of you will be displayed to indicate the presence of the vehicle if a vehicle is cruising ahead of you. Set speed is displayed in the upper-right position. Figure 8 (b) shows the displays for LDA. Thick white lines indicate the condition under LDA control. The overlapping display of (a) and (b) shows in Figure8 (c).
If the buzzer suddenly becomes inoperative in "Fail BUZZ" in Table 2, the display changes in sequence in accordance with (4-1), as shown in Figure 9.
In particular, when behavior (a) + (c) occur, the control changes conditions almost simultaneously. However, the control and diagnostic displays must be shown without flashing.
When the windshield wipers start operating at high speed as shown in "wiper operation" in Table 2, the display changes in sequence at intervals of at least 2 seconds, as shown in Figure 10.

(a) ACC normal cruising (b) LDA control (c) Simultaneous display

**Figure 8. ACC and LDA displays.**

**Figure 9. Displays for behavior (a) only.**

**Figure 10. Displays for behavior (a) + (c).**

Mediation for the above-mentioned behavior is performed within the DSS ECU.
Moreover, as a diagnostic function of the DSS ECU, unified diagnostic trouble codes (DTC) among DSS are set for the DSS to improve the ease of repair services.

## 5. Control Design

There are also four combinations of control coordination, as shown in Figure 7, and the four types of cruise control systems must be considered. DSS behavior when other systems are activated must be considered in terms of control coordination. VSC using brake control is part of this consideration.
The priority order involving VSC control is VSC>PB/PAB (brake control) >ACC>LKA.
This correlation shows in Figure 11. The arrows indicate the cancel request of control against other systems. The priority order of VSC>PB/PAB is performed within the brake ECU.
Control coordination including switch operation is shown in Table 3.

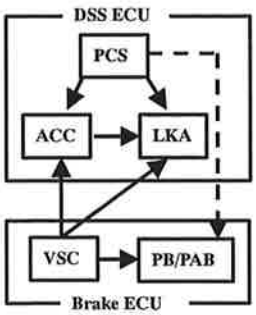



**Figure 11. Information flow of control cancel request**

**Table 3.**
**Control coordination matrix**

| No | Coordination item | AC+ | AC- | CC | CSL | LK | LDA |
|---|---|---|---|---|---|---|---|
| (1) | Fusion processing PB/PAB | r | r | r | o | r | r |
| | Switch operation | r | r | p | o | r | p |
| (2) | PB/PAB | r | r | r | o | - | - |
| (3) | Fusion processing PB/PAB | - | - | - | - | - | r |
| (4) | Switch operation | r | r | p | o | r | p |
| Other | VSC | r | r | r | o | r | r |

Note 1; r: removal of the function, o: normal,
p: depends on Switch operation, -: irrespective
Note 2; Switch operation: cruise main switch, cruise cancel switch, brake switch, Wiper switch, snow mode switch

## 6. HMI Design

(1) Combination Meter - DSS are controlled individually and their control states are displayed on the combination meter.
When one system requests the blinking of the display on the combination meter, a request from another system might be transmitted at the same time.
If the blinking request timing of two systems does not match, the meter display may flash or show another undesirable condition.
In particular, display coordination between the ACC and LDA systems can be described as an example. Figure 12 (a) shows the display for an ACC alert. When LDA is being controlled simultaneously, thick white lines are overlaid on the display, which reverts to black and white as shown in Figure 12 (b).

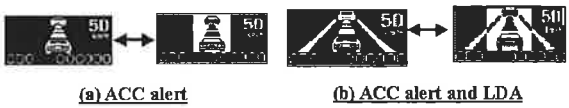



**Figure 12. Overlapping display of ACC and LDA.**

Similarly, Figure 13 shows the blinking of systems other than ACC.
The blinking frequency of these systems is set to 1 Hz on a common basis. On the other hand, CSL alert reverts to black and white without blinking.

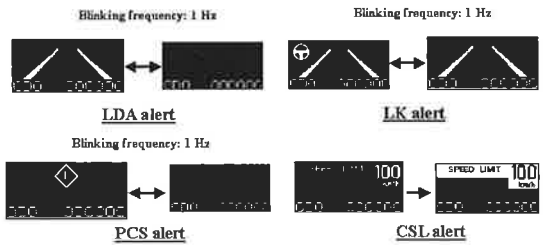



**Figure 13. LDA/LK/PCS/CSL displays.**

Moreover, the non-control states of ACC and LDA are displayed as shown in Figure 14.

**Figure 14. ACC/LDA non-control displays**

Combinations of HMI coordination are the same as those for fail-safe or control coordination as shown in Figure 7. As an example, Region (4) covers the display shown in Figure 12.

Display mediation is performed by the following procedure.
1. Mediation within the DSS ECU (6-1)
2. Mediation within the meter

2-1 Simultaneous display (6-2-1)
2-2 Priority order of display (6-2-2)
2-3 Blinking synchronization (6-2-3)

(6-1): When a request for an ACC alert occurs simultaneously with a PCS alert, the output request for the PCS alert from the DSS ECU is set to OFF. As another example, inspection displays such as for the DSS and sensor adjustment are mediated within the DSS ECU.

(6-2-1): The simultaneous display shown in Figure 8(c) is an example. Combinations of these designs should not overlap.

(6-2-2): The priority order of these systems is set as follows, and the overlapping part of lower priority systems is not displayed.

PCS alert > ACC non-control (1) and (2)/CSL control/CSL alert

(6-2-3): When the blinking of one system overlaps one of another, the blinking is synchronized. For example, when an LDA alert overlaps an ACC alert, the design delays the simultaneous display in accordance with the blinking cycle shown in Figure 15 to prevent the display from flashing.

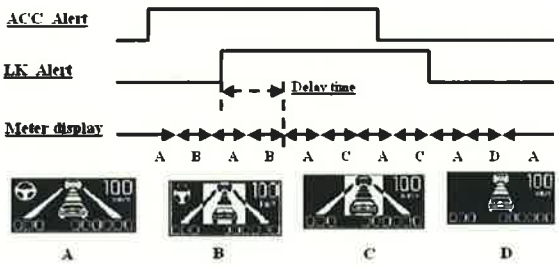



**Figure 15. Blinking synchronization.**

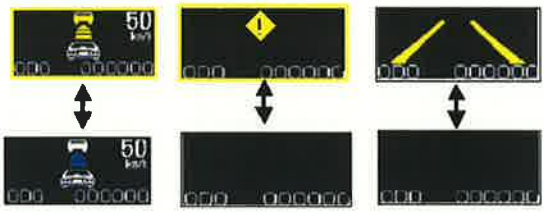
Table 4 shows an excerpt from DSS behavior. All combinations of these systems must be listed and the mediation decided in advance.

**Table 4.**
**Display coordination matrix (excerpt)**

| | Method | (6-1) | (6-2-1) | (6-2-2) | (6-2-3) |
|---|---|---|---|---|---|
| (1) | ACC Non-control (1)(2) + PCS alert + LDA control | | X | X | |
| | CC control + PCS alert + LDA alert | | X | | X |
| | CSL alert + PCS alert + LDA control | | X | X | |
| | CSL alert + PCS alert + LDA alert | | | X | X |
| (2) | ACC non-control (1)(2) + PCS alert | | X | X | |
| | ACC control + PCS alert | | X | X | |
| | ACC alert + PCS alert | X | | | |
| | CSL alert + PCS alert | | | X | |
| (3) | PCS alert + LDA control | | X | | |
| | PCS alert + LDA alert | | X | | X |
| (4) | ACC alert + LDA control | | X | | |
| | CSL alert + LDA control | | X | | |
| | ACC alert + LDA alert | | | | X |
| | CSL alert + LDA alert | | X | | |

These displays apply to monochromatic meters, but the guidelines can also be adapted to TFT meters, which can display in color.

Figure 16 shows examples of TFT alert displays from the ACC, PCS, and LDA systems. The blinking frequency of these systems is set to 2Hz to the advantage of the high response of TFT meters.




**ACC alert** **PCS alert** **LDA alert**

**Figure 16. ACC/PCS/LDA alerts on TFT display.**

**(2) Buzzer** - Table 5 shows the intermittent frequency of the buzzer and the priority order of each system.

The higher the frequency is, the more urgent the message to be conveyed to the driver.

The priority order of the controls has already been mentioned in the section on control interference design, and is as follows.

VSC>PB/PAB (brake control) >ACC>LKA

While VSC is automatically controlled, warnings from the PB system convey urgent messages to the driver to prompt avoiding action.

For this reason, the priority order of the buzzer has been decided as PB>VSC.

PCS alert includes PAB buzzer and continues to beep until PB warning in high possibility of collision.

**Table 5.**
**Priority order of buzzer requests**

| Priority | System | Intermittent frequency |
|---|---|---|
| 1 | PB warning | 10 Hz |
| 2 | VSC alert | 5.2 Hz |
| 3 | ACC alert | 5 Hz |
| 4 | PCS alert | 5 Hz |
| 5 | LKA alert | 5 Hz |
| 6 | HAC alert | 4 Hz |

## CONCLUSIONS

Logical mediation structures for Toyota's DSS have been developed.

Mediation design can be largely classified into fail-safe, control, and HMI aspects.

The important procedures of mediation are as follows.

(1) Understanding the behavior of each system
(2) Deciding which part is the most suitable to perform mediation
(3) Consideration in terms of ergonomics

These logic structures are adopted in all Toyota and

Lexus cars containing DSS.
These mediation guidelines are also expected to be considered for possible adoption in future systems.

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# EMOTIONAL AND BEHAVIORAL RESPONSE TO AUDITORY ICONS AND EARCONS IN DRIVER-VEHICLE INTERFACES

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## ABSTRACT

Adequately designed, auditory displays in Driver-Vehicle Interfaces (DVIs) may give shorter reaction times, improved attention direction, and an increased quality impression. In this paper, we argue that emotional reactions may guide the design of such auditory displays since emotion is central in our everyday life and have strong consequences for behavior and information processing. A simulator study with 30 participants (20 of which were professional drivers) was conducted to investigate the connection between emotional and behavioral responses to auditory DVIs as well as to evaluate various sound design parameters in realistic driving situations. Auditory icons were contrasted to abstract earcon sounds in more or less imminent collision scenarios and 3D sounds were tested against monophonic sounds in different lane change scenarios. Self-report measures (Self-Assessment Manikins, SAM) and physiological measures (Galvanic Skin Response, GSR and facial Electromyogram, EMG) of emotional response as well as behavioral measures (e.g. brake response time) were used.
It was found that auditory icons were more efficient and gave up to 600ms faster brake response times than abstract sounds in imminent collision scenarios and that 3D sound gave a stronger emotional response in lane change scenarios. Moreover, the results show that emotion can predict behavior, e.g. sounds rated as being more activating and negative also gave quicker response times. Contrary to our expectations however, the findings from the SAM ratings were not reflected in the physiological measurements. An explanation to this may be that the scenario itself caused a dominant stress reaction which overrode the physiological response to the warning sounds. Our findings nonetheless strengthen the importance of auditory displays as a means to enhance vehicle safety, and that emotions may be an efficient way of predicting behavioral response to auditory DVIs. Measurements of emotion may therefore facilitate the process of designing auditory DVIs.

## BACKGROUND

Sound may be a very efficient mean of providing warnings and information in vehicles, especially in situations where the visual modality is loaded with information, but can also be used to increase the quality impression of the vehicle.
A central characteristic of most auditory Driver-Vehicle Interfaces (DVIs) is that it should convey the appropriate level of urgency. Urgency can be defined as "…an indication from the sound itself as to how rapidly one should react to it." (Edworthy & Hellier, 2006). Too urgent sounds may cause annoyance, unwanted startle effects and even lead to the wrong behavior. On the other hand, if the sound is not urgent enough, reaction may be unnecessarily slow or result in that the warning is neglected.
Parameters which have been found to influence the perceived urgency of a sound include repetition speed, number of repeating units, fundamental frequency, and inharmonicity (Hellier & Edworthy, 1996). Moreover, loudness appears to be one of the stronger cues for urgency (Haas and Casali, 1995). However, the range within which loudness can be varied before the sound becomes un-ergonomic is in practice rather small; the sound should of course be loud enough to be heard over the background noise in the operator's environment and quiet enough not to cause annoyance or hearing impairment. This matter may seem trivial, but is often a central issue which is crucial for the acceptance of the sound.
Although thorough research has been conducted on the correlation between basic psychoacoustic parameters and urgency and similar perceptual aspects of sound design, the cognitive response linked to the sound is much less well understood (Edworthy & Hellier, 2006). It is therefore important to systematically investigate and be able to measure how the sound is comprehended. Edworthy and Hellier (2006) suggest that abstract sounds can be interpreted very differently depending on the many possible meanings that can be linked to a sound, in large dependent on the

surrounding environment and the listener. Designing sounds with unambiguous and appropriate meaning is perhaps the most important task in auditory warning design (Edworthy & Hellier, 2006).
A possible solution to the meaning problem is to use auditory icons. Auditory icons are representational, real world sound events that are used to signal events in Human-Machine Interfaces (HMIs). The advantage of auditory icons is that they have inherent meaning and therefore require no or little learning. Still, this meaning may not the same to all persons. As an example, the sound of a drain clearing may to some mean "Wet road" while others may interpret it the way the designer intended, namely "Low on fuel" (Winters, 1998). In general it may be difficult to find a suitable match between the function/event to be represented and the sound.

## Emotional reactions

While perceptual and cognitive aspects of sound design such as urgency and meaning of sounds are important to consider in the development of efficient DVIs, we propose here to take one step back and instead look at the emotional response to sound.
Why would we consider emotion? From an evolutionary perspective emotion can be seen as the human alarm system. Positive emotions signal that everything is safe and no specific action is needed to be undertaken to survive, while negative emotions signal a potential threat and need to take quick action. Emotions thus have strong consequences for behavior and information processing.
In our everyday life, sound often elicits emotional reactions in the listener. People can be startled by the sudden sound of a door slamming or a thunder in a storm, annoyed by the noise of cars in the street, pleased by the sound of a water stream in the forest, tired after a full day of work in a noisy environment, etc. Thus, understanding the role of sound in evoking human emotional responses might improve our quality of life by helping to design objects, spaces and media applications which are emotionally optimized (Tajadura & Västfjäll, 2008). Following this, it may be argued that designing sounds that elicit an emotion is also a way of designing sounds that will elicit a reaction and may therefore be particularly suited for design of sounds for DVIs. Another advantage is that rather than focusing solely on behavioral responses (which often are difficult and time-consuming to assess) as a measure of performance, emotion psychology has a rich flora of instruments to measure emotion that may be used as a proxy measure of behavior.
In our previous research, we have devised the Emotion Reaction Model (ERM) framework which builds on neuropsychological research showing that the human brain automatically reacts to certain sound properties, either in a very fundamental way (approach/avoidance reactions linked to survival) or by activating associative networks (primes/memories from previous exposures to situations where the sound was experienced) (see Västfjäll, 2007; Västfjäll et al., 2007). Most importantly, the ERM framework suggests that emotional or affective reactions are the driving force of behavior or action (Damasio, 1994, LeDoux, 2000). Therefore, for a warning or info sound to elicit the "correct" action, it needs to induce an emotional reaction (Västfjäll et al., 2003). A central question within this research is thus what in a sound that induces an emotional reaction.

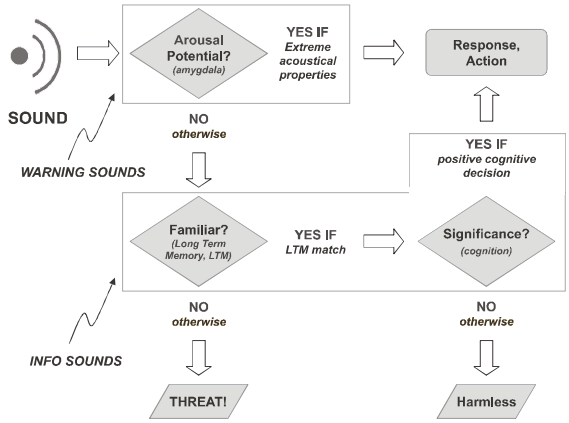


**Figure 1. Schematic of the ERM framework.**

Figure 1 shows a simplified schematic of the proposed framework where sounds (upper left corner) can be processed along two principal routes; either it will elicit immediate responses (arousal potential) or sound properties will be compared to previously stored memories of sounds (familiarity/significance check). In both cases the sound will elicit both a reaction and an evaluation of the possible danger or threat of the situation (as signaled by the sounds).
The upper route in Figure 1, arousal potential, is a preattentive warning system that has evolved to make a quick assessment of the potential threat of the situation (Jacobsen et al., 2003; LeDoux, 2000; Schröger, 1997; Tiitinen et al., 1994). This system needs to be extremely fast and elicit immediate and correct responses to ensure survival. Evidence points to that humans are hardwired to react to certain extreme acoustical characteristics (loud, sharp noises with quick rise time) (Bradley & Lang, 2000). Thus, when a sound exceeds a certain arousal threshold it will activate fight or flight tendencies (Giard et al., 1995; Lang, 1995; Rauscheker, 1998).

If the sound does not have an arousal potential that exceeds the threshold, it will be processed by other parts of the brain (Belin & Zatorre, 2000; Peretz & Zatorre, 2005); this is visualized by the lower route in Figure 1. First, the secondary auditory cortex will process the sound followed by associative and motor cortex areas (Edeline & Weinberger, 1992). Here the incoming sound will be compared to sound representations stored in long-term memory (Saarinen et al., 1992). If the sound has been encountered before (or resembles a sound that has been encountered before) it will elicit on of two possible reactions (Jääskelinen et al., 2004): If it is an unfamiliar sound, it will immediately signal the same alarm system as a sound with high arousal potential. The same holds true if the sound matches a sound representation that is associated with a previous negative experience (Damasio, 1994; Damasio et al., 2000). If the sound matches a previously stored representation it will be evaluated on basis of it significance for survival (Blood & Zatorre, 2001; Todd, 2001). If our previous experience has coded the sound as something potentially threatening or coexisting with something else that may be a threat, the system will call for an action. If, on the other hand, the sound is evaluated as non-harmful, no action will be required.

**Implications for sound design -** This simplified framework has several implications for design of warning and information sounds. First, it postulates that warning sounds should have a certain degree of arousal potential so that it evokes an immediate correct response. The main task for future research here is to map the arousal potential of various sounds and create sounds that have just the right amount of potential as too much may result in freezing behavior and incorrect responses (Panksepp & Bernatsky, 2002).
Second it suggests that both information and warning sounds would benefit from having sound elements that are familiar (such as auditory icons that rely on naturally occurring sounds to convey information). Third, the proposed framework suggest that emotional reactions to sounds is a common currency with which the urgency, behavioral significance and needed action will be evaluated against (Damasio et al., 2000). This also suggests that when assessing the effectiveness of warning and information sounds, affective reactions should be measured along with process measures (reaction time and decision) of the action.

**The affect circumplex** – It has been shown that the emotional reaction to natural and product sounds can be efficiently be described by two bipolar dimensions, activation and pleasantness-unpleasantness (valence), (Bisping, 1995, 1997; Bradley & Lang, 2000; Västfjäll et al., 2003). Taking this approach, it is assumed that any emotional state can be described by the *combination* of these two orthogonal dimensions (Russell, 1980; Russell & Feldman-Barrett, 1999). The so-called affect circumplex (Russell, 1980), shown in Figure 2, visualizes the two dimensional approach to describing emotional reactions. As an example, an emotional state such as excitement is the combination of pleasantness and high activation (upper left quadrant in Figure 2). An emotional reaction such as calmness is similar in pleasantness, but low in activation (lower left quadrant). Boredom is the combination of unpleasantness and low activation (lower right quadrant) and distress is the combination of unpleasantness and high activation (upper right quadrant).

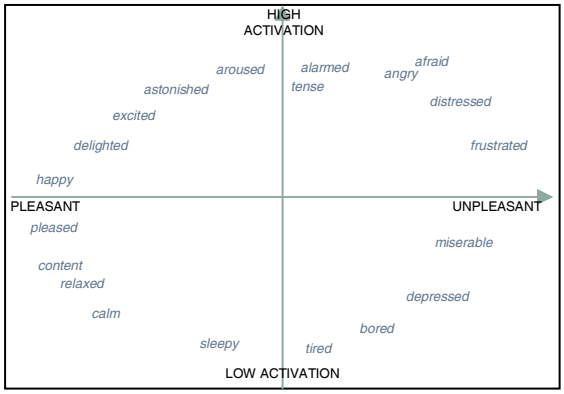


**Figure 2. The affect circumplex (Adapted from Russell, 1980).**

### Measurement of emotional reactions to sound

There is a number of different ways to measure emotional reactions, including self report, physiological measures such as EEG and behavioral measures.
Self-report measures rely on that participants accurately can report their felt emotion. The main self-report measure used in the ERM framework is the Self Assessment Manikin (SAM) scales (Bradley & Lang, 1994, see Figure 3) which aims at capturing the activation/valence dimensions described in the previous section. The advantage of the SAM measure is that it can be understood by different populations in different cultures and that it is easy to administrate.
Many different physiological processes indicate emotional experiences. For instance, video recordings of the face can obtain measures of facially expressed emotions (Sebe et al., 2002). However, emotional reactions can also be captured via physiological measures of activation and valence. The method preferred within the ERM framework to measure valence are Electromyographical (EMG) measures of facial muscle contractions (Bradley & Lang 2000).

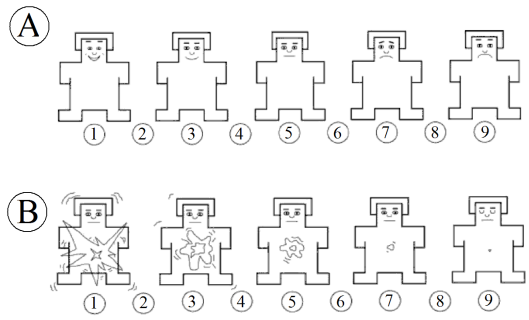


**Figure 3. The Self Assessment Manikin (SAM) scales for valence (top) and activation (bottom) (Bradley & Lang, 1994).**

This is typically measured by attaching electrodes in the facial region and measuring muscle micro-movements. Activity in the *Corrugator supercilii* (which controls eyebrow contraction) can be linked to unpleasant emotions (negative valence) whereas activity in the *Zygomaticus major* (the "smile muscle") may be linked to pleasant emotions (positive valence). The activation dimension is preferably measured physiologically using EDA (Electro- Dermal Activity) which can be obtained by measuring the galvanic skin resistance on subjects' fingers or palms (Bradley & Lang 2000).

## EXPERIMENT

The simulator experiment described in this paper aimed at testing the following hypotheses:

H1. Sounds that contain ecological components (i.e. sounds that represent naturally occurring events – auditory icons) are more efficient / urgent than earcons (entirely abstract/synthetic sounds such as the ones used in the majority of all HMI systems in trucks). According to the ERM framework, familiar information contained within the sound should facilitate the emotion response process by activating associative networks and lead to more correct and rapid action.

H2. 3D sounds are more efficient/urgent than mono sounds. By combining sound icons and 3D information it is likely that one can rapidly and efficiently convey the sensation of that something dangerous is e.g. approaching from a certain direction (using 3D directional cues). Hence, such 3D sounds should be perceived as being more urgent and lead to more rapid and correct action.

### Participants

20 professional truck drivers (19 male, age M= 42.3 SD= 9.2 years) and 10 Volvo employees with truck driving license (9 male, age M= 40.7 SD= 8.6 years) participated. The professional truck drivers received vouchers worth SEK 200 as compensation for their participation.

### Measures

Participants' reactions to sounds were measured using self-reports, physiological measurement and behavioral methods. The Self-Assessment Manikin (SAM) – scales (shown in Figure 3) were used to collect self-ratings of Activation (high to low) and Valence (positive to negative). Participants were instructed to verbally report their responses using the scales (by saying e.g."A1, B5") after hearing each sound. A sheet with the scales was placed in the middle of the steering wheel, see Figure 5. Activation was measured physiologically by Galvanic Skin Response (GSR) measurements on participants' index and middle fingers on their non-dominant hands (see Figure 4). GSR was sampled continuously through each driving session at a rate of 391 Hz. To obtain a physiological correspondence to valence, electromyogram (EMG) responses of the Corrugator and Zygomaticus muscles (the "frown and smile" muscles in the face) were measured (see Figure 4). As with the GSR, the EMG responses were sampled throughout each driving session but at a sample rate of 3125 Hz. In addition, several driving parameters such as brake, wheel, and throttle response were logged for all sessions.

### Instrumentation

**Simulator -** The simulator used in the experiment is shown in Figure 5. It consists of a stationary truck compartment and a 130-degree cylindrical display onto which 3 BARCO CRT projectors project the image. Side rear view mirrors views were simulated with LCD monitors. A Linux cluster consisting of one master and five slave computers were used to run the driving simulation and render the graphics. In-house developed software, "DriveSim", based on SGI Performer was used as the main simulation application. Moreover, a Windows computer was used for controlling communication between dashboard instruments and the master computer and one XPC computer was used for receiving and passing on CAN information from driver (throttle and steering wheel) to the main application. For the distraction task in part 2 (see "Scenarios" below), a Windows laptop with PowerPoint which presented numbers on a 19" LCD monitor placed on the floor to the right of the participants inside the truck compartment was used (see Figure 5).

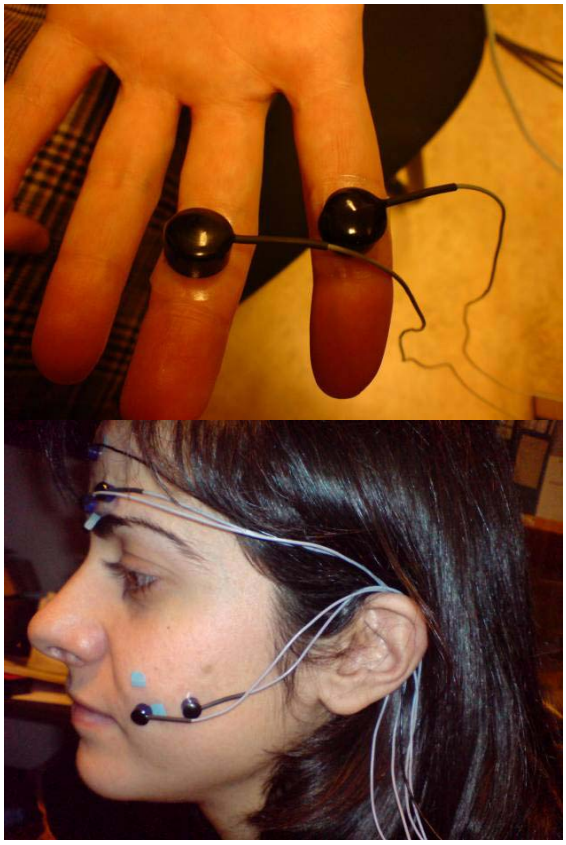

**Figure 4. GSR (top) and EMG electrodes mounted on a participant.**

**Sound** - Sound icons were presented using loudspeakers, located as shown in Figure 6, and dedicated amplifier (Creative Inspire T7700). Since only two-channel sound was available from the simulator master computer, a Dolby Pro-logic™ preamplifier (Proton AS-2620) was used to distribute the sound to the three loudspeakers. The levels of the signals sent to the amplifier/loudspeakers were adjusted in the preamplifier so that the sound was perceived equally loud from all three loudspeakers. Communication between the participant and the experiment leader (who sat at a desk approximately 6.5 m behind the simulator cab) was enabled by a talkback system consisting of two Genelec 1029A active monitors and two microphones (a Shure Prologue el. dynamic microphone at the experiment leader's desk and a Panasonic electret microphone mounted to the driver's seat) and microphone preamps. The sound inside the compartment was also recorded using a Shure BG4.1 condenser microphone and the BIOPAC system described in the next paragraph.

**Physiology** - To measure physiological responses, a BIOPAC MP150 system with Acqknowledge™ 3.8.1 running on a Windows laptop was used. Facial electromyogram (EMG) responses of the Corrugator and Zygomaticus muscles were acquired via Ag-AgCl shielded lead

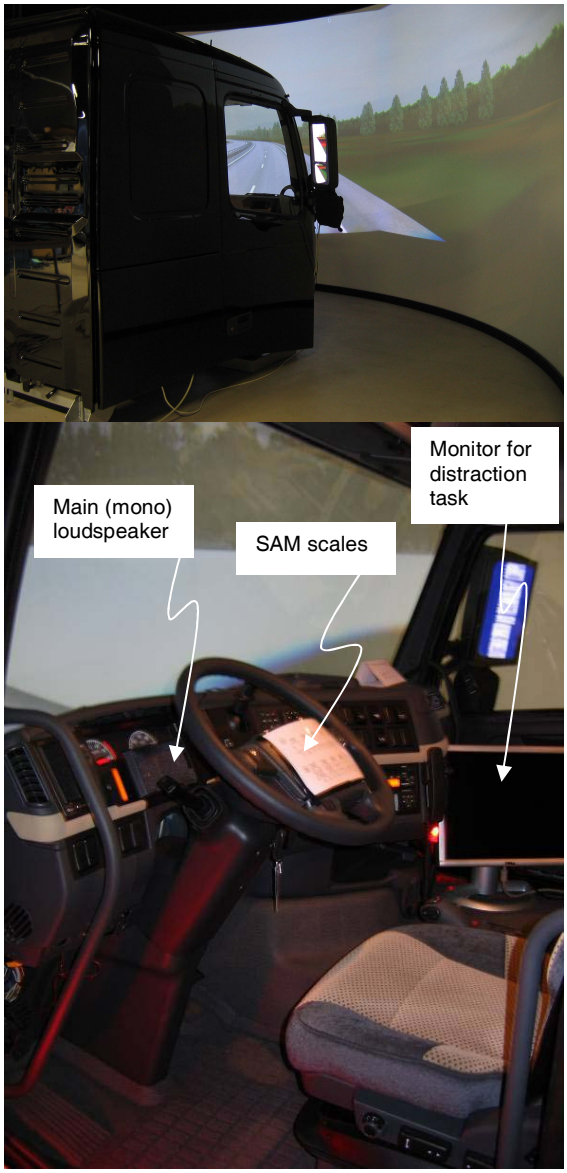


**Figure 5. The simulator (top) and inside the simulator compartment, showing the main loudspeaker, SAM scales and the distraction monitor.**

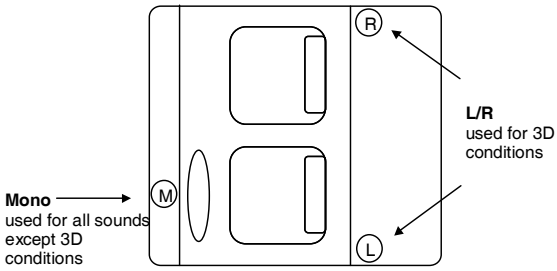


**Figure 6. Position of loudspeakers in the simulator compartment.**

electrodes and two BIOPAC EMG100C amplifiers. Galvanic Skin Responses (GSR) were acquired via Ag-AgCl electrodes and a BIOPAC GSR100C amplifier.

**Sounds**

The thirteen different warning and information sounds included in the experiment are described below. Both entirely synthetic sounds (earcons) and auditory icon-type, ecological sounds (i.e. sounds representing real events) were used.

- FCW_earcon: 4 sharp pulses of 0.1s duration and 0.01s silence between pulses. Fundamental around 207 Hz
- FCW_aicon: Auditory icon - car horn sound, continuous, 1.24 s duration. Fundamental around 417 Hz
- ACC_earcon1: 4 high-pitched pulses of 0.1s duration and 0.01s silence between pulses. Tone cluster 2482 Hz and 2631 Hz
- ACC_earcon2: 4 sharp, low-pitched pulses of 0.29s duration and 0.21s silence between pulses. Fundamental around 95 Hz
- ACC_aicon: Auditory icon - car horn sound, low pass filtered, continuous, 1.24 s duration. Fundamental around 417 Hz
- Caution_earcon1: 2 pulses of 0.1s duration and 0.2s silence between pulses – repeated once, 1.8s silence between. Fundamental around 980 Hz.
- Caution_earcon2: 2 brief tones of 0.03s duration and 0.06s silence between tones. Echo effect. Repeated once, 0.68s silence between.
- Caution_aicon: Earcon/Auditory icon hybrid: Two chime tones, 0.45s duration and the sound of a ratchet handle (symbolizing the need to contact service). Chime fundamental around 260 Hz
- LCS_mono: Auditory icon - 2 car horn honks, 0.27s duration, fundamental around 417 Hz
- LCS_3Dl: Same as LCS_mono but played in left loudspeaker
- LCS_3Dr: Same as LCS_mono but played in right loudspeaker
- LDW_earcon1: 4 very sharp pulses of 0.23s duration and 0.24s silence between pulses intended to symbolize the sound of a rumble strip. Fundamental about 74 Hz
- LDW_earcon2: 19 rapid dull pulses of 0.08s duration and 0.02s silence between pulses intended to symbolize the sound of a rumble strip. Fundamental somewhere around 68 Hz.

**Design**

The experiment was divided into two parts: The first part consisted of Forward Collision Warning (FCW), Automatic and Caution scenarios/sounds, and the second part consisted of Lane Change Support (LCS) and Lane Departure Warning (LDW) scenarios/sounds. Three different groups (orders) were used for the first part and two groups were used for the second part in order to randomize the presentation of different sounds for each scenario. The main design type was thus a within-group design (if one considers the scenarios for a certain event type, e.g. FCW, to be comparable). For practical reasons, Caution sounds could not be played more than once why this type of sound was a between-groups variable.

**Scenarios**

Thirteen different scenarios were created to test the different sounds. All roads used in the scenarios were modeled according to Swedish standards. The scenarios are described below.

1. FCW, approaching car in the wrong lane.
2. ACC, car turns into the lane in front.
3. Caution, nothing particular happens on the road but the engine warning lamp in the dashboard starts to flash for a few seconds.
4. FCW, approaching car in the wrong lane.
5. ACC, car in front brakes suddenly before intersection.
6. FCW, meeting car in intersection suddenly turns left.
7. ACC, Car turns quickly into the lane in front.
8. LCS, participant is instructed to take right to the departure lane, when a car suddenly appears in departure lane.
9. LDW, the participant is instructed to read the numbers that appears on the screen on the floor inside the simulator compartment. When the participant starts to read, the experiment leader momentarily steers the truck of the road.
10. LCS, fast bicycle crosses lane after roundabout.
11. LDW, the participant is instructed to read the numbers that appears on the screen on the floor inside the simulator compartment. When the participant starts to read, the experiment leader momentarily steers the truck of the road.
12. LCS, the participant is instructed to turn to left lane where a car suddenly appears.
13. LCS, the participant is instructed to turn to right lane where a car suddenly appears.

**Procedure**

Participants arrived individually to the simulator lab. A female or male test leader first briefed the participant generally about the experiment and the conditions for their participation. Participants were then seated in the simulator and physiological equipment (finger and facial electrodes) was attached to the participant. The use and control of the simulator was then introduced. Participants were instructed to try to drive as they normally drive and follow all instructions, road signs, speed limits etc. They were also specifically instructed that they could abort the test if they were feeling nauseous or uncomfortable in any way. Instructions on how to use the SAM scales were given and participants then commenced a short test drive during which they also rated a test sound (a sound which was not included in the main experiment) on the SAM scales. The main test then started with the first part (mean duration= 18 min) followed by a short break to let some air into the truck compartment and the second part (mean duration= 11 min). Participants were then debriefed and thanked for their participation.

**RESULTS, PART 1**

**Self reports (SAM)**

Ratings of activation were submitted to a 2 (earcon / auditory icon) x 2 (ACC / FCW) ANOVA to determine the influence of type of sound design and warning level on self reported activation. For simplicity of reading, the activation ratings were inverted from the original ratings so that high ratings indicate high activation. Bonferroni's method was used to adjust for multiple comparisons. As expected, it was found that participants rated FCW sounds as being more activating than the ACC sounds (M= 6.692 vs. M= 5.769, $p<.01$). The mean rated activation of the auditory icon sounds was slightly higher than for the earcon sounds (6.325 vs. 6.135), however this effect was not significant ($p= .547$).

Separate ANOVAs were performed to reveal any differences between individual sounds. A statistically significant difference in activation was found between FCW_aicon and FCW_earcon, where the former was rated as being more activating (M= 7.161 vs. 6.452, $p<.05$). No statistically significant differences were found between the ratings of the three ACC sounds (earcon1, earcon2 and aicon).

In a similar fashion, ratings of valence were submitted to a 2 (earcon / auditory icon) x 2 (ACC / FCW) ANOVA to determine the influence of type of sound design and warning level on self reported valence. The mean ratings indicate that participants rated the auditory icons as being more negative than the earcons and that the FCW sounds were more negative than the ACC sounds; however, the analysis showed that these differences were not statistically significant ($p= 0.365$ and $p= 0.524$ respectively).

Valence ratings were also analyzed separately for each sound. The results from this analysis showed that there was a marginally significant difference ($p=0.114$) in valence between FCW_earcon and FCW_aicon with the latter being slightly more negative (M= 5.161 and M=5.871 respectively). There were no such trends for the three ACC sounds.

Finally, activation and valence ratings of the "caution" sounds were submitted to independent samples t-tests as these sounds were a between-group variable in the current design. However, no significant group differences were found in either activation or valence for these sounds. It is likely however that significance would have been reached with more participants in each group.

The SAM ratings from the first part are summarized in Figure 7 where means are plotted in the activation-valence plane.

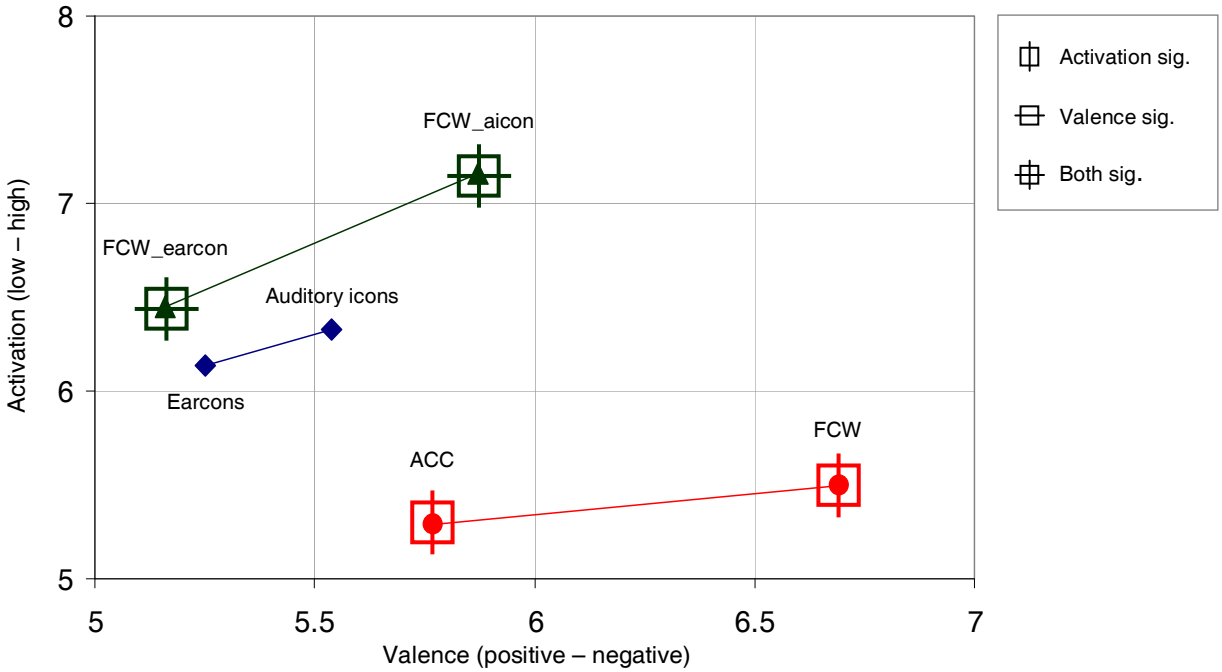


**Figure 7. SAM ratings from the first part of the experiment plotted in the activation/valence plane.**

### Physiological responses

As data recorded from GSR electrodes was recorded continuously during each driving session, the data files first had to be cut in segments around the points in time when each sound was triggered. Next, the GSR segments were downsampled to 20 Hz. Each segment was then visually inspected and the point where a steep increase GSR curve could be noted was stored as a cut point. The GSR score was then calculated as the difference between the maximum derivative up to 2 seconds after this cut point and the maximum derivative in the segment from 2 seconds before the cut point up to the cut point. An example of a GSR segment from one of the sounds and one of the participants is shown in Figure 8.

After these pre-processing steps, GSR scores were first submitted to a 3 (earcon1/earcon2/aicon) x 2 (ACC/FCW) ANOVA to determine the overall effect of type of sound design and warning level on physiological activation. No significant differences between these factors were found. Scores were also submitted to a 1x7 ANOVA to reveal differences in activation between separate sounds. The only possible effect found was between FCW_earcon and the Caution sounds, with p=0.054. (Note that the score from three different caution sounds have been grouped together in this case). For reference, means of the GSR scores are shown in Figure 9 (whiskers show standard error).

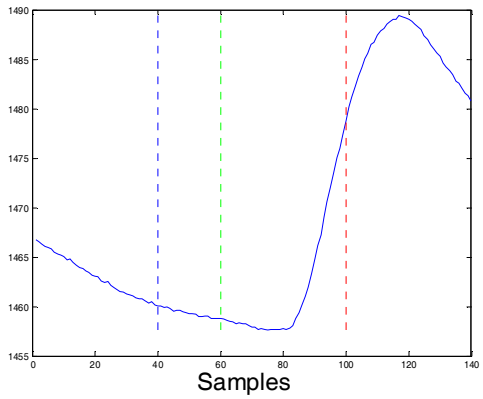


**Figure 8. Example of one of the GSR segments cut from one of the data files. The leftmost dashed line marks the start of the sound, and the two other dashed lines mark the region where it is most likely to see a response to the stimulus (1-3 seconds after stimulus start). In this case, the cut point was selected at about 80 samples (i.e. 2 seconds after stimulus start).**

Data from facial EMG (Corrigator / Zygomaticus) were first cut into segments around the points in time when each sound was triggered (in a similar way as was done with the GSR recordings). The segments were then downsampled to 1000 Hz and highpass filtered at 90 Hz to remove unwanted high- and low-frequency noise. Next, the envelope of the segments was extracted by taking the Hilbert transform of the segments. Finally, scores were calculated as the difference in means 2 seconds

after each sound was played and 2 seconds before each sound was played.

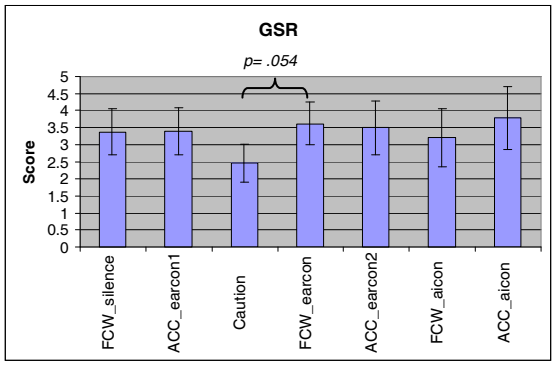


**Figure 9. Means of the GSR scores. The only difference which is close to being statistically significant is the one marked with p-value (Caution vs. FCW_concept). Note however that the Caution score is a score obtained from three different sounds.**

The Corrugator / Zygomaticus scores were then submitted to separate 3 (earcon1/earcon2/auditory icon) x 2 (ACC/FCW) ANOVAs to determine the overall effect of type of sound design and warning level on negative and positive valence. No significant differences between these factors were found. Scores were also submitted to a 1x7 ANOVA to reveal differences in physiological valence between separate sounds. An effect was found in the Zygomaticus score between FCW_aicon and the Caution sounds, with M=0.02 for the FCW_aicon and M= -0.02 for the caution sounds ($p<.05$) (note that the score from three different caution sounds have been grouped together in this case).

### Behavioral responses

Brake reaction times (BRT) were extracted from simulator log files as the time from sound start to 30% of maximum brake pressure for each participant and sound. BRTs were then analyzed in a between-groups fashion using t-test for each scenario since the scenarios were fairly different and hence probably provoked different behaviors. First, it was found that BRT was significantly lower for scenario 1 (FCW situation) for the group which received the auditory icon sound compared to the group which did not receive any sound at all (N=10, M=1.9s vs. M=2.5s, $p<.05$). BRT was also significantly lower in group 1 (auditory icon) compared to group 3 (earcon) in scenario 6 (also FCW situation) with N=10, M= 0.4 vs. M=0.7, $p<.01$. In other words, the auditory icon sound gave a brake response in the range 300-600 ms faster compared to the concept sound and when no sound was presented. These results are visualized in Figures 10-11 below.

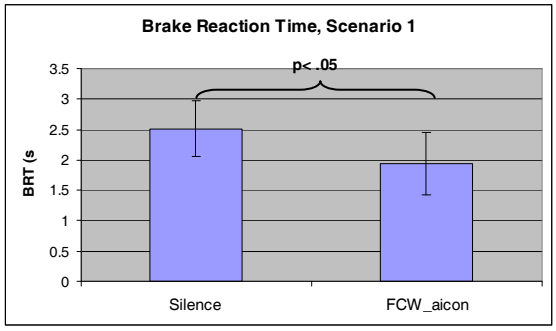


**Figure 10. Brake reaction times, no sound vs. FCW_aicon. Whiskers show standard deviation. Bold p-value indicates statistically significant difference.**

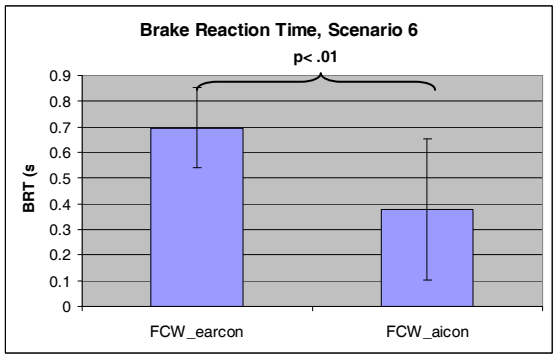


**Figure 11. Brake reaction time, FCW_earcon vs. FCW_aicon. Whiskers show standard deviation. Bold p-value indicates statistically significant difference.**

## RESULTS, PART 2

### Self reports (SAM)

Ratings of activation for the LCS sounds were submitted to a 2 (mono / 3D) x 2 (scenarios 8 and 10 / scenarios 12 and 13) ANOVA primarily to determine the influence of spatialization on self reported activation. To complete the factor analysis but also to reveal learning effects, scenario (8 and 10: highway departure & bicycle in roundabout, 12 and 13: lane change) was included as a factor. For simplicity of reading, the activation ratings were inverted from the original ratings so that high ratings indicate high activation.

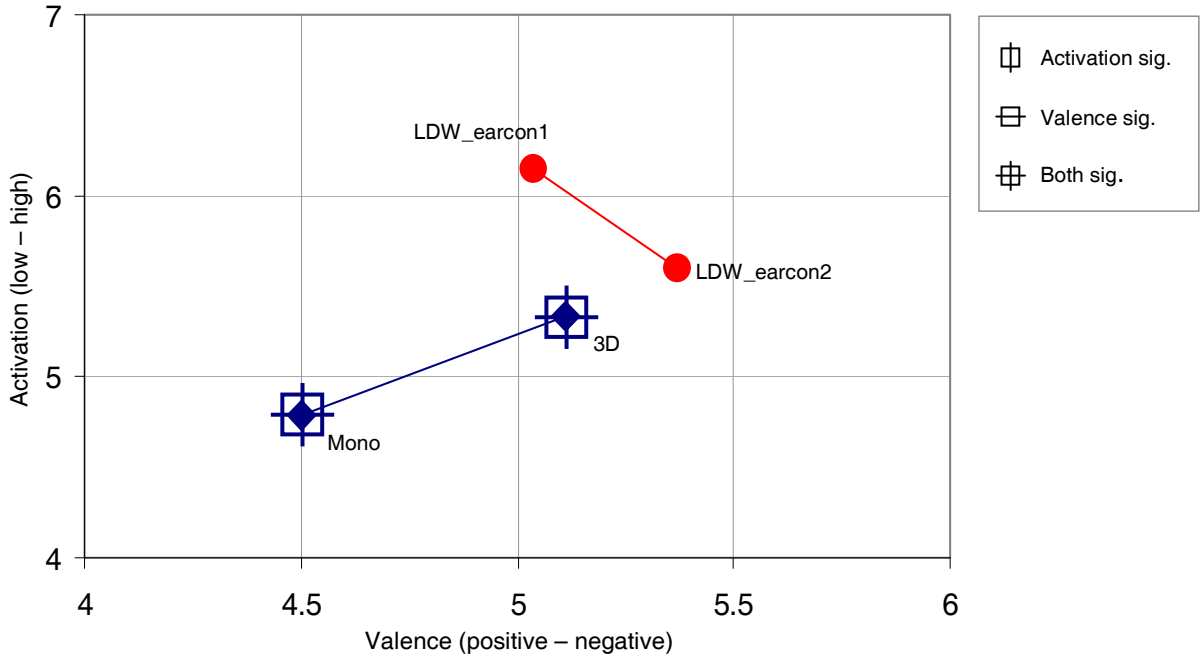


**Figure 12. SAM ratings from the second part of the experiment plotted in the activation/valence plane.**

Bonferroni's method was used to adjust for multiple comparisons. As expected, it was found that participants rated 3D sounds as being more activating than the mono sounds (M= 5.339 vs. M= 4.790, p<.01). The mean rated activation was also higher in the first two scenarios (8 and 10) compared to the second two (12 and 13) (5.435 vs. 4.694, p<.05), indicating that participants felt that the latter two situations were less serious or that they were more relaxed (or bored) towards the end of the test.

Furthermore, ratings of activation for the LWD sounds were submitted to an ANOVA to determine the influence of sound design (earcon1 / earcon2) on self reported activation. As before, the activation ratings were inverted from the original ratings so that high ratings indicate high activation. Bonferroni's method was used to adjust for multiple comparisons. It was found that the mean rating of the LDW_earcon1 sound was slightly higher than the LDW_earcon2 (M= 6.148 vs. M= 5.593; however, this effect was not significant (p= .134).

As with the activation ratings, ratings of valence for the LCS sounds were submitted to a 2 (mono / 3D) x 2 (scenarios 8 and 10 / scenarios 12 and 13) ANOVA primarily to determine the influence of spatialization on self reported valence. Bonferroni's method was used to adjust for multiple comparisons. It was found that participants rated 3D sounds as being more negative than the mono sounds (M= 5.113 vs. M= 4.500, p<.01). The mean rated valence was also slightly higher (i.e. more negative sensations) in the first two scenarios (8 and 10) compared to the second two (12 and 13) (4.984 vs. 4.629); however, this effect did not reach significance (p= 0.150).

Moreover, ratings of valence for the LWD sounds were submitted to an ANOVA to determine the influence of sound design (earcon1 / earcon2) on self reported valence. Bonferroni's method was used to adjust for multiple comparisons. It was found that the mean rating of the earcon2 LDW sound was slightly higher than the earcon1 sound (M= 5.370 vs. M= 5.037; however, this effect was not significant (p= .320).

The results from the analysis of the SAM ratings from the second part of the experiments are summarized in Figure 12.

### Physiological responses

GSR data was preprocessed in the same fashion as in part 1 and the resulting GSR scores were then first submitted to a 2 (mono / 3D) x 2 (scenarios 8 and 10 / scenarios 12 and 13) ANOVA primarily to determine the influence of spatialization on physiological activation. To complete the factor analysis but also to reveal learning effects, scenario (8 and 10: highway departure/bicycle in roundabout, 12 and 13: lane change) was included as a factor. As with the self-reports, the last two scenarios were in mean less activating than the first scenarios (M= 1.747 vs. M= 0.403), however this difference was not significant (p= 0.139). Similarly, the 3D sounds were in mean more activating than the mono sounds (M= 2.845 vs. M=-.695, shown in Figure 13), but again this difference was not statistically significant (p= 0.378). Scores resulting from the LDW sounds were then submitted to a 1x2 ANOVA to reveal

differences between sound designs (earcon1 and earcon2). It was found that the earcon1 sound was significantly more activating than the earcon2 sound (M= 3.628 vs. 0.038, p< .05), see Figure 14.

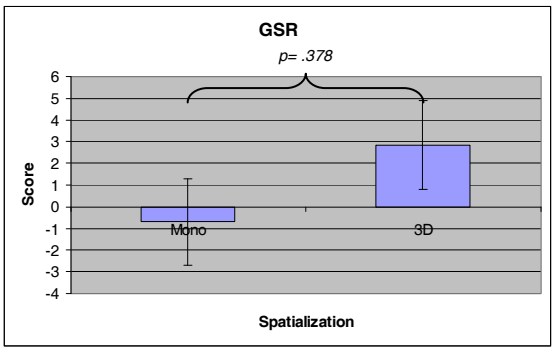


**Figure 13. Means of GSR scores, mono vs. 3D sound. P-value in italics indicates non-significant difference.**

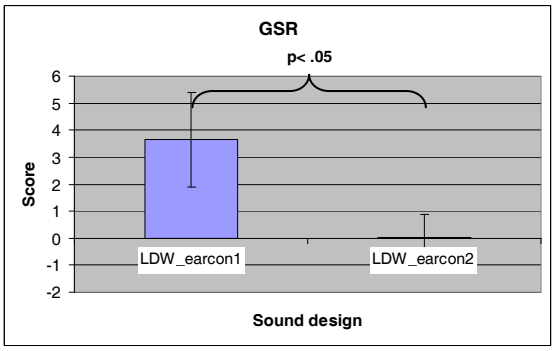


**Figure 14. Means of GSR scores, LDW_earcon1 vs. LDW_earcon2. Bold p-value indicates statistically significant difference.**

Data from facial EMG (Corrugator / Zygomaticus) were first preprocessed in a similar manner as in part 1. The Corrugator / Zygomaticus scores were the submitted to a 2 (mono / 3D) x 2 (scenarios 8 and 10 / scenarios 12 and 13) ANOVA to determine the influence of spatialization on physiological activation. As before, scenario (8 and 10: highway departure / bicycle in roundabout, 12 and 13: lane change) was included as a factor. No significant differences between these factors were found. Corrugator and Zygomaticus scores resulting from the LDW sounds were then submitted to separate 1x2 ANOVAs to reveal differences between sound designs (existing and concept). No significant effects were found in this case either.

### Behavioral responses

Brake reaction times (BRT) were extracted for the LCS scenarios only (as BRT was considered to be an inappropriate measure for the LDW scenarios) from simulator log files in a similar manner as in the first part. Due to a technical error, only responses from Scenarios 8 and 12 could be analyzed. BRTs over 4s were excluded from the dataset. These BRTs were then analyzed in a between-groups fashion using t-test for each scenario. No statistically significant differences were found. The BRTs are shown in Table 1 below. As can be seen, the number of valid sample points is low for all scenarios/conditions, about 50% for Scenario 8 and about 25-30% for Scenario 12, which simply means that the participants' response was not always to depress the brake when hearing the sound. In other words, BRT may not be the most suitable measure of behavioral response in this case.

**Table 1.**
**BRTs for the LCS scenarios 8 and 12**

| | Group | N | Mean | Std. Dev. |
|---|---|---|---|---|
| Scenario 8 | 3D | 8 | 1.039888 | 0.676731 |
| | mono | 8 | 1.797263 | 1.125288 |
| Scenario 12 | 3D | 4 | 1.9008 | 1.366652 |
| | mono | 5 | 0.85034 | 0.455207 |

## DISCUSSION

In part 1, it was found that FCW sounds were more activating than ACC sounds, which supports the overall sound design goal for these two types of sounds. Auditory icons in general were not more activating than the earcons, but specifically for the FCW sounds is seems that the auditory icon was more efficient in activating the driver. There were no significant differences in valence for the part 1 sounds, although a trend indicating that the auditory icon FCW was more negative than the earcon FCW sound could be seen. The findings from the SAM measurements were not reflected in the physiological measurements. It is likely that it is the situation/scenario itself, and not the sound, which causes the dominant stress reaction and any physiological response differences due to difference in sounds are overridden. This is supported by the fact that the only close-to-significant case in the GSR recordings was between the Caution sound (where nothing actually happened) and FCW_earcon (a collision scenario). The same effect was found also in the Zygomaticus scores between Caution and FCW_aicon (the effect was statistically significant in that case). To investigate this matter, more controlled studies with repetitions of each sound and/or a between-groups design with more participants would be required. The current GSR scores were actually analyzed also in a between-groups fashion for each scenario, but probably due to the low number of participants, this analysis did not show any statistically significant results. Brake reaction times however

confirmed the SAM ratings and hypotheses in terms of auditory icons being more urgent than earcons (i.e. more activating and more negative). Both compared to no sound at all and compared to the FCW_earcon sound, the FCW_aicon sound resulted in a much quicker brake reaction; mean reaction times were in the range 300ms – 600ms shorter for the auditory icon sound.

In part 2, strong evidence for 3D sounds being more urgent (i.e. more activating and more negative) was found in the SAM ratings. It should be again noted that the ”3D sounds” and the ”mono sounds” were exactly the same car horn sounds, but played through either the mono loudspeaker in front of the participant or through one of the rear loudspeakers. Interestingly, during the debriefing sessions with the participants, not many reported having heard any difference between the conditions; still, the ratings indicate a difference in emotional response and urgency. An explanation to the effect is that participants to greater extent associated the 3D sound with something outside the car – an approaching and potentially dangerous situation – while the mono sound was associated with their own car horn i.e. something less urgent. An effect of scenario could also be seen indicating that the latter scenarios were either less activating and less negative or that participants simply became less alert / more relaxed as the test progressed. The GSR scores partly confirmed the SAM ratings, although no significant effects were found, but as in part 1 it is likely that one has to employ a different design to reveal any physiological response differences between the types of spatialization. The behavioral measure, brake reaction time, seemed to be inappropriate for the scenarios used in part 2; few instances were participants actually pressed the brake in response to the sound occurred and no statistically significant differences could be found in the data which did pass the pre processing stage. It is likely that other behavioral measures such as gaze would be more suitable for these scenarios or in general when spatial properties of sound are to be investigated. Concerning the LDW sounds, no strong results were found in SAM ratings, although a trend was found indicating that LDW_earcon1 sound is more activating than the LDW_earcon2 sound. This finding was supported by GSR scores, where a significantly lower score was found for the LDW_earcon2 sound. One should however treat this result with some caution since large wheel deflections, which may have influenced the GSR score, often were the response to the sound in these scenarios.

In sum, strong support was found for the hypothesis that auditory icons are more efficient than conventional earcons in urgent situations. It was shown that both emotional response and brake reaction time could be significantly improved by using an auditory icon sound. Moreover, spatialized sounds were found to be more activating and more negative, i.e. more urgent, in a lateral warning situation (e.g. lane change). These findings should be considered in future DVI development, but it is recommended that more controlled studies are carried out to establish the optimal parameters of these sound design dimensions.

## ACKNOWLEDGEMENTS

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# INTERACTING DRIVERS AT INTERSECTIONS: WHAT CAN MAKE THEM MORE SAFE AND MORE EFFICIENT?

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**Paper Number 09-0240**

## ABSTRACT

Technological applications not only affect individual behaviour in traffic, but also influence interaction behaviour. However, not much research has been conducted in this area. This paper attempts to fill the gap by investigating the effects of manipulations of the time and space ("interaction space") drivers have to safely negotiate an intersection. Interaction space was manipulated by providing drivers at intersections with information about other approaching drivers, and also by varying the expectedness of the approach speed of the other driver. An experiment was conducted using an innovative and promising approach with two linked driving simulators, where participants (N=26) were provided with in-vehicle information (flashing lights in their dashboard and beeps), indicating the direction and speed with which another driver approached on the intersecting road. Based on the right of way regulation, speed could be either expected or unexpected. The use of linked simulators allowed the participants to interact with a real driver (the experimenter), rather than with pre-programmed drivers and thus provided important information concerning the interaction process . Different behavioural indicators of the safety and efficiency of the interaction process were recorded. Also, concerning the information provided, the level of acceptance and experienced mental effort is reported. The results regarding the behavioural indicators suggest a proactive and reactive stage within an intersection approach, where the latter stage seems more prone to manipulations of interaction space. The acceptance results indicated that the lights were not appreciated whereas the beeps were regarded as quite useful. Mental effort was (subjectively) lower in the condition where extra information was provided. This experiment provides a valuable indication of the effect information would have on driving behaviour, although it should be noted that the precise way information was provided here is too simplistic for direct application in real traffic.

## INTRODUCTION

Today, more and more technology finds its way into our daily lives and affects the way we interact with each other. Interactions with other road users are no exception to this observation. In a considerable number of studies technological applications have been shown to affect each road users' *individual* behaviour [e.g., 1, 2, 3, 4, 5]. A less explicitly researched aspect is the way technological applications ultimately affect the *interaction* between road users. Although there are studies [e.g., 6, 7, 8] that have included measures indicating effects of technological applications on the interactive aspect of the driving task (e.g., approach and turning behaviour at intersections, gap acceptance, braking behaviour), the interactive aspect of the driving task is rarely, if ever, the main issue in these studies. It appears that the phenomenon where one road user's behaviour is affected by what happens in the environment, *including* the behaviour of other road users, remains an undervalued topic in research on driving behaviour. This paper aims to fill the gap by focusing on the consequences for the safety and efficiency with which road users will (potentially) interact.

Interactive driving behaviour is easily observed at intersections where drivers encounter other drivers on their paths. To regulate the interaction, traffic lights are often installed, preventing drivers on conflicting paths being in the same place at the same time. However, traffic lights cannot totally prevent crashes at intersections which is partly due to the well documented "amber light dilemma". The amber light dilemma occurs on a road section upstream from a signalised intersection in which a driver approaching the intersection will neither be able to stop safely after the onset of amber, nor be able to clear the intersection before the end of the amber duration, while overall complying with the traffic regulations (i.e., not accelerating at an amber light)[9]. Besides signalised intersections, where interactive driving behaviour is largely controlled and eliminated by traffic lights, intersections without traffic lights also exist, where interactive behaviour can be observed more easily. At the latter intersections, the amber light dilemma, by definition, does not exist. However, a similar dilemma can still occur at intersections without any designated priority. Take two different drivers approaching an intersection. A third driver's approach from the right can be interpreted as a traffic light with different colours. If the driver is far away and/or approaching slowly, this can be

interpreted as a green light. If the driver is rather close and/or approaching at a high speed, this can be interpreted as a red light. Everything in between can be interpreted as the amber phase of the light and is up to the specific interpretation of the drivers approach. For example, one driver might interpret the third driver's approach as a potential conflict and decide to yield, whereas a second driver might decide to accelerate and clear the intersection before the approaching driver has reached it. These different interpretations could lead to a rear-end collision if the second driver does not anticipate the first driver braking for the approaching driver. The dilemma here is in interpreting the approach of third road user and anticipating if this will conflict with your own trajectory. How is it, that without time or facilities to negotiate who goes first, drivers usually are able to stay out of each other's way?

To be able to successfully interact in traffic, we can assume that road users need *expectations*. Adequate expectations help drivers anticipate what other road users might do allowing them to prepare for a certain action. Expectations are a way of coping with the time constraints that apply in many situations where interactive driving is required. There are also other ways to help drivers cope with the time constraints in these kinds of situations. For example, allowing drivers a better view of the intersection will help them to better anticipate what will happen. Or, by behaving as could be expected, drivers can help other drivers anticipate their behaviour better. These examples all illustrate how increasing the time and space drivers have to safely negotiate an intersection (the so-called "interaction-space" [10]) can help drivers with their interactive driving. Different manipulations of interaction space have been a central issue in the experiment discussed here. What happens with the safety and efficiency of the interaction when interaction space is increased? Are there ways that have a particularly positive effect on either safety or efficiency?

Safety might come at the cost of efficiency. For example, when confronted with another road user slowing down who has right of way (i.e. an unexpected situation), one could decide to come to a complete standstill, which increases the amount of time needed for both road users to cross the intersection. On the other hand, interactions in this particular situation can be considered to be rather safe as well. The abovementioned behaviour of the road user could be identified as a “stop and wait” strategy as opposed to a “flying” strategy, where either one or both road users adapt to the other’s behaviour so they can both cross the intersection without anyone having to come to a standstill. Perhaps when the available interaction space is sufficient to ensure a safe interaction, the road user might choose to decrease the interaction space by increasing speed, thus creating a trade-off between “excess” safety and efficiency of the interaction. Literature discussing a trade-off between safety and efficiency has focused mainly on the engineering aspects of the situation rather than on the behavioural aspects [e.g., 11]. To investigate the presumed trade-off relationship between safety and efficiency, the present experiment also included several behavioural indicators of the efficiency of the interaction.

In this experiment interaction space was manipulated by varying the expectedness of the approach speed of the other driver relating to the righthand –right of way regulation that applies in the Netherlands. Additionally, interaction space was manipulated by providing drivers at intersections with information about other approaching drivers through a (virtual) technological application.

## METHOD

Twenty-six experienced participants took part in an experiment conducted in two linked Green Dino fixed-base simulators[12]. These simulators were connected in a way that allows the drivers of both simulators to encounter each other in the same virtual world.

The experiment attempted to manipulate the interaction space through several independent variables: varying expectancy, varying visibility and varying the information provided. The approach speed of other drivers could either be *expected* or *unexpected* in relation to their right of way. The route included intersections that varied in *visibility* of the intersecting road. The final manipulation of interaction space concerned providing participants with extra information concerning the behaviour of other road users approaching the intersection. The extra information was presented through headphones (auditory information) as well as on the dashboard (visual information). Through the headphones, participants were alerted by a series of beeps, presented to the ear which corresponded to the direction from which the other driver was approaching. The length and pitch of the beeps corresponded to the approach speed of the other road user. That is, long and low pitched beeps indicated a slowly approaching road user, whereas short high pitched beeps indicated a rapidly approaching road user. A red flashing light to the left or right of the centre of the speedometer indicated road users approaching from either the left or the right. The rate of flashing of the light corresponded to speed of the other road user as well (Figure 1).

**Figure 1. Location of flashing lights on speedometer.**

**Table 1.**
**Dependent variables**

| Variable | Explanation | Range |
|---|---|---|
| TTCmin | Minimum Time to Collision[13] | ≥ 0s |
| Safety | The natural log of the difference between the time in seconds to the estimated collision point of the participant and the other road user [14], when the participant is 15m from the centre of the intersection.<br>N.B. Values >3 indicate that one of the interaction partners stood still, and cannot really discriminate anymore. | ≥ 0 |
| DTI_Brake | The participant's mean distance to the intersection (DTI) in meters when the brake is first pressed. | 0 -150m |
| Hard Braking | Indicates how often the participant pushed the brake for more than 60% | 0 (never) – 1 (always) |
| DTI_Throttle | The participant's mean distance to the intersection (DTI) in meters when the throttle is first released. | 0 -150m |
| Near miss | Indicates how often the difference in time to the estimated collision point of the participant and the other road user was less than 1.5 seconds | 0 (never) – 1 (always) |
| Collision | Did a collision occur? | 0: no; 1: yes |
| Efficiency | Sum of average speeds of both interaction partners (km/h) from when they were between 150 m. before the intersection to reaching the centre of the intersection | ≥ 0 km/h |
| Speed_after | Participant's speed at the moment of leaving the intersection | ≥ 0 km/h |
| Standstill | Indicates how often a participant's speed was < 1 km/h (proportionally over all encounters). | 0 (never) – 1 (always) |
| Mean Yield | Indicates how often a participant yielded (proportionally over all encounters). | 0 (never) – 1 (always) |
| Mental Effort | Subjectively perceived mental effort as indicated on the RSME[15] | 0-150 |
| Usefulness | Mean score on items on subscale of Acceptance[16] concerning Usefulness | |
| Pleasantness | Mean score on items on subscale of Acceptance[16] concerning Pleasantness | |

The present experiment included a wide variety of measures that could provide information concerning the safety and efficiency of the interaction (Table 1). To help interpret the quantitative behavioural data derived in this experiment, a measure indicating mental workload [15, Rating Scale Mental Effort] and a measure to assess the acceptance of new car features [16, Acceptance scale] were also included.

In total, there were 4 driving sessions; 2 with and 2 without extra information. Participants drove through a simulated urban environment with intersections where they could encounter another road user, who was controlled by the experimenter in the second driving simulator.

## RESULTS & DISCUSSION

This paper will only address the results of the experiment quite sketchily in order to focus more on the implications. For a more detailed account of the experiment and its results, the reader is referred to Houtenbos, 2008[10].

### Interaction space and safety

A large number of statistical analyses included different measures of safety. It is plausible that increasing interaction space should lead to increased safety, as the increased interaction space allows road users more time to adapt their expectancies to the situation as it develops and select an appropriate course of action. There are some results that support that idea, but also results that seem to suggest the contrary.

To start with the supporting results, the results for $TTC_{min}$ show shorter values (safety ↓) in the medium visibility condition compared with the high visibility condition (interaction space ↓). More hard braking (safety ↓) also seemed to occur in the low visibility condition (interaction space ↓). Also, more near misses (safety ↓) were found in encounters where the other road users approached while maintaining speed (interaction space ↓), in encounters where participants were not provided with extra information (interaction space ↓), when visibility was very low (interaction space ↓) and when the other road users approached in a way that would not be expected (interaction space ↓). Results suggesting the contrary include the results for the Safety index (Figure 2). The lowest scores were found when visibility was medium or high (interaction space ↑) and when the other road users approached normally (interaction space ↑). Participants tended to release the throttle and apply the brakes when they were closer to the intersection (safety ↓) when extra information was provided (interaction space ↑). Although the abovementioned results might seem contradictory, they can be explained by the differences between these measures. Near misses and hard braking are perhaps measures more closely related to the critical aspects of (unsafe) situations as they correspond to a relatively late stage in the interaction process compared with measures such as DTI_Brake, DTI_Throttle and Safety. To explain, near misses and hard braking will generally occur closer to an estimated collision point than releasing the throttle and applying the brake and also past the 15m to the intersection used to determine the Safety index. Thus, near misses and Hard Braking might be indicators of a more critical stage in the interaction process and thus more direct indicators of interaction safety, whilst early brake and throttle manipulations might be more relevant related to efficiency.

These results also imply that the interaction process consists of a stage where there is a tendency towards proactive caution, which, depending on the way the situation develops, might be followed by a stage where there is a tendency to reactive caution. Further away from the estimated collision point, a driver is more likely to be in the “proactive stage” and act accordingly by releasing the throttle or gently applying the brakes. As the driver comes closer to the estimated collision point, it is plausible that the need for reactive caution is assessed and the brakes might need to be instantly applied with considerable force and the result could be a near miss. Assuming such a distinction between a proactive and reactive stage, the results of this experiment suggest that the measures of safety related to the latter stage are more prone to the applied manipulations of interaction space.

### Interaction space and efficiency

Concerning the effect of increasing interaction space on efficiency of the interaction two opposing effects could also be imagined. It is possible a trade-off relationship exists between safety and efficiency. Charlton [17], for example, shows that the interaction space can also be too large for optimal safety results. He conducted a field test on an intersection where the intersecting road was visually restricted to improve safety and reduce approach speeds. Perhaps in situations that are experienced as sufficiently safe, “excess” safety is traded for increased interaction efficiency. If so, we would expect to find opposite effects for measures of efficiency compared to the effects we found for measures of safety. On the other hand, we could expect participants to use the increased interaction space to increase interaction efficiency, which would imply that increased efficiency should be found for situations with increased interaction space. The results for the different measures of

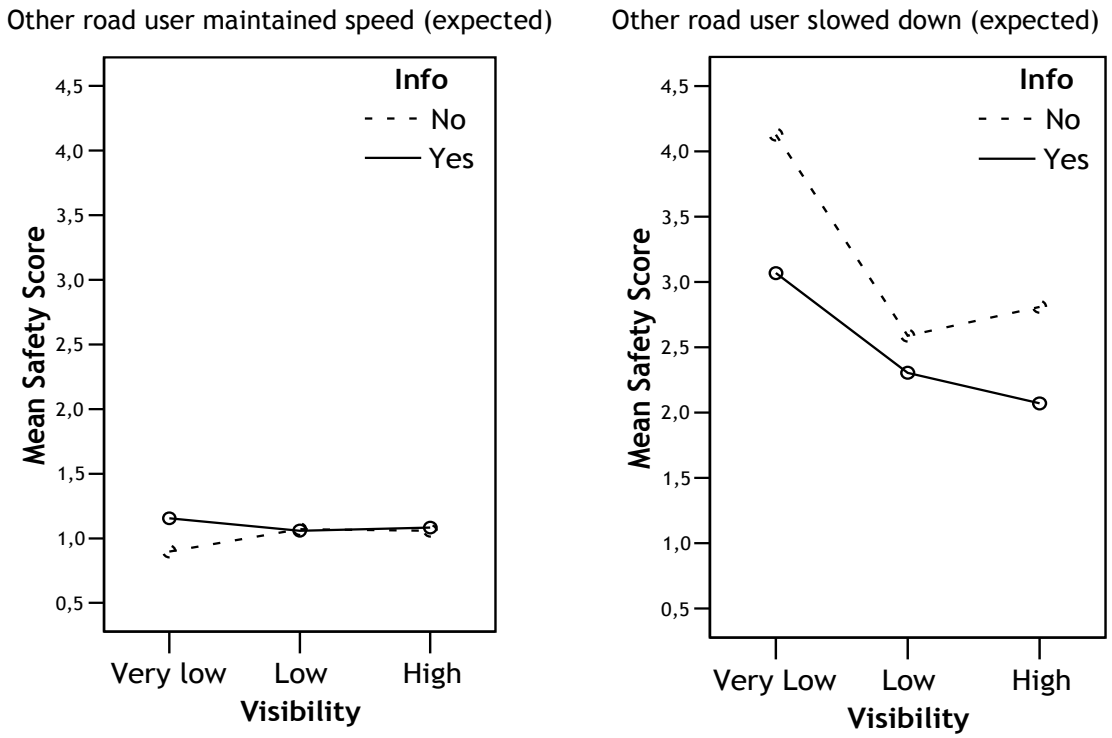


**Figure 2. Safety results for different manipulations of interaction space.**

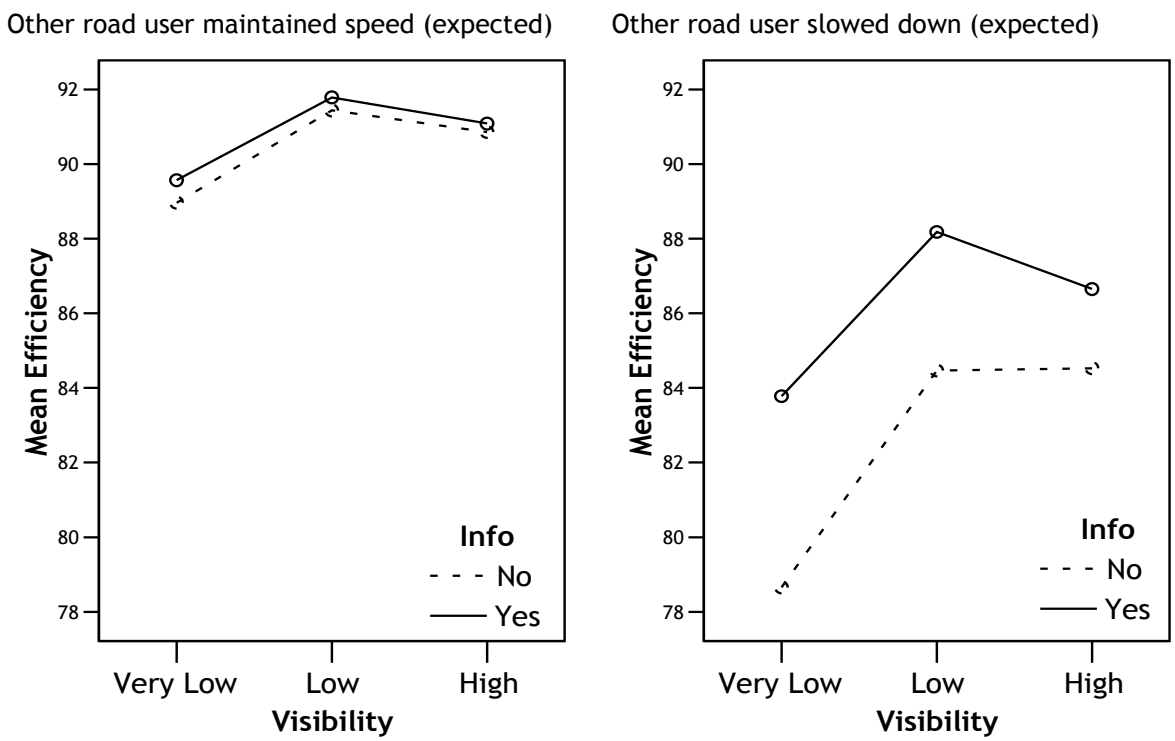


**Figure 3. Efficiency results for different manipulations of interaction space.**

efficiency seem to point in the direction of the latter hypothesis. The results for the different measures of efficiency seem to point in the direction of the latter hypothesis. The Efficiency index (Figure 3) shows higher scores (efficiency ↑) when extra information is provided, particularly in the situation where the other road user illustrated expected behaviour by slowing down (interaction space ↑), and in the medium and high Visibility conditions (interaction space ↑). Higher scores were also found when the other road user behaved as could be expected (interaction space ↑). In accordance, participants' speed when leaving the intersection was higher (efficiency ↑) when extra information was provided (interaction space ↑) and when the other road user behaved as could be expected (interaction space ↑). The final measure of efficiency also indicated less standing still by the participant in these expectancy conditions. In conclusion, the results indicate that particularly the extra information enabled participants to create a more efficient interaction (compared to when they did not receive extra information), allowing participants to cross the intersection without decreasing speed that much. When efficiency was already rather high, as was the case in the situations where the other road user approached the intersection while maintaining speed, providing extra information did not seem to increase efficiency any further.

**Trade-off Safety vs. Efficiency**

Do the abovementioned results for the safety and efficiency measures indeed indicate a trade-off relationship? If we were to divide the safety measures into measures of proactive vs. reactive behaviour, the effects found for proactive behaviour (DTI_throttle) indicate a trade-off with the effects found for the efficiency measures. For example, the results indicated that when information was not provided, participants tended to release the throttle further from the intersection. Values for the Efficiency index in those encounters were found to be lower, suggesting the existence of a trade-off relationship, in this case, efficiency being traded in for safety.

The fact that evidence for such a relationship is not found for the measures of safety relating to the "reactive stage" can be explained. Take the least safe result of an interaction process: a collision between the interaction partners. In that case, the situation is highly unsafe, but also highly inefficient, as both partners will not be moving. Perhaps the same holds for Near Misses, suggesting the existence of an optimum in the trade-off relationship between safety and efficiency, beyond which both suffer.

**Proactive and reactive**

The distinction between proactive and reactive control has also been made by, for example, Fuller [18] and Hollnagel [19]. Fuller pointed out that a driver can either make an anticipatory avoidance response (i.e. proactive) or a delayed avoidance response (reactive). The first is generally made before being certain that it is really necessary to ensure safety. If an anticipatory avoidance response is not made, a delayed avoidance response might eventually become necessary. However, in that case, less time is left to make an adequate avoidance response.

Hollnagel's Contextual Control Model (COCOM) provides a more detailed account of the distinction between proactive and reactive control [19]. He identified four control modes, which vary in the degree of forward planning and reactivity to the environment. The first two modes, "strategic" and "tactical", are based on long term planning and procedural short term planning respectively and can be considered more proactive, as they allow road users to anticipate future events. Behaviour in the latter two modes, "opportunistic" and particularly the "scrambled" mode, is much less planned but highly reactive to the immediate environment [20]. The mode is determined by several factors; the knowledge and experience of the individual, the rate of change of the process and the subjective (and objective) time available. The first two factors can be related to the concept of expectancy, as expectancy also depends on prior knowledge and experience (reflected in a rather general *long term expectancy*) and adapts to changes that occur in the process (reflected in a quite specific *short term expectancy*). The latter factor, the available time, can be linked to the concept of "interaction space", which will be discussed further on in this paper.

According to Hollnagel, people tend to move between control modes in linear fashion, which is corroborated by Stanton, Ashleigh, Roberts and Xu [20]. This suggests a continuous scale ranging from proactive control to reactive control. People should attempt to achieve strategic or at least tactical control which allows for a certain amount planning and anticipation, increasing the potential of reaching the desired outcome. The reactive modes, the opportunistic mode and particularly the scrambled mode should be avoided as these modes provide rather limited opportunities to recover from errors[21].

During the phase of the interaction process in which proactive control is most likely, the environment will provide less of the specific

information needed to adapt the long term expectancy into a detailed short term expectancy than during the phase of the interaction process, in which reactive control is more likely. For example, one road user might not even see any other road users but proactively release the throttle based on the general knowledge that the intersection ahead is often rather busy. In such a situation, the short term expectancy used to select the proactive throttle action is not so much more specific than the long term expectancy concerning how busy such an intersection can be. In contrast, during the reactive phase, the environment provides many more elements that allow the long term expectancy to become a rather specific short term expectancy.

The results of this experiment, which used a variety of measures to indicate the level of interaction safety, seem to support the distinction between a proactive phase and a reactive phase. The results suggested that the transition from the proactive phase towards the reactive phase is not only affected by the amount of situational information available, but also by the interaction space available, which is in line with Hollnagel's [19] idea about the time available determining the control mode. The Safety index and initial throttle and braking behaviour seemed to be indicators of the proactive phase, referring to behaviour more towards the start of the interaction situation, where the remaining interaction space is still relatively large. $TTC_{min}$, near misses and hard braking seemed to be indicators of a reactive phase, referring to behaviour more towards the end of the interaction situation, which generally coincides with limited interaction space.

**Supporting interacting drivers**

The results indicated that the extra information did not affect participants' decision to yield, but did affect other behavioural aspects concerning the approach to the intersection. For example, the safety indicators relating to the phase in the interaction situation in which the proactive mode is likely to be active (Safety index and throttle behaviour) indicated a decrease in safety as a result of providing extra information. However, a lower proportion of near misses occurred in the session with extra information indicating an increase in safety in the phase of the interaction in which the reactive mode is likely to be active. Thus, providing extra information seemed to weaken performance in the proactive mode and improve performance in the reactive mode. Furthermore, the efficiency indicators (Efficiency index and the participants' speed when leaving the intersection) indicated an increase in efficiency as an effect of extra information.

When asked about their experience with the extra information, participants indicated that they found the beeps to be quite useful, particularly compared to the lights, which they regarded as unpleasant and not useful at all. Participants indicated that the presentation of lights in the speedometer often went unnoticed as they tended to look towards the intersecting roads for relevant information rather than on their speedometer. This tendency could be taken as a suggestion for human machine interface design not to place information intended to aid a user at a location where the user would need to search for it before being able to perceive it. Instead, using a modality not dependent on search behaviour such as audition or touch could be a solution.

Furthermore, participants indicated that although they experienced the beeps as quite helpful, they did not experience them as pleasant to the same extent. Several participants even indicated that they experienced the driving task to be less interesting when provided with extra information. This observation corresponds to the findings regarding the decrease in subjective mental effort in sessions with extra information. Although a decrease in workload implies a road user would be better able to adequately react to unexpected situations (more resources to adapt the expectancy), it should be kept in mind that a workload that is too low is also undesirable [22].

Another consideration involves the effect technological applications will have on expectancies of drivers, which could cause behavioural adaptation. The effect of behavioural adaptation can range from positive, through neutral, to negative, where the negative effects are considered most important to be able to predict in the context of traffic safety [23]. Future research endeavours to develop a system to support the interacting driver should take the concept of behavioural adaptation in to account when discussing the potential safety effects.

The results indicated that the extra information, and in particular the beeps, did help participants to create more safe and more efficient interactions. However, it would be premature and unwise to conclude that we have proved that the extra information "works" in general to create safe and efficient interactions. All that can be concluded is that the particular way in which we provided extra information, worked in the simple and small range of situations that were presented to the participants. For example, imagine what would happen if not one, but two road users would approach the intersection at the same time or even shortly after each other. How would the participant be able to distinguish between the two approaches? It should

be noted that the aim of this experiment was not to test an application that is meant to help road users at intersections, but merely to determine the effects of different manipulations of interactions space on road users' interactive behaviour. The results of the experiment do, however, provide encouragement for further research in this direction.

## CONCLUSIONS

The results suggested that the available interaction space is primarily used for safety and if there is any additional interaction space it is used to increase efficiency. Thus safety generally has priority over efficiency. Additionally, the results indicated a trade-off relationship between proactive caution and efficiency: when participants tended to be rather cautious in the proactive phase, these interactions tended to be less efficient. Interactions where participants tended to rely on reactive control tended to be more efficient.
More studies of this interaction space-time are recommended to explore how drivers' strategies are influenced by the different parameters manipulated here, but also others that were not included in the present studies. This would need more parameters of the behaviour of both vehicles and drivers to be recorded than was the case in the experiments in this thesis, and would require more exploration of interactions with a more 'natural' behaviour of the experimenter's vehicle (as the experimenter followed a protocol in the present experiment).

This paper has discussed a start on research in a much neglected area, that of interaction behaviour in traffic. It has shown that there is a world of insight to be gained in the subtleties of how road users react to each other. Since technological applications intervene in this subtle and complex world of prediction and feedback, reaction and learning, we need to know a great deal more about how this all works if we are to avoid making expensive mistakes in introducing it, or to avoid missing opportunities which it can offer.

## ACKNOWLEDGEMENTS

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# Implications for HMI design: Understanding age induced limitations on in-vehicle task complexity

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## ABSTRACT

Recent technological advances have enabled a wide variety of information systems to be integrated into a vehicle in order to increase productivity, safety, and comfort. However, improperly deployed technology can degrade safety and annoy drivers. Especially, potential information overload problems may become acute among older drivers who are the fastest growing segment of the driving population.
This paper aims to understand the age-related driving performance decline under a series of increasingly complex in-vehicle auditory tasks (n-backs). Data was drawn from a series of single task exercise and repetitions of the tasks under simulated driving conditions. In the simulation, 63 participants aged 20's and 60's drove through either a complex city or highway paradigm, appropriately counter-balanced. At a specified location in the canter of each of the two contexts, participants were asked to complete a series of auditory tasks of increasing complexity. Before beginning and after completing the simulation, drivers were asked to complete the auditory task in stationary non-driving conditions. Comparisons of younger and older drivers' secondary task performance will be discussed. In addition, differences in driving performance including average speed, speed variability, and lane keeping performance will be used to gauge older adult's capacity to regulate the demands of complex in-vehicle tasks in safe manner.

## INTRODUCTION

Driving is a complex psychomotor task often interrupted by secondary activities that divert attention away from the roadway. Diversion of attention to secondary tasks is one of the largest contributors to inattentive driving and, consequently, to accidents (Stutts and Hunter, 2003). Therefore, an understanding of how drivers allocate attention and manage workload is important for informing both vehicle design and driver education. For the vehicle design side, voice recognition is widely used by vehicle manufacturers to reduce secondary workload. Currently voice recognition is considered the safest input user interface and is currently used as input for various infotainment, telematics and other comfort features. However, voice recognition technology also increases cognitive workload. Therefore, it is suggested that the impact on the older driver should be evaluated, since an individual's capacity for managing multiple tasks simultaneously is known to generally decrease with age (McDowd *et al.*, 1991; Rogers and Fisk, 2001). While absolute capacity declines with age, the judgment of typical drivers increases throughout the lifespan. In younger drivers, impaired judgment is often associated with excessive speed and alcohol use (Boyle *et al.*, 1996) while older drivers have been observed to recognize possible limitations and self-regulate their behavior by limiting their exposure to situations in which they may be at higher risk (D'Ambrosio *et al.*, 2008). When workload is high, there is evidence that some drivers engage in compensatory behaviors, such as moderating their driving speed, to manage workload (Harms, 1991; Reimer, 2009; Mehler *et al.*, 2009).
Therefore, when design voice recognition interface, we need to understand the older drivers' behavioral characteristics under dual task conditions.
In this study, we used an auditory cognitive task which is designed for providing increasingly complex in-vehicle auditory tasks (n-backs). The performance of younger and older drivers during single task simulated driving and in response to the added demand of a secondary cognitive task are compared. The overall simulation looked at both urban and highway driving environments.

## METHODS

### Participants

Participants were: a) required to be between the ages of 20 and 29 or 60 and 69, b) drive on average more than two times per week, c) be in good health and free from a number of major health conditions such as cancer or uncontrolled high blood pressure, d) not taking medications for chronic depression or other

psychiatric conditions, e) have a mini mental status score (Folstein *et al.*, 1975) greater than 25 and f) not previously participated in a driving simulation study. Participants were required to sign an informed consent form.

**Apparatus**

The experiment was conducted on the DGIST fixed-based driving simulator, which incorporated a Mercedes-Benz™ Smart car and STISIM Drive™ software (see Figure 1). Graphical updates to the virtual environment were computed using STISIM Drive™ based upon inputs recorded from the OEM accelerator, brake and steering wheel which were all augmented with tactile force feedback. The virtual roadway was displayed on a large, wall-mounted screen at resolution of 1024 x 768. Feedback to the driver was also provided through auditory and kinetic channels. STISIM Drive provided vehicle sounds that varied with acceleration, braking, and movements off the road. Both urban and highway settings were simulated, using only daylight and dry road conditions. Completed distance, speed, and steering, throttle, and braking inputs were captured at a sampling rate of 20-30 Hz.

**Figure 1. The DGIST fixed-based driving simulator**

**Secondary Task**

An auditory prompt and verbal response "n-back" task, which can systematically ramp-up the total task demand on a driver without requiring direct conflict with the manual control or visual processing demands of the primary driving task (Zeitlin, 1993), was employed in this study to develop a baseline of older drivers' dual task capabilities. The form of the n-back employed consisted of a series of 10 single digit numbers (0 – 9) presented aurally to the subject. Each value was presented once per test set and the order of the digits varied with each presentation. The 10 numbers were presented with an inter-stimulus interval of 2.25 seconds, thus requiring fairly rapid response from the subject to keep pace with the task. Consecutive tests appeared every 30 seconds, allowing for only a brief pause between sets.

This secondary task consisted of three levels of difficulty and presented as a block of six trials. The first two trials employed a very mild demand (0-back), the second to two trial a moderate demand (1-back) and finally two trials a high level of task demand (2-back).

In the '0-back' version, the subject was simply to repeat out loud each number immediately after it was presented. In the "1-back" condition, instead of repeating the current number, the subject was required to recall from memory and respond out loud with the number that was presented just prior to the current number (i.e., 1 back from the current number). The '2-back' form of the task required subjects to recall from memory and to verbalize the number that was presented two numbers prior to the current value (i.e. 2 items back). The overall layout of the task was designed to sequentially increase the cognitive load on the subject both in terms of absolute difficulty and sustained load (Mehler *et al.*, 2009)

**Procedure**

After an introduction to the experiment, training on each level of the n-back task was provided. To facilitate learning, participants were given a written guide to follow along with the research assistant's verbal description and presentation of practice trails. Training on each level continued until satisfactory scores were reached (less than one error on a 0-back task, less than four errors on two consecutive trials of 1-back tasks and less than five errors on two consecutive trials of 2- back tasks). Participants then entered the simulator and began a driving habituation period designed to increase participants' comfort with the simulator. This experience uses a slow "ramp up" approach to reduce the potential for simulator sickness.

Following the habituation period, participants stopped driving and completed a non-driving assessment of the n-back task (six trials) and a questionnaire. The primary simulation protocol followed. To enhance the demands of driving the simulation, a financial incentive was used to encourage people to maintain speed, obey the traffic laws, and devote attention to secondary cognitive task (Mehler *et al.*, 2009; Reimer *et al.*, 2006). During the initial briefing subjects were told that that in addition to the base compensation 25,000KRW, an additional 10,000KRW could be earned during their drive by performing a series of secondary tasks. In order to simulate the conflicting demands of

"real" automobile driving subjects were instructed that some of the incentive could be lost for non-safe driving such as a crash and traveling too fast or too slow in relation to the posted limit.

During this period participants engaged in an urban and highway driving experience each lasting approximately 15 minutes. No rest period was provided. The presentation order of the conditions was counterbalanced such that half of the participants drove in urban setting first. During a portion of the urban and highway drive, the n-back task was presented. This procedure provided three equidistant periods of roadway in which to assess driving performance. Following the simulation, a second non-driving assessment on the n-back task was carried out. Figure 2 shows the structure of suggested experimental protocol

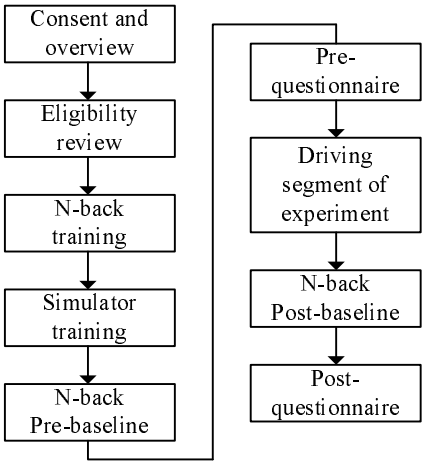


**Figure. 2 Structure of experimental protocol**

## Data Analysis

Data was normalized to reduce the impact of speed on sampling differences in time. The normalization was performed by creating 40 intervals over the 305m(1000ft) that comprised of the average raw (forward velocity and lane position) measure recorded over each consecutive 7.62m (25 ft) road segment. Overall statistical measures were then calculated over the interval data.

Statistical comparisons were computed using SPSS version 14. A level of $p<0.05$ was adopted for all significance statements. Comparisons were made using an ANOVA analysis.

# RESULTS

## Sample

The sample consisted of 63 participants, 32 in the 20's and 31 in 60's. Gender was balanced by age (one older female participant was not run). Participants averaged 24.6 (S.D. = 2.3) and 63.9 (S.D. = 2.7) years for the two age groups.

## Secondary Task Performance

Cognitive task performance was assessed as an error rate computed as the percentage of incorrect or non-responses to the total number of stimuli. Error rates are reported in Table 1. Error rate increased under dual-task conditions, $F(1,118) = 4.18$, $p = 0.043$. Older participants committed an error 28.79% more often than the younger group, $F(1,118) = 77.56$, $p < 0.001$.

**Table 1.**
**Composite accuracy scores on the secondary task**

| | | Non-driving | Dual-task |
|---|---|---|---|
| 20's | Male | 3.90(6.59) | 6.69(7.36) |
| | Female | 4.96(7.12) | 10.12(9.75) |
| Total | | 4.43(6.77) | 8.41(8.68) |
| 60's | Male | 26.92(20.60) | 35.14(17.20) |
| | Female | 30.83(27.94) | 39.39(24.82) |
| Total | | 28.81(24.09) | 37.20(20.98) |

* Note: table entries are mean percentages with the standard deviation in parentheses

Using the error rate for all tests undertaken by the participants as an index, performance was essentially perfect (1.66%) across subjects for the 0-back (see Figure 3). As the level of cognitive challenge increased, error rates of 16.7% appeared for the 1-back and 41.7% for the 2-back. The effect of task difficulty on error rate was significant across all 3 levels of the n-back task ($F(2,189) = 42.1$, $p<0.001$). The observed error rates support the assertion that workload increased across the task periods.

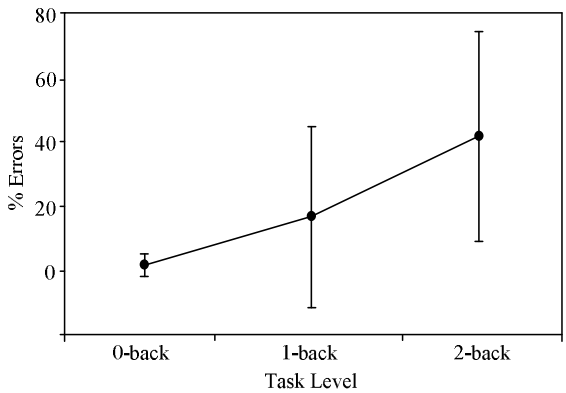


**Figure. 3 N-Back Errors as a Function of Task Difficulty**

## Driving Performance

**Forward velocity** - Forward velocity is presented in Figure 4. Consistent with Mehler et al. (2008), forward velocity is significantly affected by the secondary task, $F(2, 177) = 7.641$, $p=0.001$. Across age and gender, velocity decreased by 1.21 m/s during the secondary task and recovered by 1.43 m/s afterwards.

Age interact significantly with the secondary task on forward velocity, ($F(2, 177) = 3.812$, $p = 0.024$), but the difference between age groups, $F(2, 177) = 0.056$, $p=0.813$, and between genders, ($F(2, 177) = 2.863$, $p=0.092$), were not statistically significant.

As shown in Figure 2, participants drove slower during the dual-task and resumed near the pre-task speed following the secondary task. Especially, the older drivers were more affected by the secondary task.

During the task, younger drivers slowed 2.7% and older drivers were 10.1%. It suggested that the secondary task impacted on primary driving task and the older drivers were more significant than younger drivers.

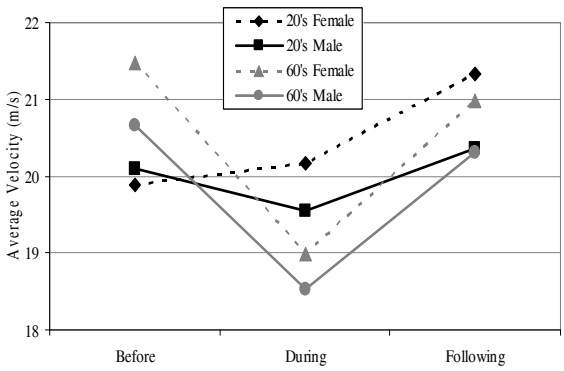


**Figure 4. Forward velocity by age and gender**

**Speed control** - Figure 5, displays speed control expressed as the percent coefficient of variation on velocity. The difference between age groups was statistically significant, $F(1,177) = 12.614$, $P<0.001$, but gender, $F(1,177) = 0.509$, $p=0.477$, and the secondary task, $F(2,177) = 1.864$, $p=0.158$, were not statistically significant.

According to Figure 3, the coefficient of the older drivers was increased during the secondary task and decreased after the task, while the younger drivers' coefficient was barely changed during secondary task but increased following the task.

During the task, the coefficient of younger drivers decreased 3.9% and older drivers increased 22.9%. This results suggested that the secondary task impacted on primary driving task, and the older and younger drivers had an opposite characteristics. The older drivers have more difficulty controlling speed during the secondary task.

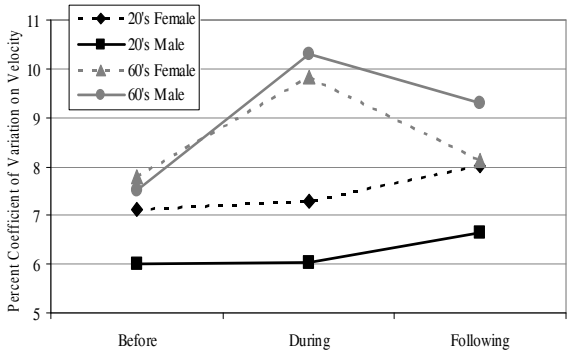


**Figure 5. Percent coefficient of variation on velocity by age and gender**

**Lateral control** - Lateral control expressed as the standard deviation of lane position is shown in Figure 6. Consistent with earlier field studies on younger participants using n-back tasks (Reimer, 2009), drivers across gender ($F(1,177) = 4.874$, $p = 0.029$) and the secondary task ($F(2,177)= 3.269$, $p = 0.040$) showed a significant reduction in lateral variation, , while no significant age effect exist, $F(1,177) = 3.137$, $p = 0.078$.

As shown in Figure 4, the standard deviation of lane control of all participants except younger male drivers was decreased during the secondary task and increased after the task. Regarding the younger drivers' behavior, we need additional subject for better understand.

During the task, the standard deviation of lane position of younger and older drivers decreased 19.1% and 18.7%, respectively. There was no significant difference across age.

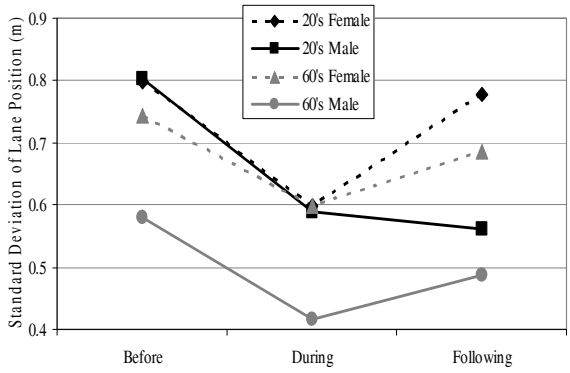


**Figure 6. Standard deviation of lane position by age and gender**

## CONCLUSION

This study aims to understand the age-related driving performance decline under a series of increasingly complex auditory cognitive tasks (n-backs). 63 participants aged 20's and 60's drove and completed the auditory cognitive tasks. From the younger and older drivers' secondary task and driving performance including average speed, speed variability, and lane keeping performance, we drew a characteristics of older drivers' dual task capabilities. Each of the age and gender subgroups showed a parallel decrement in performance on the n-back task during simulated driving relative to their performance under non-driving conditions. This may be interpreted as evidence that each group invested a comparable amount of their available cognitive resources in the n-back task during the driving phase relative to their overall capability to perform the task under single task conditions. Considering the sample as a whole, the introduction of the secondary task during driving resulted in a compensatory slowing of forward velocity during the heightened workload and an increase in driving speed following, extending previous findings (Mehler et al., 2008; Reimer, Mehler et al., 2006). Similarly there is the suggestion of a tunneling effect in which the standard deviation of lane position decreases, most likely due to a rigidification of control so that attention can be divided between the tasks (Reimer, 2009).

In summary, age appears to impact both driving performance and, consequently, compensatory behavior during dual load conditions. This suggests that the capacity declines with age should be considered when designing a in-vehicle interface system.

## LIMITATION

There are several limitations of this study. Connections between cognitive distractions such as voice recognition and cellular telephone use, and the surrogate n-back task are not well established. The use of monitored experimentation likely impacts drivers' performance versus that of truly naturalistic driving conditions. Results based upon the measure of lane performance do not include data from approximately half of the sample. Finally, the presentation of the n-back task was not randomized (always 0-back followed by 1-back and then 2-back task). Future research will attempt to address these limitations.

## ACKNOWLEDGEMENT

The authors would like to thank Junhyung Bae, Donghwan Shin for their assistance with data collection of this research.

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# EXPLOITABLE CHARACTERISTICS OF DRIVER BRAKING

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## ABSTRACT

Previous work (Perron et al., 2001) on emergency brake application concluded that driver population diversity and "the overlap of braking parameter distributions between normal conditions and emergency situations" is such, that triggering criteria cannot both detect all emergency braking actions and never activate the assistance in situations where it is not necessary. The objective of this study was to investigate driver-braking characteristics, in order that future systems might achieve greater effectiveness.

48 drivers drove an instrumented vehicle on a public road section before arriving at a test track, where they were instructed to follow at their preferred distance another vehicle towing a trailer. They were told the aim was to measure their preferred car-following distance. They were naïve to the fact that 0.2 miles down the track the trailer would be released and rapidly decelerate to a stop. The main variables analysed included "throttle-off" rate, brake pedal pressure/force, and clutch pedal pressure/operation.

The results indicate a series of relationships exploitable by an intelligent brake assist system. An intelligent brake assist system could take advantage of those characteristics and adapt its performance to individuals' braking style.

Limitations of the study include resource constraints (use of a single instrumented vehicle, time-limited access to the test track)and the contrived nature of the emergency braking scenario (need for surprise element, practically a one-off study, limitation of speed to 30mph/48kmph).

The study provides evidence of a background for a customisable brake assist system that learns from the driver and adjusts its full-brake trigger accordingly.

## INTRODUCTION

The huge potential of active safety systems can only be realised if driver input in the system is taken into account. Systems such as emergency brake assist, stability control and collision avoidance must be reliably triggered when drivers actually need assistance, but should not intervene in normal conditions. False alarms/interventions could have detrimental effects on driver acceptance of the system.

One problem with research on specific active safety systems is that because of its commercially sensitive nature, it often remains confidential to a large extent. Detailed research on ergonomic aspects of active safety systems often remains in the private domain and rarely is published. In one of the few exceptions, researchers working in the Laboratoire d' Accidentologique, Biomécanique et étude de facteur humain (LAB) published results of driver studies for the specification of active safety systems, and brake assist in particular (Perron, Kassaagi, & Brissart, 2001). Perron et al (2001) were the first to publish results of microscopic studies on driver braking in emergency conditions. They utilised both a driving simulator and an instrumented vehicle on a test truck to achieve their goal. In the simulator, four longitudinal accident configurations were examined: a vehicle coming out of a parking area into the subject's path, a vehicle stopped after a crest on a roadway, a vehicle moving at reduced speed after a crest, and a vehicle decelerating before braking strongly after being followed for 500m in an urban area. In the test track study, participants had to follow a vehicle with a trailer which was eventually released from a relative distance of 17m at a speed of 70km/h. Results indicated that while everybody braked, only 50% braked hard enough to activate ABS and only 80% of these exploited ABS function by swerving to avoid the obstacle. Authors concluded that if emergency brake assist was fitted to the vehicles, up to 40% of collisions would have been avoided and in another 30% of cases the impact speed would have been reduced by more than 15km/h. More than 70% of crashes would have been avoided if the brakes were activated at the throttle-off instant (approx 0.3 s in advance of actual braking). However, all these figures rely on "the hypothesis that the assistance is actually always triggered in emergency situations, which is an ideal case. Actually, due to the significant overlap of braking parameters distributions between normal conditions and emergency situations, triggering criteria based on a single braking parameter cannot both detect all emergency braking actions and never activate the assistance in situations in which it is not absolutely necessary"...

In an attempt to overcome this problem, researchers in LAB employed hybrid neural networks + genetic algorithm methodology in order to find parameters that could be used in combination to distinguish emergency situations from normal braking (Bouslimi, Kassaagi, Lourdeaux, & Fuchs, 2005). The result was a model that was quite successful in its purpose, however it relied on some parameters that were related to post-incident events – such as the result of the emergency manoeuvre, a fact that rendered it inapplicable in an intelligent brake assist system. Contemporarily, Schmitt and Färber (Schmitt & Färber, 2005) used Fuzzy-Logic to create a model that could distinguish successfully between normal and emergency braking. The model is based on three parameters of throttle-pedal operation: change of radius, jerk, and foot displacement time (from throttle to brake pedal). Data for this study was collected through the CAN bus of the vehicle 54 participants drove in a test-track study. Speed was restricted to 60km/h and the obstacle appeared en-route about 35m ahead of the vehicle. The authors claimed that their model predicts correctly 85% of emergency braking and 97% of braking before a corner, against 77% emergency braking and 99% braking before a bend correctly predicted by a system with a fixed trigger-level.

Recently, McCall and Trivedi (McCall & Trivedi, 2007) utilised Bayesian networks to fuse driver behavioural information with vehicle/environment information to predict an emergency or non-emergency situation. Inputs to the system include time-headway (from a LIDAR sensor), wheel speed, brake pressure, accelerator position, steering angle, vehicle longitudinal and lateral acceleration, yaw rate, steering angle and gaze and face expressions recorded using video-cameras. The authors provided supportive data of the effectiveness of the system in predicting critical situations; however they admitted that a significant problem was the number of false positives (undesired system activations). This was the case particularly when drivers covered the brake pedal but eventually decided not to brake. Although titled "brake support" by its authors the model aims more towards "brake automation" - automatic braking rather than augmented braking. It looks more towards vehicle-automation than towards driver-support.

A number of years has passed since the original introduction of (Emergency) Brake Assist systems in road vehicles and there is no published evidence that the challenge of accommodating the individual differences in driver braking has been achieved. The present paper provides an alternative approach towards the fulfilment of this goal. To achieve this, a human-centred approach is adopted. Individual differences are now seen as an exploitable opportunity rather than an obstacle towards successful human-machine interaction. The present study examines the relationships among basic parameters of driver longitudinal control and suggests how they could be exploited in an intelligent brake system to accommodate driver variability.

## METHOD

To achieve the aims of the study, 48 participants drove an instrumented vehicle on public roads and on a closed test-track. Each session allowed a combination of normal braking responses and an emergency braking episode to be recorded for each participant. The details of the study are presented below.

### Apparatus

A Ford Fiesta (2000 model year) was fitted with a camera in the footwell to record foot/pedal movements, an on-board camera provided view of the road ahead, two Tekscan Flexiforce® sensors were fixed on the brake pedal surface, one Flexiforce® on the clutch pedal surface, and a potentiometer was attached to the centre of the throttle-axis rotation. Sensors were calibrated according to Tekscan's guidelines (Tekscan, 2008). A Labjack® U12 data acquisition module was connected to a Toshiba® Tecra 3 laptop using Azeotech® DAQFactory® Express software for data logging. Power was provided through the vehicle's battery when the engine was on and through the laptop's battery when it was off.

**Figure 1: View from the on-board camera during the closed-track study**

**Figure 2: The trailer during built-up**

A lightweight (m<30kg) trailer was built for the purpose of simulating a lead vehicle's sudden braking ($a<-5m/s^2$) on the test track. The trailer's stopping properties were representative of average emergency decelerations of real vehicles in experimental (Vangi & Virga, 2007) and field studies (van der Horst, 1990). The trailer (figure 2) was three-wheeled for extra straight line stability; dimensions were 2.2m length, 1.25m rear width, 0.3m front width, and 0.4m height at the back. Wheels were 20inch standard road bicycle wheels. The structure comprised a sheet of waterproof wood reinforced with an aluminium skeleton. Two 0.75mx0.5mx0.5m cardboard boxes were filled with closed empty plastic bottles and wrapped with white plastic bags before they were attached at the rear of the trailer to create a "bulkiness" illusion (figure 1). Standard bicycle "V-brakes" were installed and were activated by the rotation of a lever which was activated by two springs upon release from the car. During testing average acceleration of the trailer after release was -6.81m/s$^2$ with an instantaneous minimum of -17.24m/s$^2$ achieved.

**The participants**

Participants were recruited through advertising in local press and local companies. Forty-eight drivers (26 male and 22 female) participated in the study. Age ranged from 21 to 84 (average 31.3) years, average driving experience was 12 years (min 1, max 48), and the average mileage was 9653 miles/year (min 2000, max 30000). They all held a full driving license (UK/EU or equivalent international) and had 3 or fewer penalty points.

**The route**

The public road section of the route driven by the participants included an urban and a rural section (11km in total) that led them from the start (Loughborough University Business Park) to the test track (Wymeswold Airfield). A section of the track was isolated and marked out with cones to provide a single lane for the emergency brake test. Sessions took place between 5 and 8pm on weekdays in daylight (Spring-Summer).

**The test protocol**

Participants provided personal details for insurance purposes before the experiment, as well as demographic data and a general health questionnaire. Just before the start of the driving session, they indicated their stress level on a 7-point Likert scale. They were told that the purpose of the study was to measure their preferred driving distance from other vehicles and for that purpose they would have to follow an instrumented trailer that would record this distance on the test track. Upon arrival to the test track they would stop at the entrance before an experimenter would check the site and give permission to proceed to the track. There, they were asked to follow another vehicle towing a trailer around the track at their preferred distance. They were told that this was the target variable of the experiment. Post-trial questioning confirmed that they were naïve to the fact that the trailer would be released after 0.2 miles (321.86 m). In each trial the lead vehicle accelerated to 30mph (speed measured using GPS) and kept a constant speed until the release of the trailer.

**Data analysis**

Participants' stress index before the study was compared to their stress rating immediately after the test-track study. Because of the non-parametric nature of the data, a Wilcoxon test was used. In order to examine the appropriateness of using brake force and/or "throttle-off" rate as single triggering criteria, mean values for the public road section were compared to the peak values during the emergency response. Paired Student's T-test and Wilcoxon test was employed for that purpose. Then, in order to examine the relationship between normal and emergency braking, each variable in the public road driving condition was plotted against the same variable in the emergency braking condition. Various regression models were tested in order to find the model with the best fit to the observed data. All the analyses were carried out using the Statistics Package for Social Sciences (SPSS) ver. 15.

## RESULTS

**Table 1.**
**Wilcoxon signed ranks test results for stress before and after test-track study**

| Stress after – stress before | Negative ranks | Positive ranks | Ties | Total |
|---|---|---|---|---|
| N | 3(a) | 33(b) | 11(c) | 47 |
| Mean Rank | 20.00 | 18.36 | | |
| Sum of Ranks | 60.00 | 606.00 | | |
| Z | -4.384(d) | | | |
| Asymp. Sig. (2-tailed) | .000 | | | |

a stress_after < stress_before
b stress_after > stress_before
c stress_after = stress_before
d Based on negative ranks.

Analysis of the drivers' self-rated stress-level before and after the emergency event on the test track indicated an increase in participants' stress-level (table 1). The resulted difference is statistically significant at $p<0.0001$ level.

Quantitative analysis of brake response indicated that about 50% of participants did not use the brake significantly, either because they swerved enough to avoid the obstacle, and/or they were following with long enough time-headway to gear-down and stop gradually. These data had to be cleaned because participants did not engage brakes to stop the vehicle. Figure 3 presents the resultant distribution of brake-force response of participants that used brakes (force on sensor>5N). To further improve the normality, three more outliers on the upper end of the distribution were removed from further analysis. Then, the relationship between the peak force during emergency and the typical force during normal driving (public roads) was explored.

**Table 2.**
**Paired T-test comparison of force between normal and emergency braking (in Newtons, measured on each sensor)**

| | Force on sensors, public road driving – Force on sensors, emergency event |
|---|---|
| Mean difference | -14.24443 |
| Std. Deviation | 11.50758 |
| t | -6.189 |
| df | 24 |
| Sig. | .000 |

Table 2 displays the results of a paired comparison between each participant's typical normal and peak emergency brake force. The difference is statistically significant at level $p<0.0001$. There seems to be a relatively constant difference between the two conditions **per individual.** Further, scatter-plot of typical normal braking against the respective emergency response (force) can be found in figure 4.

Linear and non-linear models were tested and the three best fitted ones are shown in figure 4 (linear, quadratic and cubic). Analysis of Variance (ANOVA) for each model indicated that the cubic model is yields the highest correlation value ($R=0.51$) but the worst statistic significance ($p=0.09$) of the three. The linear model explains less variance ($R=0.45$) but is more statistically significant ($p=0.02$). The quadratic model on the other hand is in between; Pearson R for this model is 0.50 and statistic significance is $p=0.03$.

Then, throttle-off characteristics for the whole dataset were examined. Figure 5 displays comparative values of throttle-off rate for each driver between normal and emergency conditions. In only 7 out of 58 cases are the respective values similar. A Wilcoxon test indicated a statistically significant difference between the two variables ($p<0.0001$).

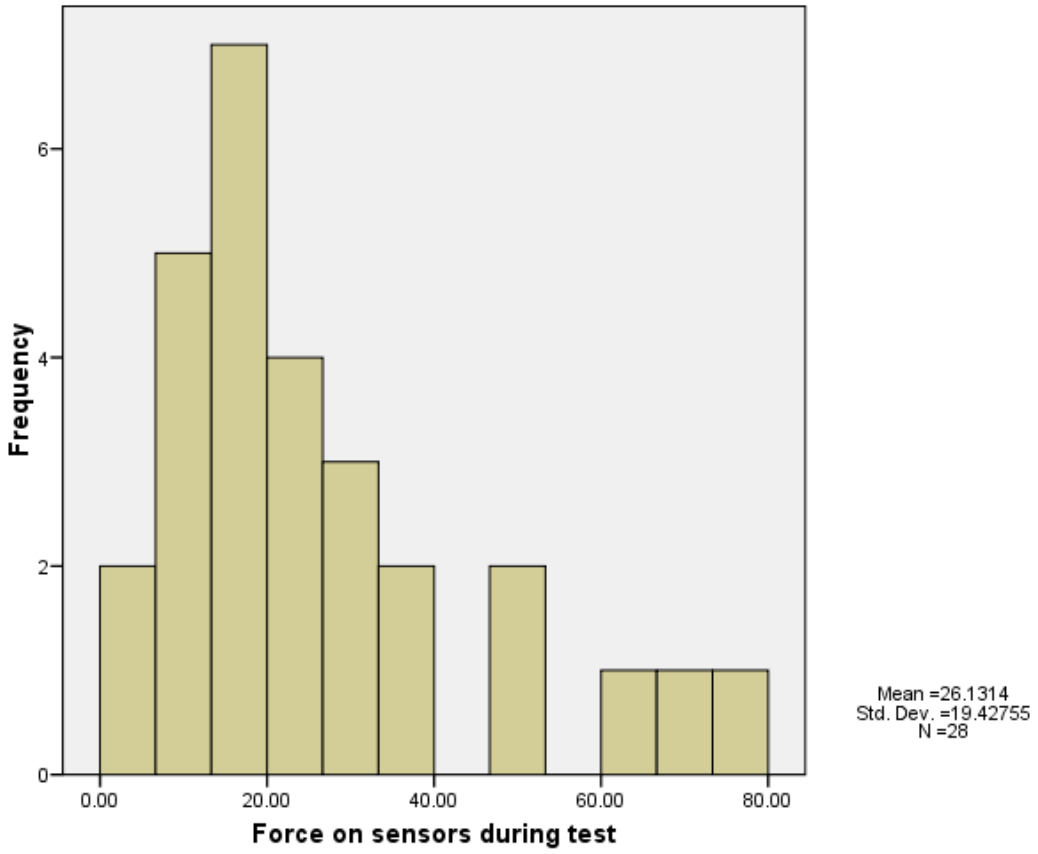


**Figure 3: Histogram of forces measured during emergency brake test after cleaning of data (force in Newtons, measured per sensor)**

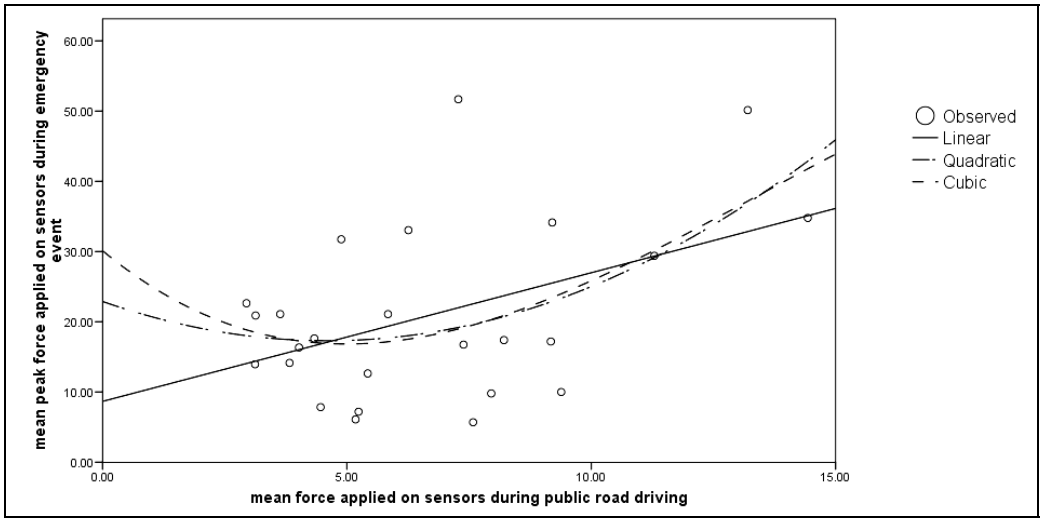


**Figure 4: Scatter-plot and best fit models of participants' normal and emergency braking in terms of force (measured in Newtons per sensor)**

## DISCUSSION

It is impressive how different the two conditions look through the paired-comparison for each participant. Both throttle-off and brake force distinguished very well ($p<0.0001$) between normal and emergency conditions per individual. However, as was the case in a previous study (Perron et al., 2001), this is not the case when drivers are mixed in a group. Some drivers' emergency response is quantitatively similar to somebody else's typical braking. There is a difference though between throttle-off and brake force.

Throttle-off distributions are much skewed (figure 5). Although the low resolution of the data acquisition equipment (8bit) plus the limited range of throttle-pedal movement in the vehicle's footwell could be partly blamed for this, the concentration of data in two groups is quite apparent. Thus, if a constant trigger-parameter is used, throttle-off has an advantage over brake-force. Actually if in our case the trigger was set to 0.6 degrees/sampling (figure 5) then it would have been correctly activated in 88% of cases and would have missed only 12%. Despite the reservation because of equipment limitations (data acquisition and vehicle properties), it should be mentioned that this is a much more effective intervention of a single/constant-trigger than the 77% quoted by Schmitt and Färber (2005).

The answer to the overlap between normal and emergency braking among drivers could be in relationships like the one portrayed in figure 4. This is because if there is a relationship that explains the variance between them in normal and emergency conditions, then the "normal" value could be used to predict the "emergency" value. For example the quadratic fit model on figure 4 could be used to predict the emergency brake value for participant X, if his/her typical (average) normal value is known (see example in next section). Now, when it comes to deciding which model to use for this purpose, each one of the three pictured in figure 4 has its merit. The linear model has more academic than practical value; it is conceptually best as a model representing the dataset ($p=0.02$), however it is worst in explaining the variance and predicting exact data points ($R=0.45$). The cubic model is best explaining variance and predicts most exact data points ($R=0.51$), however its representation of the whole dataset is problematic ($p=0.09$). The quadratic model is almost as good as the best aspect of both models ($R=0.50$, $p=0.03$) and seems to combine both merits. It remains though to be tested in practice.

Other points that need mentioning are the external validity of the study and the unusual presentation of quantitative results. The study was designed to represent real drivers in conditions that were as realistic as possible. Participants were recruited from the local population and were not restricted to university students, test drivers, customers of a specific brand or recruited through a "participants' list". Of course, the absence of active involvement by a manufacturer, made data acquisition a lot more laborious task than it would have been otherwise. As for the emergency test itself, allowing the drivers to follow at their preferred distances effectively sacrificed half the sample, however this sacrifice enhances validity as it replicates the "insignificant" braking found in 50% of rear-end collisions/longitudinal critical events (Gkikas, Richardson, & Hill, 2008; Perron et al., 2001). Furthermore, subjective stress ratings by the participants themselves (table 1) support the validity of the emergency test. Most importantly, **all** participants reported surprise. Objectively, the average deceleration of the trailer is below the maximum achievable by modern vehicles, however it is comparable to actual decelerations observed in the field (van der Horst, 1990) and measured in tests with real drivers (Vangi & Virga, 2007).

Most of the numerical values quoted here are hard to embed in any type of system as they are. We could have quoted the values in SI units or use force values for the whole brake pedal instead of just one area on it. However, the major findings are the relationships that emerge from the results and which can be exploited in a vehicle system to improve safety. In the next section an example is presented of how to exploit these.

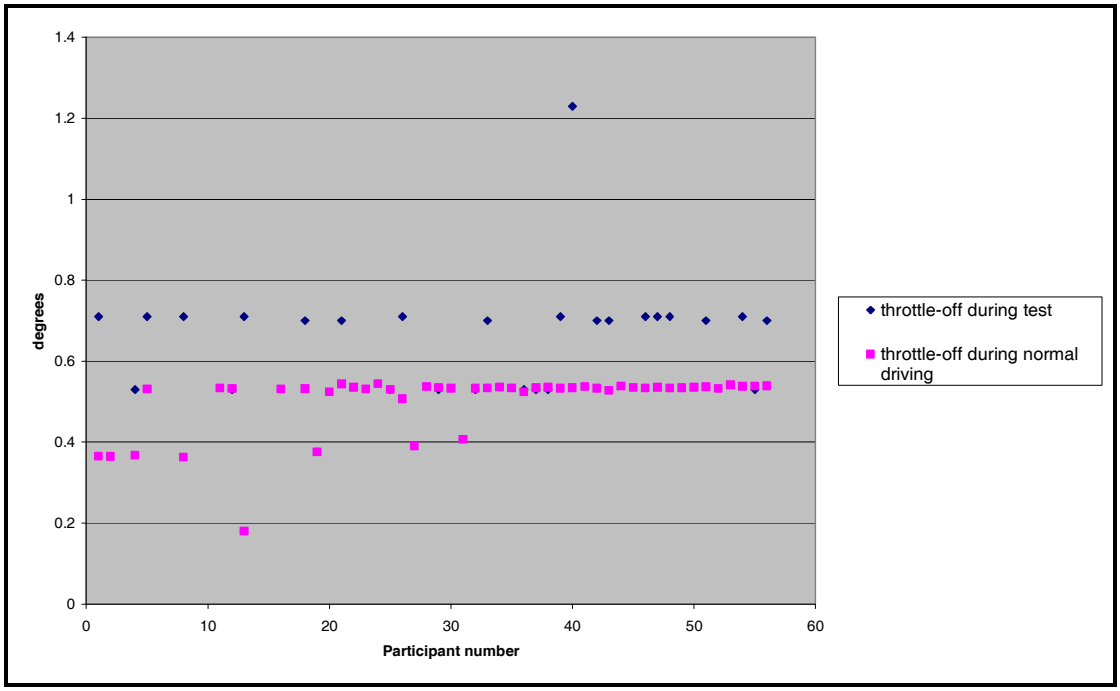


**Figure 5: Throttle-off rate in normal and emergency conditions (degree/sampling)**

## APPLICATION

In the last section of the paper, an example will be provided of how the relationship between normal and emergency braking can be exploited to accommodate driver variability. Figure 6 presents a system specification that could exploit this relationship, by incorporating the quadratic model to predict the appropriate trigger level for full-brake activation.

At the start of the drive the trigger is set to the average emergency brake level as measured in the study (Tr in figure 6). Then every time force is applied on the brake pedal, the system calculates based on the input a new trigger-level [Tr(1) in figure 6], which fuses the new [Tr(1)] with the previous (Tr) to give out the new trigger [Tr(n)]. If this value is exceeded during braking, then full-brakes are applied.

As an example, figure 7 is a simulation of how this system would work based on the drive of one participant. It is quite interesting that the system within a few seconds is below the participant's actual emergency brake force (last high-wave in the graph). In this simulation full brakes would have been engaged twice on the way to the test track. Cross-check with the video of the drive indicates that those two would happen at two urgent stops before traffic lights in yellow-phase. Of course, the system would be activated during the emergency test (far-right section of figure 7).

The above is one example of how the results from this study can be exploited by an adaptive brake assist system. Cubic or linear models can be used as well, or even different layouts of the agents in the system in figure 6. These remain to be tested on their relative merits in practical terms. It was not the purpose of this article to provide a ready solution to be implemented in brake assist systems; however it was an objective of this study to present the characteristics of driver braking that engineers can exploit when specifying the function of their systems. The authors are satisfied that this first step is achieved.

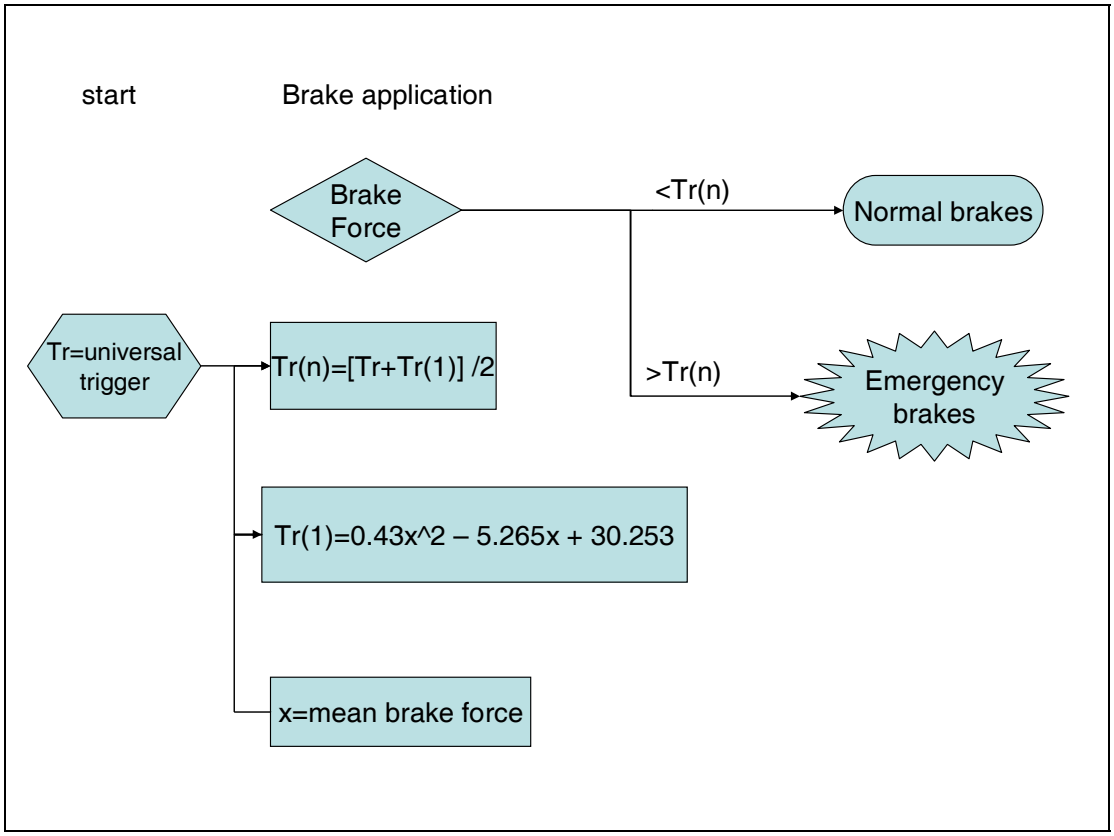


**Figure 6: Example adaptive function of the system**

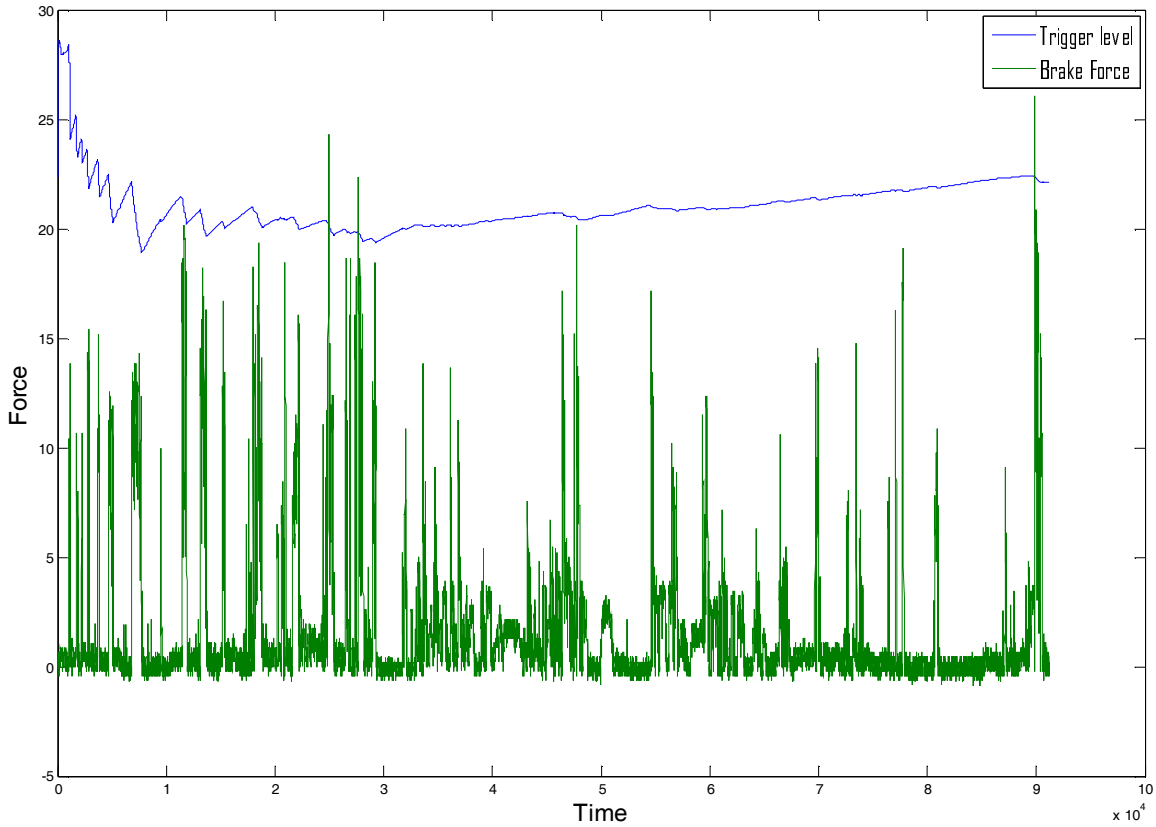


**Figure 7: The function of the system according to a participant's driving**

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# TEST AND EVALUATION OF THE COOPERATIVE INTERSECTION COLLISION AVOIDANCE SYSTEM FOR VIOLATIONS (CICAS-V) DRIVER-VEHICLE INTERFACE

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Paper Number 09-0461

## ABSTRACT

The Cooperative Intersection Collision Avoidance System for Violations (CICAS-V) project was conducted to develop and field-test a comprehensive system to assist drivers in reducing the number and severity of crashes at intersections due to violations at stop-sign and signal-controlled intersections. One essential component of such a system is the Driver-Vehicle Interface (DVI) to warn a driver of an impending violation. A series of test-track studies was conducted to support the selection of a DVI for subsequent on-road tests of the CICAS-V. In these tests, 18 naive drivers per interface were placed in a surprise intersection violation scenario and provided with a precisely timed warning presented through a variety of DVIs. Driver braking profiles and vehicle stop locations were collected and analyzed, with particular emphasis on behaviors that resulted in avoiding entering the intersection DVIs included combinations of visual, auditory, and haptic (brake pulse) warnings. Results from the tests showed that drivers exposed to a brake pulse tended to stop more often and with lower decelerations than drivers that were not exposed to the brake pulse. The effectiveness of the brake pulse warning, however, was partly moderated by the type of auditory warning that accompanied the brake pulse warning. A baseline trial was conducted to determine the benefit of the DVI over a non-warning condition. Overall, results supported the recommendation of a DVI containing the simultaneous presentation of a flashing visual (red stoplight/stop sign icon), a 'Stop Light' speech warning, and a single brake pulse. The best-performing DVI resulted in an 88% improvement over the baseline condition. Project participants included offices of the United States Department of Transportation, Daimler, Ford, General Motors, Honda, Toyota, and the Virginia Tech Transportation Institute.

## INTRODUCTION

The Cooperative Intersection Collision Avoidance System for Violations (CICAS-V) project was conducted to develop and field-test a comprehensive system to assist drivers in reducing the number and severity of crashes at intersections due to violations of traffic control devices (TCD). These crashes account for almost 400,000 injuries and fatalities in the United States every year (National Highway Traffic Safety Administration, 2008). The approach selected to reduce these crashes is to present a timely and salient in-vehicle warning to those drivers predicted to violate a TCD. The warning is intended to elicit a behavior from the driver to avoid a potential violation.

Supporting the warning are several subsystems that exchange, process, and present the required information from both the vehicle and the intersection. The Driver-Vehicle Interface (DVI), which is the means through which the warning information is presented to the potential violator, is one of these CICAS-V subsystems. The importance of this particular subsystem is based on its function: prompting the driver to take the appropriate violation avoidance maneuver. For this reason, a series of Human Factors (HF) test track studies were executed during the CICAS-V project to determine the DVI that would be integrated into the CICAS-V system for further on-road testing. To this end, experimental scenarios were developed to attain a set of test conditions that simulated a "representative" signal violation environment. Naive drivers were exposed to these scenarios while being aided by one of several DVI alternatives. Based on knowledge gaps remaining after past research efforts, these test scenarios were designed to address the following research questions:

- Within the auditory modality, how does the effectiveness of speech warnings compare to non-speech warnings?

- Is scenario outcome improved by the addition of a brake pulse warning?
- Does the availability of Panic Brake Assist (PBA) functionality improve the scenario outcomes?
- Within the context of the experimental scenario, what is the effectiveness of each different DVI warning relative to when a warning was not presented?

Although interesting data were obtained during this research addressing signal violation alert timing, this timing issue was a secondary goal of this investigation. The range of alert timings examined in the current research (as they coupled with the examined DVI approaches) was initially based upon previous research and then was later modified based on the scenario outcomes as the studies progressed. It should be noted that the current research did not directly examine potential false alarm (annoyance) issues associated with the DVIs or alert timings examined.

This paper describes the effort to select a DVI that can be used to warn a driver that is predicted to violate an intersection TCD. The approach and candidate DVIs selected for these experiments were based on previous research and consensus of stakeholders within the CICAS-V project.

**Description of Past Research**

The magnitude and prevalence of intersection crashes have prompted a variety of research efforts in recent years. Within the context of crashes resulting from intersection TCD violations, most of these efforts have examined the effect of infrastructure-based systems in mitigating this problem. This limitation has mainly been due to constraints in technology, especially that which allows the vehicle and intersection to communicate and share information. However, new wireless communications technologies (e.g., Dedicated Short Range Communications - DSRC) have bridged some of these gaps and prompted research into vehicle-based countermeasures for addressing the intersection crash problem.

The most comprehensive examination of vehicle-based intersection TCD violation collision avoidance systems to date was the Intersection Collision Avoidance-Violation (ICAV) project (Lee et al., 2005). This effort examined auditory, visual, and haptic (in the form of brake pulses and soft braking) DVIs in the context of a surprise scenario presented to naive drivers, using a visual occlusion approach. Some of the key findings from the ICAV study with respect to an intersection TCD violation scenario include:

- The effectiveness of a particular DVI is dependent upon its timing; that is, the optimal warning presentation timing for one DVI is not necessarily the optimal timing for another DVI.
- Visual warnings should be accompanied by warnings in other modalities and, in the intersection TCD violation context, help explain the warning meaning.
- Speech-based ("Red Light") auditory warnings may elicit faster and more effective driver responses than non-speech (context-free) tones.
- Brake pulses and automated soft-braking appear to be effective warning methods in the intersection TCD violation context.
- Nuisance alarms are a key consideration in defining the warning type and timing to be used in these systems.

The ICAV project results were complemented by the Intersection Decision Support (IDS) project (Neale et al., 2006), which examined a wide range of infrastructure-based countermeasures in the context of similar intersection TCD violation scenarios. The IDS effort allowed for further development and refinement of the experimental protocols used in ICAV. Lessons from both of these projects provide a strong foundation of knowledge for the studies conducted as part of the CICAS-V effort. This investigation builds upon these two efforts in two distinct ways. First, it introduces a naturalistic testing approach that will aid in the estimation of safety benefits from the countermeasures tested. Second, the warnings that are considered are the result of consensus of the project team. As such, it is likely that possible implementations of the final system will be based on the general characteristics of these warnings.

The literature examined to determine the collection of DVIs tested as part of this effort was not limited to these two projects. The types of warnings tested in this investigation have been examined, often with encouraging results, in other crash contexts. The literature examined described these previous tests and presented guidelines for the design of haptic, auditory, and visual warning systems in automotive applications (e.g., Campbell, 2004; Kiefer et al., 1999; Lee, McGehee, Brown, & Nakamoto, 2007; Lloyd, Wilson, Nowak, & Bittner, 1999; Noyes, Hellier, & Edworthy, 2006). The results of these efforts, along with the project team's experience

enabled the development of multi-modality approaches that were production-representative and technologically feasible.

**Assumptions of CICAS-V Studies**

To determine the most suitable DVI for inclusion in the CICAS-V system, a series of nine studies was conducted. There are three assumptions implicit in the results and discussion contained in this paper. First, it is expected that the surprise signal violation scenarios used in the experiments provide DVI effectiveness estimates that may approximate those that may be obtained in the real world. Furthermore, the assumption is made here that experimental rankings of warning effectiveness will be equivalent to rankings based on real-world use. Second, it was assumed that DVI rankings obtained for signalized intersection scenarios would be applicable to stop sign scenarios (stop signs were not tested as part of the experiments described in this paper). This assumption was supported by the findings of the ICAV and IDS studies, which showed equivalencies in driver stopping behaviors for surprise traffic signal and stop sign scenarios. Third, all studies used nominal intersection approach speeds of 35 mph (56.3 km/h) and one or more TTIs (times-to-intersection) at which warnings were presented (the warning presentation algorithm was based on TTI). The performance measures discussed herein are expected to be applicable to speeds that are close to the 35 mph nominal speed used, and might change at higher and lower approach speeds (in part because the alert timing approach may be influenced by driver speed). These performance measures were collected in these studies as a means of evaluating various DVIs rather than to characterize typical driver behavior across a range of intersection types. However, the DVI rankings obtained, which were the primary focus of the study, are expected to remain largely consistent across intersection approach speeds.

**METHOD**

In an effort to determine the best method to evaluate the DVIs, two protocols were developed that employed different methods to distract drivers' attention from the forward roadway. One protocol used visual occlusion, while the other protocol used a naturalistic distraction method. The ICAV and IDS studies used occlusion as the method to induce 'distraction' during the surprise trial. While the occlusion method worked well in the context of those studies (where it was sufficient to make relative comparisons between countermeasures under well-controlled experimental conditions), the question remained as to whether the output could be effectively used for the estimation of potential safety benefits (one of the goals of the CICAS-V effort). In addition, it cannot be stated with absolute certainty that the relative differences observed with the occlusion method would necessarily be preserved under more naturalistic distraction conditions. To address these issues, the occlusion approach was compared to a naturalistic distraction protocol. For a variety of reasons that are discussed in Maile et al. (in print), the naturalistic distraction method was selected as the approach of choice for the tests discussed in this paper. The nine studies conducted with this protocol, the DVI tested in each study, and the alert timings (i.e., TTIs) tested are shown in Table 1 and discussed in this paper.

**Table 1.**
**CICAS-V Studies Conducted using the Naturalistic Driving Protocol**

| Study # | DVI* | Time to Intersection (TTI, s) |
|---|---|---|
| 1 | Collision Avoidance Metrics Partnership (CAMP) Forward Collision Warning (FCW) Tone | 2.44 |
| 2 | Speech | 2.44 |
| 3 | CAMP FCW Tone and Brake Pulse | 2.44 |
| 4 | Speech and Brake Pulse | 2.44 |
| 5 | Beep Tone and Brake Pulse with PBA | 2.24 |
| 6 | Speech and Brake Pulse with PBA | 2.24 |
| 7 | Speech and Brake Pulse with PBA | 2.04 |
| 8 | Speech and Brake Pulse with PBA | 1.84 |
| 9 | No warning | 2.44** |

*All of these studies featured a visual display that performed both advisory and warning functions (only the advisory function of this display was used in Study 9).
** The yellow light change occurred at 2.44 s TTI.

The method used to conduct this series of studies is summarized in this section. More comprehensive descriptions can be found in Perez et al. (in print).

**Participants**

Participants were recruited through the newspaper, broadcast media, word of mouth, and the Virginia Tech Transportation Institute's (VTTI) database of possible participants (based on their expressed

interest). On initial contact (usually over the phone), individuals were screened to ensure their eligibility for the study. Eligibility criteria included restrictions to exclude individuals who had previously participated in a surprise-scenario experiment at VTTI (which may have predisposed them to expect a surprise scenario), health conditions or medication intake that may interfere with their ability to operate a motor vehicle, and no more than two moving violations nor any at-fault accidents within the previous three years (for liability and safety reasons). Participants also had to possess a valid driver's license.

Most experimental groups contained 18 participants, counterbalanced for age and gender. However, when it was apparent that the DVI being tested would not yield favorable results, the study was stopped early in an effort to conserve resources. Participants across three age groups were recruited for all experiments: younger drivers aged 20-30 years, middle-aged drivers aged 40-50 years, and older drivers aged 60-70 years. Altogether, 195 participants were run for the nine studies, of which 136 provided valid data points. Invalid data points resulted from drivers for whom the naturalistic distraction technique did not work as intended (e.g., drivers were looking directly at the forward roadway on or before the time of warning or yellow light onset).

**Testing Facility**

The experiments were completed on the Virginia Smart Road, a 2.2 mile controlled-access research facility. The designated path driven by participants during this series of studies spanned the upper and third turnaround areas on the two lane test-bed. The path included a pass through one signalized intersection. At this intersection, the Smart Road intersects with an additional access road, which then connects to a road that runs parallel to the upper portion of the Smart Road.

**Protocol**

Upon arriving at the Institute, participants were asked to read an informed consent form which provided specific information about the study, including the procedures, risks involved, and measures for confidentiality. The participants were initially not told the true purpose of the study in order to gain information on how naive participants react to an intersection violation warning. The purpose stated in the form described the study as an evaluation of the effect of in-vehicle tasks on driving behavior. After agreeing to the study and signing the informed consent, participants completed a health screening, a visual acuity test, and a color vision test.

Participants were then led to the vehicle where they were given time to make the necessary adjustments to the seat, mirrors, and climate control. During the pre-drive vehicle orientation, different safety systems available in the experimental vehicle, including the CICAS-V system, were briefly mentioned (e.g., forward collision warning, backing aid). The availability of PBA (when it was made available) was never mentioned. Participants were told to follow all the normal traffic rules throughout the experiment and that maintenance vehicles would occasionally be entering and leaving the road at the intersection. Unbeknownst to the participants, these maintenance vehicles were staged confederate vehicles driven by VTTI on-road crew as part of the study. At this time, the participants were given a brief tutorial and demonstration of the in-vehicle systems they would be using to perform various tasks. Participants were also provided with the opportunity to practice one of these distraction task sequences while parked. They were told that information about their speed maintenance and lane position accuracy would be recorded, including during the execution of any in-vehicle tasks. They were asked to place the car in third gear and maintain 35 mph throughout the study.

During the experiment, the front-seat experimenter (FSE) triggered a pre-recorded message at predetermined landmarks on the Smart Road that instructed the participant to complete a certain task. These tasks were based on those developed for CAMP's Driver Workload Metrics project (Angell, Auflick, Austria, Kochhar, Tijerina, Biever, et al., 2006). Tasks the participants were asked to complete included changing the radio station, changing tracks on a CD, changing properties of the heating, ventilation, and air conditioning (HVAC) system, and turning on the vehicle's hazard lights. Each message ended with the word "Now." Participants were instructed to keep both hands on the steering wheel prior to hearing the word "Now." Upon hearing the word "Now," participants were to complete the task as quickly and as accurately as possible. Once the participant finished the task, they were to say "Done," as an indication to the FSE that they had completed the task. The procedure of keeping both hands on the steering wheel prior to hearing the word "Now" helped to minimize the frequency of early glances to the task area or quick return glances to the forward roadway. This in turn helped reduce the chance that participants would be glancing away from the forward roadway when the warning and/or green-to-yellow light change were presented during

the surprise trial. The participant had the option to quit or skip any task, or to ask the FSE to play the instructions again. Additionally, for safety reasons, the FSE could instruct the participant to stop or skip any task.

The first nine trials of the experiment (all of which involved intersection crossings, most under a green light) were scripted to build the expectation of possible cross traffic at the intersection, while the last trial was a surprise scenario. Throughout the experiment, tasks were initiated at predetermined landmarks. Each 2-3 minute drive (trial) up or down the Smart Road contained four or five tasks in total. On the first trial down the Smart Road, there was a "maintenance" vehicle (Principal Other Vehicle - POV) parked on a road parallel to the Smart Road. The POV driver appeared to be performing maintenance activities on the road. After the Subject Vehicle (SV) circled through the lower turnaround and approached the intersection for the second trial, the POV drove to the adjacent stop bar at the intersection. The signal, though triggered by the on-board computer in the SV, appeared to the participant to be triggered by the waiting POV. The participant then received a common yellow-red light sequence, during which the POV crossed and exited the road.

On the sixth intersection approach, the POV re-entered the road, crossing through the intersection towards the parallel road. Again, the light sequence was triggered by the on-board computer in the SV, though appearing to change because of the presence of the POV. When the SV continued to the lower turnaround during the seventh trial and was no longer in view of the POV, the POV inconspicuously exited the road. At the start of the SV's tenth (final) intersection approach, a second confederate vehicle (Following Vehicle - FV) followed the SV up the road at approximately a 1.5 to 2 s headway. Although participants might have believed that the maintenance vehicle was again entering or leaving the road, this maintenance vehicle was not near the intersection at this time.

During this final approach (the surprise trial), a recorded set of instructions was automatically triggered by the on-board computer at 24 s TTI. A separate audio file stating "Now" was triggered at 4 s TTI. This consistent timing of events helped to maximize the probability that participants would not be glancing at the forward roadway as the light turned yellow, before the warning and/or yellow light were presented. The light turned yellow about 0.1 s before the warning onset, which occurred at 2.44, 2.24, 2.04, or 1.84 s TTI (depending on the study).

After the surprise trial was complete and participants either stopped or crossed through the intersection, a brief questionnaire about the warning(s) just received was administered. Participants were then asked to read and sign a new informed consent form that explained the true purpose of the study. The experiment was then concluded and participants returned to the VTTI main building for payment, unless additional trials were performed (see below).

Each participant took approximately 75 minutes to complete the experiment, and up to six participants could be run per day, depending on weather and amount of daylight. The study was run only when the road was dry, since the experiment involved the potential for hard braking and risk of skidding on wet pavement.

**Additional Trials**

In order to obtain additional information on braking behavior and PBA activation thresholds, several participants in Studies 5 through 8 completed up to two additional trials using different PBA activation settings following the surprise trial. After the surprise trial questionnaires had been administered, and with the participant's consent, the participant completed one or two additional approaches to the intersection. The availability of PBA, or the fact that PBA activation was the main measure of interest from the additional trials, was not discussed during the orientation for these trials. As the SV approached the stop bar, the Collision Avoidance Metrics Partnership (CAMP) Forward Collision Warning (FCW) Tone warning (as used and described in Kiefer et al., 1999) was presented at 2.0 s TTI. Upon hearing the warning tone, the participant was asked to apply the vehicle brakes as if trying to avoid an intersection crash. The FSE instructed the participants on this procedure after the surprise trial and prior to asking for their consent to participate in these additional trials. Altogether, 53 participants were run through at least one additional trial, and 88 trials were conducted.

**Instrumentation**

As previously stated, experimental scenarios were developed to attain a set of test conditions that simulated signal violation scenarios. To support that effort, the test system emulated CICAS-V functionality, but was overbuilt to operate in a more precise manner than would be necessary for real-world implementation.

Two 2006 Cadillac STSs were equipped as the SVs in this set of studies. The vehicles were equipped with anti-lock brakes, dual front and side airbags, and traction control. To minimize risk for participants and experimenters, an emergency passenger-side brake was mounted such that the experimenter (seated in the front passenger seat) could brake if needed. The confederate vehicles used for these studies included a 1999 Ford Contour, posing as cross traffic, and a 2000 Ford Explorer as the following vehicle.

The SVs were equipped with visual, auditory, and haptic warning displays. The visual display consisted of a non-reprogrammable single-icon light-emitting diode (LED) screen located in a high head-down (top of dashboard) position on the vehicle centerline near the center speaker and oriented towards the driver (Figure 1). The display was in a hooded enclosure with a low-reflection diffusion glass panel. The visual icon consisted of an outlined traffic signal and stop sign, which was developed via open-ended icon comprehension and rank order testing (Campbell, Kludt, & Kiefer, 2007). The icon was 11.6 mm (0.46 inches) high and 11.6 mm (0.46 inches) wide. Including the additional 1 mm background on all sides, the total icon size was 13.6 mm (0.54 inches) high and 13.6 mm (0.54 inches) wide. At a pre-established TTI, the figures would become blue and steady. On warning activation, the figures would become red, and flash at 4 Hz with a 50% duty cycle (125 ms on, 125 ms off).

**Figure 1. High head-down visual display LED screen.**

In addition, the vehicles had an integrated loudspeaker (located in the dashboard above the instrument cluster) used to present the auditory warnings independently of the vehicle's sound system. The sound was directed toward the driver from the location of interest (i.e., forward windshield). Three different auditory warnings were tested. The initial warning tested was the CAMP FCW Tone (Kiefer et al., 1999). The CAMP FCW Tone was presented at 74.6 dBA. A second speech warning was tested consisting of a female voice stating the word "Stop Light," presented at 72.6 dBA. A third auditory warning was a Beep Tone, which consisted of three high-pitched beeps. The Beep Tone was presented at 75.0 dBA. All sound level measures were taken at the approximate location of the driver's head.

When used, the Brake Pulse was triggered immediately before the onset of the visual and auditory warnings such that deceleration would reach ~0.10 g at approximately the same time as the visual and auditory warning onset. Total pulse duration was approximately 0.6 s. Deceleration produced by the pulse peaked around 0.25 g, and was reached between 0.25 and 0.35 s after the onset of the visual and auditory warnings. The brake pulse command was not issued if deceleration over 0.1 g and/or brake activation were detected by the on-board processing unit. The system was implemented entirely within the brake controller using the existing Anti-Lock Braking System (ABS) pump hardware.

The Data Acquisition System (DAS) contained within the vehicle was custom-built by VTTI. The DAS was located inside the trunk and out of the participant's view. Attached to the system bus was a series of custom-designed circuit boards that controlled the various functions of the acquisition device. This system included video grabbers, accelerometer/gyroscope (Crossbow VG400), a vehicle network sniffer (to pull variables from vehicle network), and power management boards. It also received data from a Differential Global Positioning System (DGPS, Novatel OEM4-G2L), which was used to acquire vehicle position (using an internal intersection map for reference) and speed. The alignment and time-stamping data retrieved from these boards was choreographed by a customized VTTI proprietary software package, which collected non-video data at 100 Hz. Hardware was contained in a custom-mounting case designed to affix instrumentation in orientations necessary for accurate measurement and durability.

The video grabbers installed in the DAS converted the National Television System Committee (NTSC) signal from the cameras into Motion Picture Experts Group 4 (MPEG-4) compressed video, which was recorded to the hard drive in real time. Small cameras (1" square by ¼" deep, seeing through a 1/32" aperture) were mounted inconspicuously within

the vehicle and collected the video data. For the current study, four cameras were installed. The camera views included the driver's face (to record eye glances), the forward road view, the driver's hand placement, and the driver's feet (to show accelerator and brake activation). Video data were recorded on the DAS computer at 30 Hz. For analysis, video data were multiplexed in a four-quadrant, split-screen display (Figure 2).

**Figure 2. Four-quadrant, split-screen video data display.**

Wireless communications needs were addressed via a second computer connected to the distributed DAS network and linked to a Denso® Wave Radio. In addition to coordinating wireless communications, this computer provided the experimenter interface, computed the algorithm, and supplied algorithm data to the DAS for synchronization with the video and driver performance data. DSRC equipment in the vehicle provided signal phase and timing information from the intersection's DSRC transceiver to the DAS and sent control commands to the intersection. Antennas were mounted underneath the front vehicle bumper and on top of the controller cabinet. VTTI developed platform-specific software to address all of these communication needs.

The DAS was independent of the CICAS-V test-bed system but remained linked as necessary to record and time-stamp key events (e.g., warning onsets). The entire DAS was unobtrusive and did not limit visibility or create a distraction.

A 700 MHz PC104 computer was used at the intersection to manage the signal configuration and wireless data transfer tasks. The PC104 received commands over the wireless communication system with regard to signal change sequence, timing, and phase change initiation. The computer physically controlled the signal state through a 110 V interface built in-house at VTTI.

**Study Variables**

The primary independent variable was DVI Type. In cases where multiple timings were tested for the same DVI, Warning Timing (i.e., TTI) was also used as a factor. A substantial number of dependent variables were collected across the studies. The majority of these variables were objective measures, but some subjective data were also collected through questionnaires. The following dependent variables were selected or derived from the raw data available from the vehicle DAS:

- Avoidance: Avoidance was determined based upon whether the driver stopped and where. Four different zones were defined, depending on the vehicle's distance with respect to the stop bar, measured from the front of the vehicle. These zones are specific to the Smart Road intersection and its approach configurations (although they could be defined for any intersection). Areas prior to the collision zone included the 'No Violation', 'Violation', and 'Intrusion' zones. Stopping in any of these zones was considered as successfully avoiding entering the intersection. If the driver did not stop or stopped in the 'Collision Zone' the result was considered unsuccessful. The zones are defined below and illustrated in Figure 3.

    - Did not Stop – Vehicles that did not stop.
    - Collision Zone – Vehicles that stopped at 9.1 m (30.0 ft) or more beyond the stop bar. For the Smart Road intersection, this distance represented the location at which crossing traffic could be expected to be first encountered.
    - Intrusion Zone – Vehicles that stopped between 4.6 m (15.0 ft) and 9.1 m (30.0 ft) beyond the stop bar. (Since the test bed vehicles measured close to 4.6 m in length, at this distance the rear end of the vehicle would be completely over the stop bar.)
    - Violation Zone – Vehicles that stopped within 4.6 m (15.0 ft) beyond the stop bar.
    - No Violation Zone – Vehicles that stopped at or before the stop bar.

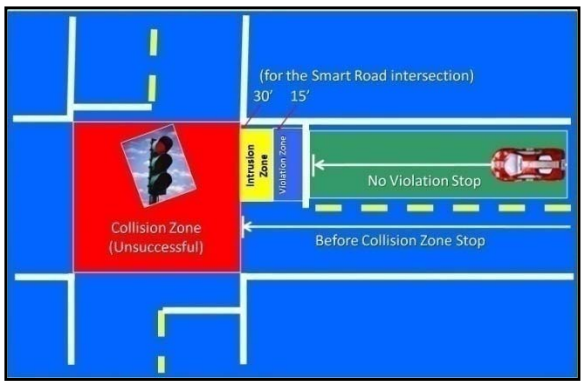


**Figure 3. Illustration of the four stopping zones on the Smart Road.**

- Distance Before the Stop Bar (ft): Vehicle distance to intersection once its speed was less than 0.2 ft/s (0.4 mph). The threshold was selected to eliminate incorrect triggers due to noise in the speed data.
- Peak Deceleration (g): Raw (i.e., non-smoothed) maximum driver-induced deceleration during the intersection stop.
- Constant Deceleration (g): Required constant deceleration to yield the observed stopping distance based on the observed brake onset distance, as calculated in Equation 1:

$$a = \frac{V^2}{2 \times g \times (D_i - D_f)} \qquad (1).$$

Where:
a = constant deceleration as a proportion of gravitational acceleration (*g*)
V = vehicle speed at the point when the driver initiated braking (m/s)
g = gravitational acceleration constant (9.81 m/s2)
Di = distance to intersection when the driver initiated braking (m)
Df = distance to intersection at which the vehicle stopped (m)

- Required Deceleration Parameter (RDP) from Braking Onset to Stop Bar (g): Required constant deceleration to come to a stop at the stop bar based on the observed brake onset distance, as calculated in Equation 2:

$$a = \frac{V^2}{2 \times g \times D_j} \qquad (2).$$

Where:
a = constant deceleration as a proportion of g
V = vehicle speed at the point when driver initiated braking (m/s)
g = gravitational acceleration constant (9.81 m/s2)
Dj = distance to intersection at braking onset (m)

For the following variables, note that stimulus onset for conditions in which a warning was issued was the warning onset. For the no-warning condition, the stimulus was the presentation of the yellow light. Note that for conditions where a warning was issued, the warning timing coincided with the presentation of the yellow light, making both warning and no-warning conditions equivalent in terms of timing.

- Time to Accelerator Release (s): Time from the onset of the stimulus to the onset of accelerator pedal release (operationally defined as the first decrease in accelerator position, after stimulus onset, of more than 2.5% in 0.1 s).
- Time to Brake (s): Time from the onset of the stimulus to the onset of brake application (operationally defined as the first increase in brake position, after stimulus onset, of more than 5% in 0.1 s).
- Time to Peak Deceleration (s): Time from the onset of the stimulus to maximum driver-induced deceleration.

**Data Reduction and Analysis Techniques**

The dependent variables for the study were examined for consistency prior to the analysis process. Custom software was created in the MATLAB® environment (MathWorks, Natick, MA) to identify the surprise trial within the data, calculate the dependent variables of interest, and produce plots that aided in data integrity verification and identification of the data that should be excluded. Figures created in MATLAB® illustrated all essential aspects of the intersection approach, and allowed the identification of incorrectly processed, incomplete, or corrupt data.

Upon completing each experiment, video collected by the on-board DAS was analyzed using VTTI's data analysis and reduction tool (DART). Participants who were not glancing down or otherwise obviously distracted were excluded from data analysis. Participants were also excluded from the study if they were traveling, at warning or yellow light onset, more than 7.9 km/h (5 mph) over or under the nominal speed for the warning condition.

Conceptually, there are two steps required for a successful intersection stop. These aspects are: (Step

1) analyze, formulate, and initiate a response plan to the stimulus requiring the stop, and (Step 2) adapt and complete the execution of the plan based on any sensory feedback. Put in another way, assuming a driver decides to stop, Step 1 characterizes pre-braking behavior and Step 2 characterizes the braking behavior.

Both steps can be quantified using different dependent variables; however, the dependent variables that characterize the second step might not be independent of those that characterize the first step. For example, it is possible that a driver that takes longer to react to the warning stimulus (Step 1) would brake harder (Step 2) in order to compensate and stop at the same point as a driver with a faster reaction time. All of the dependent variables described above can be classified according to the step that they quantify:

- Analysis, formulation, and initiation of the response plan (Step 1, plan initiation)
  - Time to accelerator release
  - Time to brake
- Adaptation and completion of the response plan (Step 2, plan execution)
  - Time to peak deceleration
  - Distance before the stop bar
  - Peak deceleration
  - Constant deceleration
  - RDP from Braking Onset to Stop Bar

In order to determine the need for correction factors, a correlation analysis was performed between the Step 1 and Step 2 variables. Given that correlation analysis quantifies the degree of linear relationship between variables, transformation of variables was also examined in this process, as a means of maximizing the correlations.

Once the correlations were completed and any relationships between Step 1 and Step 2 variables established, statistical analysis of variance (ANOVA) was performed. Dependent variables for which correction was not needed (i.e., all Step 1 variables and Step 2 variables that did not exhibit correlation with Step 1 variables) were analyzed using traditional ANOVA techniques. Dependent variables that required a correction were analyzed using Analysis of Covariance (ANCOVA).

When significant main effects were found, Student-Newman-Keuls (SNK) tests were performed to further determine the source of those differences. Significant interaction effects were examined with post hoc t-tests using the Tukey correction for multiple comparisons. A Type I error level of 0.05 was assumed for all tests.

Finally, the "Avoidance" variable was considered and analyzed separately since it was a discrete variable which did not require correction. This variable was analyzed based on proportion of occurrence for each trial. Confidence intervals (95%) were established to determine overlap between different experimental groups and infer statistically significant differences. These confidence intervals were based on the binomial distribution, which describes the probability of discrete outcomes when observations are independent.

## RESULTS AND DISCUSSION

The primary goal of these experiments was to develop a recommendation for the DVI to be integrated into the CICAS-V system for further on-road testing. In support of this goal, Table 2 shows a summary of the results obtained for each of the 9 studies; note that studies 4, 6, 7, and 8 are shown in bold. These studies used the Visual icon + Speech ('Stop Light') + Brake Pulse warning, which was ultimately recommended for use based on the observed patterns of driving behavior in reaction to this warning, including driver's success in avoiding entering the intersection.

**Table 2.**
**Summary of Results***

| Study | DVI** | TTI (s) | N and % Avoided | N and % Not Avoided | 95% Confidence Interval (Avoided) | N Avoided Activating PBA |
|---|---|---|---|---|---|---|
| 1 | CAMP FCW Tone | 2.44 | 7 (39%) | 11 (61%) | 16.4%-61.4% | -- |
| 2 | Speech | 2.44 | 7 (39%) | 11 (61%) | 16.4%-61.4% | -- |
| 3 | CAMP FCW Tone with Brake Pulse | 2.44 | 14 (78%) | 4 (22%) | 58.6%-97.0% | -- |
| **4** | **Speech with Brake Pulse** | **2.44** | **17 (94%)** | **1 (6%)** | 83.9%-100% | **--** |
| 5 | Beep Tone with Brake Pulse and PBA | 2.24 | 5 (50%) | 5 (50%) | 26.9%-73.1% | 0 |
| **6** | **Speech with Brake Pulse and PBA** | **2.24** | **16 (89%)** | **2 (11%)** | 74.4%-100% | **1** |
| **7** | **Speech with Brake Pulse and PBA** | **2.04** | **7 (78%)** | **2 (22%)** | 58.6%-97.0% | **0** |
| **8** | **Speech with Brake Pulse and PBA** | **1.84** | **3 (33%)** | **6 (67%)** | 11.6%-55.1% | **1** |
| 9 | Baseline | 2.44*** | 1 (6%) | 17 (94%) | 0%-16.1% | -- |

* Note: Studies in bold investigated the warning recommended based on the results presented in this paper.
**All of these studies featured a visual display that performed both advisory and warning functions (only the advisory function of this display was used in Study 9).
*** Yellow light change occurred at 2.44 sec.

**Key Study Comparisons**

**<u>Differences between CAMP FCW Tone and Speech Warnings and the Influence of a Brake Pulse</u> -** This section compares the results of four studies testing four different DVI Types at a 2.44 s TTI and another baseline study where a warning was not provided but a traffic light change occurred at a similar timing:

- Visual icon + CAMP FCW Tone (Study 1)
- Visual icon + 'Stop Light' Speech Warning (Study 2)
- Visual icon + CAMP FCW Tone + Brake Pulse (Study 3)
- Visual icon + 'Stop Light' Speech Warning + Brake Pulse (Study 4)
- Baseline with no warning presented (Study 9)

The Baseline condition avoidance percentage (6%) was substantially (and significantly) lower than that observed for any of the other warning conditions (which ranged from 33% to 94%). Although no other significant differences in avoidance were observed between the remaining groups that experienced warnings, there was a trend for participants who experienced the Brake Pulse as a component of the warning approach to stop more often than participants receiving a warning that did not include a Brake Pulse.

In discussing the following plan initiation and plan execution variable results, it should be noted that only one participant responded to the traffic signal during the Baseline condition. Therefore, although the performance values for this participant are provided, statistical comparisons of these values with those obtained for other conditions with substantially larger avoidance percentages was not possible. The following statistically significant results are summarized in Table 3.

Analysis of plan initiation variables showed some significant main effects:

- Time to accelerator release ($F[4,42]=11.21$, $p<0.0001$): On average, participants who experienced the Brake Pulse released the accelerator 0.42 s faster than those who did not experience the Brake Pulse.
- Time to brake ($F[4,42]=6.28$, $p=0.0005$): Participants that experienced the Brake Pulse had faster brake onset times (by 0.30 s).

Analysis of plan execution variables showed several significant main effects as well, which are mainly attributed to the presence of the Brake Pulse (since the effects were not present when auditory warnings were presented in isolation):

- Distance before stop bar ($F[5,40]=10.94$, $p<0.0001$): This variable was significantly correlated with time to brake. After accounting for the effect of this plan initiation variable, results showed that participants who received the Brake Pulse stopped roughly 6 to 7 ft closer in front of the stop bar than those who did not receive a brake pulse.
- Constant deceleration ($F[5,40]=9.77$, $p<0.0001$): This variable was significantly correlated with time to brake. Conditions with a brake pulse resulted in slightly (approximately 0.02 g) lower

constant decelerations than other conditions when the influence of Time to Brake was removed.

- RDP from braking onset to stop bar (F[5,40]=43.78, p<0.0001): After considering the large correlation of this variable with time to brake, significant differences (about 0.04 g) between the Brake Pulse and non-brake pulse conditions remained.
- Time to peak brake (F[5,40]=3.13, p=0.0176): This variable was significantly correlated with time to brake. After considering the effects of this plan initiation variable, participants who experienced the Brake Pulse reached peak deceleration faster (approximately 0.4 s) than those who did not.

**Table 3.**
**Means of Significant Main Effects of DVI Type and Brake Pulse Presence**

| Variable (N) | CAMP FCW Tone, No Brake Pulse (7) | Speech, No Brake Pulse (8) | CAMP FCW Tone with Brake Pulse (14) | Speech with Brake Pulse (17) | Baseline (1) |
|---|---|---|---|---|---|
| Time to accelerator release (s) | 0.69 | 0.62 | 0.24 | 0.26 | 0.69 |
| Time to brake (s) | 1.11 | 1.08 | 0.82 | 0.74 | 1.06 |
| Distance before stop bar (ft) | -9.9 | -8.64 | -2.04 | -0.67 | -9.63 |
| Constant decel (g) | 0.44 | 0.46 | 0.42 | 0.42 | 0.38 |
| RDP from brake to stop bar (g) | 0.48 | 0.48 | 0.44 | 0.45 | 0.40 |
| Time to peak brake (s) | 2.76 | 2.8 | 2.39 | 2.49 | 2.78 |

These results indicate that the presence of the Brake Pulse appears to directly contribute to quicker reactions, harder decelerations, and stops that were farther away from the intersection crash box (i.e., the collision zone). Most importantly, participants who experienced a warning that included the Brake Pulse tended to be more likely to respond to that warning. This evidence strongly suggests that the brake pulse should be considered an integral, primary part of the CICAS-V field test DVI.

**Differences in Timing -** Differences in timing were assessed by using the Visual icon + Speech ('Stop Light') + Brake Pulse warning at four different timings: 2.44 s TTI (Study 4), 2.24 s TTI (Study 6), 2.04 s TTI (Study 7), and 1.84 s TTI (Study 8). (Note that although the absence/presence of the PBA system and the PBA entrance criterion differed across these studies, the PBA system ultimately played a negligible role in the results since so few subjects activated the PBA system under these intersection approach experimental conditions.)

Analysis of avoidance percentages for these conditions showed that participants in the 1.84 s TTI condition responded to the warning at a much lower percentage (33%) than participants experiencing the warning at longer timings (overall, >79%). Other conditions were not statistically different, but there is a clear trend toward increased avoidance as the TTI warning timing occurred earlier (i.e., farther from the intersection).

Analysis of plan initiation variables showed no significant main effects. However, some main effects were observed for plan execution variables, which are illustrated in Table 4 and described below:

- Distance before stop bar (F[4,39]=7.78, p<0.0001): This variable was significantly correlated with time to brake. After accounting for the effects of this variable, results showed that participants in the 2.44 s group stopped significantly closer in front of the stop bar (by at least 3 ft) than all other groups. Although not significantly different, there was a tendency for participants to stop farther beyond the stop bar as the timings became shorter.
- Peak deceleration (F[3,40]=6.0, p=0.0018): Larger peak decelerations were observed as the timings became shorter. Participants in the intermediate 2.24 and 2.04 s timing groups showed statistically similar peak decelerations. However, the 1.84 s (the latest timing condition) and 2.44 s (earliest timing) groups exhibited approximately 0.17 g larger and 0.13 g smaller peak decelerations than the intermediate timing groups, respectively.

- Constant deceleration (F[3,40]=7.47, p=0.0004): Incrementally larger constant decelerations (between 0.02 and 0.06 g for each 0.2 s change in TTI warning timing) were observed as timings became shorter.
- RDP from braking onset to stop bar (F[4,38]=19.99, p<0.0001): Time to accelerator release was strongly correlated with RDP. After accounting for this variable, larger RDPs were observed as timings became shorter.
- Time to peak deceleration (F[4,38]=5.02, p=0.0024): This variable was significantly correlated with time to brake. After considering the effects of this variable, it was observed that participants in the 1.84 s timing reached peak deceleration faster (by at least 0.3 s) than participants experiencing other timings.

**Table 4.**
**Means for all Significant Main Effects of Timing**

| Variable (N) | 1.84 s TTI (3) | 2.04 s TTI (7) | 2.24 s TTI (16) | 2.44 s TTI (17) |
|---|---|---|---|---|
| Distance before stop bar (ft) | -9.23 | -7.31 | -2.25 | 1.37 |
| Peak decel (g) | 0.9 | 0.74 | 0.72 | 0.6 |
| Constant decel (g) | 0.5 | 0.48 | 0.42 | 0.4 |
| RDP: brake to stop bar (g) | 0.55 | 0.51 | 0.43 | 0.39 |
| Time to peak decel (s) | 1.94 | 2.38 | 2.34 | 2.37 |

As suggested above, although PBA was available to participants in the 2.24 s, 2.04 s, and 1.84 s conditions, only two participants engaged this system. One participant did so in the 2.24 s condition and stopped 13.89 ft before the stop bar. The second participant engaged PBA in the 1.84 s condition and stopped 17.28 ft after the stop bar. Statistical analysis of these observations was not possible due to the small representation of PBA engagement within the study sample.

Overall, these results suggest that although shorter timings elicit slightly quicker reactions and significantly harder decelerations from drivers, this does not necessarily translate to a stop that is farther away from the crash box. This suggests that there is a discretionary element that drivers use when deciding exactly where to stop relative to the stop bar. The most important observation in the timing comparison was related to response to the warning, which showed a trend toward dropping as the timings became shorter, particularly at the 1.84 s TTI warning timing condition.

Furthermore, it appears reasonable to assume that, as the TTI warning timing decreases, more drivers will decide to continue through the intersection since they may feel that it is not possible to safely stop in the distance remaining. Therefore, warnings should be presented as early as possible to the extent that their earlier presentation does not result in an unacceptable number of warnings perceived by the driver as "too early" or unnecessary.

**Differences between Speech and Beep Tone Warnings -** This section compares the results obtained for the Visual icon + Speech ('Stop Light') + Brake Pulse warning and the Visual icon + Beep Tone + Brake Pulse warning at the 2.24 s TTI warning timing (Study 5 and Study 6, respectively). The motivation for this comparison was to continue to evaluate the hypothesis that the Brake Pulse was the dominant factor behind the favorable driver behavior results obtained when a warning was presented. If this hypothesis was true, perhaps a less salient (hence, potentially less annoying) auditory warning could be coupled with the brake pulse warning without degrading warning effectiveness. (It should be noted that although PBA was active for both of these comparison studies, only one participant activated PBA during either condition [this participant was in the Speech condition and stopped 13.9 ft before the stop bar].)

Analysis of avoidance percentages indicated a trend toward participants experiencing the Speech warning avoiding at a higher percentage (89%) than participants who experienced the Beep Tone warning (50%), a difference that approached statistical significance (p=0.0940).

While analysis of plan initiation variables failed to indicate significant main effects, analysis of plan execution variables showed some significant main effects, as described below and summarized in Table 5:

- Distance before stop bar (F[2,19]=6.42, p=0.0074): Time to brake was significantly correlated with this variable. After considering the effects of this plan initiation variable, participants in the Beep Tone group were observed to stop at longer distances before the stop bar than participants in the Speech warning condition.
- Constant deceleration (F[1,20]=8.84, p=0.0075): Participants in the Beep Tone group yielded larger constant deceleration values

(approximately 0.07 g) than those in the Speech group.

- RDP from braking onset to stop bar ($F[2,18]=5.98$, $p=0.0105$): This variable significantly correlated with time to brake. After accounting for the effect of this plan initiation variable, participants in the Beep Tone group were observed to exhibit a slightly greater average RDP from braking onset to stop bar (roughly 0.05 g) than those in the Speech group.
- Time to peak deceleration ($F[2,18]=7.85$, $p=0.0035$): This variable was correlated with time to brake. After accounting for the effect of this plan initiation variable, participants in the Beep Tone group were observed to achieve peak deceleration faster (by roughly 0.15 s) than those in the Speech group.

**Table 5.**
**Means of Significant Differences between the Speech and Beep Tone Warning Conditions**

| Variable (N) | Speech Warning (16) | Beep Tone Warning (5) |
|---|---|---|
| Distance before stop bar (ft) | -4.22 | 1.88 |
| Constant deceleration (g) | 0.42 | 0.49 |
| RDP from brake to stop bar (g) | 0.43 | 0.48 |
| Time to peak deceleration (s) | 2.43 | 2.25 |

The most intriguing result of this comparison was the relative difference in avoidance percentages. Although participants in the Beep Tone group reacted more quickly and stopped farther away from the crash box, participants in the Speech group responded to the warning at a much higher percentage. It should be noted that the unbalanced number of participants across the comparison studies used for this Beep Tone versus Speech warning analysis necessarily confounds the analysis of stopping distance and deceleration behavior (which is based only on compliant participants). Hence, the main conclusion from this comparison is the observed tendency for the Speech warning, which suggests an increase in warning effectiveness relative to a Beep Tone warning when both are coupled with the brake pulse warning.

## CONCLUSIONS AND IMPLICATIONS

The results presented in the previous section showcase the substantial differences in driver performance and behavior that can result from the use of different DVIs and the timing at which those DVIs are presented for TCD violation warning. These differences were present during both plan initiation (i.e., pre-braking behavior) and plan execution (i.e., braking behavior) stages and in some cases resulted in significant differences in avoidance with the different warning combinations. In many instances, observable, sensible, and orderly trends suggested that additional statistically significant differences may have been found with larger sample sizes than those employed in the current studies. This section summarizes the key differences and trends observed in the current studies and suggests future research directions.

The main implication of the results from the nine studies is the selection of a DVI for on-road testing of the CICAS-V system. Driver behavior, performance, and response to the warnings (as well as subjective data not reported here) suggest that the Visual icon + Speech ('Stop Light') + Brake Pulse warning has the highest probability of success amongst the warnings tested. Therefore, this warning is recommended for further on-road testing of the CICAS-V system. The warning, which contains elements from the visual, auditory, and haptic modalities, also performed well across a number of relatively late presentation timings. Since both brake pulse and speech warnings have the potential to be annoying to drivers if false alarms occur too frequently (Kiefer et al., 1999), a Field Operation Trial with the CICAS-V system would provide useful information regarding user acceptance of these warnings. The following sections describe the conclusions reached for each of the four research questions that the series of studies was intended to address.

**Within the auditory modality, how does the effectiveness of speech warnings compare to non-speech warnings?**

There were two auditory warnings of primary interest, the CAMP FCW Tone and the Speech ('Stop Light') warning. There were no significant differences observed between the CAMP FCW Tone and Speech ('Stop Light') warnings with or without the brake pulse warning. However, avoidance rates suggested there may be a slightly increased likelihood of stopping before the intersection 'collision zone' with the Speech ('Stop Light') warning over the CAMP FCW Tone.

A third auditory warning, in the form of a Beep Tone, was also tested on an exploratory basis in an attempt to potentially reduce potential driver annoyance issues associated with the CAMP FCW Tone. This tone was accompanied by a brake pulse. The main

goal of using this tone was to determine if the lack of observable differences between the CAMP FCW Tone and the Speech ('Stop Light') warnings also transferred to a less urgent (hence, less annoying) sound. Since the tone was accompanied by a brake pulse, this would also determine the extent to which the Brake Pulse was the main factor in eliciting an avoidance response (see the next section for further discussion of this topic). Results showed that the Beep Tone elicited a significantly lower avoidance percentage than the Speech warning. Although participants that responded to the traffic signal after receiving the Beep Tone stopped slightly harder than those in the Speech warning condition, these differences are small from a practical perspective and may be the result of unbalanced data. Therefore, the Beep Tone was considered a less effective warning alternative and its use did not extend beyond the initial exploratory study.

**Is scenario outcome improved by the addition of a brake pulse warning?**
Results suggested that the brake pulse warning (i.e., a single, brief vehicle jerk cue) substantially improved driver performance with the warning (relative to conditions without a brake pulse). This tendency towards improved avoidance appears to be due to significant differences in plan initiation (i.e., pre-braking behavior) and plan execution (i.e., braking behavior) variables. Drivers receiving a brake pulse were faster to react and reached peak deceleration faster than drivers who did not experience a brake pulse warning. This, in turn, required slightly less braking effort from drivers receiving a brake pulse warning than for drivers not receiving a brake pulse, even though drivers receiving a brake pulse were also able to brake to a stop in less distance.

Given that these results were observed across two different types of auditory warnings (CAMP FCW Tone and Speech), it appears that the Brake Pulse was indeed a primary elicitor of response. However, recall that results with a Beep Tone auditory warning showed lower avoidance levels than those observed for the Speech auditory warning. Therefore, although the Brake Pulse warning appears to be the primary factor in eliciting an avoidance response, it is recommended based on the observed results that this warning be paired with a speech warning rather than a non-speech auditory warning (since the former provides more specific warning context to the driver).

**Does the availability of Panic Brake Assist (PBA) functionality improve the scenario outcomes?**
The availability of the PBA system, as well as the alteration of the PBA system entrance criterion across studies, had either a negligible or no effect towards improving the avoidance rates. Across the studies in which it was available, PBA was seldom activated by drivers. Although every instance of PBA system activation resulted in avoidance, it usually resulted in drivers stopping well short of the intersection stop bar. This suggests that the driver may have also avoided without assistance from the activated PBA system. Therefore, PBA was not recommended as a feature of the CICAS-V DVI.

**Within the context of the experimental scenario, what is the effectiveness of each different DVI warning relative to when a warning was not presented?**
This question would ideally be answered by examining driver performance and behaviors during the surprise trial. However, comparisons of driver performance and behaviors beyond avoidance were not possible, since only one driver responded to the traffic signal when a warning was not presented. This result, however, produced a significant difference in avoidance between the Baseline condition (in which drivers did not receive a warning) and all other similarly timed warning conditions. As shown earlier in Table 2, baseline drivers were substantially less likely to respond to the traffic signal. While the real-world magnitude of these differences is subject to statistical confidence, differences in avoidance rates suggest substantial improvements for most of the warnings, especially those employing a brake pulse. Future research should use data from real-world exposure to these systems to validate the avoidance levels and performance measures obtained in these test track experiments.

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# AN ANALYSIS OF SPEED-RELATED UK ACCIDENTS USING A HUMAN FUNCTIONAL FAILURE METHODOLOGY

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## ABSTRACT

Accidents involving either illegal or inappropriate speeding play a part in a large proportion of accidents involving cars. The types of typical failure generating scenarios found in car accidents where illegal speeding or inappropriate speeding is contributory are compared using the detailed human functional failure methodology developed in the European TRACE project (TRaffic Accident Causation in Europe), funded by the European Commission.

Using on-scene cases from the UK 'On The Spot' database (funded by the UK Department for Transport and Highways Agency), a sample of cases where speed is contributory have been analysed. An overview of speeding cases from the 4,000 in-depth cases available in the dataset is also presented.

The results highlight not only the differences between inappropriate and illegal speeding cases, but also the differences in the functional failures experienced by both the 'at fault' and 'not at fault' road users in both types of speed-related accidents.

The results form a unique base of knowledge for future work on the human-related issues associated with speeding of both types, for all crash participants. Also considered is how new technologies can address speeding accidents.

## INTRODUCTION

This paper describes part of an analysis undertaken by the Vehicle Safety Research Centre at Loughborough University, UK, in the EC funded TRACE project (TRaffic Accident Causation in Europe). The work investigated the main characteristics of accidents which involve driving task related factors.

In this study, driving task related factors are defined as being 'directly and causally contributing to the accident occurrence, very specific and detailed, are short-term lasting or dynamic in nature, and refer to the actual conditions of the components'. They can be present in all or part of an overall trip, but will only affect the road user when undertaking a certain part of the driving task. Examples of driving task related factors include speed, weather conditions and risk taking. They are thought to be effects of the wider trip related factors (e.g. alcohol impairment, road geometry, vehicle maintenance), which are in turn effects of background factors (i.e. pre-existing factors that are sometimes sociological such as education, income residence etc…).

From the main types of driving task related factors identified, the factor 'speeding' was chosen to be analysed using data from the UK Department for Transport and Highways Agency joint funded 'On The Spot' (OTS) project, firstly because of the large number of detailed cases available, but secondly because it is possible to identify two separate types of 'speeding' cases. Therefore, an interesting comparison of accidents involving these two types of speeding is possible. The two types of speeding identified are:

- Inappropriate speeding - where a road user in the accident travels too fast for the conditions (e.g. surface, visibility, layout, traffic);
- Illegal speeding – where a road user in the accident travels above the posted speed limit.

**Keywords:** Inappropriate speeding, Illegal speeding, Human Functional Failure, Causation factors

## METHODOLOGY

Two types of analysis are described in this paper:

- A general statistical overview of accidents where either inappropriate speeding or illegal speeding is a contributory factor (frequency and characteristics);
- A detailed case-by-case analysis of a sample of 40 cases where either inappropriate speeding or illegal speeding is a contributory factor using the Human Functional Failure (HFF) methodology developed in the EC TRACE project (Van Elslande et al. 2007).

### The On The Spot Database

The data source utilised is the UK Department for Transport and Highways Agency joint funded 'On

The Spot' (OTS) project. There are two investigation teams working on the OTS project in the UK, the Vehicle Safety Research Centre (VSRC) at Loughborough University, working in the Nottinghamshire region and the Transport Research Laboratory (TRL), working in the Berkshire region. The OTS teams attend and investigate, in total, 500 real-world collisions per year on a rolling shift pattern, covering all times and days of the week. The OTS teams investigate all collision types including all road users, all injury severities (from non-injury to fatal) and all road classifications. OTS cases include a wealth of information available to the analyst, as derived from physical examinations and interviews made on-scene followed by detailed analysis of findings and calculations made to reconstruct events and speeds. Both teams work in slightly different road network areas, which collectively are broadly representative of the UK. The study has been running since 2000 and has investigated over 4,000 real world collisions. The detailed methodology has been described elsewhere by Hill et al. (2001 and 2005).

The OTS database includes a number of advanced systems for coding accident causation. The method used in this study to identify speeding-related cases is the 'Contributory Factors 2005' system, which is the same coding system used by the Great Britain national accident data collection system since 2005. All cases in the OTS database have also been coded using this system, including those from before 2005. Each contributory factor can be coded at one of two levels of confidence, either a 'very likely' or a 'possible' cause.

Analysis has focussed on accidents involving at least one passenger car. Therefore, cases including each type of speeding causation factor are selected for analysis from the 3,663 cases involving at least one car currently in the OTS database.

**Definitions and Sample Selection: Inappropriate Speeding**

The contributory factor 'travelling too fast for conditions' is used to identify cases where 'inappropriate speeding' was causative. The on-scene accident investigators use their expert judgement of the evidence available to them at the scene to determine the likelihood that the road user was travelling too fast for the conditions they were confronted with. The type of 'conditions' included could be the road surface conditions (e.g. wet road, ice, diesel, defective surface), conditions reducing visibility (e.g. rain, fog, vehicle smoke, sun glare, road geometry, roadside objects, other vehicles), high winds and also traffic condition (e.g. traffic flow/speed).

Only cases where inappropriate speeding was recorded as being a very likely cause (rather than just possible) are included in the sample of cases. In order that there is no overlap with the sample of illegal speeding cases, cases are not included if road users were also recorded with illegal speeding (i.e. driving above the speed limit). Therefore, inappropriate speeding is defined as a road user who is not travelling above the speed limit set for the road, but the speed is inappropriate for the road conditions. In the OTS database, 564 cases involving cars are identified, which involved 885 vehicles, including 788 cars.

**Definitions and Sample Selection: Illegal Speeding**

Cases in the OTS database where 'exceeding speed limit' was recorded as a contributory factor are included in the sample of 'illegal speeding' cases. The on-scene accident investigator will use their expert judgement using the evidence available to them at the scene (e.g. skid marks and vehicle damage) to determine the likelihood that the road user was travelling above the posted speed limit of the road at/on approach to the accident scene and whether this was contributory.

In this sample, cases are included if inappropriate speeding was also a factor. The reason for this is that it is likely that in most cases where illegal speeding occurs, the speed will also be inappropriate for the conditions (i.e. this is denoted by the speed limit itself). As with inappropriate speeding, only cases where illegal speeding was recorded as a very likely cause (rather than just possible) are included in the sample of cases. In the OTS database, 307 cases involving cars are identified, which involved 487 vehicles, including 441 cars.

**Statistical Analysis: Explanatory Variables**

The explanatory variables listed in Table 1 are included in the general statistical overview to describe the typical characteristics of accidents involving either inappropriate speeding or illegal speeding.

**Table 1.**
**Explanatory variables in statistical overview**

| Explanatory variables | Values | Analysis level |
|---|---|---|
| Intersection | Yes / No | Accident |
| Manoeuvre | Yes / No | Car drivers |
| Accident configuration | Single car<br>Car v pedestrian<br>Car v car<br>Car v PTW<br>Car v pedal cycle<br>Car v large vehicle<br>>3 cars only<br>Others involving a car | Accident |
| Traffic density | Light / Moderate / Heavy / Congested | Accident |
| Area type | Rural / Urban | Accident |
| Road class | Motorway / Major / Minor | Accident |
| Carriageway type | Single / Dual | Accident |
| Speed limit | <10 / 20 / 30 / 40 / 50 / 60 / 70 mph | Accident |
| Horizontal geometry | Straight / Bend | Accident |
| Weather | Good / Poor | Accident |
| Road surface condition | Good / Poor | Accident |
| Lighting condition | Daylight / Darkness<br>Dusk / Dawn | Accident |
| Vehicle type | Car / Van / Truck / Bus / Motorcycle / Pedal cycle / Pedestrian | All road users* |
| Impact type | Front / Side / Rear / Top / Bottom | Vehicles (no pedestrians) |
| Age | <25 / 25-44 / 45-64 / >65 | All road users* |
| Gender | Male / Female | All road users* |

*Including pedestrians

For both the contributory factors (inappropriate speeding and illegal speeding) and for each explanatory variable analysed, cross-tabulations have been produced to compare the distribution of all cases with only cases where inappropriate speeding or illegal speeding was/was not a causation factor. The results were displayed in tables, such as the example shown in Table 2. It was therefore possible to determine whether accidents involving either causation factor appear to be more likely to occur when a specific type of explanatory variable is present (e.g. more likely on rural roads than urban roads).

**Table 2.**
**Example of results cross-tabulation**

| Area type | Inappropriate speeding a causation factor? | | All cases |
|---|---|---|---|
| | Yes | No | |
| Rural | - | - | - |
| Urban | - | - | - |
| Unknown | - | - | - |
| All | - | - | - |

To determine whether any differences found are significant enough to be a result of the speeding, and not due to chance, two-tailed chi-squared tests (using known-data only) were undertaken to test for statistical significance. A result was significant when $p \leq 0.05$ (i.e. the probability that the results were due to due chance were 5% or less).

**In-depth Analysis of Cases Using the Human Functional Failure (HFF) Methodology**

To analyse further the type of accidents where either inappropriate speeding or illegal speeding is a contributory factor, an in-depth analysis of a sample of cases involving either inappropriate speeding or illegal speeding has been undertaken using human factors methodologies developed in the EC TRACE project (Van Elslande et al. 2007).

The aim of the HFF methodology is to be able to clearly define the types of functional failures that humans experience in road collisions, using a sequential approach to the driving task which defines five main stages that the road user goes through when undertaking the driving task (perception, diagnosis, prognosis, decision-making and taking action). These failures can occur at any of the stages in the chain and it has been possible to classify five main types of failures that can occur during the driving task, as outlined in Figure 1. In addition to failures occurring at the five main stages of driving, there are also failures which are directly related to the overall capacities of the human which affect the whole functional chain. For example, the loss of psycho-physiological capacities (e.g. falling asleep, loss of consciousness), the alteration of the sensori-motor and cognitive capacities (e.g. alcohol/drug impaired) and the overstretching of the cognitive capacities (e.g. infrequent driving, age) (Van Elslande et al. 2007).

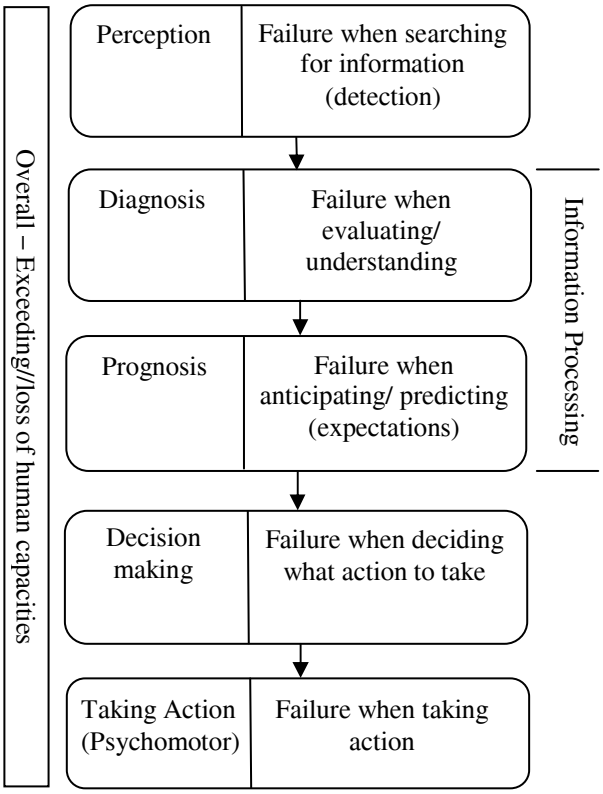


**Figure 1: Description of Human Functional Failures (TRACE Deliverable 5.1)**

In this methodology, a clear distinction is made between human failures and human factors. Human factors are defined as 'characteristics of the system which have weakened its capacity to function safely', whereas human failures are defined as 'the unwanted outcome of a confrontation of the driver with a task in which a difficulty was met'. Human failures are not defined as 'faults', as failures can also be found for 'not at fault' road users. The aim is to use the failures to identify the limits (physical and mental) of human capacity and therefore be able to understand better the types of countermeasures (i.e. safety systems) that would assist in overcoming these human limitations.

Grids of contributory factors and pre-accident driving situations were also developed as part of the TRACE study, to be used alongside the classification model of human functional failures to determine typical failure generating scenarios in samples of accidents. The grids were developed using current accident causation systems included in existing data collection systems from countries across Europe. See Naing et al (2007) for further details.

Closely related to the pre-accident driving situation is the 'conflict', which is also identified for each road user in each accident analysed. This is defined as the initial conflict that the road user was faced with prior to the accident (e.g. another road user or object in the road). It is possible for a road user to have no conflict (e.g. losing control of vehicle when falling asleep or unconscious, or being distracted by another task or person).

Also, distinctions are made between the road users who are 'primary active' in each accident, and those who are not. In the majority of accidents, the primary active road user is the one who is at the centre of the 'destabilisation of the process', and either intentionally or unintentionally initiate the point at which events start to go wrong (i.e. traditionally 'at fault'). The remaining road users in the accident (i.e. those 'not at fault') are described as 'other road users' in this paper.

To utilise the HFF methodology on OTS cases, detailed recoding of existing cases and in-depth analysis of each individual case was necessary to identify failure generating scenarios in each sample.

The selection criteria for these cases were as follows:

- Cases with injured casualties;
- Cases with an appropriate level of detail to undertake the analysis;
- Cases specifically from the local area so that the investigator's first hand experience of the cases could be utilised, if necessary.

The cases were sourced from the 564 OTS cases where inappropriate speeding was a cause and the 307 OTS cases where illegal speeding was a cause. From the sample of cases which met the above selection criteria, 20 inappropriate speeding and 20 illegal speeding cases were selected, taking care not to introduce any bias into the sample.

## RESULTS

### Statistical Analysis - Inappropriate Speeding

An overview of the typical characteristics of the 564 accidents where inappropriate speeding was a cause has been undertaken using the list of explanatory variables given in Table 1. Table 3 shows an example of the cross-tabulation results calculated, in this instance area type.

**Table 3.**
**Area type when inappropriate speeding was/was not contributory**

| % of cases | Inappropriate speeding a causation factor? | | All cases |
|---|---|---|---|
| | Yes | No | |
| Rural | 64% | 43% | 46% |
| Urban | 36% | 57% | 54% |
| All | 100% | 100% | 100% |

Table 3 shows that the proportion of accidents involving cars on rural roads is larger when inappropriate speeding is a causation factor compared with accidents when inappropriate speeding is not recorded as a causation factor. Statistical testing reveals that the differences in the results are statistically significant ($p \leq 0.05$).

Similar analysis has been undertaken for the remaining explanatory variables listed in Table 1. The results reveal that the following accident characteristics are statistically significantly ($p \leq 0.05$) more prevalent when inappropriate speeding is a cause compared with when it is not:

- Minor roads (UK classification <"A");
- Single carriageway roads;
- Not at an intersection;
- No manoeuvre was being undertaken (i.e. 'going ahead');
- Single car accident (no pedestrian or other vehicle involvement);
- Car drivers;
- Frontal impacts;
- 60mph (97km/h) roads (less prevalent on 30mph (48km/h) or 70mph (113km/h) roads);
- Bend in road;
- Poor weather conditions (e.g. raining, snowing, foggy, windy...);
- Poor road surface conditions (e.g. wet, icy, oil, diesel, defective...);
- Night conditions;
- Light density traffic conditions;
- Drivers under the age of 25 years;
- Male drivers.

**Statistical Analysis - Illegal Speeding**

The results of the statistical analysis of the 307 OTS accidents where illegal speeding was a cause reveal that the following accident characteristics are statistically significantly ($p \leq 0.05$) more prevalent when illegal speeding is a cause compared with when it is not:

- Minor roads (UK classification <"A");
- Single carriageway roads;
- Not at an intersection;
- No manoeuvre was being undertaken (i.e. 'going ahead');
- Single car accident (no pedestrian or other vehicle involvement);
- Car drivers;
- Frontal impacts;
- 30mph (48km/h) roads (less prevalent on 60 or 70mph (97 or 113km/h) roads);
- Bend in road;
- Night conditions;
- Light density traffic conditions;
- Drivers under the age of 25 years;
- Male drivers.

**In-depth Analysis Using the Human Functional Failure (HFF) Methodology - Inappropriate Speeding**

From the OTS database, 20 cases have been analysed from the 564 cases where inappropriate speeding was a contributory factor in the accident. There are 6 serious injury cases and 14 slight injury cases, according to the UK police classification system (UK, DfT 2004). There are 46 road users in total, of which 20 are primary active road users (one in each accident) and 26 are other road users. An overview of the vehicle involvement is given in Table 4.

**Table 4.**
**Vehicle involvement - Inappropriate speeding**

| Vehicle involvement | Number of cases |
|---|---|
| **Single car** | 4 |
| **Car v car** | 4 |
| **Car v PTW** | 2 |
| **Car v pedal cycle** | 1 |
| **Car v truck** | 1 |
| **Car v van** | 1 |
| **3 cars** | 3 |
| **Van v 2 cars** | 1 |
| **Van v 3 cars** | 2 |
| **4 cars** | 1 |

## Pre-accident Driving Situations and Conflicts

Figure 2 shows the most frequent driving situations for the primary active road users in the 20 inappropriate speeding accidents.

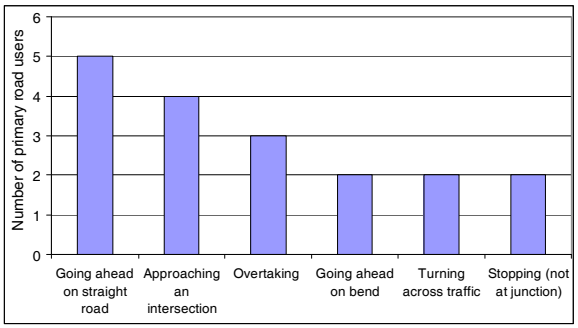


**Figure 2: Most frequent driving situations for primary active road users - Inappropriate speeding**

Figure 2 shows that the majority of primary active road users are going ahead and not undertaking a manoeuvre at the time of the accident. The most frequent 'conflict' comes from vehicles ahead, travelling in the same direction (either stationary or moving – 11 road users).

For the 26 other road users, the most frequent situation involves the road user being stationary (11 road users), while 7 road users are stopping or starting from stationary in a traffic queue. The most prevalent conflict comes from a vehicle following behind.

## Human Functional Failures

Figure 3 shows the main types of human functional failures that occur in the 20 inappropriate speeding accidents analysed.

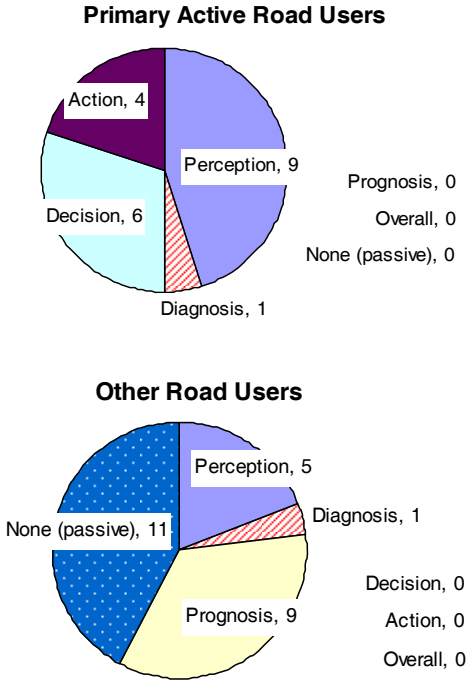


**Figure 3: Human Functional Failures for road users in inappropriate speeding cases**

Figure 3 shows that for the primary active road user in each accident, the most frequent type of human functional failure is related to a failure in perception (9 road users). When these cases are looked at in more detail, in the majority of cases (7 road users) the road user 'neglects the need to search for information' (i.e. does not search, therefore does not detect a danger).

Of the 26 other road users, 11 do not experience a human functional failure. In other words, they are passive in the accident (stationary). Of the remaining other road users, 8 experienced a prognosis failure - actively expecting another user to take regulating action.

## Other Factors Which Lead to the Human Functional Failures Occurring

Table 5 outlines the most frequent (≥3 road users) other factors which are found to contribute to the human functional failures occurring (in addition to inappropriate speeding).

**Table 5.**
**Most prevalent other factors contributing to the HFFs - Inappropriate speeding**

| Other factors which lead to the human functional failures | Number of road users | |
|---|---|---|
| | Primary active | Other |
| User state - In a hurry | 14 | 3 |
| User state - Right of way status | | 3 |
| User inexperience - Driving | 3 | |
| User behaviour - Distraction within user | 5 | |
| User behaviour - Risk taking (vehicle positioning) | 11 | 3 |
| User behaviour – Risk taking ('eccentric' motives) | 4 | |
| Road surface condition | 7 | |
| Road geometry | 4 | |
| Traffic condition – Flow | | 4 |
| Traffic condition – Speed | 5 | |
| Traffic condition - Other road user | | 14 |

In Table 5 it can be seen that, for the primary active road user, in addition to inappropriate speeding, other user behaviour-related factors are most frequent in the sample, in particular the road user being in a hurry and the road user 'risk taking – vehicle positioning' (driving too close to the vehicle in front).

For other road users involved in these accidents, it is the behaviour of the other road user(s) (usually the primary active road user) which most frequently contributes to their failure (absence or ambiguity of clues to their manoeuvre or atypical manoeuvre).

**In-depth Analysis Using Human Functional Failure (HFF) Methodology - Illegal Speeding**

From the OTS database, 20 cases have been analysed from the 307 cases where illegal speeding was a contributory factor in the accident using the selection criterion outlined previously. There is 1 fatal case, 5 serious injury cases and 14 slight injury cases. There are 34 road users in total, of which 20 are primary active (one in each accident), and 14 are other road users. An overview of the vehicle involvement in the sample of cases is given in Table 6.

**Table 6.**
**Vehicle involvement - Illegal speeding**

| Vehicle involvement | Number of cases |
|---|---|
| Single car | 10 |
| Car v car | 4 |
| Car v pedestrian | 3 |
| Car v motorcycle | 2 |
| 6 vehicles (4 cars v 2 vans) | 1 |

**Pre-accident Driving Situations and Conflicts**

Figure 4 shows the most frequent driving situations for the primary active road users in the 20 illegal speeding accidents.

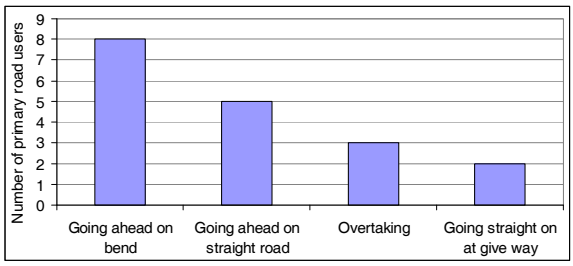


**Figure 4: Most frequent driving situations for primary active road users - Illegal speeding**

From Figure 4, it can be seen that the majority of the 20 primary active road users are going ahead at the time of the accident and are not at or approaching an intersection. When a manoeuvre is taking place, the road user is overtaking.

For half of the 20 primary active road users in the sample, there is no 'conflict', meaning the road user loses control for reasons which do not involve another road user or object on the road and, as a result, leave the carriageway before a collision. When there is a conflict, it comes from either ahead (oncoming or travelling in same direction) or from the side (from a side road or a pedestrian crossing the road).

For the 14 other road users, going ahead on a straight road is the most frequent pre-accident driving situation (7 road users). The most frequent conflict amongst the other road users involves another road user ahead (7 road users), most frequently travelling in the same direction. However, there are also instances of conflicts from behind (4 road users) and from the side (5 road users).

### Human Functional Failures

Figure 5 shows the main types of human functional failures that occur in the 20 illegal speeding accidents analysed.

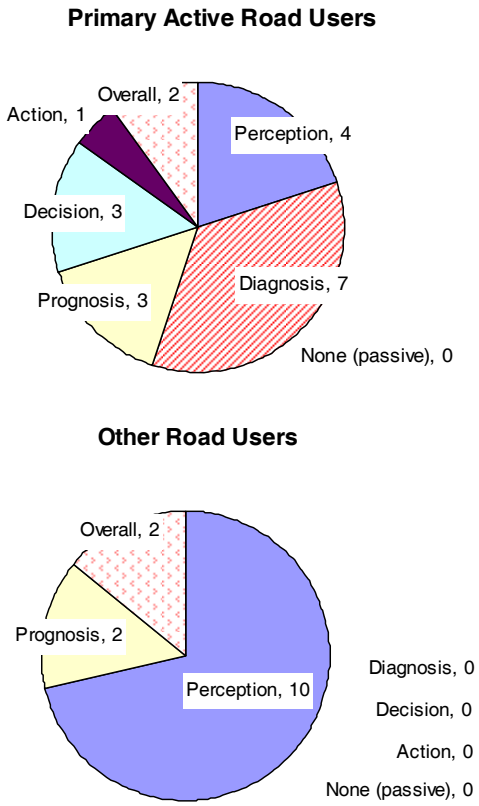


**Figure 5: Human Functional Failures for road users in illegal speeding accidents**

Figure 5 shows that for the primary active road user in each accident, the most frequent type of human functional failure is related to the diagnosis of the situation (7 road users). When these cases are looked at in more detail, in the majority of cases, the road user makes an erroneous evaluation of a passing road difficulty (6 road users) meaning the road user misjudges the layout (or conditions) of the road ahead (e.g. under-estimating the tightness of a bend or the surface friction on the road).

The most frequent type of human functional failure experienced by the 14 other road users in the sample is a failure in perception (10 road users), with half of these failures involving the road user neglecting the need to search for information.

### Other Factors Which Lead to the Human Functional Failures Occurring

Table 7 outlines the most prevalent (≥3 road users) other factors which are found to contribute to the human functional failure occurring (in addition to illegal speeding).

**Table 7.**
**Most prevalent other factors contributing to the HFFs - Illegal speeding**

| Other factors which lead to the human functional failures | Number of road users | |
|---|---|---|
| | Primary active | Other |
| User state – Substances taken (alcohol) | 3 | |
| User state – In a hurry | 14 | |
| User state – Right of way status | | 3 |
| User behaviour – Distraction within user | 8 | |
| User behaviour – Risk taking (vehicle positioning) | | 4 |
| User behaviour – Risk taking ('eccentric' motives) | 6 | |
| Road surface condition | 3 | |
| Road geometry | 9 | |
| Traffic condition – Other road user manoeuvre | | 13 |

From Table 7, it can be seen that, for the primary active road user, in addition to the speeding, in a hurry is the most frequent type of factor in the sample (14 road users). Road geometry is the most frequently occurring environmental factor in the sample for primary active road users.

For all but 1 of the 14 other road users in the sample, it is an atypical manoeuvre, or the ambiguity or lack of clues to a manoeuvre of other road user(s) (most likely the primary active) in the surrounding environment that contributes to the functional failure.

## DISCUSSION

### Inappropriate Speeding – Statistical Analysis

From the statistical overview of the 564 cases in the OTS database where inappropriate speeding is a contributory factor, a number of explanatory variables are found to be more likely to be present when inappropriate speeding (i.e. travelling too fast for the conditions) is a cause. A combination of these circumstances could increase the likelihood of an accident occurring when a road user is travelling at an inappropriate speed.

The results give an indication of the type of characteristics more likely to be involved in accidents where inappropriate speeding was contributory. These appear to be high speed limits (60mph, 97km/h) minor rural roads during low density traffic at night when the environmental conditions are poor, involving young, male car drivers going ahead on a bend. This suggests that

the conditions in question - which mean that the driver is driving at an 'inappropriate' speed - could either be the poor weather conditions, poor road conditions, the road geometry (bend) or the night (darkness) conditions. However this also suggests that it can be the posted speed limit itself that is inappropriate for the road conditions (i.e. too high), which leads to the driver travelling at an 'inappropriate' speed.

**Inappropriate Speeding – HFF Analysis**

The analysis of the sample of 20 cases using the Human Functional Failure methodology finds a number of different accident scenarios where inappropriate speeding is a cause. The 46 road users involved in these cases are split into 2 categories:

- Primary active road users (20)
- Other road users (26)

**Primary active road users** When bringing the information together to identify typical human functional failure generating scenarios for primary active road users in accidents where inappropriate speeding is a cause, the most frequent scenario involves a perception-related failure (9 road users), in particular a late detection of a vehicle slowing down ahead (in 7 cases). When looking in more depth at the 7 road users who experienced this type of scenario, in all instances, the road user does not detect the slowing/stationary vehicle(s) ahead until it is too late to avoid a collision. The reason given for this lack of detection is that the road user does not feel the need to search for information. In these scenarios, it is likely that this is either due to the stationary/slow vehicle being at an unexpected location (e.g. not at a junction, when a vehicle is turning into a side road or private driveway), or, in the scenarios where the accident does occur at or near a junction, the road user had not expected a traffic queue as far back from the junction as it was, so did not undertake a detection for stationary traffic. Therefore, in these scenarios, the inappropriate speeding is related to the traffic condition (i.e. the sudden change in the traffic speed), rather than the road geometry or surface conditions.

When looking at the other type of factors (in addition to inappropriate speeding) which contribute to these 'failure in perception' accidents, the road user being in a hurry, being positioned too close to the vehicle in front, the sudden slow speed of the traffic ahead and the visibility being impaired by the weather are contributory factors that feature in at least 2 of these 7 accidents. Therefore, this is building up a picture of one type of 'typical scenario' which involves inappropriate speeding as a cause, where the road user approaches unexpected stationary vehicle(s) but does not detect them early enough because it was not expected. In addition, their high (but not illegal) speed, coupled with other factors present, such as the road user being in a hurry to get to their destination, their close positioning to the vehicle in front, the poor visibility conditions and the slowing traffic itself, leads to a collision occurring.

Closely related to the scenarios of these 7 road users, 2 additional road users experience a scenario which involves them not seeing the slowing vehicle(s) ahead due to an internal/external distraction. Although the reason for the non-detection is different, the outcome is the same as with the 7 previously discussed road users.

Other failure generating scenarios which occur in the sample include decision-making failures (6 road users), in particular a scenario related to the intentional risk taking of the primary road user (5 road users). In the sample of cases, this includes a road user overtaking another road user on a curved road during wet conditions, a road user weaving through traffic on a busy dual carriageway road and also a road user overtaking another road user at an intersection just as the second road user is about to turn across traffic (turning right in UK) into a side road. In all of these cases, the road user is travelling under the road speed limit, but it is still too fast to be able to undertake any emergency avoidance when it is needed. Certain risk taking factors are found to be contributory in these accident scenarios, including the road user driving too close to other road users ('vehicle positioning'), and road users thrill-seeking/competing with other vehicles ('eccentric motives'). The road user being in a hurry and also user inexperience are causative in a number of these scenarios.

The final reoccurring type of scenario identified involves a failure when taking action (4 road users). In 2 cases, the road user loses control on a bend with road surface contaminants present, and in both cases it is the combination of this external disruption, the bend and the road user's inappropriate speed that leads to the loss of control. In the third case, the road user loses control on a pool of standing water (aquaplaned) on a straight dual carriageway road. Therefore, it is the sudden wet road surface, coupled with the road user's inappropriate speed that leads to the loss of control. In the final case, the road user is driving a vehicle adapted with hand controls for disabled drivers. The road user accidentally presses the incorrect hand control on approach to a traffic queue, which accelerates the vehicle. Due to the inappropriate (but not illegal) speed at which the road user is approaching the intersection, the road user is unable to regain control of their vehicle and collides with a

number of vehicles in the traffic queue ahead. It could be said that if the road user had been driving at a more appropriate (i.e. slower) speed for the approaching conditions ahead, this would have given the road user more time to regain control after this sudden unexpected 'disruption' in the driving task.

**Other road users** Bringing the information together to identify typical failure generating scenarios for other road users in inappropriate speeding accidents, the most frequent failure generating scenario is found to involve a prognosis failure (9 road users), in particular, actively expecting another road user behind to take regulating action when braking (8 road users). This scenario is linked to the human functional failure 'actively expecting another road user to take regulating action' (Van Elslande et al, 2007) and often involves contributory factors such as the behaviour of other road users and traffic flow. In this scenario, when a road user starts to brake, they actively expect the (primary active) road user behind to also be able to brake safely. However, due to the vehicle behind travelling too close and also too fast for the traffic condition, the vehicle behind is unable to brake in time to avoid a collision.

Using the HFF methodology, this is seen as not only a functional failure of the primary active road user in terms of their speed and positioning, but also of the non primary active road user, as their expectations of the road user behind and also the 'rules of the road' ('right of way status') mean that they are concentrating on avoiding the road user ahead, and expect the road user behind to avoid them.

This is not implying that road users should also be responsible for avoiding vehicles behind them. On many occasions, it might be beyond human capability to avoid impacting a vehicle ahead and a vehicle behind. However, this has highlighted an area where certain types of safety systems in a vehicle may be able to assist the road user to avoid collisions which a human alone may not find possible to do.

In addition to accident scenarios involving prognosis failures, there are also a number of accident scenarios involving perception failures (5 road users). This failure in detection is due to a number of reasons, including an obstruction to visibility, the road user focussing on only one part of the scene, the road user only undertaking a quick detection of the scene (e.g. due to being in a hurry) or the road user doesn't think there is a need to undertake any detection at all.

**Inappropriate Speeding – Possible Solutions**

From the analysis undertaken, possible current and future solutions for helping to reduce the type of accidents where inappropriate speeding is found to be a contributory factor could include the following:

- Educating less experienced drivers about the dangers of inappropriate speeding as well as illegal speeding;
- Current in-vehicle technologies such as ABS, brake assist and ESC could help road users who find themselves travelling too fast for the conditions to overcome difficulties they might encounter and avoid possible collisions;
- Advance warnings of the dangers ahead (e.g. of bends in road) at higher risk locations which can also be seen at night will assist road users to travel at a more appropriately safe speed on approach to these high risk locations;
- Signs giving advisory speed limits on approach to high risk locations, although such systems cannot take weather and road surface conditions into account unless equipped with environmental sensors;
- Future solutions such as in-vehicle devices which provide road users with advance notification of the road geometry/surface conditions and hazards ahead and possibly also assist by automatically reducing the vehicle speed on approach to these high risk locations. Full collision avoidance technologies could also be integrated into such systems.
- Further improved definitions of speed limits, considering the road conditions, geometry, traffic conditions etc, which will provide better guidance to road users on the driving limits of the road.

Before implementation, it would be necessary to evaluate some of these potential solutions for their effect on the mental workload of the driver, to determine whether overload could be possible. Field Operation Tests and simulator trials could inform such work. It is also important to more fully understand any risk compensation effects. That is to say any possibilities that driver perceptions of increased safety due to the presence of in-vehicle technologies, such as brake assist, may encourage inappropriate speeding.

Changing attitudes to inappropriate speeding can be expected to have a "knock-on" effect whereby drivers are also less likely to speed illegally.

As the definition of inappropriate speeding is 'travelling too fast for the conditions', conditions which can change, it is clear that the most effective advance warnings systems will rely on the

development of environmental sensors integrated into the highway infrastructure and vehicle to infrastructure communication.

**Illegal Speeding – Statistical Analysis**

From the statistical overview of the 307 cases in the OTS database where illegal speeding is a contributory factor, a number of explanatory variables are found to be more likely to be present when illegal speeding (i.e. travelling above the road speed limit) is a cause.

These results give a good indication of these characteristics, which appears to be low speed (30mph, 48km/h) minor roads during low density traffic at night (not at an intersection), with a young male car driver going ahead on a bend.

**Illegal Speeding – HFF Analysis**

The analysis of the sample of 20 cases using the HFF methodology found a number of different accident scenarios where illegal speeding is a causation factor. The 34 road users involved in these cases are split into 2 categories:

- Primary active road users (20)
- Other road users (14)

**Primary active road users** The most frequent type of failure generating scenario for primary road users in illegal speeding accidents has been found to involve a diagnosis failure (7 road users), in particular an incorrect evaluation of an approaching road difficulty (6 road users). In this scenario, the primary road user is negotiating a bend and it is a single vehicle accident (i.e. no impact with other road user on road). They either have knowledge of the bend ahead and therefore are more complacent than if they were negotiating an unfamiliar bend, or think they will be able to negotiate it faster, and therefore misdiagnose the conditions on this bend on this particular occasion. Or, they are focusing more on the thrill-seeking aspects of driving an unknown bend rather than evaluating the road conditions. In this scenario, it is found that the road user being in a hurry, the eccentric risk-taking motives of the road user and the road geometry (i.e. the bend) are also often contributory to the functional failure occurring (in addition to the illegal speed).

In addition to diagnosis-related failure generating scenarios, perception-related scenarios are also identified in the sample of primary active road users (4 road users). The types of perception failure in each scenario vary, and are shown below:

- A primary road user undertakes a hasty search for information whilst attempting to overtake another road user ahead who is attempting to turn across traffic (turning right in the UK) from a main road into a side road (the road user fails to detect that the vehicle was indicating);
- In two instances, the road user detects a pedestrian crossing the road/slow vehicle ahead too late due to their belief that there is no need to search for information (i.e. encountering a conflict that was not usual at the road location);
- A primary road user who does not detect a vehicle approaching from the side when they are about to cross because they are distracted.

In a hurry and "distraction within user" (i.e. lost in thought), and road surface condition are additional factors to illegal speeding.

**Other road users** The majority of failure generating scenarios identified for other road users involved in the illegal speeding cases involve a perception failure (10 road users), more specifically the road user neglecting the need to search for information (5 road users). In these cases, the road user does not detect until too late a road user ahead (either another vehicle or a pedestrian). The reason for the lack of detection is either because they do not expect another road user (a possible conflict) to appear at this location or do not expect to encounter slow vehicles ahead at this location, as it is not a crossing or intersection. The main factors which contribute to this failure in this type of scenario include their rigid attachment to the right of way status, their close positioning to another vehicle ahead and the atypical manoeuvre of another road user (i.e. the primary road user).

Scenarios involving prognosis failures are also indentified in the sample (2 road users). One involves the road user failing to expect another road user in an opposing lane to carry out an overtaking manoeuvre in heavy traffic. The other, the road user actively expects a road user behind to also take regulating action when they start to slow down because of slowing traffic ahead. In both scenarios, it was the atypical manoeuvre of another road user that was the main contributory factor to the failures.

There are also 2 cases in the sample which involve a scenario with the 'overall' failure of 'exceeding sensorimotor/cognitive capacities'. In both cases, the main contributory factor for the road user is alcohol impairment and the road user was a pedestrian crossing the road. In the first scenario, the road user is half way across the road just beyond a bend when the primary road user approaches the bend at speed, entering the opposing carriageway where the pedestrian is located. Because of the alcohol impairment, the road user is unable to react at all and a collision occurs. It was decided that due to the alcohol impairment of the pedestrian, that even without the poor visibility due

to the bend, the pedestrian would have been too alcohol impaired to react. In the second scenario, the alcohol impaired pedestrian is trying to cross the road when a collision occurs with the primary road user's vehicle, which is speeding. In this case it was concluded that the pedestrian may have been able to avoid the collision if there had been no alcohol impairment, so the pedestrian's main failure was directly related to the alcohol impairment.

**Illegal Speeding – Possible Solutions**

From the analysis undertaken, possible current and future solutions for helping to reduce the type of accidents where illegal speeding is found to be a contributory factor could include the following:

- On lower speed limit roads, in particular at night, stricter enforcement of the speed limits;
- Better education of higher risk road users (i.e. those found most at risk of speeding in this study), of the dangers of driving above the speed limit, not only for others, but for themselves;
- Speed limiters in vehicles of the highest risk road users (e.g. young/new drivers; convicted speeders), the limiters working in particular on higher risk roads, especially at night. This would be a focused application of a mandatory Intelligent Speed Adaption system (ISA);
- Educating road users of the increased risk of making errors when driving at high speeds (i.e. not only less time to evaluate their surroundings, but also to detect potential dangers and make correct decisions);
- Advance warning devices (and collision avoidance systems) to help road users avoid a collision with a speeding motorist.
- The introduction of traffic calming procedures, in particular those which are more subtle to the road user, will help to promote a natural reduction in driving speeds.

**Comparison between Inappropriate Speeding and Illegal Speeding Cases**

As opposed to inappropriate speeding, poor weather and surface conditions are not more likely to be found in accidents where illegal speeding is a cause, which implies that the increased risk of travelling above the speed limit as opposed to just travelling too fast for the conditions, over-rides the risk of the presence of poor weather and conditions.

Whereas rural roads lead to a greater likelihood of an accident occurring when inappropriate speeding occurs, neither rural nor urban roads are more likely to lead to collisions where illegal speeding is causative. However, as with inappropriate speeding accidents, minor roads still have the greater accident likelihood when illegal speeding occurs. Another difference observed between the inappropriate speeding accidents and the illegal speeding accidents is that roads with low speed limits (30mph or 48km/h) are more likely in illegal speeding accidents, whereas roads with high speed limits (60mph or 97km/h) are more likely in inappropriate speeding cases.

When comparing the results of the Human Functional Failure analysis, the illegal speeding accidents most often involve a scenario where the primary road user misdiagnoses the road geometry ahead, either due to over-familiarity or thrill seeking. Whereas in the inappropriate speeding accidents, primary road users are more frequently travelling too fast (and too close) for the conditions and often fail to detect a conflict in time to react.

When comparing the frequent failure generating scenario between both speeding samples for the non primary road users, the first main difference observed is the high number of non primary active road users who do not experience a failure generating scenario in the sample of inappropriate speeding cases compared to the illegal speeding cases, where there are no passive road users. This is mainly due to the stationary road users in the inappropriate speeding cases, who are impacted from behind by the primary road user who is considered to be driving too fast for the conditions (i.e. the erratic traffic flow). Also, the other main difference observed is that for the illegal speeding cases, a scenario involving a perception failure is most frequent, whereas a scenario with a prognosis failure is most frequent in the inappropriate speeding sample. However, both of these scenarios do involve the road user's expectations. In the perception-related failure, the road user fails to detect because they do not undertake any search at all, because they feel there is no need for it at that location (i.e. they're not expecting to encounter a conflict). In the prognosis-related failure, the road user has detected a possible conflict (i.e. another road user in their path), but because they have right of way, they expect the other road user to undertake the avoiding action.

It is interesting to note that in the inappropriate speeding cases, the most frequent scenario for the primary active road user involves a perception failure and for the non primary active road user, the most frequent scenario involves a failure in information processing, whereas in the sample of illegal speeding cases, it is vice-versa.

**Future Work**

Using the HFF methodology on a larger sample of cases could inform the development and implementation of Intelligent Speed Adaption

(ISA). Whilst the current ISA systems themselves are only concerned with illegal speeding, adaptations utilising advanced warning systems to deal with inappropriate speeding could be of benefit. It would also be interesting to consider that an ISA system may incorrectly reassure a driver that their speed is appropriate, because they know the system is fitted and it hasn't activated, when in fact they are travelling too fast for the conditions. For example, whilst travelling on a rural road with a posted speed limit of 60 mph (97 km/h) but with sharp bends.

## CONCLUSIONS

This study finds that the driving task-related factors inappropriate speeding and illegal speeding significantly contribute to accidents occurring with the accident likelihood increasing when specific conditions (e.g. road type, area, road user type…) are present.

The statistical analysis reveals distinct differences in accident characteristics between the two types of speeding. A positive link with high speed limit (60mph, 97km/h) roads, rural roads, poor surface conditions and weather conditions is found when inappropriate speeding is a cause, which is not found when illegal speeding is a cause. However, accidents on low speed (30mph, 48km/h) roads are found to be prevalent when illegal speeding is a cause.

This study also shows that the presence of these two speed-related factors leads to failures at various stages of the driving process, from the initial perception (detection) stage, during information processing (diagnosis/prognosis stage), through to the decision making stage or when undertaking the resulting action. However, as with the statistical analysis, differences in the prevalence of the failures between the two types of speeding are found when undertaking the Human Functional Failure analysis.

For primary active road users, scenarios with a perception-related failure are most frequent in the sample of inappropriate speeding cases and scenarios with an information processing diagnosis-related failure are most frequent in the sample of illegal speeding cases. Whereas for other ('not at fault') road users involved in each type of speed-related accident, the opposite was found to be the case (i.e. information processing prognosis failures in inappropriate speeding cases and perception failures in illegal speeding cases).

These findings imply that different solutions to prevent accidents involving these two types of speeding-related factors are needed. Also, this outlines the importance of ensuring that in future analysis, these two types of speeding-related factors are considered separately, as it has been shown from this work that the failures behind inappropriate speeding and illegal speeding accidents and their characteristics are often not the same.

Road users could benefit from current and future technologies to help avoid travelling at inappropriate speeds, including better advance warning/advisory signage, driver education, and in-vehicle technologies such as advance warning systems. It will be important for future research to monitor the proliferation of in-vehicle systems such as brake assist, ESC and collision avoidance as they may prove able to prevent accidents at speeds currently judged to be inappropriate. However, accidents may not be prevented if drivers continue to drive at inappropriate speeds due to any increased perceptions of safety resulting from these new technologies. Risk compensation as well as any distraction or mental loading aspects of new technologies should therefore be evaluated. It is, furthermore, likely that fully effective warning systems will require a step change in infrastructure (highway sensors and communication systems).

Road users would also benefit from technologies to help avoid travelling at illegal speeds (such as ISA), or being involved in a conflict with a road user who is travelling above the speed limit. In addition stricter enforcement of speed limits at high risk locations (as outlined in this study), improved education to new drivers, speed limiters in vehicles, and advance warning mechanisms to help road users to avoid collisions with speeding motorists would be of benefit.

It has been possible, using the TRACE HFF methodology, to identify a number of typical scenarios that road users are faced with when either travelling too fast for the conditions or above the road speed limit and the failures they encounter. While the current sample is small, and results should therefore be interpreted with appropriate caution, this study has shown the methodology to be a useful tool in accident causation analysis by highlighting the differences between the characteristics of accidents where inappropriate speeding is a cause and accidents where illegal speeding is a cause.

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# COMPARISON BETWEEN ADAPTIVE AND BASIC MODEL METRICS IN LANE CHANGE TEST TO ASSESS IN-VEHICLE SECONDARY TASK DEMAND

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## ABSTRACT

The evaluation of driver's distraction due to driving assistance use requires the development of methods, which allow measuring the driving performance degradation. This paper aims to describe and discuss the metrics utilized in the Lane Change Test, which is developed to become a standard within the ISO framework.

The LCT consists in driving on a three lane road and performing lane changes according to signs displayed on each side of the road. The main metrics are based on deviation measures between a reference trajectory and the current driver trajectory. Two types of reference trajectories can be calculated following an adaptive or a basic model. The adaptive model calculates a reference trajectory different for each participant, while the basic one utilizes an identical one for all participants.

The differences between the two measures have been investigated through an experiment carried out with thirty participants, performing LCT in single and dual task conditions (using auditory and visual manual tasks).

Qualitative analyses of trajectories show the advantage of the adaptive model which better fits to the diversity of real driver's behaviour. Data analyses also show divergent results according to the models, especially in terms of correctness of lane changes. A greater number of correct lane changes is obtained with the adaptive model than with the basic one. These differences are mainly induced by trajectories classified as loss of control errors using the basic model due to usual positions in the lanes of the driver (tendency to drive on the right or left part of the lanes), that are considered as correct ones using the adaptive model.

The adaptive model allows a better description of lane change errors due to secondary task demand. Such a method is now used by different laboratories involved in ISO group.

## INTRODUCTION

As described by Mattes and Hallen (2008), the LCT allows evaluating driver's demand while performing a secondary task, such as operating an in-vehicle system. This method is currently being discussed in ISO working group TC22/SC13/WG8 as the basis of a standard to assess driver demand (ISO, 2008).

A simulated driving task is performed, which is based on lane change trials. The distractive impact of the secondary task on the driving is evaluated by analysing the lateral positioning on the simulated route with respect to a reference lateral position. Then, a mean deviation of the driver's trajectory is processed, and used to give the driving performance and the impact of the secondary task on it. The percent of correct Lane Changes is also of interest to better explain this performance.

Two types of reference trajectories can be calculated following an adaptive or a basic model. The adaptive model calculates a reference trajectory for each participant, while the basic one utilizes an identical one for all participants. This paper aims to describe and to compare the two measurement methods. Experimental results are then given both in terms of mean deviation and in terms of correctness of the lane changes according to the way they have been computed.

## LANE CHANGE TEST

The primary task is a simulated driving task, which consists in driving along a straight 3 lane road at a system-limited speed of 60 km/h. Participants are asked to use a steering wheel to maintain the vehicle position in the centre of the indicated lane.

Lane change signs appear on both side of the simulated road to inform the driver which lane to drive. The signs are always visible but blank, until the lane change instruction is given at a distance of 40 meters before the sign position. For each task under investigation a driver has to perform a 3 000 meter run composed of 18 lane changes, each lane change sign being spaced approximately with 150 meters.

A lane change is characterized by the lateral displacement of the vehicle from one lane to another one (across one or two lanes). The impact of the secondary task on the driving is evaluated in terms of degradation of the lane change trajectory. For each run, a mean deviation is calculated between the trajectory of a participant (dotted line) and a reference model (solid line), which corresponds to the area between the two curves (Figure 1).

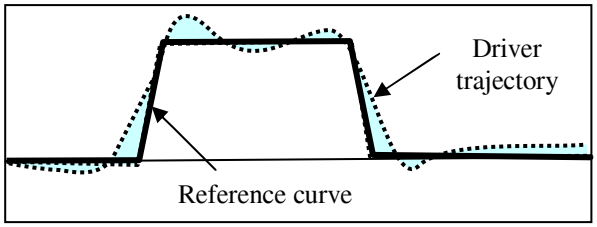


**Figure 1. Mean deviation calculation.**

Two methods are used to calculate the reference trajectory:

- a *Basic Method*
- an *Adaptive Method*

***Basic method***

Using a *basic measurement* (Figure 2), the current driver's trajectory is compared to a reference one, which is the same for each driver. Such a curve is defined according two variables:

- The *Start Lane Change distance,* which corresponds to the distance between the lane change sign and the beginning of the reference lane change.
- *The Lane Change Length* corresponds to the distance needed to perform the lane change.

Each basic reference lane change starts 30 meters before the lane change sign and lasts for 10 meters.

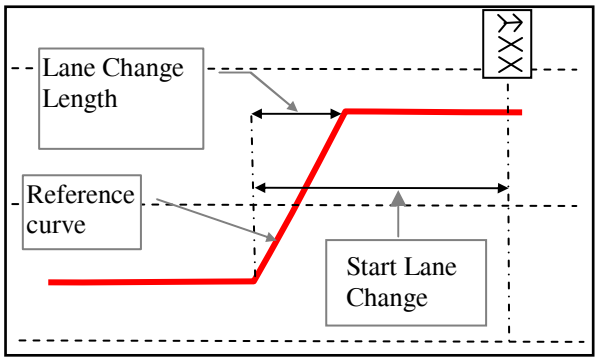


**Figure 2. Variables used to calculate the basic reference curve**

***Adaptive method***

Using the adaptive method, the same two variables are used as for the above basic model, namely the *Start Lane Change distance and the Lane Change Length*. However, new variables are now added: the *Average Distance* and the $AdaptedPosXlane_i$ (Figure 3).

- The *Average distance* corresponds to the distance between the lane change sign and the middle of the lane change.
- The $AdaptedPosXlane_1$ corresponds to the mean lateral position calculated for the first lane, the $AdaptedPosXlane_2$ for the second one and the $AdaptedPosXlane_3$ for the third one.

All these parameters are then adjusted to obtain a curve the closest as possible to the driver's trajectory.

Only baseline runs, which are performed without any added task, are used to calculate the adapted reference.

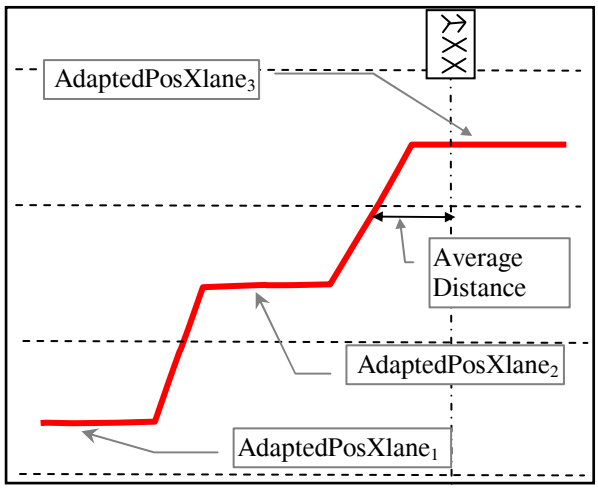


**Figure 3. Variables used to calculate the adapted curve**

## ADAPTED METHOD DEVELOPMENT

The *Adapted reference curve* is obtained in two steps. First, the *Average Distance*, which is the distance from the lane change sign to the middle of the performed lane change, is calculated. This distance being calculated, the *Lane Change Length* and the $AdaptedPosX_i$ (mean position on each lane) can be computed.

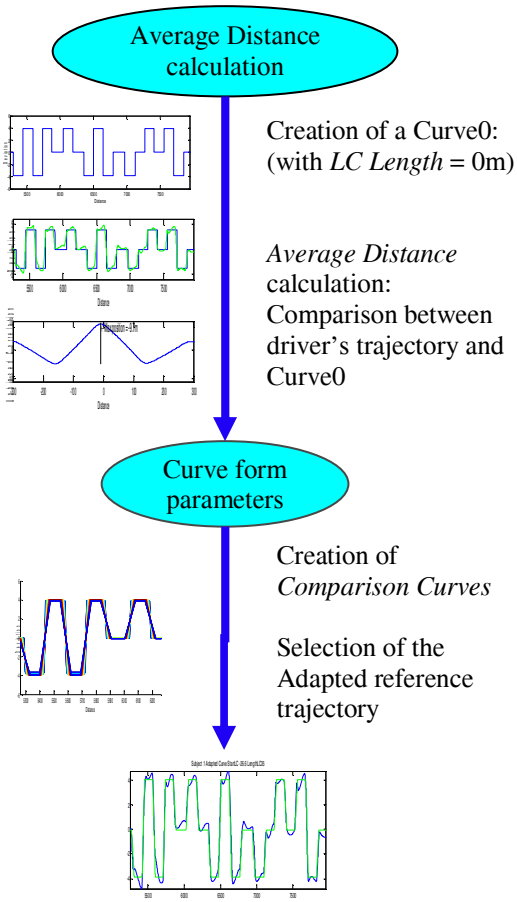


**Figure 4. Method steps**

### *Average distance calculation*

A curve with a 0 meter *Lane Change Length* is calculated for each lane change sign. This curve, the *Curve0*, corresponds to the attended position on each lane (Figure 5).

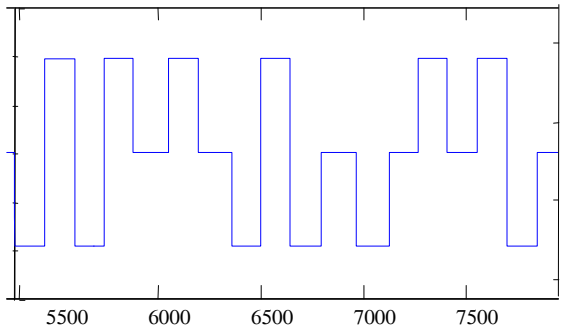


**Figure 5. Curve with *Lane Change Lengths=0m***

Then, the participant's trajectory is compared with this curve using correlation metrics (Figures 6 & 7).

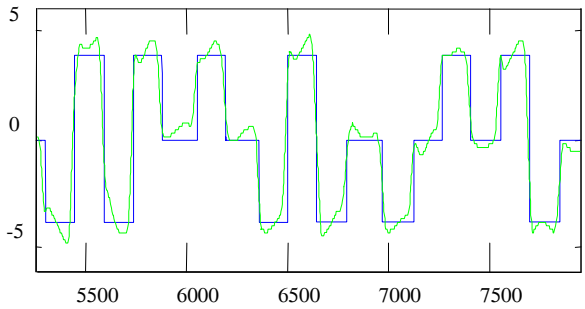


**Figure 6. Comparison between driver's trajectory and *Curve0***

To precisely evaluate the *Average Distance*, a high precision of the peak position of the correlation is needed. This precision is obtained by unbiased correlation, which is calculated between the two curves using the formula:

$$\begin{aligned} &\forall m \in [0 : N-1] \\ &R(m) = \frac{1}{N-|m|} \sum_{n=0}^{N-m-1} baseline_{x,n+m} curve0_{x,n} \\ &\forall m \in [-N+1 : -1] \\ &R(m) = \frac{1}{N-|m|} \sum_{n=0}^{N-|m|-1} baseline_{x,n} curve0_{x,n-m} \end{aligned} \quad \textbf{(1)}$$

The correlation obtained by this method presents a peak around 0. The position of this peak gives the distance shift, which has to be applied to the *Curve0* to make it the closest to the driver's trajectory. This distance shift corresponds to the participant's *Average Distance*.

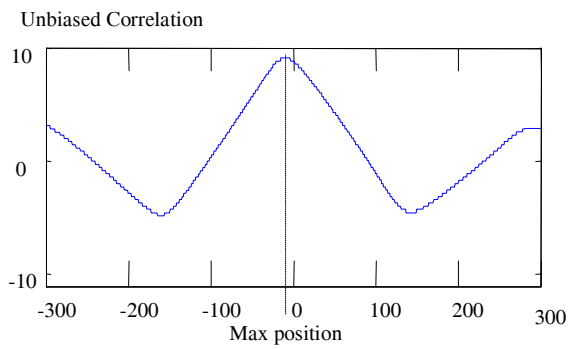


**Figure 7: Correlation between driver's trajectory and *Curve0***

***Shape variables of the adapted curve***

Various curves, the *Comparison Curves*, are calculated using the *Average Distance* defined above and *Lane Change Lengths* (Figure 8). These *Lane Change Lengths* are comprised between 10 meters and 80 meters, and a different $LaneChangeLength_k$ is assigned to each curve. Then, for each of these *Comparison Curves*, three positions are calculated, which correspond to the lateral position of the driver on the three lane road: left, centre and right lanes.

Segments of the driver's trajectory obtained for each lane (lane changes being excluded of these segments) are added and averaged, for each *Comparison Curve*. This allows obtaining the $AdaptedPosXlane_i$.

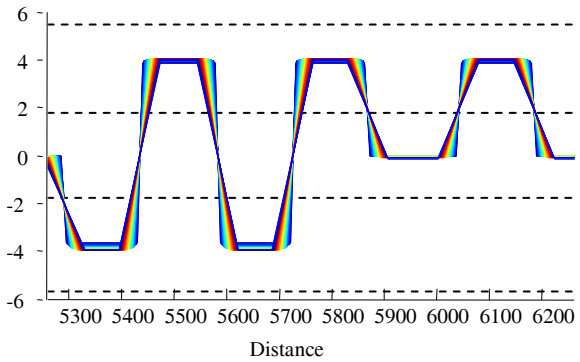


**Figure 8. Set of comparison curves**

Each of the *Comparison Curves* is then compared with the driver's trajectory. At this step, the peak value is more important than its position. Then, the correlations are normalized by the norms of the two curves using the following formulas:

$$\forall m \in [0 : N-1]$$
$$R_k(m) = \frac{1}{|curve_k|}\frac{1}{|baseline|}\sum_{n=0}^{N-m-1} baseline_{x,n+m}\, curve_{x,k,n}$$
$$\forall m \in [-N+1 : -1]$$
$$R_k(m) = \frac{1}{|curve_k|}\frac{1}{|baseline|}\sum_{n=0}^{N-|m|-1} baseline_{x,n}\, curve_{x,k,n-m}$$
$$|baseline| = \sqrt{\sum_{n=0}^{N-1} baseline_{x,n}^2}$$
$$|curve_k| = \sqrt{\sum_{n=0}^{N-1} curve_{x,k,n}^2}$$

**(2)**

The curve obtaining the maximum peak value is then selected to become the *Adapted Reference Trajectory* of the driver.

## EXPERIMENT

An experiment was conducted with 16 drivers (8 males and 8 females) aged between 26 and 45 years (mean = 34; SD = 5.8). The experiment was run on the INRETS fixed-base simulator in Lyon, which has a front screen with a horizontal visual field of 50°. The car body is a Renault Espace with a manual gearbox and all the standard passenger compartment features, displays and controls. Software, conforming to the ISO draft standard, was developed by the INRETS-MSIS team.

Prior to the experiment itself, all participants performed a learning phase consisting of four runs without any added task to enable them to become familiar with the LCT. The experiment then always began and ended with a run without an added task. Such a run was also performed in the middle. These three runs provided the baseline data.
Four added tasks were performed in four different orders to limit potential task order effects. Each task was first executed without the LCT during about 90 seconds, to let participants get acquainted with it. They were then invited to perform the task with the LCT.

***Secondary tasks***

Two types of secondary tasks were performed: 2 auditory ones and 2 visual manual ones.

<u>Auditory tasks:</u>

- The first one (AT1) consisted of a series of statements pronounced by an experimenter. The participants had to listen to each statement, to repeat it, and to answer "Yes" if it was true, and "No" if it was false. Each assertion was randomly presented so that each driver had a single series.

- The second task (AT2) involved inventing sentences by creating a chain. To begin with, the participants were given a first sentence comparing animals. They then used the last word of the sentence to create the following one. For example: "A horse is taller than a rat", "a rat is smaller than an elephant"...

Visual manual tasks:
To perform the visual-manual tasks a screen was placed on the dashboard. Position and size recommended by the ISO draft standard were respected. A numeric keypad was laid out under the screen so that the driver could carry out the commands related to the two tasks.

- The first visual-manual task (VM1) was the Surrogate Reference Task (SuRT). The objective was to look at a screen and to locate a circle among distractors (smaller circles). To select the target, the participants moved a cursor to the relevant zone by using right and left arrows. Then a button allowed them to validate the choice and a new configuration was given by the system. Three levels of difficulty could be activated. All drivers performed the "Intermediate" level.
- The second task (VM2) was the Critical Tracking Test (CTT) designed by Dynamic Research. Participants were faced with a moving black line. To begin with, this line was displayed in the centre of the screen but then went up and down. The objective was to keep it as close as possible to the centre part of the screen, by using the up and down arrows of a keypad. Various difficulty levels could be activated. All drivers performed an easy level (lambda = 1, gain = 20).

***Performances measures***

Two measures of performance have been used:

- The Mean Deviations: as specified in the LCT ISO draft, the driving performance is mainly evaluated by the driver's mean deviation. Two mean deviations were obtained for each run as compared with the two reference trajectories (basic and adapted): the *Basic Mean Deviation* and the *Adapted Mean Deviation*.
- The *Percent of Correct Lane Changes ( LC)* indicated the correctness of the responses to lane change signs. Between two lane change signs an observational zone was defined to determine the lane where the vehicle was most frequently positioned. If this lane corresponded to the sign indication, the LC was considered as correct (Engström and Markkula, 2007; ISO, 2008)

Most of the data that will be presented here consisted in data obtained during baseline conditions (without any added task). Results obtained for the different added tasks will be given mainly in terms of *Percent of Correct LC*.
First, qualitative observations of the driver trajectories will be presented to compare the two methods.

## REFERENCE TRAJECTORIES FROM BASIC AND ADAPTED METHODS

Comparisons have been made between the current driver trajectory and the two reference trajectories obtained with the two measurement methods. All the following examples have been obtained in baseline conditions (without performing any dual task).

Figure 9 gives an example of trajectories obtained for a whole run. The *Basic reference trajectory,* which is the same for each driver, is represented with a red dotted line, the *Adapted reference trajectory*, which is calculated for each driver as explained above, is represented with a green dotted line, while the current participant's trajectory is represented with a blue solid curve.

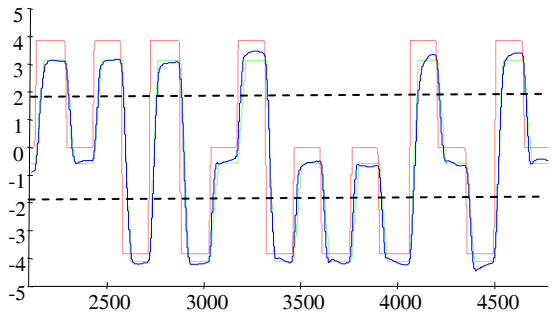


**Figure 9: Comparison between Adapted curve and Basic curve**

In this figure, the *Basic reference trajectory* seems to be very different from the realized trajectory, which appears to be closer to the *Adapted one*. The figures given below will give some reasons to explain such a result.

Detailed analyses have been made on different runs performed by the participants. Although the following examples are representative of whole runs, only short segments are given here, to better show the effect to be highlighted.

Tendency to drive on the right part of the lane

The driver whose part of a baseline is shown in Figure 10 adopted a tendency to drive on the right part of each lane of the baseline run. His/Her performance based on the *Basic Reference Trajectory* appeared to be poor. This participant obtained a *Basic Mean Deviation* of 1.32. Such a performance is higher than the level of 1.2 required retaining a participant in the ISO draft (ISO, 2008), meaning that this driver should be excluded from the participants.
The calculation of his/her performance based on the Adapted reference trajectory takes into account his/her tendency to drive on the right part of the lanes. In this case, he/she obtained an *Adapted Mean Deviation* of 0.28, which remained below the adaptive model acceptability criterion of less than 0.7 as it is mentioned in the ISO draft.

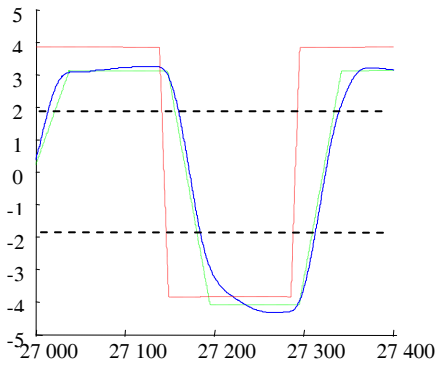


**Figure 10: Tendency to drive on the right part of the lane**

<u>Tendency to long lane changes</u>
The driver whose part of a baseline is shown in Figure 11 tended to make long lane changes. In this case, the *Lane Change Length* was higher than the one defined by the *Basic Reference Trajectory*. Such behaviour had an effect on the performance. As a consequence, his/her performance based on the *Basic Mean Deviation* was poor (*Basic Mean Deviation* of 1.49), and higher than the level of 1.2. However, the performance based on the *Adapted Reference Trajectory* appeared to be acceptable and below the acceptability criterion of 0.7 (*Adapted Mean Deviation* of 0.33).

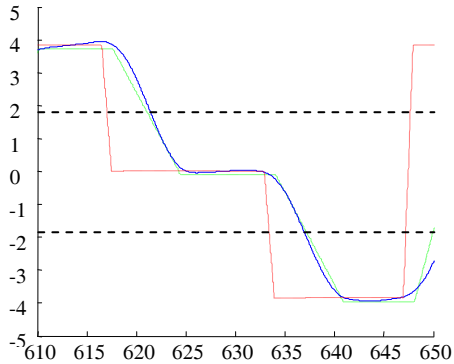


**Figure 11: Tendency to long Lane Changes**

The above results have been obtained for 2 of our 16 participants. But such behaviors have been observed for other drivers, even if it was not always in such an extreme way. The question which remains is that these drivers should have been excluded from the data in case of using the *Basic Model*. And so, even if they correctly changed lane each time during the baseline conditions. Comparatively, their performances were considered as being good enough with the adaptive model.

The comparison between the two methods shows that using the *Adaptive Model*, the realized trajectories are closer to the *Adapted reference trajectories* than using the *Basic one*. The performances are then better (with lower Mean deviation). The reason is that in the former case, the reference trajectory takes into account the participant's "driving style", for examples his/her tendency to drive on the right/left part of the lanes or to perform longer lane change than shown by the *Basic Model*.

## PERCENT OF CORRECT LANE CHANGES

### *Measurement description*

The correctness of a Lane Change is defined by the driver's position before and after its realization. To determine this position, the 3 lane-road has been divided into different zones, corresponding to parts of the lanes. The ISO draft (2008) recommends using segments of 40 to 140 meters after each lane change. The lane change signs being spaced approximately with 150 meters and the lane change instruction being displayed at a distance of 40 meters before the sign position, it was decided here to reduce these segments to 110 meters. By this way, we could avoid taking into account part of the trajectory corresponding to the next lane change in a given zone.

The zones $L_1$ to $L_3$ correspond to a correct position in $lane_1$ (left lane), $lane_2$ (centre lane) or $lane_3$ (right

lane), while the zones "O" correspond to *out of lane* positions (Figure 12).
The lateral position of the driver is defined by the zone which contains the longest part of his/her trajectory. However, when no zone contains at least half of the trajectory, then the position is considered as being *out of lane*.

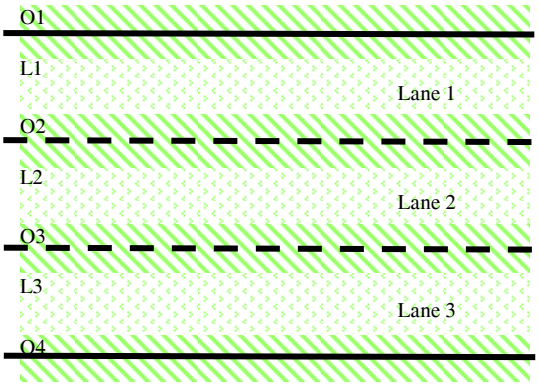


**Figure 12. Lane change zones**

The correctness of each lane change has been defined as follow:

- "Correct LC": the end position of the driver is in the attended lane,
- "No LC": the driver is in the same $L_i$ zone at start and end positions,
- "Erroneous LC": the end position of the driver is in another lane than in the attended one.
- "Loss of Control LC": the end position of the driver is in one of the $O_i$ zone,

At this step, differences between *Basic* and *Adapted methods* are registered, in terms of characterisation of the zones. Using the *Basic Method* the zones are centred on the middle of each lane, while using the *Adapted Method* they are centred on the $AdaptedPosXlane_i$. In both methods the zones consist in 2 meters wide and 70 meters length.

***Comparison between the two methods***

The lane changes performed by the participants have been categorised according to their correctness into "Correct LC", "No LC", "Erroneous LC" and "Loss of control". Global percents of lane changes taking into account all the performed lane changes have been first calculated according to the two methods. Then, such percents have been calculated for each condition under investigation: baseline condition, auditory tasks: AT1 and AT2 and Visual manual ones: VM1 and VM2 (Tables 1 and 2).

**Table 1. Correctness of LC using *Basic Method***

| *Basic* | Global | Baseline | AT1 | AT2 | VM1 | VM2 |
|---|---|---|---|---|---|---|
| Correct LC | 92.7% | 96.6% | 96.5% | 91.3% | 90.6% | 80.6% |
| No LC | 0.1% | | | 0.7% | | 0.3% |
| Erroneous LC | 0.3% | | | 1.4% | 0.7% | 0.3% |
| Loss of control | 6.8% | 3.4% | 3.5% | 6.6% | 8.7% | 18.8% |

**Table 2. Correctness of LC using *Adapted Method***

| *Adapted* | Global | Baseline | AT1 | AT2 | VM1 | VM2 |
|---|---|---|---|---|---|---|
| Correct LC | 97.8% | 100.0% | 99.7% | 96.5% | 96.5% | 92.0% |
| No LC | 0.2% | | | 1.0% | | 0.3% |
| Erroneous LC | 0.3% | | | 1.4% | 1.0% | |
| Loss of control | 1.6% | | 0.3% | 1.0% | 2.4% | 7.6% |

First, comparison of the global results showed that the number of errors calculated using the *Basic Method* was much higher (5.1% more), than the one calculated with the *Adaptive Method*. Most of these errors were categorized as "Loss of control" errors.

Moreover, no error was registered in the baseline condition, using the *Adaptive Method*, while 3.4% (N=29) of the lane changes were considered as errors using the *Basic Method*. Only 6 of the 16 drivers were responsible for these errors obtained in Baseline condition and 22 of these 29 errors were due to only 3 drivers.

To illustrate what occurs in such situations, Figure 13 gives the trajectory of one of these drivers, in baseline condition. The blue solid line gives the driver's trajectory, while the dotted red and green ones give respectively the *Basic* and the *Adapted Reference Trajectories*. The 6 red circles indicate errors calculated with the *Basic Measurement*.
In this case, the participant tended to drive on the right part of the lanes. This tendency was taken into account by calculating his/her *Adapted Reference Trajectory*. In this case, his/her position after lane changing was compared with his/her $AdaptedPosXlane_i$ that was considered as being correct. Using the *Basic Model*, this position being too far from the reference trajectory was considered as being out of lane.

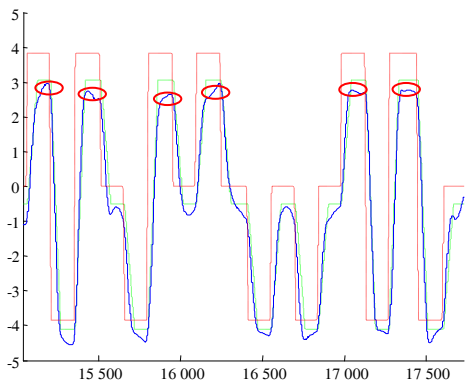


**Figure 13. "Loss of control" errors in Baseline condition**

Another example is given with Figure 14 in the Visual Manual task VM2 condition. Two "Loss of control" errors were registered (black circles) using both *Methods*. In these cases, the position of the driver appeared to be very far from the attended one, which explains the fact they were considered as out of the lane, whatever their calculation. However, 2 other "Loss of control" errors (red circles) were also registered using the *Basic Method*. In these later cases, the driver's position was closer to his/her *Adapted Reference Trajectory*, and considered as being correct using the *Adapted Method*.

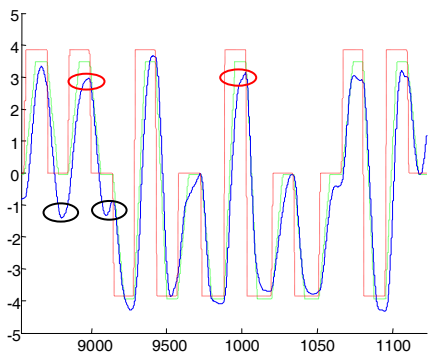


**Figure 14. "Loss of control" errors in VM2 condition**

More generally, the main differences obtained between both methods concerned the number of "Loss of control" errors, which seemed to increase with the task difficulty: from the easier auditory task to the harder one and from the easier visual manual task to the more difficult. However the number of these errors was higher using the *Basic Method* than the *Adaptive one*. Moreover, the difference between both measurements increased for the visual manual tasks. This could be explained due to the fact while performing the later tasks, the driver's trajectory was more impaired and then more difficult to interpret in terms of correct lane changes or 'Loss of control" errors.

## CONCLUSIONS

From these analyses, it has been shown that using the *Adapted Method* allowed to obtain a *Reference Trajectory*, which was closer to the driver's one, than using the *Basic Method*. As a result, the mean deviation obtained in baseline condition was sometimes of a better quality. As a consequence, some drivers who would have been excluded using the *Basic Method* could pursue the experiment. Taking into account the correctness of the lane changes, differences between both methods were highlighted, especially in terms of "Loss of control" errors, whose number was higher with the *Basic Method*. It was shown that some of these errors could be attributed to driving specificities of the participants (tendency to drive on the right part of the lanes, to make long lane changes…) when was using the *Basic Model*. By taking into account the driving style of the participant, the *Adaptive Method* reduced the number of such errors. Moreover, it is believed that such a measurement would allow for a more naturalistic driving, as the driver could perform, for example, longer lane changes, without being stressed to terminate them before each sign position.

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# COMPUTER VISION SYSTEMS FOR 'CONTEXT-AWARE' ACTIVE VEHICLE SAFETY AND DRIVER ASSISTANCE

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**Paper No: 09-0266**

## ABSTRACT

The last decade has witnessed the introduction of several driver assistance and active safety systems in modern vehicles. Considering only systems that depend on computer vision, several independent applications have emerged such as lane tracking, road/traffic sign recognition, and pedestrian/vehicle detection. Although these methods can assist the driver for lane keeping, navigation, and collision avoidance with vehicles/pedestrians, conflict warnings of individual systems may expose the driver to greater risk due to information overload, especially in cluttered city driving conditions. As a solution to this problem, these individual systems can be combined to form an overall higher level of knowledge on traffic scenarios in real time. The integration of these computer vision modules for a 'context-aware' vehicle is desired to resolve conflicts between sub-systems as well as simplifying in-vehicle computer vision system design with a low cost approach. In this study, the video database is a subset of the UTDrive Corpus, which contains driver monitoring video, road scene video, driver audio capture and CAN-Bus modalities for vehicle dynamics. The corpus includes at present 77 drivers' realistic driving data under neutral and distracted conditions. In this study, a monocular color camera output is used to serve as a single sensor for lane tracking and road sign recognition. Finally, higher level traffic scene analysis will be demonstrated, reporting on the integrated system in terms of reliability and accuracy.

## INTRODUCTION

It has been reported that the fatality rate is 40,000-45,000 per year with annual cost of 6M [1] in USA. Although each year the number and the scope of vehicle safety systems (ABS, brake assist, traction control, EPS) are increased, these figures have reached a plateau, and further reduction in the number of accidents and associated costs require a pro-active approach. It is known that 90% of the accidents have drivers as a contributing factor while 57% are solely caused by human errors [2]. These figures reveal another explanation for the constant level of accident rates despite the increased efforts for safety systems: However well equipped the vehicles, and however well-designed the infrastructure, accidents generally happen due to human error. This does not necessarily mean that most accidents are inevitable. On the contrary, if all available road scene analysis, lane tracking, collision avoidance and driver monitoring technologies are applied, it is estimated that at least 30% of the fatal accidents (including several accident types) can be averted [3]. The obstacle preventing these systems from being applied is primarily cost-related. Therefore, resolving this problem lies in system integration to reduce the cost in order to obtain more compact and reliable active safety systems. In this study, a proposed integration is studied in the scope of in-vehicle computer vision systems. Video streams, whether processed on-line or off-line contains rich information content regarding road scene. It is possible to detect and track vehicle, lane markings, and pedestrians and recognize the road signs using a frontal camera and some additional sensors such as radar. It is of crucial importance to be able to detect, recognize and track road objects for effective collision avoidance. However, we believe that higher level context information can be extracted as well from the video stream for better integration of these individual computer vision systems. By interpreting the traffic scene for the driver, these systems can be employed for driver assistance systems as well as providing input for collision systems. In the scope of the work presented here, a lane tracking and road sign recognition algorithm is combined for future context-aware active vehicle safety applications. This paper first presents the proposed system, and then provides details on each individual computer vision algorithm. Next, the individual algorithms are combined to (1) extract higher level context

information on traffic scene, (2) lower the computational cost of road sign recognition using lane position cues from lane tracking algorithm. Experimental results and performance evaluation of the system is proposed in the following section. Finally, prospective applications for active safety and driver assistance are discussed together with conclusions.

**Proposed system**

The proposed system offers the ability to extract high-level context information using a video stream of the road scene. The videos considered form a sub-database of multi-media naturalistic driving corpus UTDrive. In fact, CAN-Bus information from OBD-II port is used to improve the performance of the designed lane tracker. The system distinguishes itself from existing in-vehicle computer vision approaches in two ways: (1) the lane tracking algorithm is used to feed the road sign recognition algorithm with spatial cues providing a top-down search strategy which improves process speed, (2) detected lane and road signs are combined using a rule-base interpretation to represent the traffic scene ahead at a higher level. The signal flow of the final system is presented in Fig.1. Three main blocks in this diagram (i.e. lane tracking, road sign recognition and rule base) are addressed in the next sections.

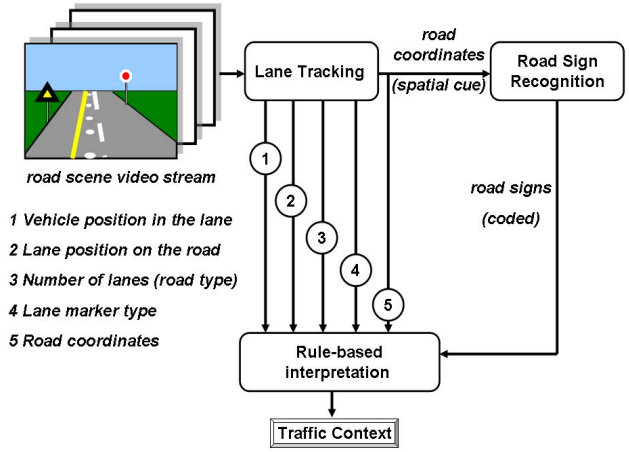



**Figure 1. Signal flow in computer vision system**

**<u>Lane Tracking Algorithm</u>**

There has been extensive work in developing lane tracking systems in the area of computer vision. These systems can be potentially utilized in driver assistance systems related to lane keeping and lane change. In [4], a comprehensive comparison of various lane-position detection and tracking techniques is presented. From that comparison, it is clearly seen that most lane tracking algorithms do not perform adequately to be employed in actual safety-related systems, however, there are encouraging advancements towards obtaining a robust lane tracker. A generic lane tracking algorithm has the following modules: a road model, feature extraction, post-processing (verification), and tracking. The road model can be implicitly incorporated as in [5] using features such as starting position, direction and gray level intensity. Model based approaches are found to be more robust compared to feature-based methods, for example in [6] B-snake is used to represent the road. Tracking lanes in real traffic environment is an extremely difficult problem due to moving vehicles, unclear/degraded lane markings, and variation of lane marks, illumination changes, and weather conditions. In [7] a probabilistic framework and particle filtering was suggested to track the lane candidates selected from a group of lane hypotheses. A color based scheme is used in [8]; shape and motion cues are employed to deal with moving vehicles in the traffic scene. Based on this previous research, we propose a lane tracking algorithm as presented in Fig. 2 to operate robustly in real traffic environment.

The lane tracking algorithm presented here uses conventional methods seen in the literature; however, the advancement here is the combination of a number of them in a unique way to obtain robust tracking performance. It utilizes a geometric road model represented by two lines. These lines represent the road edges and are updated by a combination of road color probability and road spatial coordinate probability distributions which are built using road pixels from 9 videos each at least containing 200 frames. The detection module of the algorithm employs three different operators, namely, steerable filters [9] to detect line-type lane markers, yellow color filter, and circle detectors. These three operators are chosen to capture three different lane-marker types existing in Dallas, TX where data collection took place. After application of the operators, the resultant images are combined since it is bow believed to have all the lane-mark features that could be extracted. This combined image is shown as the 'lane mark image' block in Fig.2. Next, Hough transform is applied to extract the lines together with their angles and sizes in the image. The extracted lines go through a post-processing step name as 'lane

verification' in Fig.2. Verification involves elimination of lane candidates which do not comply with the angle restrictions imposed by the geometric road model. From the lane tracking algorithm, 5 individual outputs are obtained: (i) lane mark type, (ii)lane positions and (iii)number of lanes in the image plane, (iv) relative vehicle position within its lane, and (v) road coordinates.

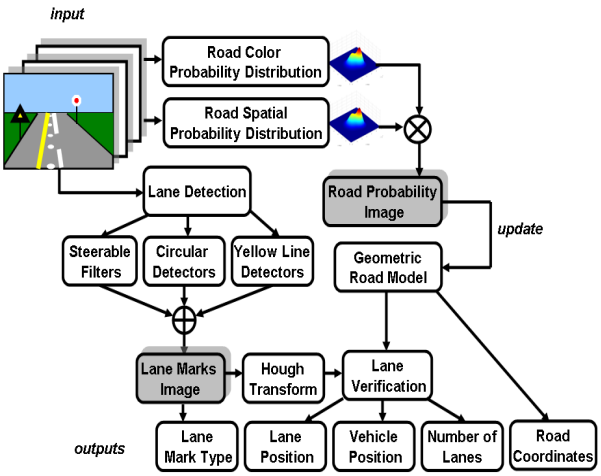



**Figure2. Lane Tracking Algorithm**

Two different types of updates are needed in the lane tracking algorithm. First, the road probability image updates the geometric road model for each frame and runs simultaneously with lane detection. Some of the false lane candidates are eliminated by the imposed angle limits of the geometrical road model; however, it is not adequate for robustness. The prominent lane candidates which exist in each *n* consecutive frame are held in a track-list, supplying the system with a time coherency or memory. A lateral vehicle dynamics model is applied together with Kalman filter to smooth the lane position measurement given by the lane candidates in the tracking list.

A sample output of the lane detection algorithm is given in Fig. 3(a). To observe the performance of the lane detection part the raw lane position measurement is compared with the lane position calculated by the vehicle model (see Fig.3(b)). In Fig.3 (c), the road area and possible lane candidates are marked by the algorithm.

The full evaluation will be presented in section 'Results and Performance Analysis'.

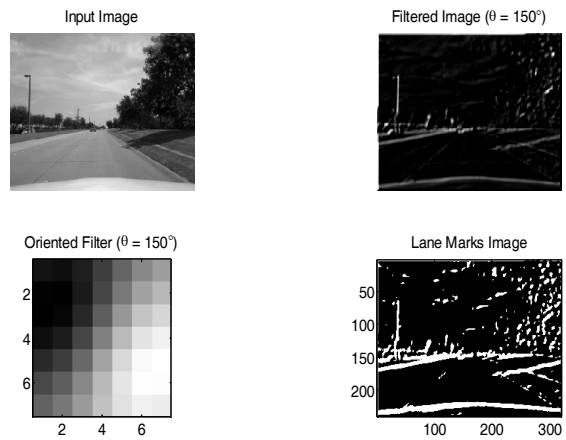



**Figure3(a) .Sample output from lane detection algorithm**

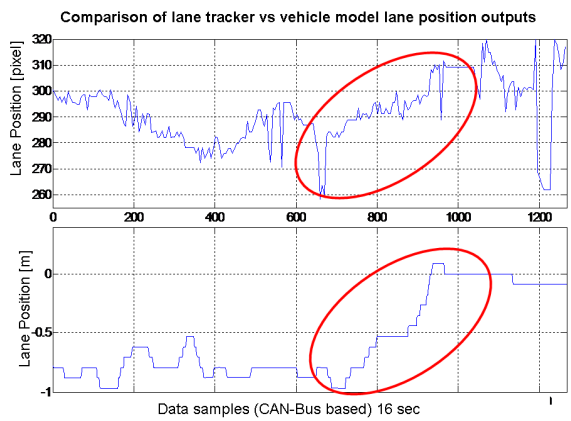



**Figure3(b). Comparison of lane position measurement from raw lane detection (top) and vehicle model calculation (bottom) before outlier removal and tracking**

**Figure3(c). Road area and prominent lane candidates are projected on image (top), detected lanes after outlier & false candidate removal**

The performance of the lane tracker algorithm depends heavily on feature (i.e. lane mark) detection; and feature detection based vision systems are vulnerable since they are affected by illumination change, occlusion, imperfect representations (i.e. degraded lane marks) plane distortion and vibration in our case since the road surface is not flat. Some of these disadvantages of feature based lane detection are overcome by employing a vehicle model for correcting the measurements in time domain and road model helps removing the outliers in spatial domain in the image. Since vehicle and road model are crucial for reliability and accuracy of the resultant system, they are briefly presented here.

**Vehicle Model**

The vehicle model used is known as 'bicycle model' [10] for calculating the lateral dynamics of the vehicle and linearized at a constant longitudinal velocity. In order to obtain more realistic behaviour from this model, it is updated by changing longitudinal velocity at discrete time steps. Therefore the resulting vehicle model is a hybrid system containing a set of continuous time LTI vehicle models switched by a discrete update driven by longitudinal speed changes. As a consequence the resultant model is non-linear and closer to realistic vehicle response. The model inputs are steering wheel angle, longitudinal vehicle velocity and outputs are lateral acceleration and side slip angle. The lateral acceleration output of this model is used to calculate the lateral speed and finally lateral position of the vehicle employing numerical integration by trapezoids. The variables of model are given in Table 1.

**Table1. Variables of vehicle model**

| Symbol | Meaning |
|---|---|
| $c_f$ or $c_r$ | cornering stiffness coefficients for front and back tire |
| $J$ | Yaw moment of inertia about z-axis passing at CG |
| $m$ | Mass of the vehicle |
| $r$ | Yaw rate of vehicle at CG |
| $U$ | Vehicle speed at CG |
| $y_c$ | Lateral offset or deviation at CG |
| $\tau$ | Wheel steering angle of the front tyre |
| $\alpha_f$ or $\alpha_r$ | Slip angle of front or rear tyre |
| $\beta$ | Vehicle side slip angle at CG |
| $\rho_{ref}$ | Reference road curvature |
| $\psi$ | Yaw/ heading angle |
| $\psi_d$ | Desired yaw angle |
| $\omega$ | Angular frequency of the vehicle |

The equations of motion using the variables given in Table 1 are presented in equations (1-2).

$$\begin{bmatrix} \dot{\beta} \\ r \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{bmatrix} \beta \\ r \end{bmatrix} + \begin{bmatrix} b_1 \\ b_2 \end{bmatrix} \tau \qquad (1)$$

Where, in a format $\dot{x} = Ax + Bu$,

$$\dot{x} = \begin{bmatrix} \dot{\beta} \\ r \end{bmatrix}, \; A = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}, \; B = \begin{bmatrix} b_1 \\ b_2 \end{bmatrix}, \; u = \tau$$

And in the output format, $y = Cx + Du$

$$\begin{bmatrix} a_s \\ \beta \\ r \end{bmatrix} = \begin{bmatrix} c_{11} & c_{12} \\ 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \beta \\ r \end{bmatrix} + \begin{bmatrix} d_1 \\ 0 \\ 0 \end{bmatrix} \tau$$

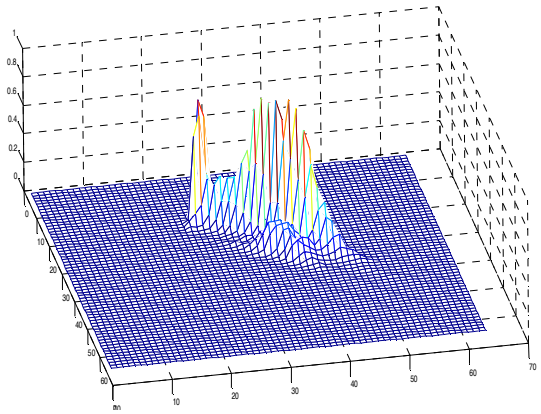
Where, $y = \begin{bmatrix} a_s \\ \beta \\ r \end{bmatrix}, C = \begin{bmatrix} c_{11} & c_{12} \\ 1 & 0 \\ 0 & 1 \end{bmatrix}$ and $D = \begin{bmatrix} d_1 \\ 0 \\ 0 \end{bmatrix}$.

The elements of the matrices are given explicitly here:

$$a_{11} = -(C_f + C_r)/mU \quad ,$$
$$a_{12} = -1 + [(h_r C_r - h_f C_f)/mU^2]$$
$$a_{21} = (h_r C_r - h_f C_f)/J \; , \; a_{22} = -(h_f^2 C_f + h_r^2)/JU$$
$$b_1 = C_f/mU \; , \; b_2 = h_f C_f / J$$
$$c_{11} = -[(C_f + C_r)/m] + [l_s(h_r C_r - h_f C_f)/J]$$
$$c_{12} = [(h_r C_r - h_f C_f)/mU] - l_s[(h_f^2 C_f + h_r^2 C_r)/JU]$$
$$d_1 = [(C_f/m) + l_s(h_f C_f / J)] \qquad (2)$$

**Road Model**

The road area is the main region of interest (ROI) in the image since it contains important cues on where the lane marks and road signs might be located. In other words, it allows performing a top-down search for the road objects that needs to be segmented. The color of the road is an important cue for detecting the road area, however it is affected by illumination and the surface does not always have the same reflection/color properties on all roads. Therefore, road and non-road color histograms using R, G and B channels are formed using 9 videos. The color histogram is normalized to obtain road color probability which is a joint measure in 3-D color space. The probability surface is shown in 2D R-B space in Figure 4. Also, probability image and the extracted road area is shown together with updated road model.



(a) 2-D color probability surface in R-B space

(b) Road area extraction and update process: updated road model(top), probability image (bottom left), extracted road area (bottom right)

**Figure4. Road color probability model and its implementation**

In addition to color probability, spatial coordinates of the road area is also used to obtain a location probability surface.

**Road Sign Recognition Algorithm**

The methods used for automatic road sign recognition can be classified into three groups: color based, shape based and others. The challenges in recognition of road signs from real traffic scenes using a camera in a moving vehicle has been listed as lighting condition, blurring effect, sign distortion, occlusion by other objects, sensor limitations. In [11] a nonlinear correlation scheme using filter banks is proposed to tolerate in/out of plane distortion, illumination variance, background noise and partial occlusions. However, the method has not been tested on different signs in a moving vehicle. [12] has addressed real time road signs recognition in three steps: color segmentation, shape detection and classification via neural networks, however, vehicle motion problem is not explicitly addressed. [13] used FFT signatures of the road sign shapes and SVM based classifier. The algorithm is claimed to be robust in adverse conditions such as scaling, rotations, and projection deformations and occlusions.

The road sign recognition algorithm employed in this paper (see Fig.5) uses a spatial coordinate cue from the lane tracking algorithm to achieve a top-down processing of the image; therefore, it does not need the whole frame but particular regions of interest, which are sides of the road area. This provides faster processing of the image and reduces the computational cost as well as eliminating the number of false candidates that might exist after color filtering.

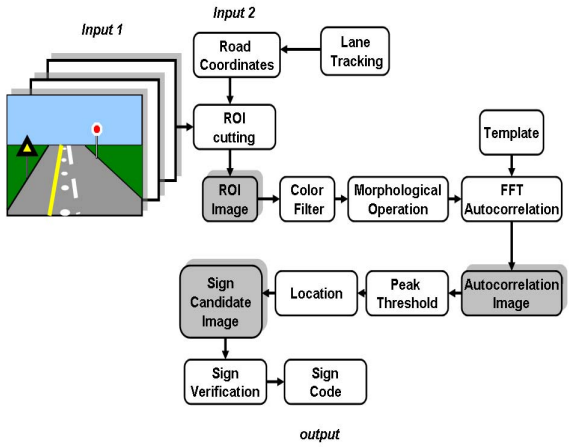



**Figure 5. Road Sign Recognition Algorithm**

After ROI cutting, color filters (designed for red, yellow and white) are used to perform the initial segmentation. Since they are critical for safety applications, we include only stop, pedestrian crossing and speed limit signs in our analysis for this stage. These signs have distinctive features related to color and shapes that are not shared, therefore classification becomes an easier problem since determining color and the shape is enough for recognizing the particular sign. Most of the time the speed limit sign segmentation ends with multiple sign candidates from the scene since the road scene might

contain road objects in that color range. Furthermore, the challenges exist due to moving vehicle vibrations, illumination change, scaling and distortion. An example of color segmentation for speed sign is presented in Fig.6.

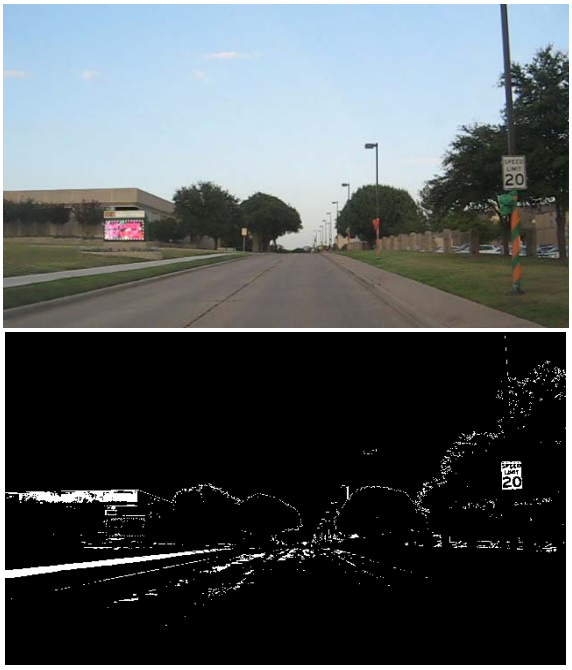


**Figure 6. Sample output for white color filter segmenting the speed limit sign**

Since the road sign shape edges are not clear, morphological operators (dilation and erosion) are used to correct this with a structural element of line or disk; an example of resultant image is given in Fig.7 for a road scene containing stop signs.

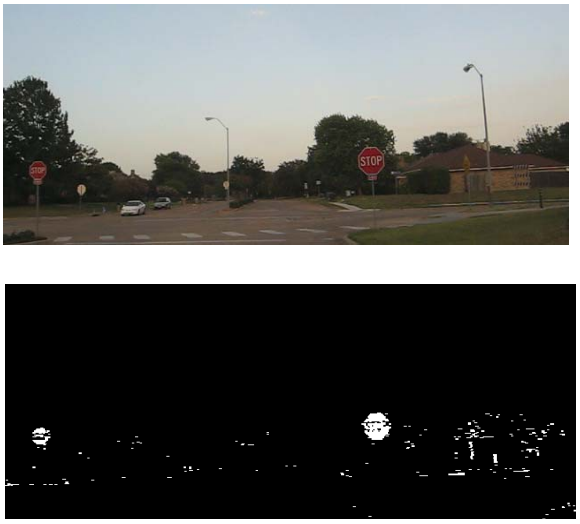


**Figure7. Color segmented stop signs after dilation**

The next step involves FFT correlation of the predetermined road sign shape templates (octagon, rectangle and triangle) with the ROIs in the image. The resultant image can be interpreted as location map of prospective sign. After application of a threshold the peak value of correlation image yields the location of the searched template. An example FFT correlation between the original frame seen in Figure 5 and rectangle template is given in Fig. 8. The speed limit sign gives a peak in this image and the location of the sign can be extracted easily by a threshold.

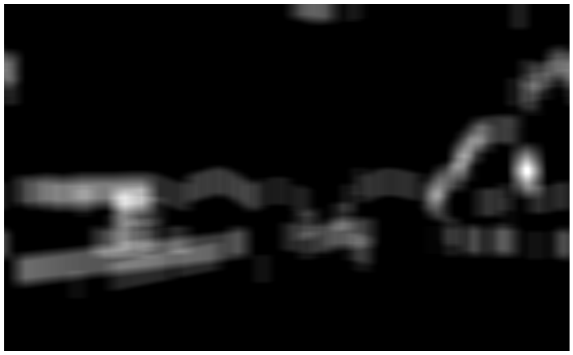


**Figure8. FFT Correlation result with a rectangular template showing a peak in the location of speed limit sign**

Although rare, false sign candidates may exist in the image after the threshold operation or multiple versions of the same sign may require distinguishing (i.e., speed limit signs are the same although the limits written on them are different) therefore an subsequent verification step/classification is needed. This is achieved via Artificial Neural Networks. For each sign a separate ANN is trained for negative and positive examples using at least 50 real world images of the aforementioned road signs and 50 negative candidates. The candidate sign images are obtained by cutting the image area around the row and column suggested by threshold image attained after FFT correlation. In order to obtain false candidates the threshold is lowered, therefore obtaining more candidates from FFT correlation image. The output of the initial sign classification and verification by ANN is a sign code (1, 2, 3) corresponding to speed limit, stop and pedestrian crossing signs in order. If there is no sign in the scene or if ANN verifies the sign is a false candidate the output is 0.

**Integration of Algorithms for Context-aware Computer Vision**

Previous studies such as [14] has combined different computer vision algorithms for a vehicle guidance system using road detection, obstacle detection and sign recognition at the same time. However, to the best knowledge of the authors very few studies if any focused on the traffic scene interpretation for extracting driving-related context information in real-time. This study proposes a framework for the fusion of outputs from individual computer vision algorithms to obtain higher level information on the context. The awareness of the context can pave the way in design of truly adaptive and intelligent vehicles. The fusion of information can be realized using a rule based expert system as a first step. We present a set of rules combining the outputs of vision algorithms with output options of warning, information message, and activation of safety features.

***Case 1:*** *If road sign is 0, standard deviation of lane position< 10 pixels, standard deviation of vehicle speed <10 km/h, context: normal cruise.*

***Case 2:*** *If road sign is 0, standard deviation of lane position<10 pixels, standard deviation of vehicle speed >10 km/h, context: stop-go traffic, likely congestion, and output: send information to traffic control center.*

***Case 2:*** *If road sign is 1, vehicle speed >20 km/h, context: speed limit is approaching, output: warning.*

***Case 3:*** *If road sign is 2, vehicle speed >20 km/h, context: stop sign is approaching and the driver did not reduce the vehicle speed yet, output: warning and activation of speed control and brake assist.*

***Case 4:*** *If road sign is 3, vehicle speed >20 km/h, context: pedestrian sign is approaching, output: warning and activation of brake assist.*

The cases represented here are only a subset of the rule-base and it can be possible to use more advanced rule-base construction methods such as fuzzy logic. An inference engine acting as a co-pilot monitoring the context and driver status continuously can be designed with more inputs from other vision systems and in-vehicle sensors such as pedestrian and vehicle tracking, CAN-Bus analyzer, audio signals.

**Results and Performance Analysis**

Lane tracker and road sign recognition algorithms are tested on 9 videos each having at least 200 frames. The lane tracker with the help of probabilistic road model can overcome difficult situations such as passing cars as demonstrated in Fig.8. A similar recovery is observed when there is shadow on the road surface.

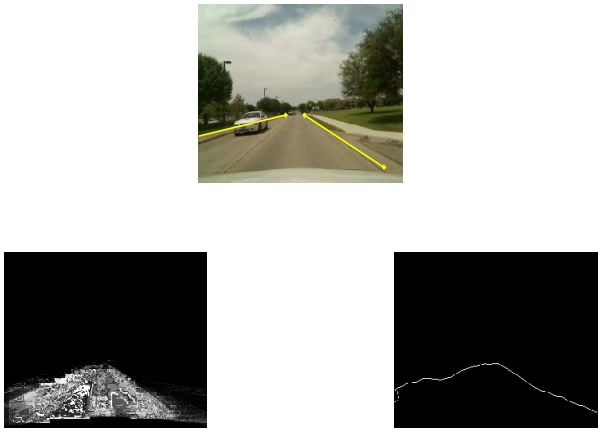


**Figure8. Road model overcoming the occlusion**

In order to assess the accuracy of the lane tracking algorithm the error between the lane position measured by the algorithm and the ground truth lane position marked manually on the videos is calculated. As an error measurement the angle of the lanes is taken. Table 2 shows the mean square error and standard deviation of the error in lane position measurement.

**Table 2. Mean square error and standard deviation of the error in lane measurement**

| | MSE | STD |
|---|---|---|
| Left Lanes | 15.24 | 3.86 |
| Right Lanes | 28.02 | 4.67 |

The algorithm runs close to real-time and the speed is increased by using lane position measurement as a cue for top-down search for road signs. The improvement in speed can go up to 3-fold based on the processed image area. The road sign recognition algorithm is capable of detecting the signs in 5-30 m range without failure. If the road sign occupies less than 10x20 pixel area, the recognition is not possible.

## CONCLUSIONS

A context-aware computer vision system for active safety applications is proposed. The system is able to detect and track the lane marks and road area with acceptable accuracy. The system is observed to be highly robust to shadows, occlusion and illumination change thanks to road and vehicle model based feedback and correction. Road sign algorithm uses multiple cues such as color, shape and location cues. Although it can recognize the signs after the correlation result, a verification step is added to eliminate false candidates that might exist due to existence of similar road objects. Lastly, two algorithms are combined under a rule-based system to interpret the current traffic/driving context. This system has at least three possible end uses: driver assistance, adaptive active safety applications and lastly it can be used as mobile probes reporting back to the centre responsible for traffic management.

In our future work, more modules are planned to be added to detect and track more road objects and fuse additional in-vehicle signals (audio, CAN-Bus) to obtain a fully developed cyber co-pilot system to monitor the context and driver status.

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# Single-trial detection of cognitive processes for increasing traffic safety

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## ABSTRACT

To increase driver's interaction with vehicles, research interest is growing to develop new approaches that allow for detecting the driver's intention. The extraction of features from electroencephalograph (EEG) data enables establishing a new communication channel by the use of brain signals as additional interaction channel. So far, the applicability of EEG data in the context of driving is strongly limited by the robustness and ambiguity of the chosen features. The major goal of the presented approach is the robust discrimination of EEG patterns preceding intended actions of the driver for predicting upcoming manoeuvres.
A pilot study on a test track containing elements of driver safety trainings was carried out. While driving, the manoeuvres the brain activity (64/32 EEG channels) and data from the car controller area network (CAN) was recorded.
In this paper we present the bottom layer of a classification model for upcoming driver's movements by classifying left against right foot movement as well as left and right obstacle avoidance manoeuvres as sub-classes of the classes hand and feet movements.
This way, we present two ways in which features extracted from EEG can be used: (1) by exploiting event-related potentials of independent components for identifying sources of consolidated neural activity, and (2) to establish the fundamentals of an approach for an EEG-based rapid-response system that can predict the upcoming action of the driver. The latter was done by an offline classification of variances in certain frequency bands of the EEG. Feature validation was implemented by spatial and functional filtering driven by independent components of the corresponding EEG datasets.

## INTRODUCTION

The year 2007 saw a number of 335.845 injured and 4949 fatalities as a result of traffic accidents in Germany [1]. In comparison with the last decade, the decreasing number of injured and fatalities indicates that vehicle-safety research has proven to be very effective. Nevertheless, this positive trend suffers from the constant high number of traffic accidents and also from the fact that there are still a high number of fatalities.
To reduce these numbers, a new approach in vehicle safety research is necessary.
One possible approach focused on this context is an absolutely driver-centred point of view. The idea is to use the driver's intention to improve and trigger existing drive-dynamic and driver support systems. Therefore, cognitive processes before an intended action, particularly movement preparations and decisions, can be identified as a possible source for such a trigger-support system.
In this manner the EEG allows associating mental processes with measurable electrical recordings which reflect brain activity and dynamics with a precision in the range of milliseconds. This way, changes in the EEG data could be analyzed that are induced by intended actions (e.g. emergency braking or left/right steering) as well as decision-making processes during driving (Fig. 1). Hence, the major goal is the robust discrimination of EEG patterns correlated to different mental processes in this context. Therefore, a pilot experiment was carried out for analysing EEG signals in a real-world driving scenario with an unforeseen obstacle. Hence, the first research question is whether it is possible to find EEG features which reflect cognitive processes following the popped up obstacle, and second, the possibility to transfer the idea of using this information to discriminate the upcoming driver's action or manoeuvres (Fig.2).

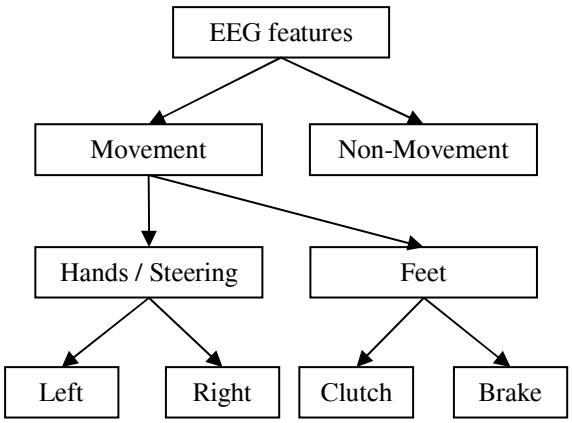


**Figure 1. The figure shows a general approach for a hierarchical classification model of upcoming drivers movements based on brain dynamics.**

The following section gives an overview of the neuropsychological background of the presented approach. Then we explain the used experimental environment and setting and go on describing the experiment, the data acquisition, and the used methods for analyzing the EEG data. Finally, we show how the findings of the presented experiment can be used for answering the research questions.

**Neuropsychological background**

In the domain of neuropsychological research, it is well known that aspects of the human information processing, expectation and movement preparation can be examined by means of event-related potentials (ERPs) and event-related desynchronisations (ERD). The potentials not only reflect direct brain activity with a latency and precision in the range of milliseconds, but also allow for a qualitative discrimination of various cognitive processes.

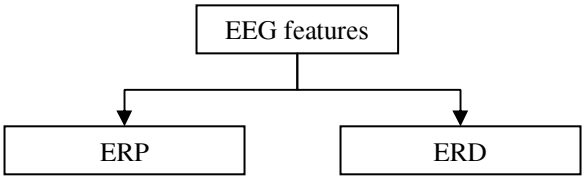


**Figure 2. The figure shows a general categorization of EEG features that reflects event-related brain activity.**

One category of ERPs is related to a given stimulus and occurs only by averaging EEG data from different trials locked to the given stimulus. The other category is locked to the response of the participant e.g. a keystroke.

Both, the stimulus-locked and the response-locked ERPs can be induced by the processing of e.g. visual, auditory or semantic information and also due preparing motor tasks.

Different neuropsychological consolidated ERPs are suitable as a possible source for projecting the abstract concept of *driver's intention* to features in EEG data. This way, for feature selection the readiness potential or the contingent negative variation (CNV) could be applied.

In the field of response-related ERPs the pre-motor or readiness potential (BP) seems to be a useful ERP for approaching the representation of the driver's movement intention in EEG data. In preparation of motor tasks, this potential precedes the actual execution. Before accomplishing motor tasks, this potential is characterized by a negative shift in the averaged EEG data at the scalp, reflecting the motor preparation.

The CNV is both, stimulus-locked, but also response orientated. This ERP is also known as a potential related to expectancy. This kind of CNV can be induced by a 2-stimuli paradigm. The first stimulus is the request to prepare an action and the second stimulus is the corresponding *go-signal* e.g. for a motor response. Between these two stimuli a negative shift in the averaged EEG data can be observed at the scalp, reflecting the expectation of a task.

To transfer the idea of using these potentials for predicting the upcoming driver's action the extracted information from these potentials has to be related to the upcoming movement. Therefore, the spatial information of the negative shifts induced by BP and CNV could be used to discriminate the upcoming movement.

Different studies figured out that several brain areas contribute to the readiness potential (BP). Activity of the medial-wall motor areas as well as activity of the primary motor cortex MI affect this potential [2,3]. Multi-channel EEG recordings of unilateral finger movements show that this negative shift originates on the frontal lobe in the area of the corresponding motor cortex (homunculus) contra-lateral to the performing hand [4,5]. This spatial information used as feature allows for discriminating EEG recordings towards upcoming left from right hand movements [4,5,6]. The literature does not suggest any information towards comparable characteristics of the CNV. On the other hand, event-related desynchronisation in certain frequency ranges of the EEG also accompanies brain activity.

It is well known from neuroscience that for instance the mu rhythm is induced by idle motor neurons. These neural networks tend to exhibit locally synchronous polarity oscillations which can be observed above the motor cortex. Performance of motor actions causes this synchrony to break down

and as a result, the measured amplitudes in the affected EEG signal spectra drop accordingly. This can be used to infer the laterality of the ongoing motion [7]. This fundamental finding is also known from the occipital area of the human brain. The well known *alpha-block* in the alpha rhythm can be caused by an abruptly opening of the eyes after a period of closed eyes. In the latter condition the neural structures of the occipital brain that are responsible for visual information processing generate these locally synchronous polarity alpha oscillation.
In sum, there are a lot of features in EEG data preceding and accompanying neural processes which allow differentiating between these diverse cognitive processes. The application of methods from the area of statistical machine learning has proven to be very practical and efficient for extracting and classifying EEG features in this kind of research [4,5,6,8].

## METHODS

### Experiment

The presented pilot experiment was carried out at the ADAC Fahrsicherheitszentrum Berlin-Brandenburg. Participants were requested to repeatedly perform obstacle avoidance manoeuvres when the obstacle (water wall) popped up (Fig. 3, obstacles in red).
The direction of the manoeuvres was self-paced decided by the drivers. With reference to a two-way traffic scenario the participants were required to pass a water gate at the end of the track. The whole experiment lasted one day totally (half day for each participant). The car utilized for this study was a VW Touran from the Chair of HMS, TU Berlin.

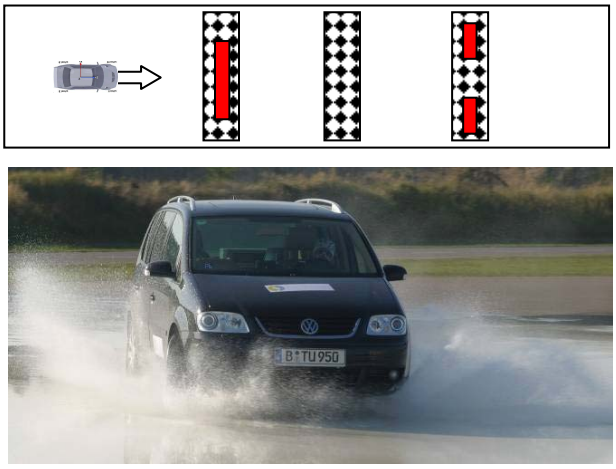


**Figure 3. The figure shows the setup and the research car (VW Touran) with participant.**

### Participants

A female (age 28, participant S) and a male (age 28, participant T) participant took part in this pilot experiment. Both of them are free from neurological/psychiatric disorders.

### Data Acquisition

While performing the driving task brain activity was recorded with 62 Ag/AgCl (participant T) and 32 Ag/AgCl (participant S) impedance-optimized electrodes (ActiCap, Brain Products), referenced to a signal measured at the intersection of the frontal and two nasal bones of the skull (Nasion) were no neural activity occurs. This was used as baseline of the electrical measurement. Finally, brain activity was sampled 1000 Hz and wide-band filtered. The horizontal eye-movement of participant T was recorded using the Electrooculogram (EOG).
Data from the car controller area network (CAN) was sampled with 50 Hz and recorded as well as videos (30 fps) of the driver's action and the view through the windshield. All of the data was synchronized by an external sync signal.

### Data Pre-processing

For ERP analysis, the EEG data was digitally filtered using a high pass filter (1 Hz) to minimize drifts. In a next step, the recorded data was divided into causal epochs related to the drivers' actions like the steering response (increase of the steering speed [deg/s]) or to slam on the brake or clutch (switch [0 1]). Data epochs were extracted from 5000ms before the driver's response, until 4000ms after the taken action. The average of time range [-5s,-2s] was chosen as baseline. The corresponding baselines were removed from every epoch.
For ERD analysis, data was sub-sampled to 200 Hz and digital filtered between 1 Hz and 90 Hz.

### ERD Feature Extraction and Classification

To extract ERD features from the EEG data, the Common Spatial Patterns (CSP) algorithm was used [9]. The rationale behind CSP is to find few, e.g. 4 to 6, linear combinations of EEG channels such that the variance in each trial projected according to these patterns is most discriminative (i.e. differs maximally between two classes). Subsequently, the EEG data for each trial is projected according to each pattern and the logarithmic power spectral density is calculated similar to the above method, yielding 4 to 6 features.
To estimate conservative classification accuracy, features from the EEG data (sub-sampled to 200Hz) were extracted using a moving window with a length

of 150 ms and an overlap of 125ms. The CSP-based feature distributions generated for this window were classified using the Linear Discriminate Analysis (LDA) for each of the time windows [10]. The classification accuracy was computed by using a 10-fold cross-validation (CV) for a comparable number of trials per class. This was implemented for every bin of the Fast-Fourier-Transformation (FFT) with a micro band range (± 2 bins) around each measured band for the CSP computation. Consequently, the resulting plot contains information about the estimated classification accuracy depending on class specific variances for each time window and corresponding frequency range.

### Analysis

In the analysis we concentrated on the EEG data obtained where the participants performed the obstacle avoidance manoeuvres. In this manner an ERP and ERD analysis of the EEG data was carried out. EEG recordings involve plenty of influences (artefacts) to the quality of the EEG signal, such as eye movements, muscle noise, cardiac signals and coincidental noise patterns. In this study, two methods, Independent Components Analysis (ICA) and Average Re-reference, were used to improve the data quality for identifying ERP components and for verification of ERD features.
To improve the data quality we used a method to re-reference the data to the average potential across the whole head [11], termed Average Re-reference. Therefore, the average time course of all electrodes was calculated and removed from each electrode.
The ICA decomposes EEG data into temporally independent and spatially fixed components, which account for artefacts, stimulus and response locked events and spontaneous EEG activities. Recently, it has been considered as a powerful tool for EEG components identification and artefacts removal as well as source identification [12, 13, 14, 15, 16, 17].
After calculation of independent components (IC), we followed the following procedure to remove artefacts:

- Rejection of Independent Components (IC) that are related to eye and muscle movement from the neck as well as ICs that reflects the heart beat and
- Rejection of IC-dipoles outside the head.

The following section gives an overview over the ERP analysis for each participant driven by events inferred from the CAN data (i.e. de-clutch) and go on analysing the ICs for each participant separately since this depends on each of the dimensionalities of the recorded EEG. Finally we show the estimated classification accuracy for clutching vs. braking as well as obstacle avoidance to the left vs. right side based on oscillatory features for both participants.

## RESULTS

### ERP analysis and ICA – participant T

On Figure 4, the EEG signal at electrodes C1, Cz and C2 averaged over all extracted clutch presses (left foot) shows characteristic waveforms. The time range represents the clutching procedure with an onset around 1500 ms before the CAN-bus indicates that the driver has de-clutched (Figure 4, point of origin).
This pre-processed data shows significant components across the central part of the brain with a two-peak maximum at the latency of around 400 ms before and after the foot response (clutch). The same characteristic was observed using the common averaged reference. For taking the brake or steering in both directions no clear ERP could be observed in the raw data.

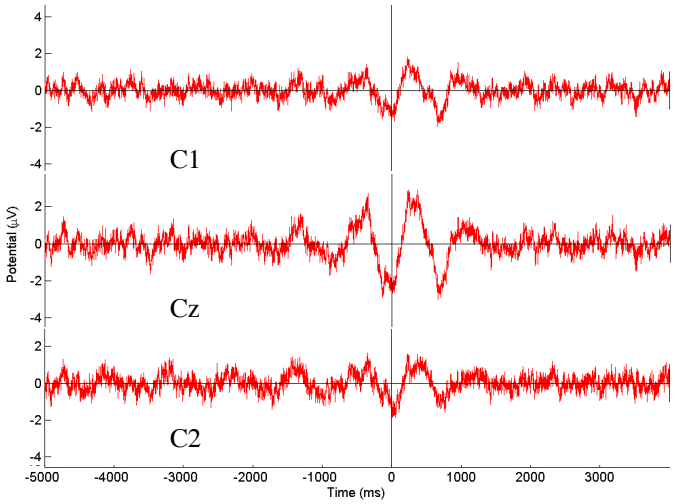


**Figure 4. Averaged EEG signal from 244 clutch presses of participant T at electrodes C1, Cz and C2.**

### Independent Component Analysis

The independent component analysis (ICA) decomposes the EEG into temporally independent and spatially locked components.
These components could either be the result of task events or stimulus, or account for artefacts. Figure 5 shows some of the independent components from the EEG set of participant T.
Figure 5(1) shows an Independent Component which contains noise that is spread over the whole head (this component is missing when the ICA was computed on a common averaged EEG set); while Figure 5 (2 and 3) demonstrates clear ICs which decomposes vertical and horizontal eye-movements.

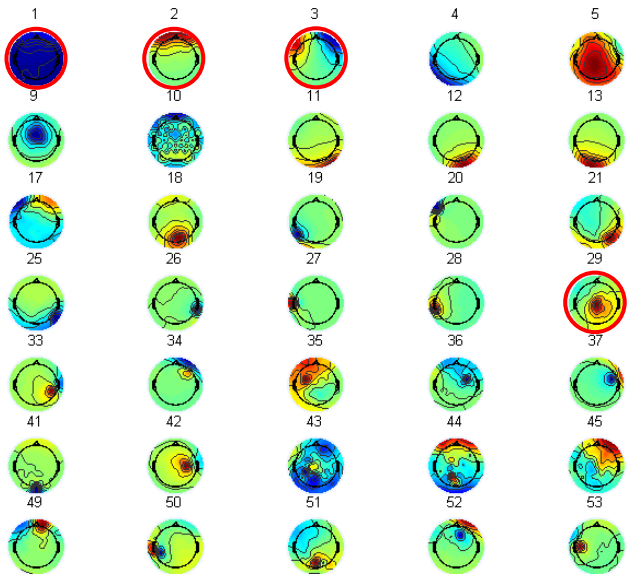


**Figure 5. Selected scalp maps of the independent components of the EEG set from participant T.**

In contrast Figure 5 (29) shows an IC dipole that seems to contain neural information of the central area of the brain. These components are of particular interest since they should represent only real movement related brain activity (cf. homunculus).

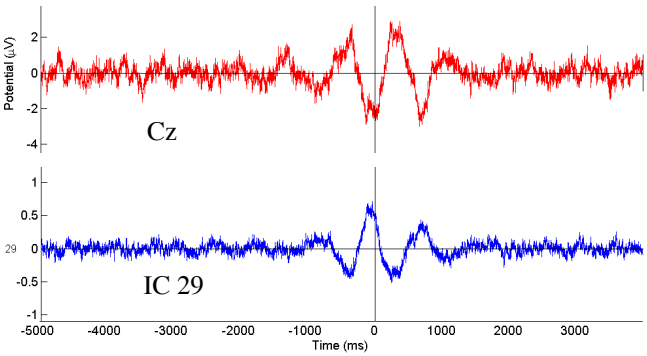


**Figure 6. Averaged EEG signal [Cz] and IC 29 activity from 244 clutch presses [T].**

Figure 6 shows the IC activity across the time for an extracted epoch determined by slamming the clutch. The IC activity shows a hight correlation to the the observed ERP at electrode Cz (cf. Fig. 4).

The spatial information given in Figure 7 allows for interpreting the source of the observed potential at Cz in comparison to the observed activity of IC 29. The IC 29-based dipole is located in the motor cortex of subject T for the used head model.

To transfer the idea of using spatial information of negative shifts induced by the readiness potential or the location of the IC-based dipole for discriminating the upcoming drivers action, these features have to be class-specific. Otherwise they are not suitable for an EEG-based classification system for upcoming driver's movements.

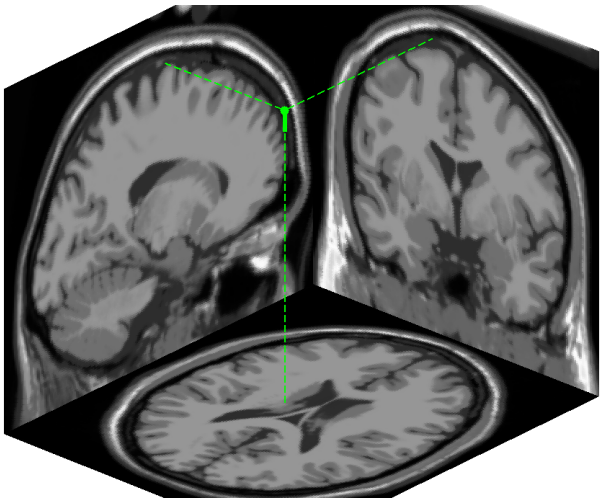

**Figure 7. Dipole fitting of IC 29 for a boundary head model with warped electrode positions of participant T.**

The spectral properties of the ICs can also be used for selecting brain based components. By exploiting differences in known movement-related EEG spectra it is possible to separate movement related independent components which contain information of activity in the motor cortex. This way, it is well known from the neuropsychological literature that the movement imagination as well as the movement execution is accompanied by variances in the alpha and beta band of the corresponding EEG [6, 8].

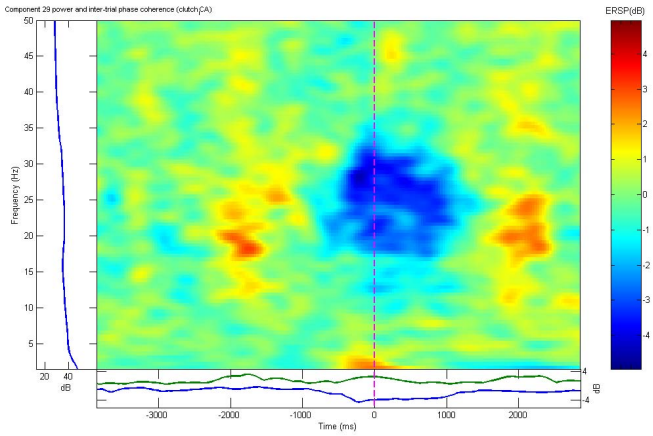


**Figure 8. Event-related spectral perturbation of IC 29 (baseline [-5 to -4]) – participant T.**

Figure 8 shows the event-related spectral perturbation of the activity in component 29. Here, clear changes in different frequency bands could be observed. Changes in self-contained and characteristic spectral ranges of the EEG spectrum could be used as indicator for a brain based component. Such a component is suitable as carrier of information preceding the driver's movement.

**ERP analysis and ICA – participant S**

The average of each extracted epoch shows no clear ERP for participants S in the raw EEG data.
In Figure 8 the ICs that are computed for the continuous EEG set of participant S are presented. A clear decomposition of noise and eye-movement could be observed (Fig. 8 1-3).
Figure 9 shows the averaged time course of the activity from component 26 that is also located in the middle of the primary motor cortex. Here, a weak ERP could be observed in the component activity that is comparable to the observed ERP of IC 29 from participant T (see Fig. 6). The dipole fitting of the computed independent components reveals that the decomposition was not so clear like for participant T.

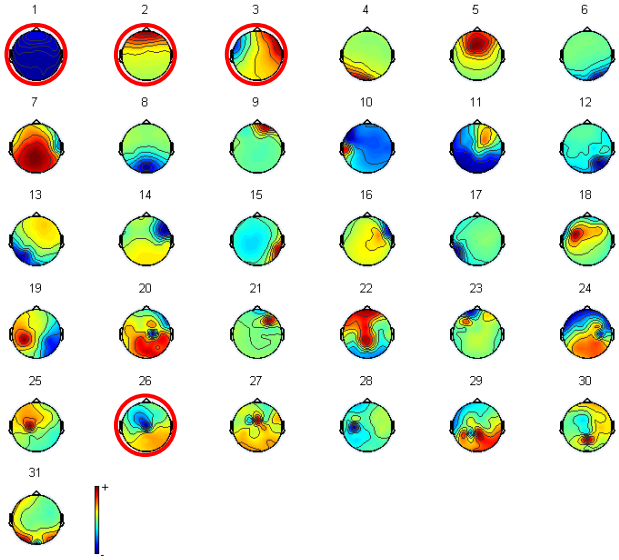


**Figure 8. Scalp maps of computed independent components – participant S.**

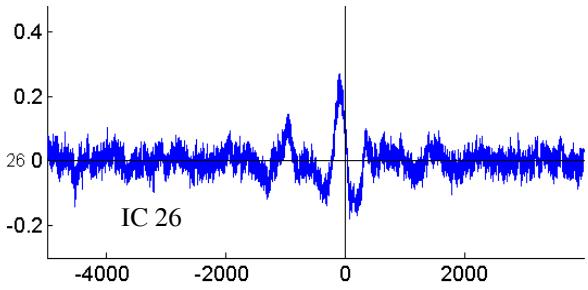


**Figure 9. Time course of IC 26 for de-clutching – participant S**

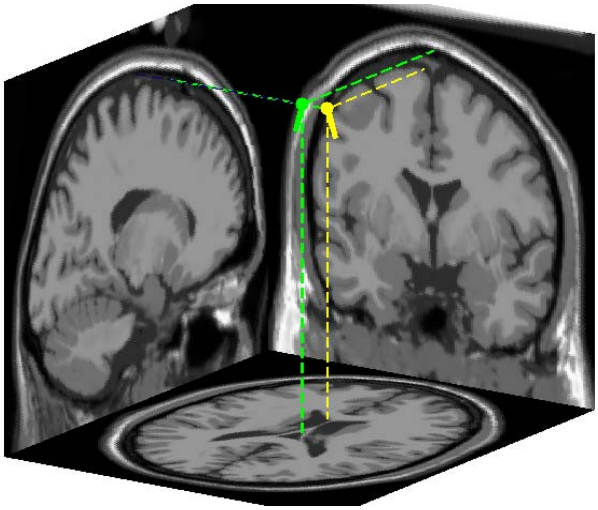

**Figure 10. Dipole fitting of IC 26 (green) and IC 30 (yellow) for a boundary head model with warped electrode positions of participant S.**

There are two diploes located in the expected area of the motor cortex containing information of this source. No other ERP in the component activity could be observed by averaging epochs based on the driver's responses (clutch, brake and steering).

**ERD Classification**

One of the central research questions in this research area is whether the analysis and extraction of EEG features is suitable for projecting the driver's intention. Therefore the chosen EEG features have to be related to the cognitive process.
Furthermore, they have to be detectable in single trial conditions. The analysis of the induced ERPs revealed that there are potentials preceding the movement execution.
The extraction and classification of ERD features is an approach for establishing an EEG-based driver support system, too. Of particular interest here is the classification of ERDs between different drivers' movement representations in the EEG data.
To define the class-specificity of the ERDs preceding the driver's action, the classifier output was estimated based on a data-driven approach (see ERD-Feature Extraction and Classification).

According to machine learning methodology, the machine will be trained on the extracted spectral features [18]. Especially in this phase, the EEG data typically consists of underlying cognitive processes but also coincidental noise patterns and artefacts. This additional information has to be removed from the recorded EEG data before the classifier can be trained to stress the neural source of the feature.

Therefore, for participant T, 14 out of 61 and for participant S 18 out of 31 independent components were selected as brain based.
To estimate the ERD-based classification accuracy these *brain* components where re-projected to the EEG data. In a second step the presented data-driven feature extraction was computed. To compare and validate, both the raw EEG set and the re-projected EEG set were used as input for the data-driven feature selection and classification.
Figure 11 (top) and 13 (top) shows the estimated classification accuracy based on variances in certain frequency bands of the EEG spectra preceding the feet movement execution on raw data. The results are going up to more than 75% accuracy around the movement execution. There are also good classification estimations around 500 ms before the movement in different frequency bands. As seen in Figure 5 and 8, the EEG dataset contains a lot of components which have probably no neural source. To validate the data-driven ERD-features, the spatial information of these components was used for functional filtering. All of the components which do not reflect brain activity were rejected. To separate the brain ICs from the artefact ICs the spatial localisation of the IC-based dipole was used as well as the properties of the components.
Figure 11 (bottom) shows that there are very different results from those estimated without the rejection of components that are containing information from eye and muscle movements. For both participants, a new weakly class-specific area in the range of 45Hz to 65Hz at 1500ms before the foot movement becomes evident.
Figure 12 and 14 show the estimated classification accuracy for the left and right obstacle avoidance manoeuvre. Here the exact point in time of the driver's response was inferred from the increase of the steering speed following the unforeseen obstacle (i.e. water wall). The classification of raw data shows for both participants very good results in the beginning of the taken avoidance manoeuvre. Preceding the steering act there are also areas of class-specific variances in the spectra of the data sets. The back-projection of the *brain components* reveals other areas of interest for classification. These areas become evident in the beta band as well as in the gamma band of the EEG data sets.

## DISCUSSION

The presented results indicate (1) that there is the possibility to decompose EEG data into independent components representing artefacts caused by the driver's movement and the car environment to some degree and (2) that the presented data-driven approach for feature extraction is highly applicable, but fragile in the presence of coincidental noise patterns and artefacts.

### ICA and feature extraction

The main challenge of this approach is that the decomposition of the EEG implies that the neural sources are really independent from each other. This question cannot be answered finally. Also, the residual variance of the dipole fitting indicates that the source identification is not definite in each case. Rejecting components that contain for instance eye-movements could also contain suitable parts of real class-specific brain dynamics.
The results also reveal that an observed ERP in the raw data can be found in independent components. This indicates that the ICA is able to decompose EEG data under very hard experimental conditions. The fact that an ERP for de-clutching can be observed in the components for both of the subjects indicates that there are similar neural processes preceding and accompanying the de-clutch procedure while driving.
Furthermore, the time course of this ERP allows for an extraction of clutch-specific features up to 700ms before the action can be observed in the EEG data. Unfortunately, this feature is only related to the left feet movement and does not allow for a classification of braking against clutching. Furthermore, the observed ERP does not match to any of the expected related motor ERPs. It seems to be a mixture of readiness potentials and CNV. Although, the observed ERP is well located at Cz and the IC also reflects the characteristic of the raw data, the behaviour of this signals could be affected by a haptic process. It could be that the EEG signal is affected by the process of de-clutch and clutch-in or due to a clutch sensor that induces this kind of signal characteristic. But an ERP only reflects the linear parts of the epoched EEG data. More and other information preceding the driver action could be present in the frequency domain.
Regarding the presented classification results, the good classification of brake against clutching implies that these two feet movements are really comparable and only body-side specific. But this comparison suffers from the fact that for breaking a foot movement from the accelerator to the braking pedal precedes the actual braking. The shown classification results are probably affected by this foot movement. This foot movement preceding the actual braking probably affected also the absence of a braking response related ERP.
To validate the classification accuracy, a 10-fold cross-validation was carried out. Nevertheless, the number of trials for the obstacle avoidance manoeuvre was too small for a significant computation of the ability to classify.

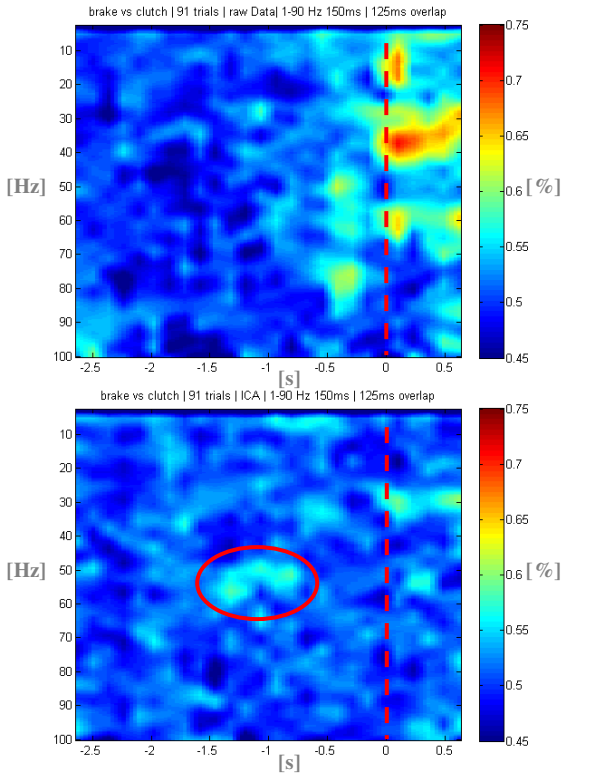


**Figure 11. Estimated classification accuracy before using the clutch against brake on EEG raw data (top) and IC-filtered EEG data (bottom) [T].**

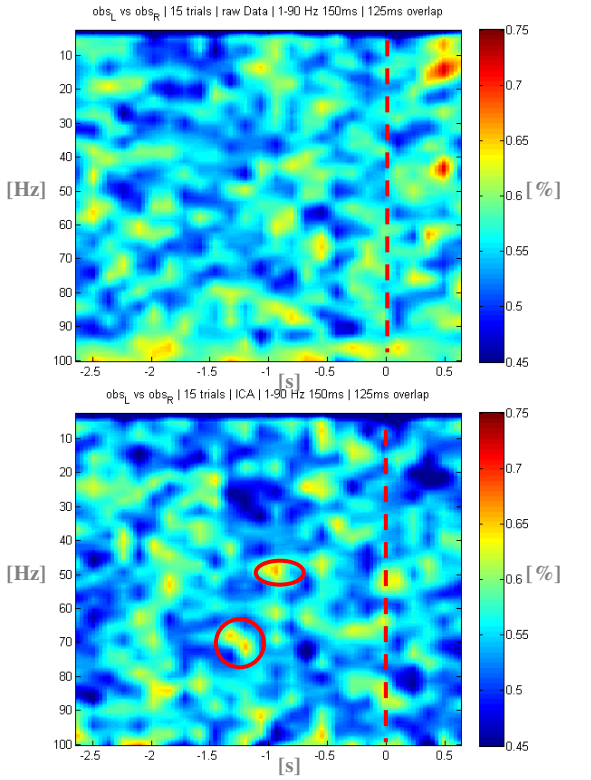


**Figure 12. Estimated classification accuracy before the obstacle avoidance to left or right side on EEG raw data (top) and IC-filtered EEG data (bottom) [T].**

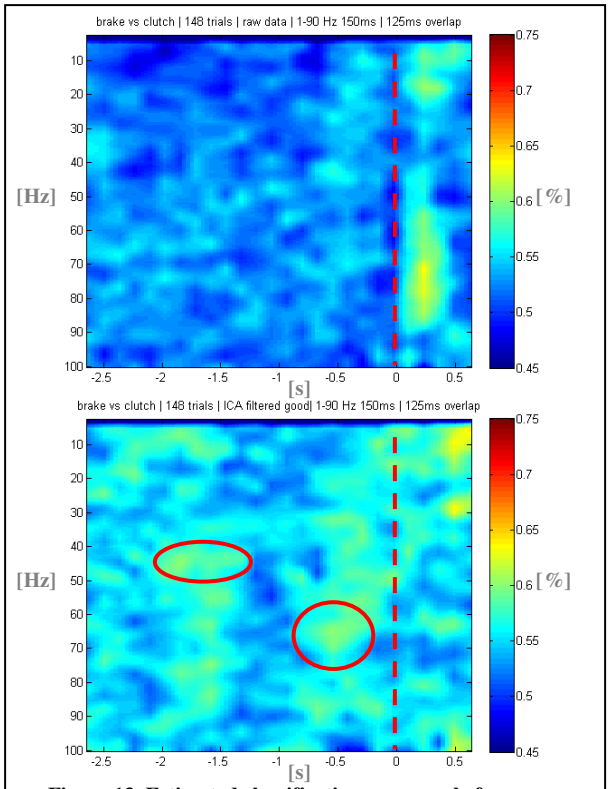


**Figure 13. Estimated classification accuracy before using the clutch against brake on EEG raw data (top) and IC- filtered EEG data (bottom) [S].**

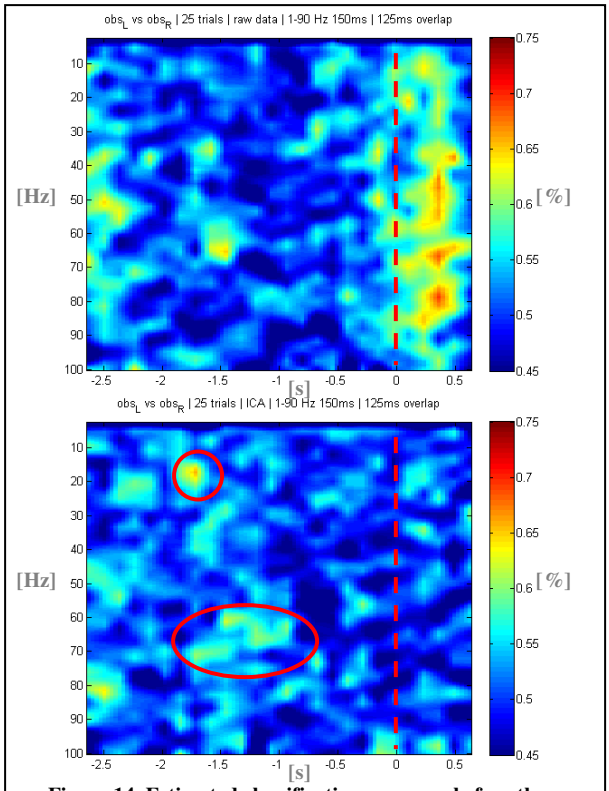


**Figure 14. Estimated classification accuracy before the obstacle avoidance to left or right side on EEG raw data (top) and IC-filtered EEG data (bottom) [S].**

## CONCLUSION

Conclusively, we have presented a pilot study for exploring the electrical brain dynamics (i.e. EEG) preceding intended actions of the driver in a real-world environment. This way, a hierarchical classification scheme was used for predicting the upcoming movement of the driver.

### Potential

We have shown that the human brain contains information preceding the movement execution that can be extracted from the EEG and that these features can be used for single trial detestability. We also presented a useful approach for validating these extracted features by decomposing the EEG data into independent components. This way, it is possible to select features which contain information of real brain based EEG representations in single trial conditions.
Hence, the brain as origin of intentions and distributor of information preceding an action has a very high potential to increase traffic safety since data from the cat area network only reflects the driver's action but not the corresponding intention.
We observed a potential in the EEG raw data related to the process of de-clutch and clutch in for participant T. The analysis of the corresponding independent components reveals that one of these components clarifies this ERP to a high degree. This indicates that the ICA was able to separate real brain sources from sources that contain other sources of electrical activity. Furthermore, this kind of analysis enables a better understanding of ERP observations in the EEG since the decomposition of EEG into ICs contains information about the localisation of the source in the brain.
The presented results of an ERD-based classification of upcoming feet movements as well as the direction of obstacle manoeuvres promises a good possibility the extract features from the EEG containing information about the driver's movement intention in these conditions. This additional information can be used in a driver support system i.e. to prepare the braking system

### Challenges

To classify different foot movement, the extracted feature has to be definite and class-specific. The observed ERP was only descriptive to the class of left foot movements (clutch). Furthermore it is well known from the neurophysiologic literature that ERPs reflect brain activity in the range of milliseconds but only by averaging a couple of trials. This way, ERPs are not well qualified to predict the upcoming driver's movement in single trial conditions. The ERD representation of brain dynamics is much more applicable. Nevertheless, this estimated classification accuracy indicates that there is class-specific information in the EEG data. The estimated classification accuracy is in fact too imprecise as suitable definite information channel for a driver support system.
To validate these findings this analysis has to be carried out for more subjects. Due to the fact that the number of independent components depends on the dimensionality of the recorded EEG, this study should be carried out with more EEG electrodes. This should affect the decomposition positively and would allow for a better identification of non-artefact affected EEG representations of brain dynamics. Furthermore, to classify the feature distributions only a simple but robust classifier (LDA) was used. Here, a lot of other classifiers (i.e. support vector machines) are also suitable for this kind of classification approach.

## ACKNOWLEDGEMENTS

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# STUDY OF FACE DESIGN, LIGHTING SYSTEM DESIGN FOR ENHANCED DETECTION RATE OF MOTORCYCLES

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## ABSTRACT

The FACE (Facial Attention for Conspicuity Enhancement) design, a lighting system design that enhances motorcycle conspicuity with regard to the detection rate from the view of a driver at night, is described in this paper. Past research has shown that there is part of the human brain that reacts to the image of a face[1] and we thought of a method to enhance the detection rate of a motorcycle by incorporating the element of a face in the front design of the motorcycle. The effect of a simple FACE design, a reverse triangular arrangement of lamps, is evaluated and its effectiveness is shown. Moreover, we develop a simulation method that could be used to evaluate the enhanced detection rate of a FACE design motorcycle under conditions that are close to some real traffic environments. The method is evaluated by comparing it with the results of a full-scale test and demonstrates the method could be used to evaluate the detection rate of a motorcycle

## INTRODUCTION

We obtained the motorcycle fatal accident data in which car drivers were deemed most at fault, and thus were designated as the “Primary Party”*, from the database of "Japanese traffic accident statistics"[2]. The data was analyzed to determine the cause of each accident. This analysis resulted in a conclusion that an car driver’s failure to detect the motorcycle was one of the key factors in the accidents. (Fig. 1).

*Primary Party:

: In the Japanese integrated database, vehicles whose drivers were most at fault in traffic accidents are called the “primary party,” and the other vehicles are called the “secondary party.”

Compared to a car, a motorcycle is smaller in size and presentment, and the possibility of non-detection is relatively high in a mixed traffic environment where there are many large-sized vehicles, such as trucks and passenger cars. In Japan, a countermeasure against the lack of motorcycle detection, Automatic Headlight On, was mandated in 1998. Its positive effect has been recognized.

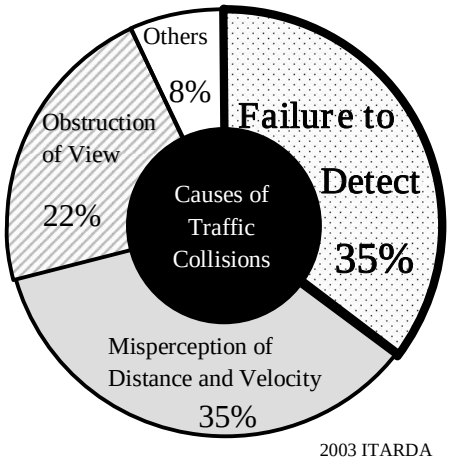


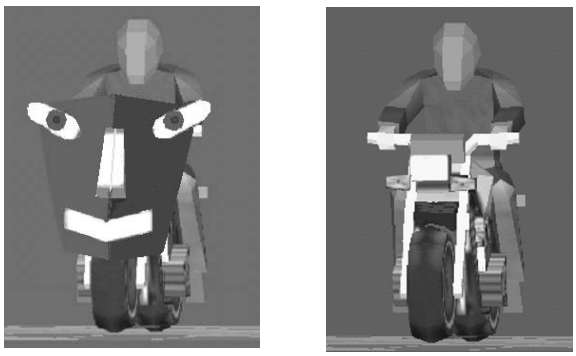

**Figure 1. Analysis of motorcycle traffic accidents in Japan.**

However, the positive effect of Automatic Headlight On could not be expected at night when cars are also using their headlights. Moreover, recently, many cars and trucks are also equipped with Daytime Running Lights (DRLs) and many countries are considering laws that require use of DRLs. Thus, if more and more various types of vehicles are equipped with DRLs, a further reduction of motorcycle conspicuity is possible. Based on these facts, a countermeasure that enhances the conspicuity of a motorcycle under a complicated mixed traffic environment was sought. To this end, we tried to enhance the detection rate by incorporating the elements of a face in the front design of a motorcycle because it has been found that people naturally show a high recognition capability to specific figures including a "face". We decided to call lighting system designs that utilize the elements of a face to enhance motorcycle detection rate FACE (Facial Attention for Conspicuity Enhancement) design. A simple example of FACE design was evaluated to confirm its effect. The details of the evaluation method developed for this research are also discussed.

## Enhancement Effect in Conspicuity of FACE

A "face" is one of the stimuli seen most frequently. Humans are able to understand detailed information, such as visual line and facial expressions, in a "face" instantaneously [3]. Significant research about the high-level facial recognition capability of primates, including human beings, has been performed for many years and several conclusions have been reached. For example, Bruce reported that the part of the brain that reacts to a face picture exists in the lower temporal lobe of a monkey [3]. Recently, research using Functional Magnetic Resonance Imaging (fMRI) has confirmed that the same kind of reaction also exists in a human's brain [1]. It has also been confirmed that the Fusiform Face Area (FFA) of the fusiform gyrus in the temporal lobe and Occipital Face Area (OFA) of the inferior occipital gyrus have a high sensitivity to a face figure[4]. Since part of the human brain specializes in the recognition of a face, it is thought that humans can rapidly recognize a face. Given this, it is reasonable to believe that motorcycle conspicuity might be enhanced by incorporating the elements of a "face" in the front design.

In order to investigate the feasibility of enhanced motorcycle conspicuity by using the elements of a "face" in the front design, we first measured the detection rate of a motorcycle in traffic using an image. Fig. 2a shows the motorcycle that utilized the elements of a "face" in its front design that was used in the experiment. (Hereafter, a motorcycle which uses the elements of a "face" is called a "FACE design" motorcycle.) Fig.2b shows a single headlight motorcycle used as the standard for comparison.

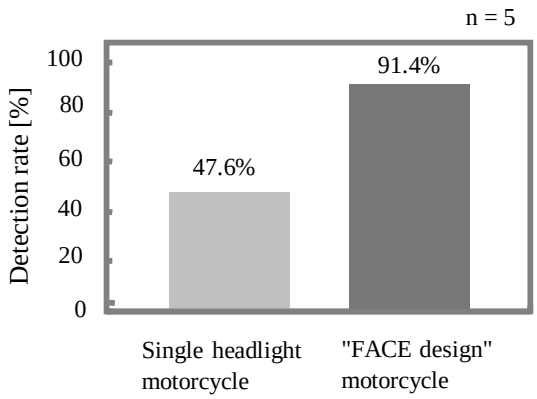


a) "FACE design" motorcycle b) single headlight motorcycle

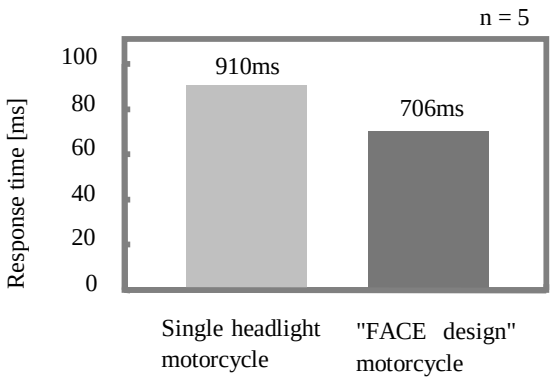
**Figure 2. Motorcycles used for proving our hypothesis that FACE design enhances conspicuity.**

Five subjects (four men aged 20 - 40 and one woman in her 20's) were tested. Each subject drives a car daily. The presentation time of the image was 0.5 seconds. After image presentation, a black screen was presented until the subject answers. 144 measurements per subject were carried out. The result of measurement is shown in Fig. 3.

Fig. 3a shows the average motorcycle detection rate by the subjects. The detection rate of a single headlight motorcycle was 47.6% and the detection rate of the FACE design motorcycle was 91.4%. Fig. 3b shows the time after a subject was shown the image until a reply button was pushed. The average response time in the case of the single headlight motorcycle was 910ms, while the average response time in the case of FACE design motorcycle was 706ms. These results show that the conspicuity of a FACE design motorcycle was increased compared to a single headlight motorcycle and this may enhance the motorcycle's detection rate by drivers of other vehicles.




a) Detection rate of motorcycle




b) Response time

**Figure 3. Enhanced conspicuity by FACE design.**

## Motorcycle Detection Rate Evaluation Method

In a past study, Sugawara et al. confirmed that cerebral activation could be measured by using fMRI. So, it is possible that a quantitative evaluation of Facial levels of the front design of a motorcycle could be carried out [5]. However, fMRI equipment is large-scale and cannot be used for measurement in a real traffic environment. On the other hand, it is difficult to measure the detection of a motorcycle under the actual traffic environment in which large-sized vehicles, such as trucks, and passenger cars are driving. Therefore, we developed a simulation method that can measure the detection rate a similar, real traffic environment. This section reports on the simulation technique.

For an enhancement in conspicuity at night, the key point of motorcycle front design is the lighting system. It is difficult to recognize the form of a vehicle emitting high luminous intensity light, such as from a headlight, due to the vision phenomenon referred to as “glare” The overall evaluation of conspicuity requires the evaluation of the lighting system and how it was seen. In this method, paying close attention to "contrast ratio" and "expression of glare", and by calibrating them to a real traffic environment, computer graphics (CG) that is equivalent to a real traffic environment was produced. In order to evaluate the simulation method , a CG of the test track was created, and comparison with a real vehicle was performed. The creation method of the CG and the comparison result between the full-scale test and the simulation test are described below.

Contrast Ratio - In past research it has been shown that the detection rate of a motorcycle during a short-time presentation can be measured using a simulated computer graphic image as long as the contrast ratio of the real environment and the simulated environment are matched. [6][7][8]. This information was used to create CG of various vehicle arrangements to be used in the evaluation of the FACE design motorcycle.

First, we created CG of the test track. The reason was it then easy for a real vehicle to perform the same test as the simulation. Thus, it was possible to verify the validity of the simulation method that used CG instead of actual environments.

In creating CG, the important elements are the position of the display and its hi-resolution performance. The display was set at a 1.3m distance from the subject in order to set the horizontal field angle at 45 degrees. The viewing height of the CG was 1.2m from the ground. The actual measurement luminosity of the test track was 1 cd/m2 for the dark part of the road surface and 1500 cd/m2 to 3000 cd/m2 for a headlight. A display that could reproduce 3000 or more contrast ratios was required. We used a plasma display to satisfy the requirements. The size of this display was 50 inches, luminosity was 0.1 cd/m2 for the dark area and 400 cd/m2 for the bright area, and it has 4000 contrast ratios. The contrast ratio of the CG of the simulated test track was calibrated with the real environment on this display.

Glare - Another visual phenomenon important in this research is glare. Glare is the light that appears to be generated around a light source, causing things in the area around the light source to fade to white, such as when people look at a bright light. Since the physical luminosity of the display was limited, it was difficult to actually generate this glare. As an alternative, expressing a high-intensity light in simulation is often performed by adding glare artificially with CG [9][10][11][12][13]. This research utilized a method of inserting a mathematically generated glare pattern.

The pattern of the glare was verified by comparative experiments with a real vehicle that is described in the next part of this paper.

CG of the simulated test track is shown in Fig. 4.

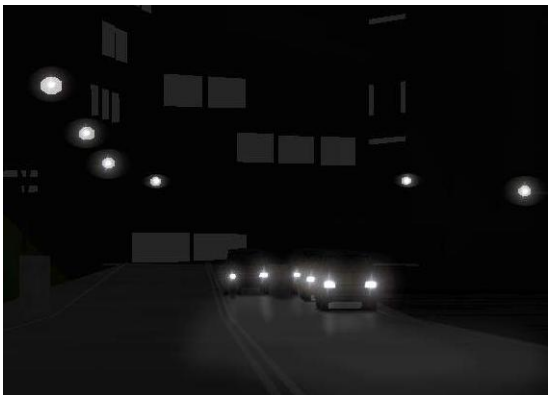
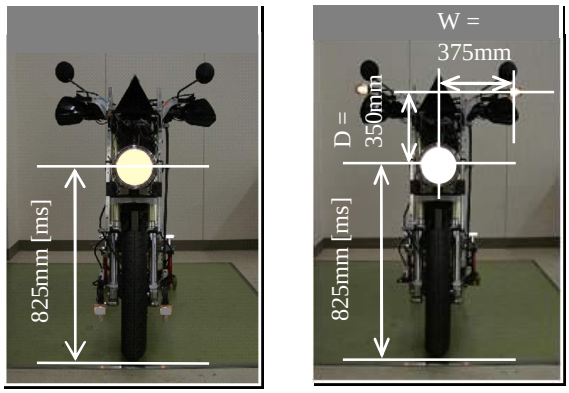


**Figure 4. CG example of test track.**

Comparative experiments with a real vehicle - In order to verify whether the simulation method was an effective way to evaluate motorcycle conspicuity, we conducted an experiment comparing a simulation environment to one with real vehicles. Fig. 5 shows the experiment scenery in a real vehicle. The vehicles used for the experiment are four cars and one motorcycle.

**Figure 5. Experiment scene at the test course.**

The motorcycles used were a single headlight motorcycle and a motorcycle with a three light, inverted triangle arrangement formed by the headlamp and two auxiliary lights (5W 16cd for each) (Fig. 6). The reason for using three lights, inverted triangle arrangement was that it was reported to be one of simple arrangement that was reminiscent of a face [14].




a) Single headlight motorcycle

b) FACE design Motorcycle (Three light, inverted triangle arrangement)

**Figure 6. The motorcycles used for the experiment.**

There were three arrangements of vehicles utilized for the test. The first included a single headlight motorcycle, the second included a FACE design motorcycle, and the third did not include a motorcycle. The first two are shown in Fig.7.

The subjects were 16 men aged 20 – 40 who operate a car daily. Each subject was shown a vehicle arrangement at random. Each arrangement was shown two times for 0.5 sec per a metronome. The subject then had to identify the number of vehicles and how they were arranged. Twenty-four measurements were taken for each subject.

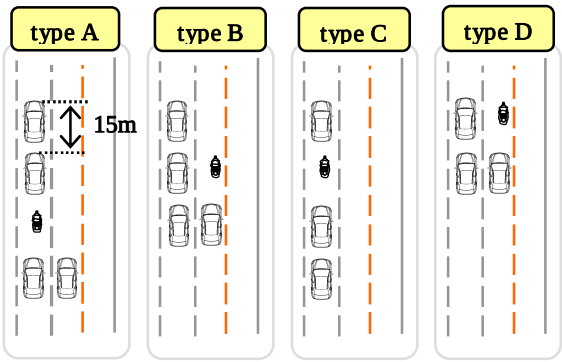



**Figure 7. Arrangements of vehicles used for test.**

Fig. 8 shows a comparison of the FACE design detection rate between tests using actual vehicles and the simulation tests. In order to cancel the influence of the environmental factor, such as the numbers of vehicles, the detection rate of a FACE design motorcycle was shown divided by the detection rate of a single headlight motorcycle.

The result shows that there was no significant difference in 5% level, so it was concluded that the simulation can be used as for a test method.

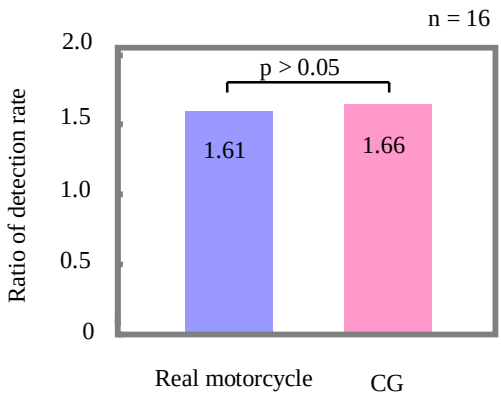



**Figure 8. Comparison of detection rate between real motorcycle and CG.**

## Actual Traffic Environment for Comparison Experiment

Next, in order to carry out the evaluation in the real traffic environment, the image of actual intersection was created with CG. The intersection has 4 lanes in each direction, and has heavy traffic, including many motorcycles. (Fig. 9)

Fig. 10 shows examples of CG. The viewpoint position in the simulations was a car driver who was waiting to make a right-turn in the center of an intersection. Two intersections were simulated, and for each intersection images of seven different car and truck traffic arrangements were created.

**Figure 9. View of an intersection.**

a) Example A

b) Example B

**Figure 10. Examples of CG simulations.**

The motorcycle was placed 20 to 140 meters from the viewpoint of the car driver. In each of the 14 traffic arrangements, 1 to 3 motorcycles were introduced in the traffic mix for a total of 28 different images. Finally, 84 images were created; 28 with a standard single headlight motorcycle, 28 with a "FACE" design motorcycle and 28 with no motorcycle were included.

## Effect of Face Element

By using the CG simulations described in the preceding section, the detection rate of the FACE design was measured. The measured FACE design was a lighting-system of three lights in an inverted triangle arrangement. Horizontal distance W from the headlight to the additional light was set to 375mm, and perpendicular distance D was set to 350mm. The measured control motorcycle utilized a lighting-system arrangement in which W was set to 375mm and D was set to 0mm as a control condition. Luminous intensity of the additional lights was set to 16 cd. The luminosity of the additional light was adjusted based on the distribution of luminous intensity characteristic of position lamps. The composition of test equipment is shown in Fig. 11.

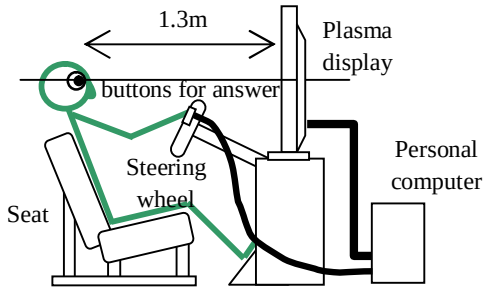



**Figure 11. Composition of the experiment system.**

Twelve men aged 20 - 40 who drive a car daily were selected as subjects. Subjects were shown each of the 84 traffic simulation images for 0.5 seconds at random, and then answered whether a motorcycle appeared on the screen by pressing either Yes or No button on the steering wheel. After the CG was shown, a black screen was presented until the subject answers. Each traffic simulation image was shown 2 times for a total of 168 answers per subject.

Only the cases where the distance of the motorcycle was 80m or more from the driver were included in the final results. This is because our past research has shown that traffic at 80m distance from a car turning right is the threshold for making the turn or not [15].

The results are shown in Fig. 12. The graph shows the increase in detection rate of motorcycles with additional lighting compared to a standard single headlight motorcycle.

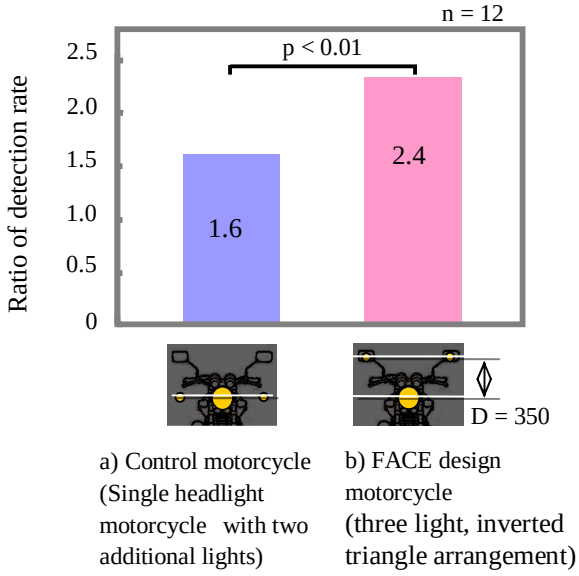



**Figure 12. Comparison of detection rate between FACE design and control motorcycle.**

The FACE design (W=375mm, D=350mm) was detected 2.4 times more often than the standard motorcycle. The control motorcycle lighting system design (W=375mm, D=0mm) was detected 1.6 times more often than the standard single headlight motorcycle.

## CONCLUSION

Under the limited scope of study reported here, it was shown that the FACE design using three lights, inverted triangle arrangement, which was one of the simple figures reminiscent of a face, could enhance the detection rate of a motorcycle from the point of view of a car driver.

In order to evaluate the detection rate of the motorcycle by a car driver, a simulation method that reproduced real traffic environments was developed. A comparison between actual vehicles and the simulation was carried out, and it was shown that the simulation was effective.

Additionally, the effect on the detection rate of motorcycles using FACE design motorcycles (using a lighting design of three lights, inverted triangle arrangement) was measured using this simulation. It is shown that the detection rate of a FACE design is 2.4 times greater than that of a single headlight motorcycle.

We would like to make an effort to further advance "FACE design", to enhance the detection rate of motorcycles in various traffic environments, in the future.

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