Department of Electrical Engineering and Information Technology
Institute for Media Technology
Prof. Dr.-Ing. Eckehard Steinbach

Development of a Tool for Automotive Warning Screen Evaluation

Yu Yan

Master Thesis

Author: Yu Yan
Address: ███████████████████
                    ████████████
Matriculation Number: ████████
Professor: Prof. Dr.-Ing. Eckehard Steinbach
Advisor: Dipl.-Ing. (Univ.) Stefan Diewald
Begin: 01.04.2013
End: 30.09.2013

Department of Electrical Engineering and Information Technology
Institute for Media Technology
Prof. Dr.-Ing. Eckehard Steinbach

Declaration

I declare under penalty of perjury that I wrote this Master Thesis entitled

Development of a Tool for Automotive Warning Screen Evaluation

by myself and that I used no other than the specified sources and tools.

Munich, 30.09.2013

_____

Yu Yan

Yu Yan

Abstract

Road traffic injuries are a leading cause of death globally. One of its solutions is to adopt driver warning systems, which are getting prevalently applied in today's Intelligent Transportation System (ITS) as an essential way to reduce the traffic accident probability as well as to create a driving experience with enhanced safety.

Different warning displays are adopted in current driver warning systems, for instance the visual warning display, the auditory warning display and the haptic warning display, etc. In this thesis those different driver warning displays are studied individually, with visual warning display to be the emphasis: different warning screens are possible candidates to be displayed to alert the drivers, and it is of our interest to investigate their warning effectiveness and acceptance. To achieve this, we develop and implement a tool for the warning screen evaluation. In addition, the evaluated warning screens are supposed to be applied in a an Android-based, Vehicle-to-X (V2X) driver assistance system named *DriveAssist*.

An established requirement is that the evaluation tool should be event-driven, say warning screens are triggered by some JavaScript Object Notation (JSON) format traffic event messages. The evaluation tool is thus divided into two parts following this requirement, namely the server side and the client side. The client side sends JSON format triggering messages of different traffic events, and the server side responses dynamically by updating the information shown in the warning screen. In order to provide a higher-degree freedom for the evaluators, the evaluation tool allows Graphical User Interface (GUI) customization through self-defined Extensible Markup Language (XML) files and no modification of the source code are needed. The evaluation tool also incorporates some pre-defined online questionnaires to collect the evaluation result.

Finally, the evaluation tool is evaluated under a driving simulating environment. An open-source driving simulator is used and the participants keep driving normally while exposed to the warning screens generated by the evaluation tool. After the simulation test participants are asked to judge and evaluate the displayed warning screens. A set of feedbacks including live interview results and online questionnaire statistics are collected successfully, which are pivotal evidence in the warning screen effectiveness validation and important reference for further modification/improvement of the warning screen designs.

Contents

Chapter 1.

Introduction

1.1. Motivation

Vehicular traffic accidents are continuing to be a major global problem which causes severe tragedies including death, disabling bodily injury and heavy damage to personal property nowadays. According to the global status report on road safety 2013 of World Health Organization (WHO)[1], more than 1.2 million people lost their lives in different road traffic accidents, and up to 50 million may suffer non-fatal injuries. In the USA alone, the estimated cost of vehicular traffic accidents is approaching $280 billion per year[2].

It has been shown driver hypovigilance like distraction, drowsiness and inattentiveness has generally been acknowledged to be one of the main reasons causing the aforementioned traffic accidents, responsible for more than 26% of road traffic accidents in the entire world [1, 2]. Speaking of driving drowsiness alone, each in four highway traffic fatalities is the result of momentary driver drowsiness according to the annual report 2012 of the German Road Safety Council (DVR)[3]. The yearly release of the American National Sleep Foundation (NSF) in 2013 has also given a conclusion that 54% of adult drivers had driven a vehicle while feeling drowsy and 28% had actually fallen asleep[4]. The impairment of driving concentration or alertness is usually caused by the following reasons: prolonged sleepiness, or short term inattention. Either one tends to weaken the drivers' controlling ability of their automobiles and thus sharply increase the probability of having a vehicular accident [3].

Given all the aforementioned facts about how drivers' inattention give rise to traffic accidents, it comes with no surprise that drivers should be properly and punctually alerted to the impending specific traffic events, as to prevent potential traffic accidents from happening. However, with the developing of modern automobile industries, the past several decades do witness various kinds

---

[1] http://www.who.int/violence_injury_prevention/road_safety_status/2013/en/index.html
[2] http://www-nrd.nhtsa.dot.gov/Pubs/811216.PDF
[3] http://www.dvr.de/presse/jahresbericht/3584.htm
[4] http://www.sleepfoundation.org/press-releases/2013

of different driver warning and alerting techniques being raised and investigated, like displaying warning screens/sounds to the drivers or vibrating the driving wheel and the driver seat to get the drivers alerted. Many of those newly-developed warning techniques are combined together and get integrated in contemporary ITS, contributing to the warning information delivering process during which the interface operators' driving awareness is enhanced.

In short, driver warning displays are triggered by a certain traffic event (say the driver is having a lane-departure) which is monitored by the ITS, and drivers would be more aware of that specific event as their hypovigilance is mitigated (say the driver seat vibrates to warn the driver). This will ultimately lead to an easier and more comfortable driving experience where better road safety condition are guaranteed by keeping the drivers vigilant.

1.2. Goals & Tasks

An overview of state-of-the-art driver warning techniques should be carried out as a priori, serving as the background introduction and theoretical preparation for to better develop the evaluation tool. As the purpose of the evaluation tool is to evaluate the warning screens used in the visual warning display, more aspects related to the visual warning technique should be elaborated, like the warning reaction time and warning screen design guidelines. And speaking of the evaluation tool, following features should be guaranteed in particular:

- The evaluation tool provides a larger degree of freedom to the evaluators by allowing evaluation tool GUI customization, say they can define their own layout of the warning screen tests and warning screen evaluations without modifying the source code.

- The evaluation tool consists of two separate parts: a client side which sends messages containing information and commands remotely, and a a server side which displays warning screens dynamically in response to the received messages.

- The evaluation tool should provide a user testing methodology to collect the feedbacks of the warning screens displayed; say an online survey/questionnaire.

1.3. Thesis Scope

Introductions of different driver warning techniques are given in the beginning part in the following thesis and later contents elaborate on the visual driver warning issues. Topics which are closely related to the visual driver warning display are discussed in details, including the response time settings and the guidelines of visual driver warning display design.

However the primary goal of this thesis, as the title goes, is to develop a tool for the evaluation of automotive warning screens. Notice those warning screens are intended to be applied in an Android-based driver assistance system named *DriveAssist* [4]. The implementation as well as the evaluation of the software tool is emphasized in the latter half of the thesis.

1.4. Thesis Structure

The structure of this thesis is arranged as the following:

Chapter 2 elaborates on the topic how could the drivers be warned. Three state-of-the-art driver warning techniques are examined in details, namely the visual warning display, the auditory warning display and the haptic warning display. Furthermore, a comparison between uni-modality warning & multi-modality warning is provided.

Chapter 3 discusses the timing issues for impending event warnings. Two elements which are closely associated with the total reaction time are addressed, including the human reaction time and the device response time. Several conclusions about proper display time settings are given in the end.

Chapter 4 concludes a series of guidelines in the process of visual driver warning display designing. General guidelines and specific guidelines (font legibility/readability, color and luminance design guidelines, etc.) are both presented.

Chapter 5 devotes to illustrate how the evaluation tool is implemented in a thorough way. The implementation environment is described at the beginning, following a block diagram of the evaluation tool. The application requirements and designed functions of the tool are outlined and in particular, the tutorials of the evaluation tool are documented in the ending part.

Chapter 6 presents the evaluation of the evaluation tool through a driving-simulator test. Test results and conclusions are summarized according to the feedbacks and questionnaire statistics collected from the test participants.

Chapter 7 summarizes the most pivotal results of the thesis. Besides, a concise outlook of further enhancements is also given.

Chapter 2.

Overview of Different Driver Warning Displays

State-of-the-art solutions of driver warning usually fall into the following three categories:

1. Visual warning technique. Drivers are warned visually. For instance, Liquid Crystal Display (LCD) screens are usually adopted to show certain alerting messages.

2. Auditory warning technique. Drivers are warned through the auditory sense. Some predefined ear beacons, auditory icons or speeches are played through the loudspeakers when necessary.

3. Haptic warning technique. Drivers are alerted through the haptic sense; e.g. the steering wheel or the vehicle seat might generate high-frequency vibration.

There is another driver warning alternative, the olfactory warning technique, namely the drivers are alerted via odor stimulation. Pungent odor or odor with special smell will be released to raise or regenerate the drivers' alertness. For instance, some researchers tried to present pleasant scents to the interface operators, lowering down their driving aggressiveness or preventing them from feeling sleepy, depending on the specific scent adopted [5]. Notice this driver-warning technique will not be further elaborated in the scope of this thesis, as it is still a conceptual proposal and has never been widely used in modern commercial driver warning systems [6].

Besides as the evaluation tool developed is to evaluate the warning screens, more attention are paid to the visual warning technique. Apart from this chapter, there are two additional chapters elaborating on the displaying timing issues and visual driver warning display design guidelines, see Chapter 3 and Chapter 4.

2.1. Visual Driver Warning

2.1.1. In-vehicle Visual Driver Warning Display Varieties

Modern vehicles rely on different visual display media to present information to the interface operators, e.g. through the automobile dashboard, the head-up display or the LCD screen mounted in the console (i.e., the infotainment system). For example, the automobile dashboard integrates most of the common instruments which provide pivotal driving information like vehicle speed and shaft rotation speed.

Fig 2.1 demonstrates a 10.25-inch multifunctional instrument display (a dashboard) from BMW, which registers and displays speedometer/tachometer information as well as other relevant car status information. Depending on the equipment, the information originates from some established functions provided by the car manufacturer like the high guiding function, the speed limit information including no overtaking display and some other warnings.

Figure 2.1.: Multifunctional instrument display from BMW: key information during the driving process is shown through the instrument display, including the speedometer/tachometer information, gear status, remaining gasoline and in-vehicle temperature, etc[1].

Furthermore, visual icons are also adopted to warn the interface operators, representing varying events about the vehicle status like ABS warning, low fuel notification or seat belt reminder, see Fig 2.2.

Illustration of interactive information in the form of visual icons via more advanced algorithms is also plausible, like the road sign detection system which display the detected content in the dashboard, see Fig 2.3.

---

[1]http://www.bmw.com/com/en/insights/technology/technology_guide/articles/multifunctional_instrument_display.html?source=categories&article=multifunctional_instrument_display
[2]http://suaveignition.wordpress.com/2013/08/02/your-cars-dashboard-lights/

Figure 2.2.: Dashboard lights illustration: the dashboard lights reflect the current status of the vehicle and make the drivers aware of potential mechanical problems. For instance, if the traffic light number 49 is on, it indicates that there is something wrong with the anti-lock brake system[2].

The second practical way of information presentation, yet still not commercially widespread (cost is the main obstacle, usually an option package for the head-up display costs from 1000 dollars up to 5000 dollars[3]), is the head-up display. A head-up display refers to a transparent display system that presents information without distracting users from their usual viewing directions.

Initially developed for military aviation though, head-up displays are becoming gradually available in production cars. The head-up display system usually comprises of a projector and a set of mirrors which beam a certain image onto a translucent film sticking on the windscreen. By projecting relevant driving information directly into the driver's line of sight, it produces a noticeable decrease in processing time by up to 50 %[4], while the drivers' attention is still kept at where it should be: the road.

The projected image may contain different kinds of driving information, ranging from general driving information like speed limits to navigation directions and urgent warning signals. BMW is the first European manufacturer to offer head-up displays (launched in 2003[5]), and Fig 2.4 provides such an illustration.

---

[3] http://ask.cars.com/2013/02/which-cars-have-head-up-displays.html
[4] http://www.bmw.com/com/en//insights/technology/technology_guide/articles/head_up_display.html
[5] http://www.autonews.com
[6] http://www.focus.de/fotos/bei-bmw-wird-die-navigation-optional-in-die-windschutzscheibe_mid_805648.html

Figure 2.3.: Road sign reflection system of Mercedes Benz: a road sign indicating 80 km/h speed limitation has been detected and a same speed limit reminder has been illustrated in the dashboard [7].

The presentation of even more complicated warning information like "pedestrian in the road" could be realized with the support of the pedestrian recognition system. Fig 2.5 demonstrates such a functionality from BMW.

Another crucial visual display source is the rectangular LCD screen. Whether integrated in the console or mounted independently above the head unit, it acts as an indispensable part of the modern In-Vehicle Information System (IVIS). Fig 2.6 shows the transflexive LCD adopted in the latest BMW 7 series[8].

The application of additional visual information and warning displays in applied interface environments has been receiving a huge amount of both commercial and investigative interests since the beginning of this century [8]. The sharp development of the liquid crystal display industries (LCD

---

[7]http://www.bmw.com/com/en/insights/technology/connecteddrive/2013/driver_assistance/intelligent_vision.html

[8]http://www.bmw.com/com/en/insights/technology/technology_guide/articles/control_display.html?content_type=/com/en/insights/technology/technology_guide/articles/navigation_system.html&source=/com/en/insights/technology/technology_guide/articles/idrive.html&article=control_display

[9]http://www.drivearabia.com/news/2012/06/03/bmw-7-series-gcc-facelift-for-2013/

Figure 2.4.: Navigation through head-up display: the navigation information has been projected directly onto the windscreen and the driver does not have to look away from the road[6].

surpassed CRTs in worldwide sales in the fourth quarter of 2007[10]) combining with the prevalence of personal Mobile Terminals (MT) makes the visual information display more prevalent.

Besides, as the intelligent auxiliary driving system using visual display has been a mature product, it is widely equipped in the premium car models of the automobile manufacturers. To illustrate, the iDrive system from BMW allows the driver controlling over different of the vehicles functions (say CD, radio, telephone and navigation) while still keeping him concentrating on the road[11]. It comprises a main functional entity named control display, which allows the driver quickly and easily accessing all important information through the visual sense. In Fig 2.7, an illustration of an assistant parking application on such a control display is given.

---

[10]http://prezi.com/egkg0zmoopya/lcd/
[11]http://www.bmw.com/com/en/insights/technology/technology_guide/articles/idrive.html
[12]http://www.bmw.com/com/en/insights/technology/connecteddrive/2013/driver_assistance/intelligent_parking.html

Figure 2.5.: Pedestrian recognition at night through head-up display: the night vision system of BWM recognizes people on the road in dark environments, and a yellow symbol indicating people ahead is shown through the head-up display[7].

2.1.2. Mobile Visual Driver Warning Display Extension

Some modern automobile models provide an IVIS extension function, through which drivers could easily integrate their own mobile terminals (say smart phones) into the in-car information system, see Fig 2.8.

For compact car models which do not provide in-car LCD by default, a smart phone fixed somewhere could also well serve the same functions [9]. Contemporary smart phones are generally exposed to millions of different applications, among which some are specially designed for visual driver warning.

Diewald et al. [4] had concluded the easy availability of mobile devices makes them proper alternatives to be applied in IVIS (modern mobile devices are usually equipped with power mobile CPU/GPU combinations). For instance, they have developed a V2X-based driver assistance system [10] for Android devices, named DriveAssist [?]. This application "allows the visualization of traffic information that originates from V2X communication services as well as from Central Traffic Service (CTS) on the user's smart phone" [4] and is capable of presenting the drivers with an overview of the surrounding traffic on a map view [4].

---

[13]http://www.engadget.com/2011/10/26/toyota-introduces-touch-life-smartphone-mirroring-system-your-p/

Figure 2.6.: An illustration of BMW 7 transflexive LCD: the LCD displays information (say the navigation map) from the available driver assistance systems. A light sensor measures the cabin brightness and the LCD brightness will be adjusted automatically to guarantee screen readability, whether in darkness or in strong sun-light[9].

Figure 2.7.: An illustration of the BMW assistant parking system: ultrasound sensors mounted at the front and rear measure the distance to the nearest large object surrounding the vehicle. A visual representation is given on the LCD[12].

An illustration of the map view function is shown in Fig 2.9. The driver's vehicle is represented by a centered black car and the triangular traffic sign in the bottom left indicates the newly received traffic event. The small triangular traffic signs along the road (indicated by the bold blue line) illustrate the relative positions of different traffic events on the map.
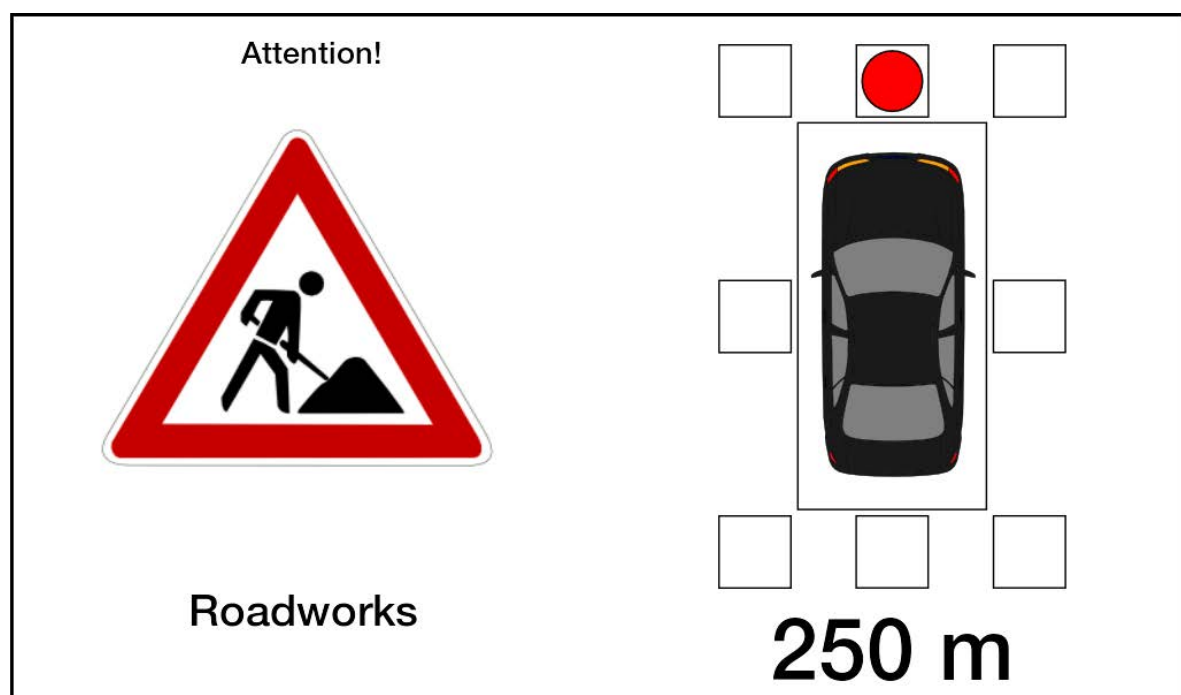
Figure 2.8.: An illustration of the Touch Life smart phone mirroring system from Toyota: the smart phone is synchronized with the vehicle infotainment system[13].

A warning screen would be initiated when drivers are approaching a certain traffic event ahead, and the relative position of the traffic event to the car could also be shown, see Fig 2.10.

Interface operators (drivers) could be clearly informed of the impending traffic event through the left part of the warning screen where a well-known, standardized traffic symbol is illustrated, just like the working area warning symbol shown in Fig 2.10. A relative direction of the traffic event to the car is additionally provided on the right part of the screen. The red dot shining in front of the car represents that the working area is directly 250 meters ahead.

2.1.3. In-vehicle Visual Driver Warning Display Varieties Comparison

In a research carried out by Ganzhorn et al. [7], they discussed the possibilities of presenting warning information (like integrated icons in dashboards or highlighted points of interests on the navigation map) through different visual displays to enhance the reproduction of road signs for a better protection of school children. Possible mounting positions of these visual displays include the following: the Head-Up Display (HUD), the Dash Board (DB), the Center Column (CC) and the Infotainment Display (ID), see Fig 2.11.
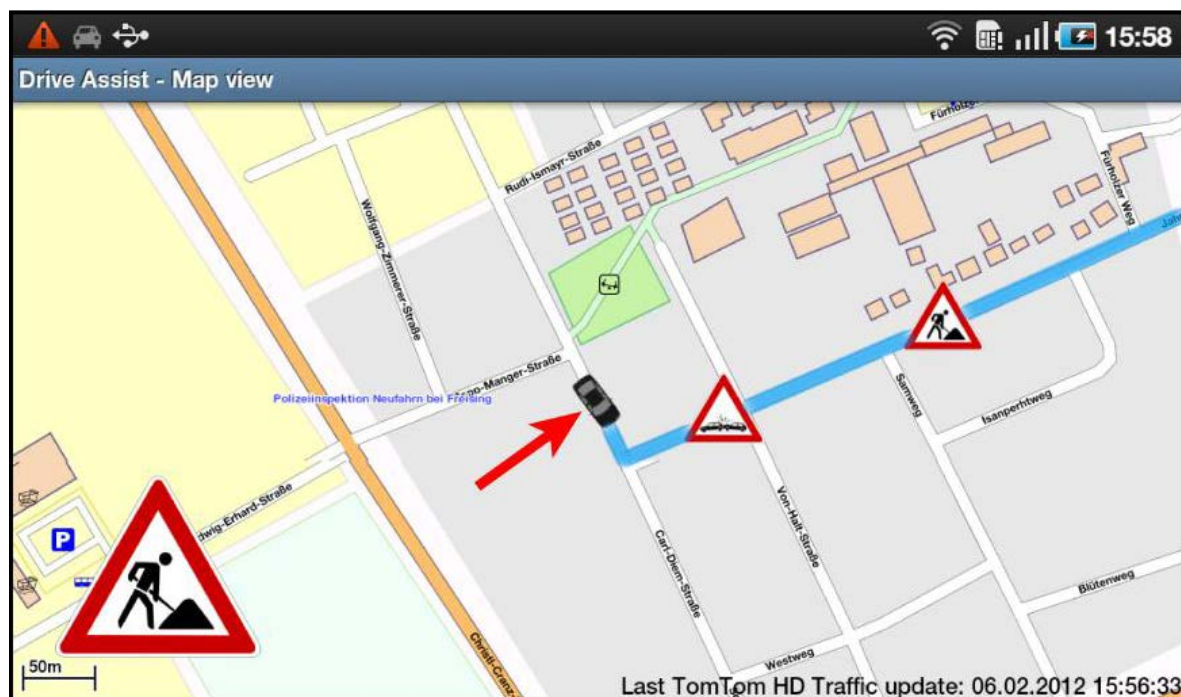
Figure 2.9.: A map view activated by *DriveAssist* [4]

Figure 2.10.: A warning screen activated by the *DriveAssist* [4]

---

[14]Background image from: http://http://www.autospies.com/news/NEW-YORK-AUTO-SHOW-Infiniti-Debuts-LE-Concept-Zero-Emission-Luxury-Sedan-70001/

Figure 2.11.: Varying mounting positions of in-car visual displays[14], with HUD to be the Head-Up-Display, DB to be the Dash Board, CC to be the Center Column and ID to be the Infotainment Display.

Their research pointed out that the adoption of an elaborately designed road sign warning system generally reduces the accident possibilities and such a system is accepted by the interface operators, which could be helpful in protecting vulnerable road users like school children.

However, they have also observed that the alerting effectiveness exerted by different warning displays is not necessarily the same. For instance, among those four possible visual display positions for the road sign warning system, the center column and the infotainment display are inferior to the other two as both cause higher distraction to the drivers: the period during which their eyes are off the road would be longer. On the other hand, since checking the dashboard is already a regular practice while driving, to put the road sign warning display there will not add excessive visual distraction to the drivers [7]. It is also worth to note that the center column as well as the infotainment display are proved to be more suitable in other visual information presentation tasks. To illustrate, it is suggested the center column should be used to"inform"the drivers (e.g., traffic condition or navigation information, see Fig 2.12), instead of delivering more urgent event information like road sign warning.

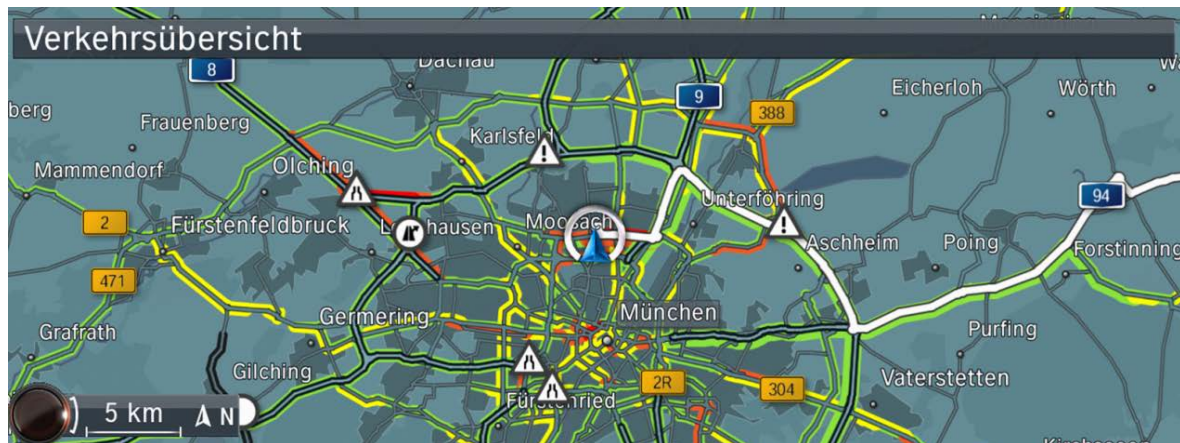[15]http://www.caricos.com/cars/b/bmw/2013_bmw_7-series/1024x768/102.html

Figure 2.12.: Navigation illustration of BMW 7-series[15]: those non-urgent but still complex information should be displayed through the center column or infotainment display, just like the detailed map and road status information shown above. It would be both difficult and distractive to display such information via the dash board or the head-up display.

Positions in the secondary field of view (e.g. the center column and the infotainment display) are less intrusive compared to those with a primary view like the dashboard, and therefore they are associated the displayed information with a lower urgency. Contrary to the urgent information which calls for immediate reaction, the lower urgency information allows the driver a longer reading and thinking time, without causing severe result. Therefore drivers are capable of grabbing more details and remember more aspects [7].

2.2. Auditory Driver Warning

Approaches to warn the drivers which differ from the traditional visual warning display have been investigated and developed, known as non-visual warning signals. Among those, a common-seen one is the auditory warning display. The usage of auditory warning signals either in the form of speech warning (verbal sounds) or the form of synthetic warning (tonal and nonverbal sounds, also known as earcons, see Blattner et al. [11]) as well its advanced version known as auditory icons (representational, nonverbal sounds) are getting prevalently used in the modern vehicle warning system, as car audio systems have become an indispensable equipment in modern car models, see Fig 2.13.

The perceptibility of auditory warning signals depends on the following acoustic properties: the signal loudness, the background noise loudness and the complexity of the auditory signal (say its tempo, pattern, information conveyed, etc.). A research conducted by Green et al. [12] suggests

---

[16]http://www.drivearabia.com/news/2012/06/03/bmw-7-series-gcc-facelift-for-2013/

Figure 2.13.: A Bang & Olufsen center loudspeaker in a BMW 7-series[16]: the loudspeaker system serves more than an entertainment facility of playing radio and music. It is also an indispensable part of the auditory driver warning system where auditory earcons/icons and speeches can be displayed.

that auditory signals should be at least 15 dB louder than the background noise to break through all the ambient sounds and make them clearly heard. Besides, the absolute loudness of the presented warning signals should not exceed 115 dB for hearing protection.

2.2.1. Auditory Earcons

Auditory earcons are the simplest form of auditory warning (yet this simplicity of auditory earcons does not come without its disadvantage: they could only convey limited information). They are computer-synthetic, cautionary messages with a regular sound pattern but a varying tempo. A typical example of such signals is the short and continuing beep sound generated by the loudspeakers if the vehicle is approaching some obstacle when backing. The closer the vehicle to the obstacle, the higher the warning tone frequency will be.

Auditory earcons have four basic acoustic properties: the fundamental frequency, the frequency oscillation and the sound pattern intensity. Different auditory earcons should differ in at least two aspects to be distinguishable [13]. A research conducted by Hagenmeyer [14] has shown that a proper selection of the earcon fundamental frequency lays within 500 Hz to 1500 Hz. For instance, a conventional auditory earcon could be a pulsed 1000 Hz pure tone with a 1 s period and 50 %

duty cycle [15]. Usually a higher fundamental frequency corresponds to a more urgent event, so does a larger oscillation frequency [3]. In the BMW park distance control system, the frequency of the warning tone will keep increasing till it sounds to be unbroken when the vehicle is within 30 cm from an obstacle, indicating an immediate brake action[17].

2.2.2. Auditory Icons

Previous introductions and discussing about the auditory earcon shortcomings seem to make auditory earcons less promising to be adopted in an auditory warning system. However, in the past decades many researchers have dedicated further efforts to investigate whether an upgrading form of auditory earcons, the auditory icon will make a difference: Gaver raised the concept of auditory icon first in 1986 [16], following many other researchers further investigating and discussing its application scenarios like Keller and Stevens [17], McKeown [18], etc.

Unlike the synthesized and monotonous earcons, an auditory icon is a frequently environmental or everyday sound imitating real-world events, like the sound of baby crying or the sound of glass breaking. This inherently meaning-conveying feature of auditory icons could be beneficial, as it renders auditory icons better associated with human-beings' intuitive responses since it contains a strong metaphorical link [19]. And unlike auditory earcons, there is simply no such associating process between hearing the sound and perceiving its specific meaning; the meaning has been signified by the icons themselves already. Reconsider the scenario where a dangerous, fast-reaction demanding traffic event happens, drivers are capable of implementing relating actions quickly as it is intuitive.

The better reaction time brought by auditory icons has been fully authenticated by lots of experiments conducted by different, independent researchers, like what had been stated in their works by Belz et al. in 2004 [20] and Ho and Spence in 2005 [21], respectively. For instance, the experiment conducted by Belz et al. [22] had shown truck drivers responded much more rapidly to the auditory warning icons than to the conventional tonal warning earcons, where the participants are requested to brake when different combinations of road scenes and auditory warning signals are given, see Fig 2.14.

Though it is observed that auditory icons demonstrate superior performance in the response time, still it is remarkable to note that this advantage does not come without the process of elaborately selecting the audio icon sounds [19]. Essential issues include the sounds should represent stereotypical meanings across large portions of the population (the less ambiguity and confusion the sound causes, the better it will be) and they should be capable of stimulating instinctive behavioral responses which make the drivers more alerted and concentrated (apparently not all sounds

---

[17]http://www.bmw.com/com/en/insights/technology/technology_guide/articles/park_distance_control.html
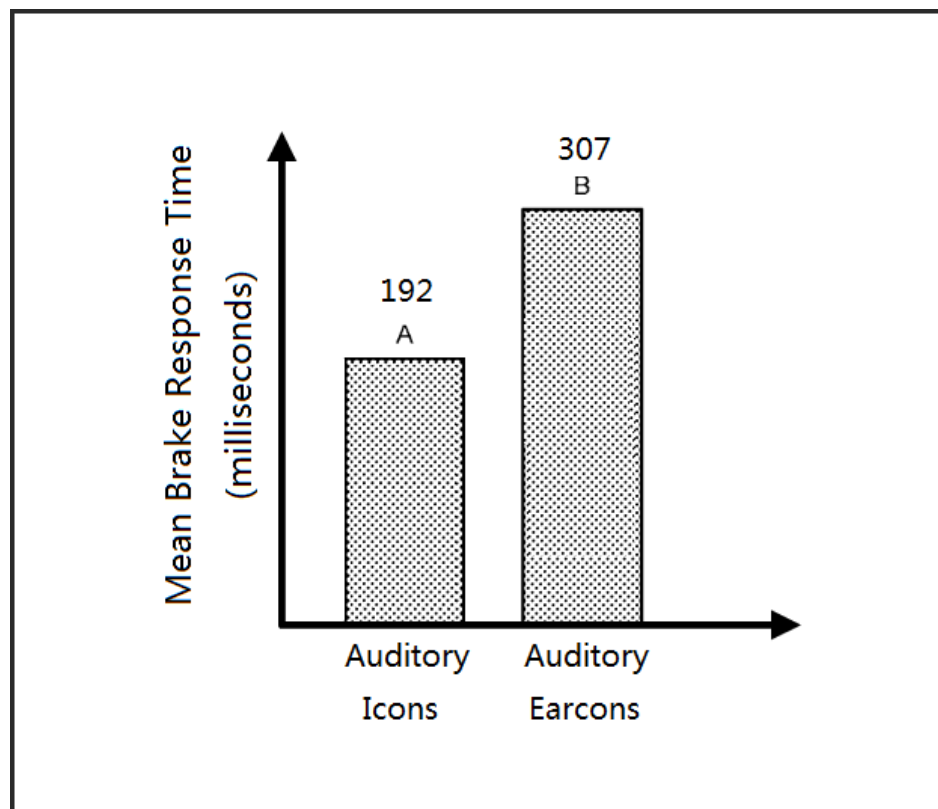
Figure 2.14.: Auditory icons vs. auditory earcons response time in a simulation test [22]

do that; think about a lullaby). According to the report of McAdams in 1993 [23], the sound of a car horn was one of the most effective auditory warning signals; following are missile alarms, yelper sirens, falcon horn sounds, etc. For instance, in the braking simulating experiment conducted by Graham [24], the sounds of car tire screeching and car horning are used as the auditory warning icons. Both sounds led to satisfying results in capturing the participants' attention.

An attempt to develop a systematic methodology for selecting and evaluating auditory icons based on normal drivers' (including civilian drivers and commercial vehicle operators) preference was presented by Belz et al. in 1997 [25]. Before that, some other researchers relied heavily on experts' opinions to match a specific meaning to an auditory icon [19]. In Belz's test, participants are required to assign meanings to different auditory icons, rate their perceived urgencies as well as their levels of association with the intended (experimenter-selected) meaning, and their findings and discussions may act as a reference in formalizing the auditory icon design and selection process.

It has been stated that auditory icons take an advantage over auditory earcons in the reaction time, especially under the urgent scenarios. However, as the research went thorough and detailed, one potential problem of such urgent auditory warning icons got revealed: over-reaction. Researchers have reached the general conclusion that people do respond more rapidly to auditory warning icons

as the perceived level of urgency sharply increases (e.g. Haas et al. [26]), but Bliss' and Acton's research in 2003 [27] suggested that the presentation of these auditory icons actually renders participants response inappropriately, compared to other forms of common auditory warning signals, say speech warnings or auditory earcons [19].

The previous phenomenon is triggered by the following reason: an intuitive reaction does not necessarily have to be an appropriate one [19]. People may get terrified to varying degrees by the urgent meaning hinted in the auditory warning icon, which stimulates them to act before they really have sufficient time to evaluate the specific traffic event encountered carefully and decide what the most proper response that should be implemented is.

Another disadvantage noticed is, as nobody wants to get terrified by his or her own vehicle while driving, those auditory icons conveying very urgent warning information could hardly be defined as pleasant and welcome. McKeown and Isherwood [28] tried to assess the perceived unpleasantness of 20 different environmental sounds in their experiment and they found the higher perceived urgency of the sounds, the more unpleasant people rated them to be. This is somewhat contradictory as drivers need to be exposed to more annoying, unpleasant auditory sounds in order to perceive a high level urgency. Therefore, though the idea of adopting intuitive warning sounds to get people alerted and respond naturally sounds to be illuminating at the beginning, it will probably end up in being marked as a noisy and unwelcome auxiliary driving function by the users.

2.2.3. Verbal Warnings

Another kind of auditory warning signals is the verbal warning, say voice messages or speeches. Verbal warning signals lead a huge advantage that no training process is needed for an operator to understand the showing up event [29]. There is no need for the operators to associate the received auditory information with a certain meaning of a traffic event and they can give reactions directly.

The natural and inherent information-conveying property makes verbal warning a perfect methodology in specifying the confronted traffic event through descriptions and giving corresponding instructions (could be brief or detailed). The former feature would not be an easy task via other auditory warning ways as remembering dozens of signal-event matching pairs could be a challenging job for the interface operators, and the later one is not that plausible.

Verbal warning signals are capable of representing different urgency levels by changing acoustic parameters like varying the intensity or changing the presentation level (louder voice when emergency happens), just like other common auditory warning ways. Notice in the way of raising the perceived sense of urgency, more severe annoyance is also introduced. It is noteworthy that the best way trying to attract an interface operator's attraction is simply to "annoy" him, see Fig 2.15.
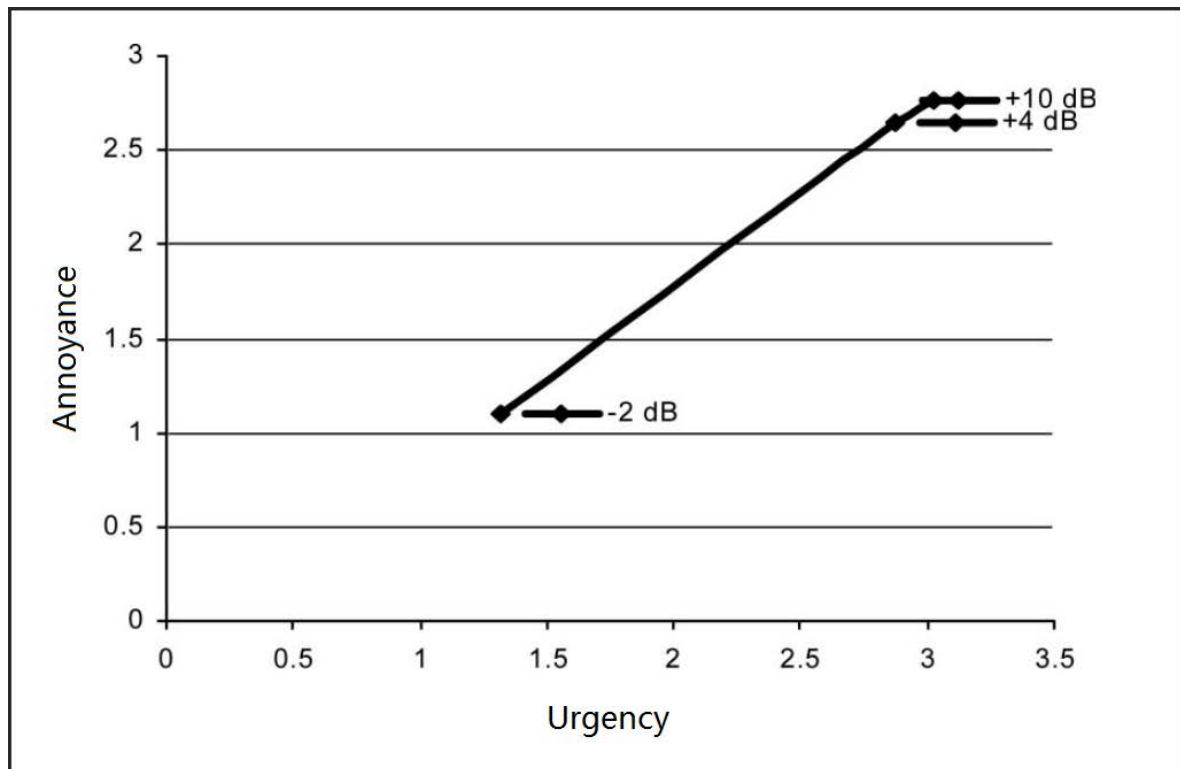
Figure 2.15.: Perceived urgency levels and the corresponding annoyance levels: the higher the sound intensity is, the higher the ratings of the perceived urgency and annoyance are. Notice the sound intensity increases linearly from -2 dB S/N ratio up to +10 dB S/N ratio [30].

Not least, verbal warning is found to be less annoying when compared to its two counterparts (auditory earcons/icons) if they all produce the same acoustic pressure, according to the report published by McKeown and Isherwood in 2007 [28]. This actually gives us a hint regarding reducing annoyance: if the interface operators are bound to be annoyed when emergencies happen, implement that with verbal warnings.

Another notable fact about verbal warning signals originates from its unique ability of creating semantic content. For instance, McKeown and Isherwood [28] reported verbal warnings are easier to be identified as the drivers learn the current situation from the verbal messages. Some other researches have also shown different choices of signal words could affect ratings of the perceived urgency (see Hellier et al. [31]).

In the experiment designed and carried by Baldwin in 2010 [30], four warning signal words have been presented to 14 young undergraduate students to check their abilities in vigilance invoking. It has been shown that the signal word 'danger' is perceived to indicate the greatest alerting effectiveness and highest urgency level while the word 'notice' illustrates the worst performance on both dimensions, see Fig 2.16.
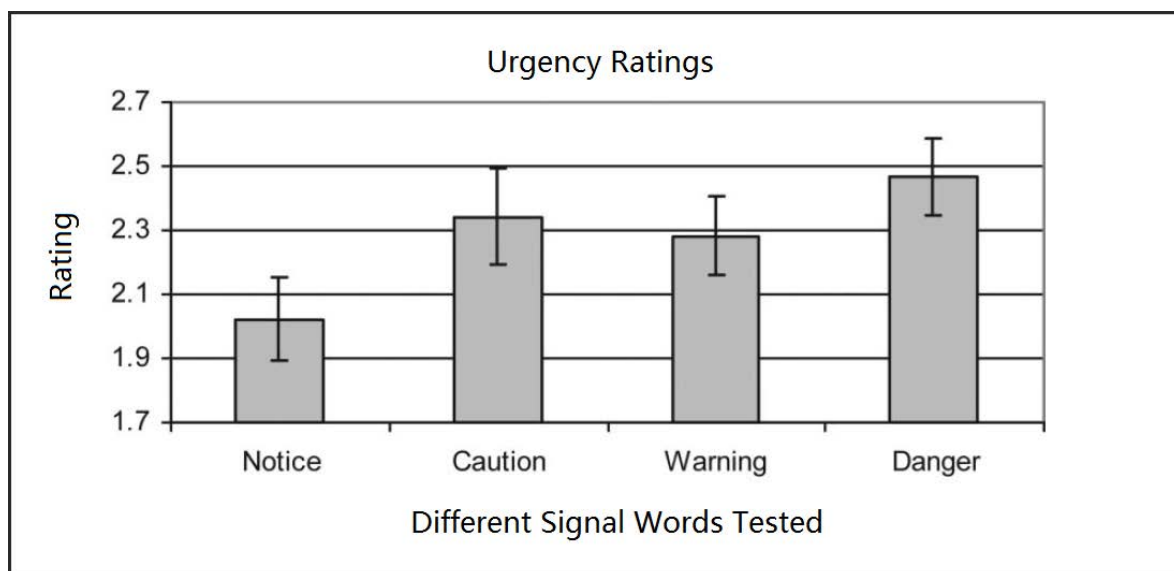
Figure 2.16.: Perceived urgency ratings of different signal word [30]: "Danger: is the word perceived to be the most urgent following the word "caution" and "warning", and "notice" has the least perceived urgency.

Note that this semantic content conveying property may also bring some negative effects. Edworthy and Hellier [29] had pointed out a potential problem of verbal warning signals in their systematic survey of different auditory warning ways: the intelligibility of speech warnings by listeners could be affected by the surrounding environment.

Drivers get frequently involved in various speaking tasks like talking on a phone, having conversations with other passengers or simply following the music played by the loudspeakers. Notice all those speaking behaviors might still be continuing when the verbal warning system is activated, thus reducing the efficiency of the concurrent speech warnings [32], especially for those detailed and long-lasting ones like auditory navigation messages. As it is absurd to suggest drivers not to talk or enjoy their music while driving, this utility-limited shortcoming is something inevitable that verbal warning designers have to endure.

The second semantic defect originates from the grammar structures of some languages in which the exact meaning of a sentence will not be determined until the sentence is totally finished. This property will be problematic under emergency situations since it takes too long for the drivers to learn the meaning of the verbal warning [33].

In conclusion, speech warnings have the benefits of being able to inform, alert as well as guide drivers when encountering different traffic events. The very information-bearing property of speech warnings is of great value when drivers must implement prompt and appropriate actions after analyzing the complex situation, such as at intersections. There is some information collecting and processing process involved in those complicated driving scenarios; it is not simply push the

brake pedal following the instinct and no other auditory warning ways could serve better than verbal warnings under such scenarios [34]. Notwithstanding the previously mentioned semantic defects, auditory verbal warning still counts for one of the most important and promising auditory warning way.

2.2.4. Summary of Different Auditory Warning Signals and Their Comparisons

In a well-designed auditory auxiliary warning system, any form of auditory warning technique might be used to achieve a certain warning purpose. Our previous reviews on three common auditory warning techniques have shown that they may well serve a wide variety of warning functions within vehicles, ranging from regular status reporting to emergency or hazard alerting. However their warning abilities in different driving scenarios could be completely different, therefore it is pivotal to select the most appropriate warning technique in real applications. A natural way to classify them could be specifying them according to their priorities.

To warn the drivers about an approaching hazard like a vehicle is overtaking in the blind spot requires immediate attention and proper reactions. Some researchers suggest setting the highest priority warning signals to be abstract alarms (like the auditory earcons) as they could be easily distinguished from all the background noise, environmental and speech sounds [28].

Indeed earcons are easy to be captured in a noisy, mixed sounding environment because of their plain but unique acoustic properties, but it might not be enough to just capture the interface operator's attention [19]. There are two aspects to be considered when evaluating the comprehensive warning performance of a certain warning signal: how fast the warning signal captures the interface operator's attention and how fast the warning signal triggers the following-up reactions. It is true that the earcons do quickly attract the operator's attention, but as what has been elaborated in the previous section, earcons may cast such effect that drivers fail to recall the appropriate actions straight away as they are suddenly presented with a rather unfamiliar sound. Unless those auditory earcons could be associated with intuitive responses [24], they are not that suitable to be applied in dangerous situations.

It is worthwhile to note that verbal or speech warning should not be used to warn emergent traffic events, either. It takes too much time for the interface operators to learn the exact meaning of the warning and this is definitely unwanted and unacceptable. A feasible practice could be to endow auditory icons the highest warning priority and adopt them when encountering urgent traffic events. It demonstrates even shorter attention-capturing time than the earcon and leads to an intuitive reaction as well. Though we also address the problem of overreaction in the previous section, still we could reduce this side-effect through more dedicated auditory icon sound design.

To alert drivers keep vigilant (e.g. a sudden rain when the outside temperature is freezing may lead to icy road condition), say to implement some advisory functions, verbal warning through

speech is a practical choice. There is no strict timing demand and speech warning could well explain everything in an elegant way.

An auditory warning display (no matter whether it is auditory earcon, icon or verbal warning) would be just a failure if it cannot present the necessary warning information and accomplish its warning task. Successful auditory warning design should concentrate on creating appropriate mapping relationships between different levels of priority of the events to be signaled and different forms of auditory warning [28].

The most classic way in manipulating the mapping relationships of auditory earcons is differing acoustic parameters of the auditory sounds; loudness and frequency are the two fundamental factors in deciding the perceived urgency level. For auditory icons, drivers learn the meanings of real-world sounds as well as the urgency of the events they signify in an intuitive way. This leads to a shorter processing time and also a more rapid responding action, when compared with users who "have to rely on a more exhaustive assessment of acoustic parameters of the sounds" (Guillaume et al. [35]). Speaking of verbal warnings, the urgency level could be well coded in the sentences to be announced. Notice that for auditory icons and verbal warnings, the manipulations of acoustic parameters could also be adopted as long as users are still capable of understanding them, say the speech should not be played too fast.

It has been briefly addressed that car horns and sirens are the two most effective sounds serving as audio icons and apparently neither of them could be described as pleasant and welcome. In fact, Lazarus and Höge [36] have concluded their finding that better warning effects are generated from larger difference between the danger signals and pleasant situations. There is also a close connection between the degree of annoyance and the acoustic characteristics of the sounds. A positive correlation between annoyance and loudness has been observed [30] and high-pitched sounds are also more annoying than low-pitched ones, both are easy to comprehend. It is worthwhile to note that these very features like being loud or high-pitched which both attract attentions and annoy drivers are actually rather valuable in dangerous situations. Some warning sounds just should never be switched off in order to warn the drivers under emergency cases, definitely (drivers will not complain about those infrequently-occurred warnings which may save their lives, even they are annoying). But for those more frequently employed auditory warnings, they should be both acceptable and understandable.

Mckeown and Isherwood conducted a comprehensive experiment to compare performances of different auditory warning displays in 2004 [28]. Ten participants took part in a simulation test where they needed to assess situational urgency of the driving events first, then match auditory displays to driving events and finally make the modulus-free magnitude judgments. Table 2.1 illustrates the tested driving events and the specific realizations of warning auditory beacons, auditory icons as well as verbal speeches.

Table 2.1.: Tested driving events and the corresponding auditory displays [28]

Driving Events	Auditory Beacons	Auditory Icons	Verbal Speeches
Low petrol level	Single bell ding	Water pouring	"Petrol is low"
Low oil level	Low-rate tapping	Steam and water sounds	"Oil is low"
Low tire pressure	Low-rate and low-pitched warbling tone	Air release blast	"Tire pressure is low"
Opened driver door	Moderate-rate siren	Car door shutting	"Driver door is open"
Exceeding speed limit	Moderate-rate fire bell	Car speeding past	"Exceeding speed limit"
Hand brake on	Moderate-rate tone alarm	Squeaking sound	"Hand brake is on"
Blind spot overtaking	High-rate and high-pitched warbling tone	Car horn blasts	"Car in blind spot"
Car drifting off the road	High-rate and high-pitched tone alarm	Driving over rumble strips	"Drifting off road"
Rear end collision possible	High-rate and high-pitched zapping pulse	Car crashing	"Headway closing fast"

Two diagrams, Fig 2.17 and Fig 2.18 demonstrate the results of the modulus-free magnitude estimations. The computer task performance for accuracy and response time in matching the sounds to the referent driving events are shown respectively.

One can well observe that verbal speeches and auditory icons demonstrate both fastest response time and sharpest accuracy in this computer-based, event-matching task, as they show the best mapping relationships to their referents. On the other hand, auditory earcons fail to show satisfying performance on both aspects. It seems that these abstract, synthesized sounds are less capable of associating a certain sound with a specific driving event.

2.3. Haptic Driver Warning

Using haptic modality to convey information to the interface operators is another plausible choice in driver warning. Lots of efforts have been devoted to adopting haptic displays to present information to interface operators by researchers (e.g. Spence and Ho [37]). For instance, Janssen and Thomas have concluded that increasing the counterforce on the accelerator pedal (e.g. combined proprioceptive and tactile cuing) would lead to a better performance in the collision avoidance system [38]. Not an isolated case, Ho has noticed a reaction improvement up to 24.7 % in her brief report about driver warning through the haptic display [39].
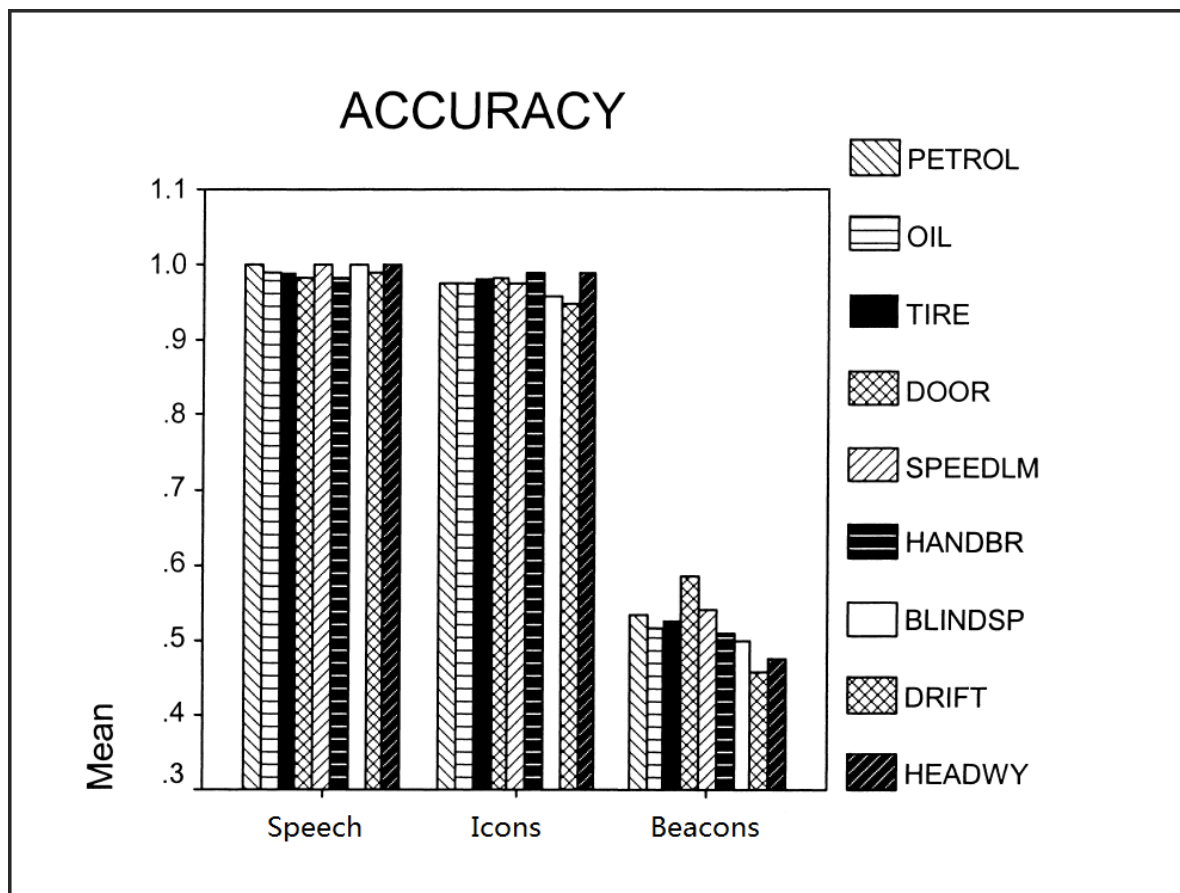
Figure 2.17.: Computer task performance estimations for traffic-event distinguish accuracy: different driving events like low petrol level, low tire pressure etc. represented by verbal speech, auditory icons and auditory beacons are tested. Verbal speech and auditory icons demonstrate similar accuracy performance while auditory beacons are the least accurate [28].

Haptic display is gradually becoming a new alternative to traditional driver warning displays as cheap and effective ways to achieve vibration-tactile stimulation have been made possible by the booming development of automotive industries. Several automobile manufacturers like Mercedes and Citroën have integrated vibrating functions in their in-vehicle warning systems of some newly-released car models, say the vibrating steering wheel of Mercedes E-class or the haptic seat of Citroën C6, both are used in the lane-departure warning.

Note haptic warning displays have an advantage over the other warning displays: warning signals conveyed by visual or auditory signals are exposed to a potential risk of being-missed (due to driver inattentiveness, driver drowsiness, ambient noise etc.), whilst the vibration generated from the steering wheel or the seat could hardly be ignored as long as the drivers are still sitting there, controlling their vehicles [40]. This advantage also comes with a limitation: the vibrating sources need to have a direct contact with the interface operator, say the driver seat, the seat belt, the
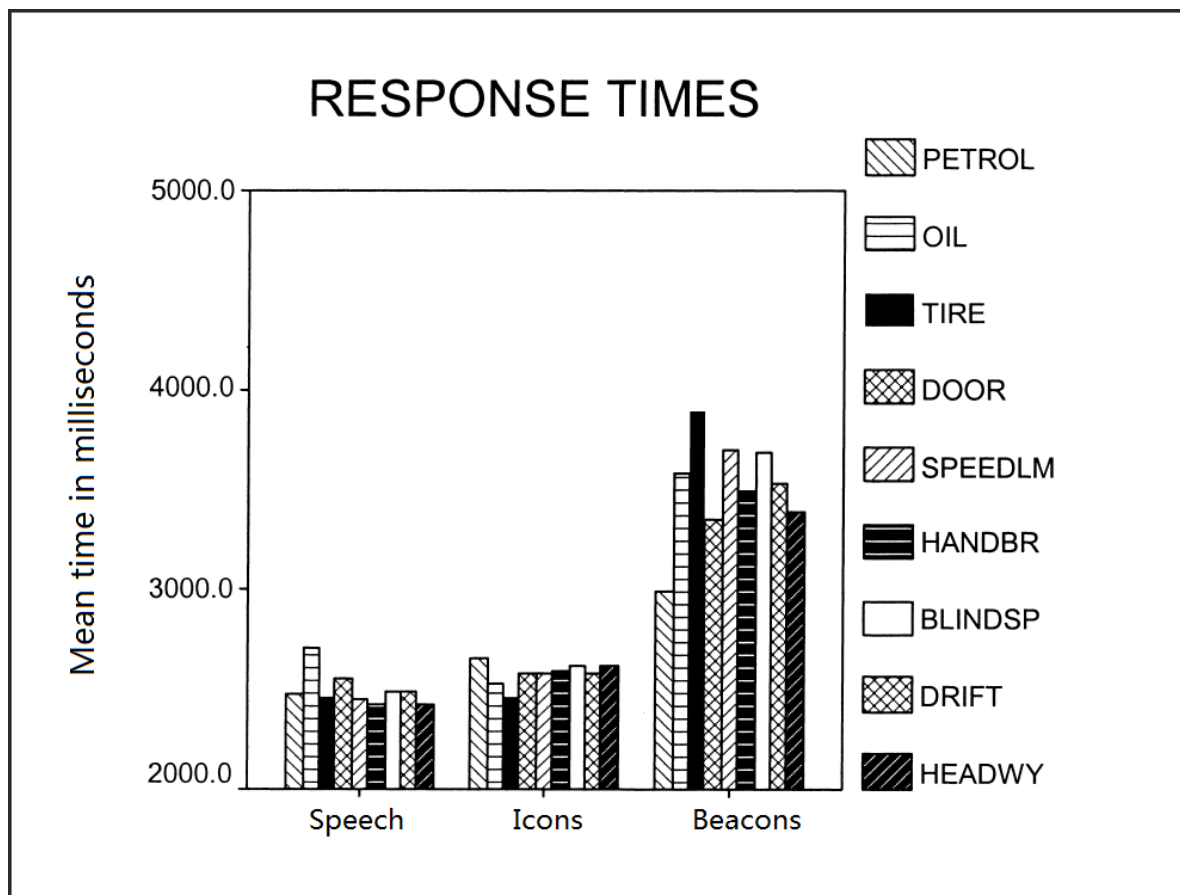
Figure 2.18.: Computer task performance estimations for response times in milliseconds: different driving events like low petrol level, low tire pressure etc. represented by verbal speech, auditory icons and auditory beacons are tested. Verbal speech leads a marginal advantage over auditory icons in the response times, and both are much better than auditory beacons [28].

pedals or the steering wheel [37].

Among all those candidates to be applied in a haptic warning system, the steering wheel is a primary actuator for vehicle lateral control [37]. For example, a typical scenario where haptic display could be used is lane departure warning. Drivers could be informed of a coming lane departure through synthetic steering wheel torque or vibration. In the research carried out by Beruscha et al. [41], they had proved that the application of synthetic haptic signals at the steering wheel could actually help the driver inducing a steering reaction (shorter reaction time observed). The d river seat also acts as a possible position where a vibration generating source could be put: Horowitz and Dingus [42] had shown that graded haptic alerts given by the driver seat are particularly effective in guaranteeing better driving safety in their comprehensive survey of graded warning sequences.

Some research investigations comparing the warning performances of haptic displays and other traditional warning displays like visual or auditory warnings have been implemented in the last few decades. Schumann et al. (1993) [43] reported their finding that more sensitive responses are recorded when drivers are stimulated with tactile/proprioceptive cues like steering wheel vibration or steering wheel rotating-counterforce increase compared to auditory warnings like verbal speeches, after a lane departure test. This observation seems to indicate that haptic warnings are more directly perceived than the auditory warnings. Apart from the feature of being more intuitive, haptic displays are less annoying as well. Lee et al. [44] also contrasted the performance of haptic and auditory warning signals in a collision avoidance test where the experiment result suggests that haptic displays are more pleasant and user-friendly.

2.4. Uni-modal Warning & Multi-modal Warning

The application range of the previously discussed three different warning displays is limited to the uni-modality, in which each warning display works on its own and does not combine with other warning displays. An ongoing investigation is, whether multi-modal warning signals like double-modal or triple-modal could be more effective in the task of driver warning. There are several published reports contrasting uni- and multi-modal warnings and their conclusions seem to demonstrate that multi-modal warnings do show certain superiority to uni-modal warnings (Spence and Driver [45], Jan and Hendrik [46]).

For instance, a driving simulator-based study implemented by Hendrik et al. [46] had investigated varying directional information conveying effectiveness of uni-modal visual, uni-modal haptic and double-modal (visual plus haptic) warning signals in a route guidance system. They have concluded participants of the driving simulating test responded much more rapidly to the double-modal warning signals than to the other two uni-modal warning signals.

Notice there is an important distinction between two different types of multi-modal warning signals: signals conveying redundant warning information about a certain traffic event and signals depicting different, independent aspects about the same traffic event. In effect, some researchers had confirmed the benefits of introducing redundant warning information, speaking of the former case (Selcon et.al [47]). For the latter case, however, it seems that there is only one pivotal warning signal dominating the actual warning effect; that is, when an interface operator is given some multi-modal warning signals with different aspects of the impending traffic event being portrayed, the warning effectiveness achieved would not be better than barely selecting the uni-modal signal that the interface operator is most sensitive to [19]. In summary, the currently appropriate way of adopting multi-modal signals is to use redundant signals instead of combining inter-independent warning signals.

Given the conclusion that multi-modal warning is more effective, one may consider just simply mixing all the alerting techniques developed to make sure the drivers get the warning messages and therefore achieving superior warning performance. However, the problem is that drivers are not necessarily best warned this way [19]: the major concern is that too many distracting message resources could a heavy burden to the drivers. As it is usually impossible or at least very inefficient for a normal person to process information resources with large diversity simultaneously, elaborate cautiousness should be taken when designing a driving warning system for vehicles (e.g. Spence and Driver [48]).

So naturally the quantity of the uni-modal warning signals used in forming multi-modal warning signals is the key aspect to be determined. In most studies concerning multi-modal warning performance conducted so far, double-modal warning signals are adopted, say combined warning display of audio and haptic warning signals. A hypothesis is that interface operators tend to get somewhat "over-warned" (being nervous) and become less concentrated on the very traffic event to be dealt when applying the triple-modal warning signals or modality with even higher degrees.

Ho compared the performance of uni-modal auditory and haptic warning signals against double-modal warning signals in a driver simulator test [39]. The effectiveness of the aforementioned warning modalities in alerting drivers about an impending front-to-rear-end collision had been recorded. The result of this performance contrasting study is illustrated in Fig 2.19.

It could be seen the presentation of bi-modal warning signals serves as a more effective means in the driver warning purpose: the adoption of bi-modal warnings immediately leads to a reduction of the braking response latency up to approximately 40 % whereas for auditory uni-modal and haptic uni-modal warnings, the latency reductions are 32 % and 24 % correspondingly.
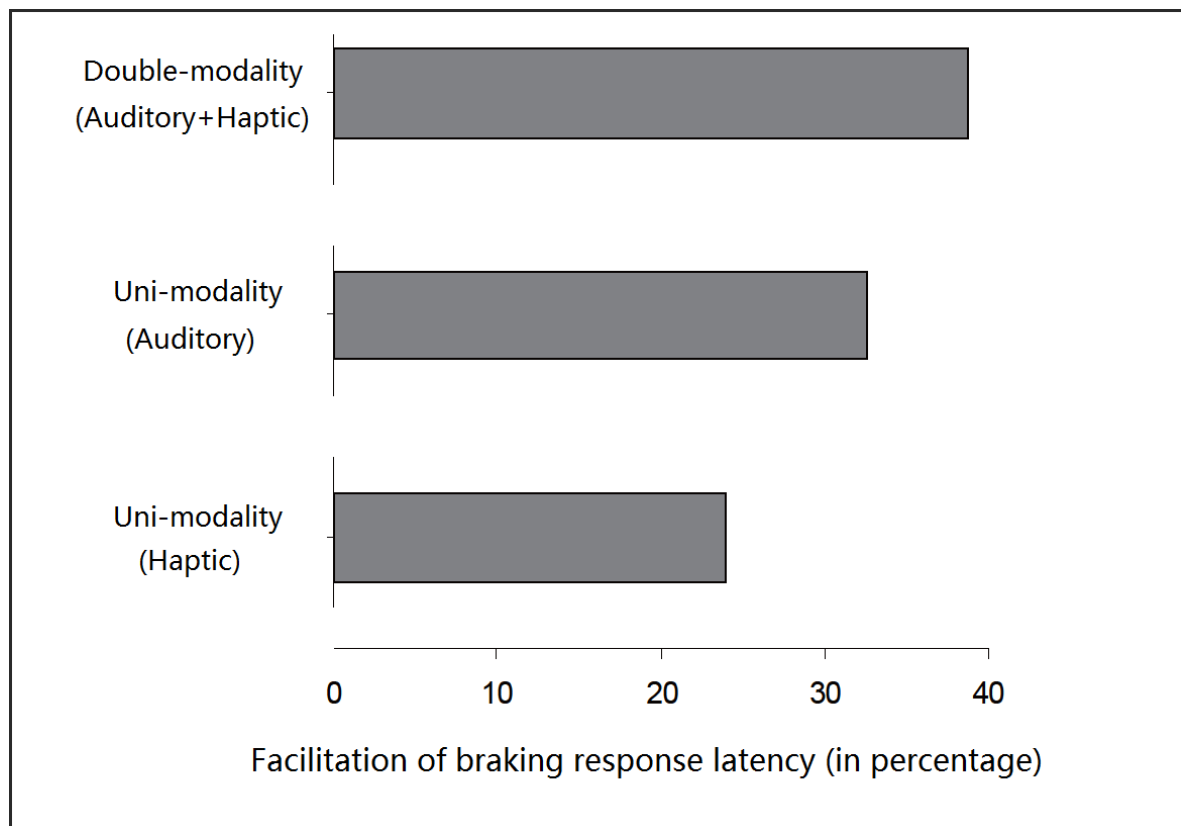
Figure 2.19.: A comparison of uni-modal auditory warning, uni-modal haptic warning and double-modal warning responses latencies facilitation: the graph demonstrates the facilitation of braking latencies when using different modal warning signals, compared to no warning signals are used. It is obtained from a simulator-based driving test [39].

Chapter 3.

Timing Issues for Impending Events Warning

In this chapter, several aspects closely related to the reaction time regarding impending (and usually emergent) traffic events are examined, which serve as a solid base when setting the timing parameters for the later practical warning display program. For non-emergency events like general direction indicating or driving tips delivering say traffic congestion ahead, there is no such strict demands on the timing issue. On the contrary, the timing demands could be rather loose and thus will not be elaborated here.

Two general elements contributing to the total reaction time are introduced at the beginning, namely the human reaction time and the device response time. Then proper settings of the displaying time, the time interval during which the warning screen are created and illustrated.

3.1. Human Reaction Time Components

Generally speaking, the total reaction time counted when an individual corresponds to certain stimulation, whether it is in visual or auditory or haptic sense, could be decomposed into two different logically sequential time periods: nerve reaction and mental process time, and the movement time (see the works by Green [49] and Summala [50]). They are explained one by one in the following sections.

3.1.1. Nerve Reaction & Mental Process Time

When a certain kind of stimulation occurs, it takes some time for the human nerve system to perceive that due to human nervous latency, and it costs additional time for the brain to go through the information processing and movement ordering phases.

For the nervous reaction time, three most pivotal timing parameters measured in several experiments by different researchers have been concluded below, regarding visual, auditory and haptic senses correspondingly [51]:

- Visual stimulus needs 20-40 ms before reaching the brain

- Auditory stimulus needs 8-10 ms before reaching the brain

- Haptic stimulus needs 15-25 ms before reaching the brain

The statistic listed above demonstrates that the human nerve system reacts to different sense stimulus with varying speeds. Given all those research findings confirming this phenomenon, it is necessary to take this point into consideration when designing driving warning display systems.

The mental processing time is the time interval between the perception of a certain traffic event and the implementation of a response ordered by the human-brain. For instance, it takes some time before the driver decides to give way to a passing ambulance, once the driver receives a related warning.

The general nerve reaction and mental process time, viewed as a whole process, could be further decomposed into 4 sub-stages, based on the related work published by Green [49]:

1. Sensation time. The sensation itself is a phase during which an individual notices something or something happening in the surrounding environments. This process is non-conscious and the stronger the signal intensity (like shape, size, brightness and color) is, the shorter the process will be. Assume there is a giant red object which even illuminates above the road; it would trigger a super-fast sensation process.

2. Perception time. There is a very close logic connection between the sensation time and the perception time: the perception time is the time needed to realize the meaning of the sensation. That is, we realize that the shining giant red object is actually a neon billboard. The length of the perception time varies depending on the driver's familiarity with the sensed object. For instance, a novel or obscure sensing signal will lead to a longer perception time. Loiukkonen has concluded some reference values for this perception time period:

   - 190-215 ms needed to process the visual stimuli

   - 160 ms needed to process the auditory stimuli (See works by Fieandt et al. [52], Welford et al. [53])

   A convincing argument explaining why visual stimulus still takes longer time is the visual information is much more complicated than all the other sensory information, thereby demanding the longest processing time even the visual perception system has evolved to be highly sophisticated [1].

3. Situation awareness time. During the situation awareness phase, the driver would map the sensed signal to the very situation in which he is, and then interpret the scene and deduce what is likely to happen. By way of illustration, the driver realizes if he keeps driving at the

---

[1] http://www.sparknotes.com/psychology/psych101/sensation/section2.rhtml

same speed, he will miss the detailed content of the neon billboard (assume the car is at a relatively high speed).

4. Response and arrangement time. Once the driver is aware of the situation, he needs to decide what should be done and arrange the corresponding response. The driver is interested at the neon billboard, so he decides to slow down and arrange the following movement like move the foot away from the accelerator pedal first and then move to the brake one. Those decisions made by the driver are generally based on the concrete situation and his own experience. A given conclusion is that the additional latency introduced by the response and arrangement process is 100-200 ms (Boff et al. [54]).

Consider all the mentioned time periods, the aforementioned four sub-stages added up will take about 500-800 ms [51].

Movement Time

Put simply, movement time is the time to implement the arranged movements through muscle planned in the mentally phase. It should be noted that this time interval heavily depends on the movement itself and the driver, for instance complicated movements take longer time and young drivers move faster than the senior drivers. For the most common seen driving movements — limb movements we usually assume they take around 200-400 ms to be implemented [49].

3.1.2. Device Response Time

The counterpart of the human reaction time is the device response time. Vehicles need some additional time when they responded to the drivers' operations. A simple example is the time interval between the driver's brake movement and the vehicle becomes stationary.

Different from the human reaction time, the device response time depends solely on the device itself plus some external environmental factors (imagine the vehicle braking time under raining situation will definitely be prolonged) instead of the drivers and therefore we just need to give an experiential value for reference. Based on the sample calculation given by Green [49], we assume the lower limit of the device response time to be the sum of the maximums of the first two time intervals (nerve reaction & mental process time and the movement time), say 1200 ms.

3.1.3. Total Reaction Time

The total reaction time we need to consider when designing the timing parameters of the warning displays consists of the following two time intervals: human reaction time and device response time. According to the statistic given previously, the human reaction time varies from 700 ms to

1200 ms, while the device response time is set to be 1200 ms in this chapter. Add them together and the range of the total reaction time is from 1900 ms to 2400 ms.

Some researchers did not count in the vehicle response time when they concluded their driver warning experiment results, and for them a number less than 1900 ms is usually adopted [49]. A reason accounting for this might be that all those experiments are simulator based and therefore they are less practical, leaving out the physical device response time. However even if the timing parameters are different, the conclusions the reports trying to illustrate could still be convincing and effective.

This range is still a rough estimation instead of an exact measurement which could be safely applied anywhere. In effect, researches have illustrated factors like age and gender will exert varying influences on the human reaction time, let alone the device response time: there are just so many different road conditions and vehicle models. As it goes in Green's report, "while the basic principles generalize to estimating reaction times (say the total reaction time are divided into the human reaction time and device response time to be calculated) , the exact numbers do not" [49].

3.2. Displaying Time Setting

This section tackles the following question: how should we configure the timing of the warning signal presentation? Or in more details, when do we need to release the warning display and how long should the optimal displaying timing window possibly last?

What we have discussed and concluded in the previous three sections actually serve as a necessary preparation for this final question: since the minimum of the total reaction time is 1900 ms (the range is from 1900 ms to 2400 ms), the driver warning display should come into effect at least 1900 ms before the impending event really happens. As long as we have obtained a lower bound for the advance time of the warning display, one might intuitively think that any timing parameter larger than this lower bound would work and the earlier the warning is displayed, the better warning effectiveness will be. Although generally speaking, it might be beneficial that the driver is allowed a long preparation time, this is not necessarily the case here.

Researches have shown that earlier warning signals suffers from the potential risk of being perceived to be false warning, and the earlier the signal, the higher the risk [55]. This could be well imagined in the following sample: a warning signal is displayed 1 minute before an impending dangerous traffic event. The driver would pay attention to this warning message in the following seconds for the possible upcoming event while nothing actually happens during this time interval. Then this warning message goes out of effect and falls into the category of "false warnings" for the driver. And when that traffic event really happens, the driver would complain that he/she is not even

warned at all; there is hardly any interface operator who would associate an impending traffic event with a warning message displayed 1 minute ago. However a possible solution is that the impending event distance to the vehicle could be displayed in a regularly-updated way to remind the drivers.

To make things even worse, once the false alarm rate of a warning signal rises up, drivers tend to perceive it as a disturbance and become to ignore it (see the works of Chambrin [56] and Spence and Ho [19]). This distrust of a certain warning signal would soon get spread into other different warning signals and even the whole warning system, and drivers would try to switch the warning system off [27].

One might ask, can we set a proper upper bound for the advance time of a warning signal? In the comprehensive report about warning displays written by Spence et al. [19], they had mentioned such timing issues and set the maximum advance warning time to be 800 ms before the lower bound of the advance warning time. As our lower bound is set to be 1900 ms, the upper bound here is 2700 ms, see Fig 3.1.
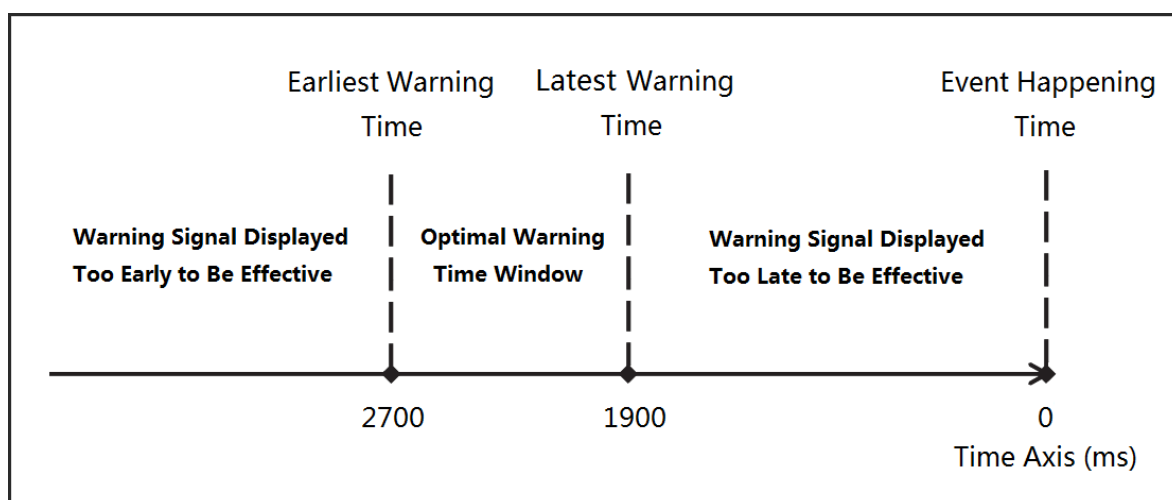
Figure 3.1.: Warning time settings illustration

A warning signal displayed within 1900 ms will leave too short time for the driver and the device to response and a warning signal displayed over 2700 ms will be perceived to be false and therefore also becomes ineffective. Pay attention that this conclusion is only valid for the emergent traffic events, but not suitable for non-emergent ones.

Once the displaying time of the warning signal falls into the optimal warning time window, a larger value could be more beneficial, generally. McGehee et al. [57] carried out a driving simulator experiment aiming at assessing the effectiveness of displaying warning signals to prevent an impending collision event in 2002, and in their study they had concluded that an earlier warning signal could actually improve the drivers' response performance (judging from the response time)

compared to a late one. For instance, 2700 ms would be better than 1900 ms here, according to this theory (see Fig 3.1).

Chapter 4.

Visual Driver Warning Display Design Guidelines

Visual vehicle instrumentation has always been developed by engineers coping with some industrial designers for a long time. However, for the current IVIS systems, the traditional roles played by the industrial designers tend to replace by computer programmers, who are often uninitiated to ergonomics and human factor design principles [12]. The purpose of this chapter is to provide an insight of the design guidelines for driver warning systems applied in modern vehicles from computer programmers' view.

To begin with, the necessity of visual driver warning display design guidelines should not be ignored. Plenty of researchers have revealed the alerting effectiveness of driver warning displays (e.g. Ho et al. [37]), but the fundamental prerequisite is: the warning displays need to be properly designed. A properly designed warning display indicates its Human Machine Interface (HMI) sticks to basic human factor design guidelines. On the contrary, an improper GUI may add extra visual burden to the interface operators and distract their attention and increase the accident risk instead [7].

However, notice we are not attempting to complete a thorough series of design requirements nor draft a set of design standards, but we intent to provide some useful and practical references during the warning system designing phase (those guidelines have been adopted for the design of the demo of our testing tool for driver warning). The design goal is that the driver warning system is effective and easy to handle by the interface operators. For instance, the driver warning display should avoid distracting the drivers from concentrating on their driving, and the participants of our driver warning evaluation application should be able to start the testing immediately, without any further instruction or referring to some manual. The principles discussed in this chapter are largely based on the work done by Green et al. in their technical report about suggested human factors design guidelines for driver Information systems [12].

4.1. General Guidelines

Guideline 1: Omit all dispensable information

Make the interface operators (drives here) focus on what is truly essential and minimize the information quantity presented, therefore decreasing the information distraction side effects to the minimum. For instance, in the so called black panel technology (Fig 4.1) from BMW, drivers are barely presented with a matte and black surface while driving. Only a few and requested details, like the scale markings on the dials, are kept visible. The instruments, limited to those selected by the driver or relevant to his current needs will appear.

Figure 4.1.: An illustration of black panel technology from BMW: only the selected or driving related information is shown and unnecessary information is hiden. [1]

The reduction of the to-be-read information will shrink the time period the drivers spend on reading it, thus help keeping the operators' eyes on the road. A basic concept is that drivers cannot, nor should they read some long and comprehensive paragraphs which contain detailed descriptions while driving. With respect to the content of a certain message, an essential consideration is some information could stay hidden.

More information appearing in the screen steps up the reading time not only because of a larger information load; as the screen space is limited, the size of both text fonts and relating images need to be shrunk to make room for the excessive information, which further weakens the reading legibility. A related example is a speedometer reading research carried out by Galer et al. [58]. They have demonstrated that drivers spent twice or even more time in reading a numeric speedometer when compared with an analog one. If both are presented, the time spent in reading is the longest, due to the information clutter. On the whole, an elaborated driver warning display system will

---

[1] http://www.bmw.com/com/en/insights/technology/technology_guide/articles/black_panel_technology.html

avoid information redundancy.

Guideline 2: Try keeping critical information close to the line of sight

Research has concluded that drivers need to move their heads to look at an object which is more than 30 degrees from the current in-sight center point [59]. When a driver implements a head movement and stares at the information display, his attention has already shifted from the road, which is undesirable for safety concerns. In short, information displayed closer to the line of sight means a less disturbing information obtaining process.

Current trend is to put all the critical information on the head-up display system, as it is more than close to, but coincide with the driver's line of sight. One might cast the doubt that whether the head-up display would introduce a new way of driving distraction by obscuring the road scene, so the layout of the information provided by the head-up display system should be carefully designed. Fig 4.2 illustrates such an elaborated design: the navigation information displayed by the head-up display system in a BMW integrates naturally with the actual road scene. An easy-to-read and high-contrast image is projected onto the windscreen, and this system is stated to reduce the time it takes for eyes to shift focus from road to the instruments mounted somewhere else by half[2].

Figure 4.2.: Head-up display: provides information at the same direction with the line of sight[3]

---

[2] http://www.bmw.com/com/en/insights/technology/technology_guide/articles/head_up_display.html
[3] http://www.bimmertoday.de/2011/10/10/video-das-bmw-head-up-display-mit-augmented-reality-im-simulator/p90083051-9

Another practical instance comes from where the navigation information should be put, given there is no head-up display system in the vehicle at all (which is an usual case). As the navigation display is frequently used while driving, placing it in a low position of the center console violates the rule of staying close to the line of sight. A comparatively top position like where the infotainment system is put would be a reasonable choice [12].

4.2. Font Legibility and Readability Guidelines

Font legibility and readability are essential elements in a successful visual driver warning display design. Font legibility is more concerned with how easily the individual letters could be distinguished, while font readability emphasizes on the ease with which the interface operators could go through the titles and paragraphs in the screen. Generally speaking, font legibility depends more on the chosen typeface, and font readability is closely associated with the way how the font is manipulated or handled.

Guideline 3 Adopt plain typefaces

In their report on alphanumeric character legibilities, Cornog and Rose [60] had illustrated the impact generated by modern typefaces on the information legibility is less than the internal properties of the font, like size and contrast.

However, the choice of the typefaces still makes a difference in the information legibility. There is already research [61] stating that those plain typefaces like Arial and Verdana are more legible than decorative ones, say Curlz, see Fig 4.3.

Figure 4.3.: Illustrations of a plain typeface named "Verdana" (the upper one) and a decorative typeface named "Curlz": the plain typeface is more easier to be recognized by the interface operators, comparing with the decorative typeface.

Guideline 4 Be careful when use all capital letters

Lowercase letters come with better readability, not only just because they appear more frequently than the capital ones, but they also ease the reading process by having recognizable shapes[4]. On the contrary, the shapes of capital letters are less distinctive; say they all share a same height. See a comparison in Fig 4.4.
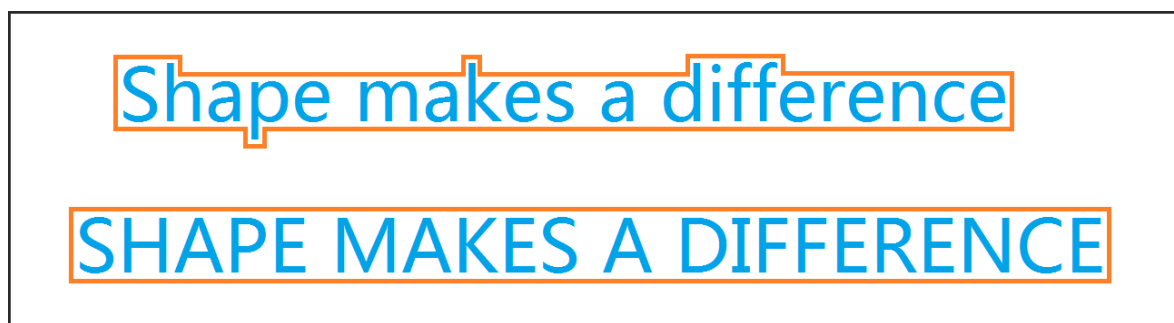
Figure 4.4.: Word shapes make a difference in the readability: all capital letters are less distinctive as their shapes are similar, thus weakening the readability. By contrast, the recognizable shapes of lowercase letters enhance the readability.

Research [12] has suggested that the typeface layout of the in-vehicle display is preferred to be similar with the external one (a highway warning sign) by the drivers, and it could be the case that the message on the external sign is written in capitals. Under such scenarios, the typeface of the in-vehicle display should be modified to be compatible with the external display [12]. To sum up, the prudently usage of all capital letters is worth designers' attention: though they serve better in capturing the drivers' attentions due to the starkness, all capital letters reduce the information readability. The trade-off between eye-catching and easy-to-comprehend should be carefully balanced.

Guideline 5: Provide ample line spacing

Line spacing serves as a guideline to the next line and proper line space settings help promoting readability. If the spacing is too tight, the functionality of guidelines is weakened and may lead to an undesirable result: interface operators tend to skip lines as they find it difficult to locate the next line. Moreover, the type also appears to be dark and less inviting, which further degenerate the readability. In comparison, if the spacing is too loose, it will distract the interface operators' attention and add unnecessary space redundancy to the screen.

A reference value for the line spacing is no less than 0.64 mm [12]. A concept named height to stroke-width ratio had been proposed, and for plain fonts like Verdana it is set to be 10 : 1. So in order to be readily discriminated, the minimum line spacing should not be more than 10 times

---

[4]http://www.mightyfinegraphics.com/cg/typography.html

smaller than the font height, see Fig 4.5. As the minimum font height is 6.4 mm, the minimum line spacing is 0.64 mm.
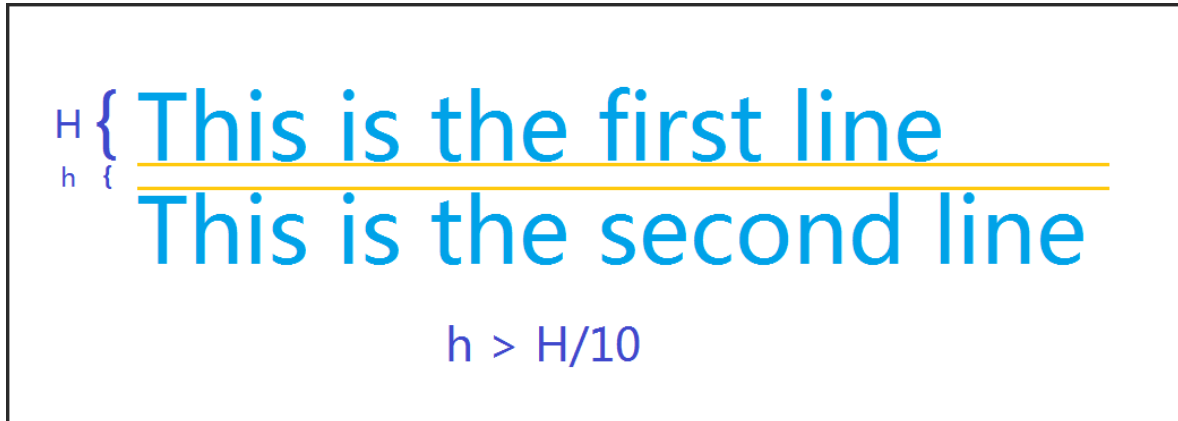
Figure 4.5.: The font height should not exceed 10 times larger than the line spacing to guarantee readability.

4.3. Color and Luminance Design Guideline

Guideline 6: Use discriminable color matches

A general principle regarding color issues in the user interface design is to use discriminable color matches (more details see the work of Silverstein and Merrifield [62]). Discrimination is generated from strong contrast between the background color and the font color. By way of illustration, use fonts of light-color on a dark background, see Fig 4.6.

Though dark fonts on a light-color background generate a high contrast as well, it is less wanted. This comes from another guiding principle in in-vehicle display design: to minimize glare (Paul Green et al. [12]). As there are more pixels used for the background than the text, assigning a dark color to the background will reduce the luminous output, therefore cutting down the screen glare. The worst reading situation for liquid crystal display occurs when the external light becomes strong, especially the bright sunlight, and the display content is hard to recognize; a darker background also helps to relieve the external light interfering problem (Fig 4.6).

4.4. General Legibility Guidelines

Guideline 7: Use plain works to warn the drivers

---

[5]http://www.caricos.com/cars/b/bmw/2013_bmw_7-series/1280x960/99.html

Figure 4.6.: The transflexive LCD from BMW: the background has been set to be black and high-contrast light colors like white, yellow and red have been applied to display information[5].

The most pivotal purpose of driver warning messages are to make the drivers aware of an impending driving event within a certain time limit while giving the proper event priority, instead of getting the drivers confused and failing to deliver the needed information.

In a research conducted by Williams, Hoekstra and Green, they have confirmed that there are quite a few warning messages which are poorly known by the drivers [63]. To illustrate, few drivers comprehend the meaning of the warning message "Electrical fault in unit 3470, no current at power up" and change it to "Tire pressure sensor malfunction" would make more sense to the drivers.

Another counter example discussed in the report of Green et al. [12] shows car manufactures may go too far in exhibiting their expertise. The SRS warning, an abbreviation of Supplemental Restraint System is commonly seen in the warning messages and many drivers might not be able to understand it. In effect, the "supplemental restraint system" only means one thing: the air bag. To sum up, designers should avoid using technical terms or perplexing abbreviations in the warning messages and plain words are always a better choice.

Guideline 8: Adopt international symbols as a supplement

There has been research proving that a proper combination of both symbols and words perform best in delivering the wanted information, instead of only using one of them [64]. In the report from Green et al. [12], they stated that a certain symbol could be seen at double the distance (or be half the size) compared to its counterpart, an alternative text label when given similar lighting

conditions.

However, it is necessary to note the symbols should comply with universal standards, say the International Standards Organization (ISO) standard 39001 about road traffic safety management[6] to make sure they could be understood by the majority, see Fig 4.7. In short, a set of traffic warning symbols obeying the ISO standard need to be detectable, durable and comprehensible[7].
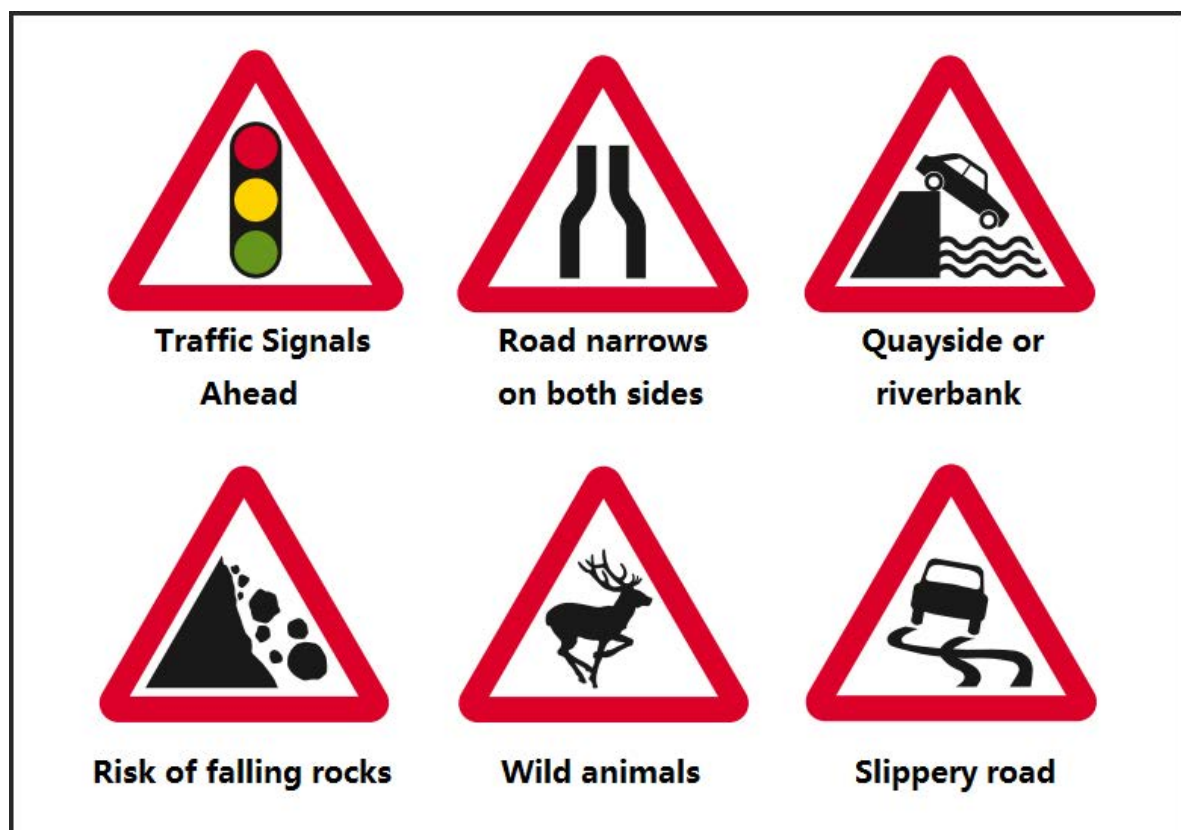
Figure 4.7.: An illustration of some standard traffic symbols[8]

---

[6] http://www.bsigroup.com/en-GB/iso-39001-road-traffic-safety/
[7] http://www.safetysign.us/my_weblog/iso-standards/
[8] https://www.gov.uk/traffic-signs

Chapter 5.

Evaluation Tool Implementation

This chapter elaborates on how the automotive warning screen evaluation tool is developed and how to operate the evaluation tool. The software development environment is introduced in Section 5.1 and the designed functions and application requirements to be implemented are specified in Section 5.2. Section 5.3 portrays the evaluation block diagram. The final part of this chapter, Section 5.4, gives detailed tutorials of the evaluation tool.

5.1. Evaluation Tool Development Environment

The evaluation tool is written in the object-oriented programming language Java. The following software tools are adopted during the developing process to present the final executable software product:

1. Java Development Kit (JDK) from Java Standard Edition (SE) 7u25: Java Platform, Standard Edition enables the developers to develop and deploy Java applications on desktops as well as servers. The JDK includes a complete Java Runtime Environment (JRE) plus tools for developing, debugging, and monitoring Java applications[1].

2. Eclipse Standard 4.3: Eclipse is a multi-language Integrated Development Environment (IDE), which consists of a base workspace and an extensible plug-in system to customize the environment[2].

3. EditPlus: EditPlus is a text editor, HTML/XML editor, PHP editor and Java editor for Windows[3].

4. SoSci Survey: SoSci Survey web service is a professional tool for generating online surveys[4].

Additionally the following three external Java libraries have been used:

---

[1] http://www.oracle.com/technetwork/java/javase/downloads/index.html
[2] http://www.eclipse.org/downloads/
[3] http://www.editplus.com/download.html
[4] https://www.soscisurvey.de/index.php?page=home&l=eng

1. CookSwing: A library which builds Java Swing GUI from XML documents[5].

2. NativeSwing: A library which allows an easy integration of the native components into Swing applications, and other native utilities to enhance the API of Swing could also be provided[6].

3. Json-simple: A library which serves as a simple Java toolkit for JSON and allows JSON text encoding and decoding[7].

The complete development environment was done on the operating system Windows 7 Ultimate, 64 bit.

5.2. Application Requirements and Designed Functions

The fundamental purpose of the evaluation tool is to evaluate the driver warning screens adopted in the Android application *DriveAssist*, see an sample warning screen used in *DriveAssist* in Fig 5.1.
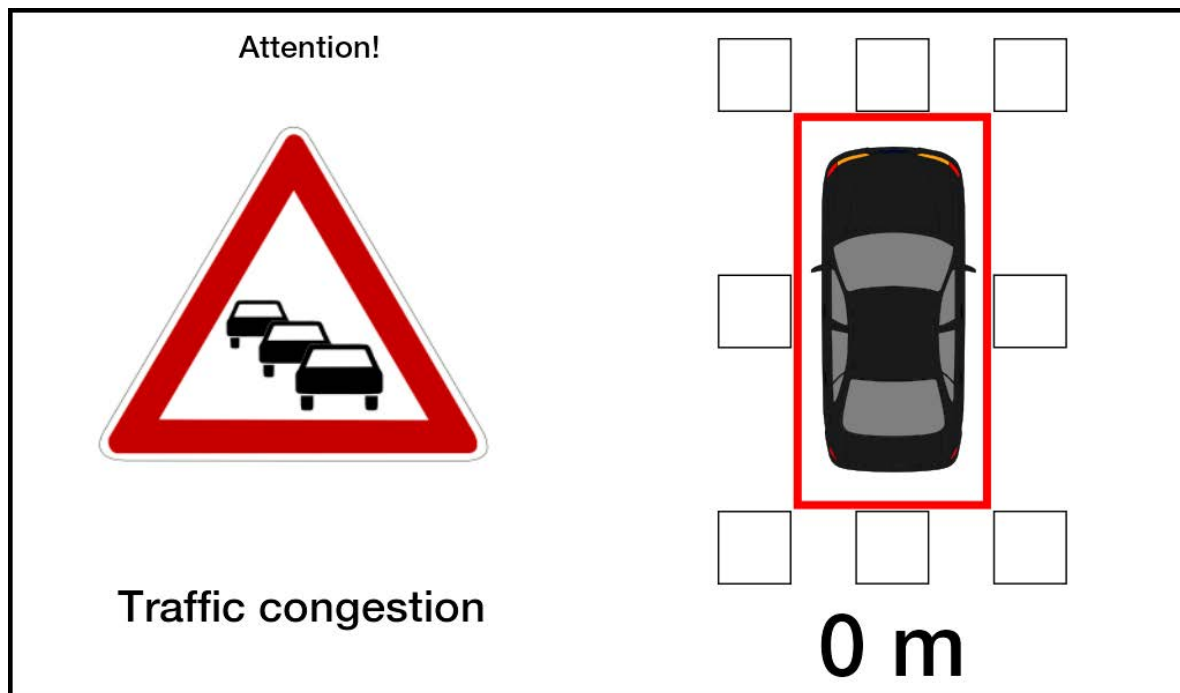
Figure 5.1.: A sample warning screen activated by *DriveAssist* [4]

For this purpose, the following applications requirements are raised:

---

[5]http://cookxml.yuanheng.org/cookswing/index.html
[6]http://djproject.sourceforge.net/ns/
[7]https://code.google.com/p/json-simple/

1. The structure and contents of the evaluation tool GUI shall be configurable by the evaluator without modifying the Java source code.

2. The evaluation process shall be remotely controllable.

3. The warning screen to be displayed shall be arbitrarily choosable.

4. The warning screen shall be dynamically updated.

5. The evaluation tool shall provide an evaluation module.

The previous requirements are implemented through the following designed functions, respectively:

1. The layout of the evaluation tool GUI is not specified directly though Java AWT/Swing, but in XML files. The XML files describe how the evaluation GUI looks like and evaluators modify the GUI by defining their own XML files.

2. The evaluation program consists of a client side and a server side. The client side is handled by the evaluator and is capable of sending JSON-format information. The server side receives the JSON data sent by the client and responds correspondingly.

3. The warning screen is displayed at the server side and it is written in HTML/CSS (i.e. it is a webpage). The default warning screen to be displayed once the evaluation begins is specified in the XML file which describes the GUI layout, and further modifications are possible through the operation at the client side.

4. In order to dynamically update the warning screen, a set of JavaScript methods need to be pre-defined in the HTML file which describes the warning screen. The server side will call those methods to change the displayed information.

5. There is an entry towards a questionnaire in the evaluation tool GUI, once the warning screen displaying process is done. The questionnaire result is saved online for later analysis.

5.3. Evaluation Tool Block Diagram

Given what has been stated in the previous section, the block diagram for the evaluation tool is shown in Fig 5.2.

Once the server side is initiated, it reads the XML file which defines the GUI layout to generate the GUI through Java Swing. A default warning screen is ready to show via reading the HTML file which describes the warning screen.

New warning screens could be specified arbitrarily through the client side. The client sends some JSON data indicating the wanted traffic event, as well as the latest value of the approaching distance and the approaching angle. The server side calls the JavaScript methods defined in the
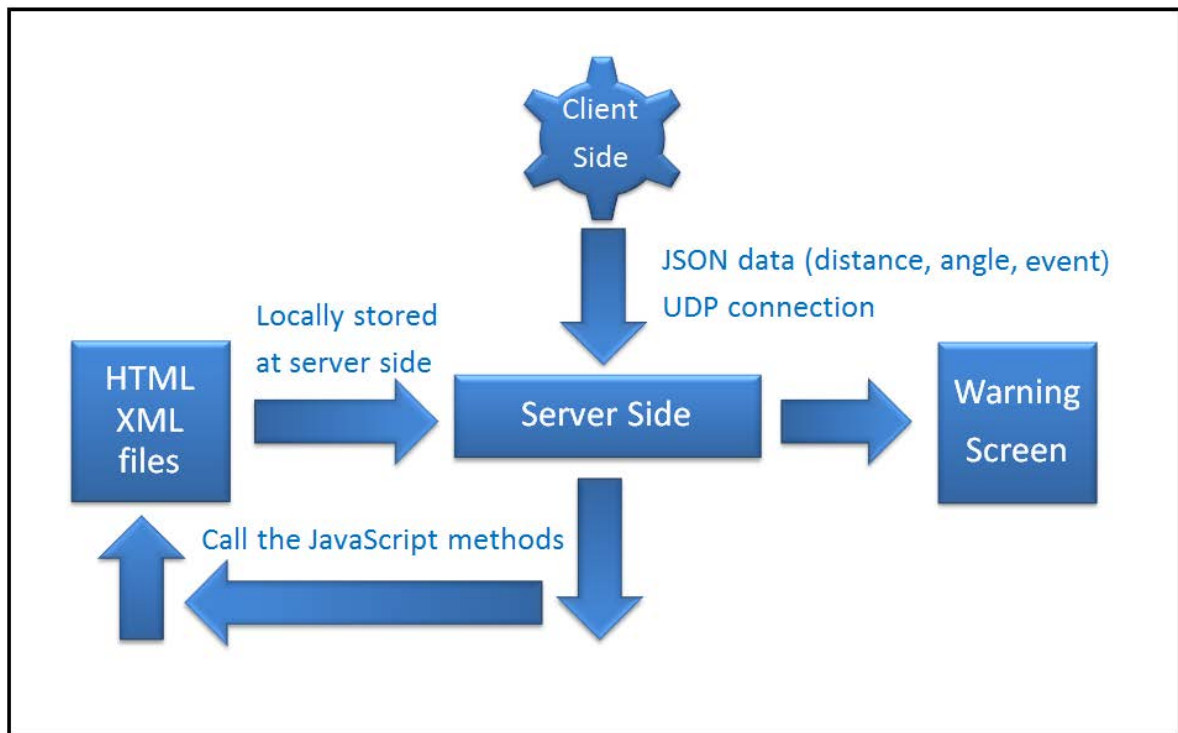
Figure 5.2.: Evaluation tool block diagram

HTML file to generate the final warning screen presented to the evaluation participants after receiving the JSON data.

5.4. Evaluation Tool Tutorials

The evaluation tool consists of a server side (Fig 5.3) and a client side (Fig 5.4).

5.4.1. Server Side

Server GUI Layout Defined by XML

The layout of the server side GUI is fully customizable to present a higher degree of design freedom. It is written in a XML document defined by the evaluator and the evaluation tool will build Java Swing GUI from the XML document.

Three sample layouts have been given, and the sample layout shown in Fig 5.5 contains three warning test & questionnaire combinations.

The sample XML document is written as a template and allows a simple construction of one warning test & questionnaire combination up to six. If the evaluator seeks for more, a totally different
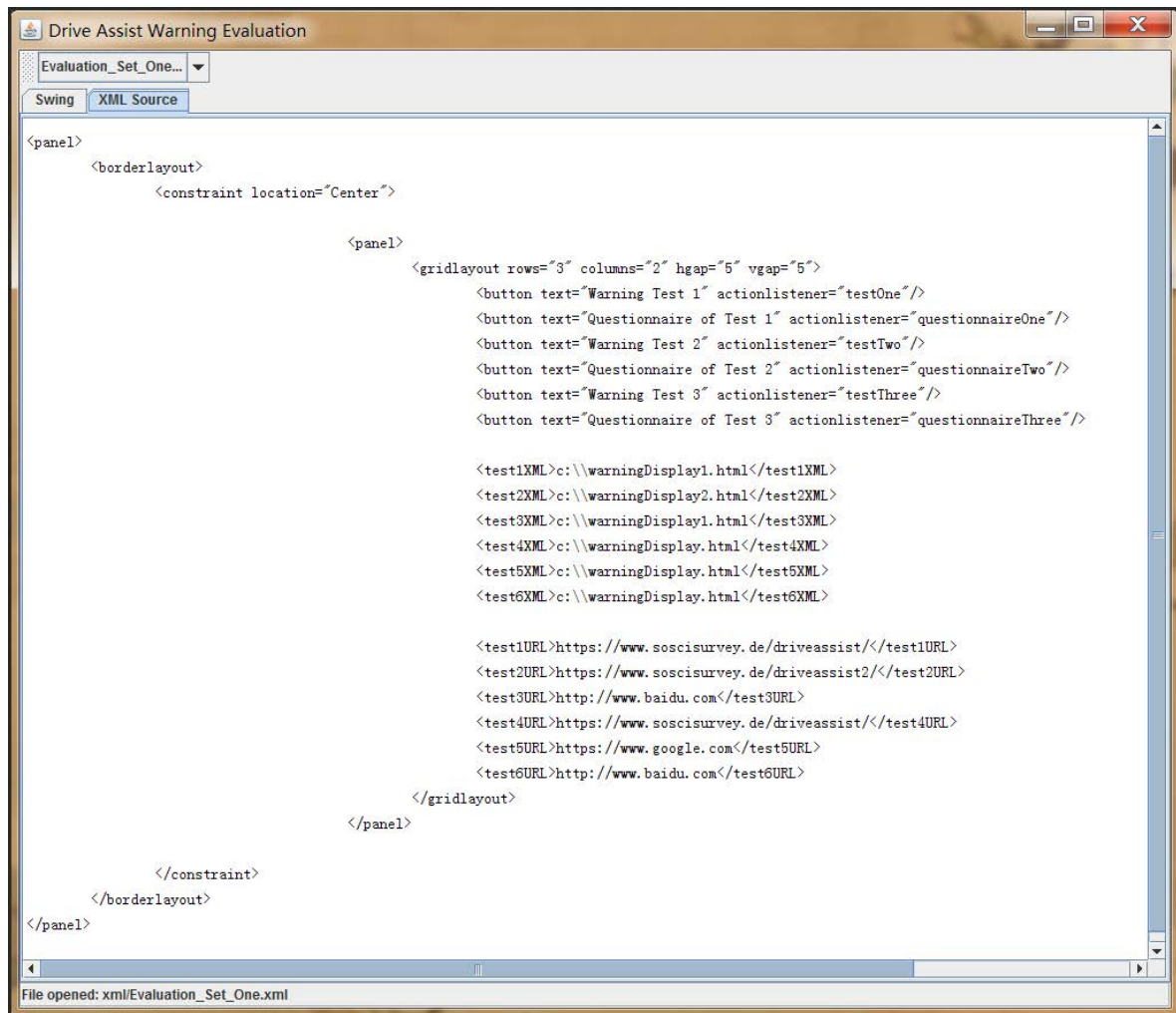
Figure 5.3.: Evaluation tool server side illustration: the pre-defined XML file describing the structure and content of the server side GUI.
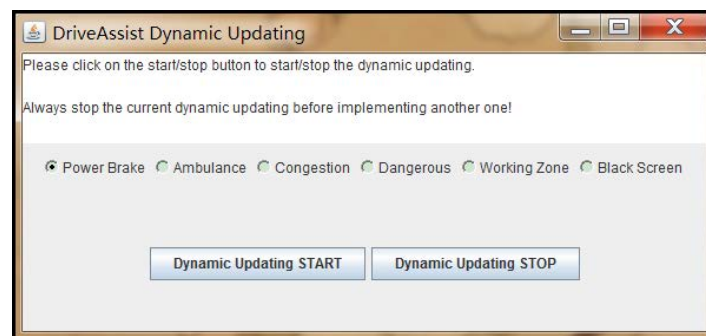
Figure 5.4.: Evaluation tool client side illustration: evaluators specify the warning screen to be displayed by selecting the corresponding traffic event.
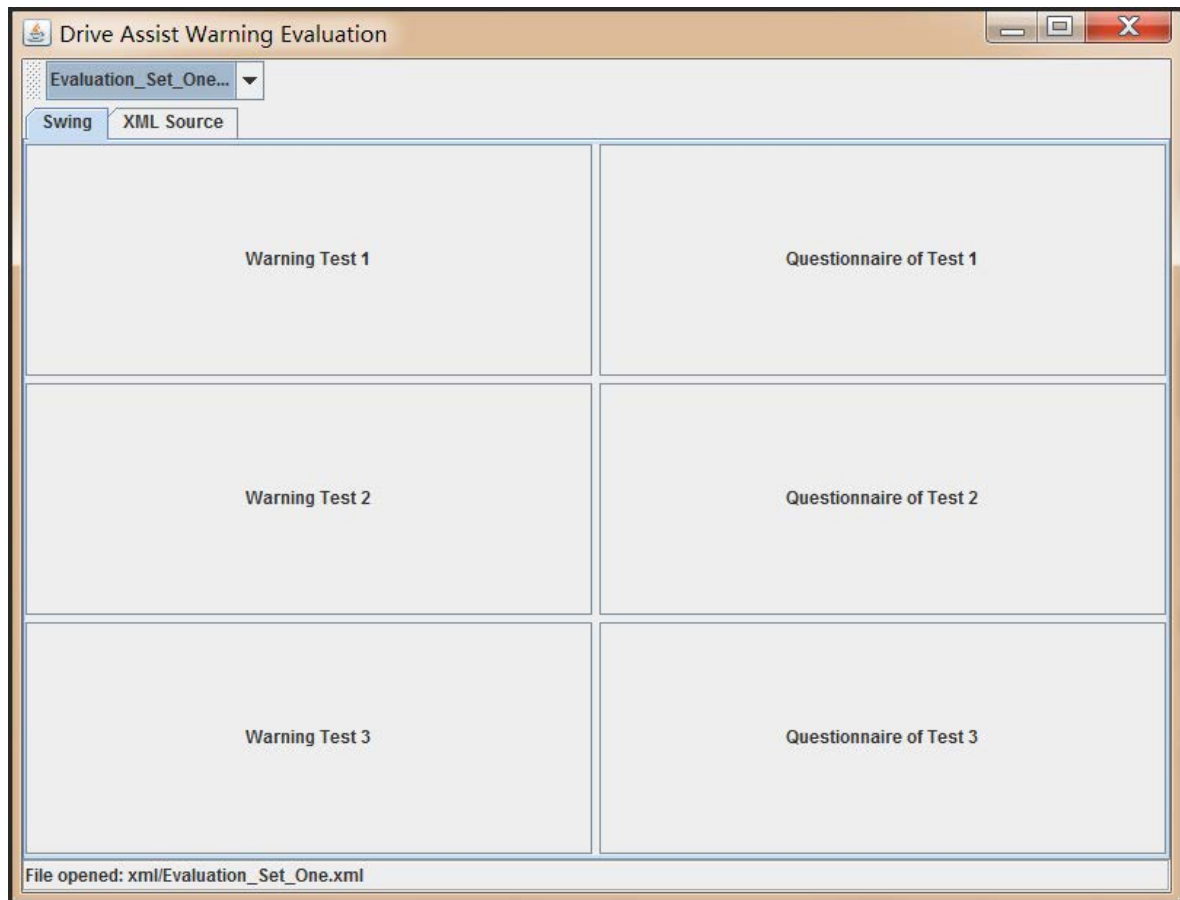
Figure 5.5.: Default sample layout containing three warning test sets of the evaluation tool

layout design is also possible as CookSwing provides configurations of all Swing components and layout managers, following the GUI design tutorial of CookSwing[8].

Warning Screen Defined by HTML

By clicking on one of the warning test buttons, the corresponding warning screen will be displayed. As has been stated in the previous section, the warning screen is defined through HTML. The evaluation tool provides two built-in sample warning screens differing in layout and color setting for demonstration, see Fig 5.6 and Fig 5.7. Notice the design of the sample warning screens resembles the warning screen used in *DriveAssist* [4], see Fig 2.10.

Both warning screen samples consist of four functional areas:

1. The title area: displays the title of the traffic event.

2. The traffic event position area: displays the relative position the event to the vehicle.

---

[8]http://cookxml.yuanheng.org/cookswing/tutorial_gui.html

Figure 5.6.: Built-in sample warning screen one
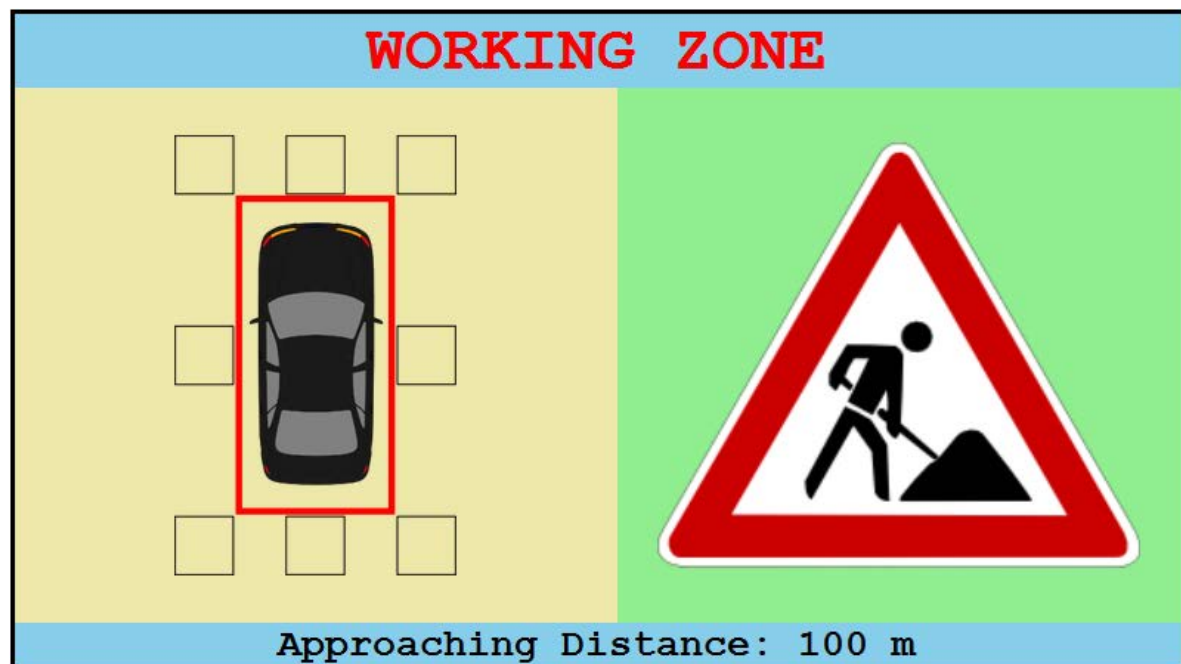
Figure 5.7.: Built-in sample warning screen two

3. The traffic event image area: displays the image associated with the traffic event. A traffic sign complying with the ISO standard 39001 is used.

4. The footer area: displays the distance between the event. The vehicle using the latest updated data.

In order to exhibit the dynamic warning screen updating property, it is requested that the HTML file contains the corresponding updating functions written in JavaScript. For instance, for the given sample warning screens, contents in the following areas could all be changed: the title area, the traffic event image/information area as well as the footer area. Consequently, the following functions are to be implemented:

- *updateTitle(String name)*
  Modify the title of the warning screen according to the input variable *name*.

- *updateEvent(String source)*
  Modify the traffic event image according to the address (in a form of absolute-path) provided by the input variable *source*.

- *updateDistance(String distance)*
  Modify the distance information according to the input variable *distance*.

- *updateDirection(String direction)*
  Modify the direction information according to the input variable *direction*.

Consider the warning screen should be visible only when it is triggered, there is an additional function named blackScreen(), which will make the warning screen invisible upon triggering:

- *blackScreen()*
  Set the warning screen to be invisible.

Notice evaluators need to write up the HTML documents for their own warning screen design and implement proper updating functions depending on the specific design, resembling what has been done in the demonstration warning screens.

SoSci survey Questionnaire

By clicking on one of the questionnaire buttons, a questionnaire webpage will be shown (Fig 5.8). This webpage leads directly to a survey generated by the *SoSci* survey. Consider the *DriveAssist* is an Android-based application where the area of the displaying screen is limited (e.g. a smart phone screen), the questionnaire webpage has been integrated into a Java Swing frame to control its size by using the NativeSwing library.

Other online survey tools catering to the evaluators' needs could be used as well and the URL is located in the layout XML document.

Figure 5.8.: SoSci survey Questionnaire Illustration

5.4.2. Client Side

The client side is in charge of sending JSON-format updating information to the server side. The JSON-format data used in the evaluation tool is in the following form, containing information about the traffic event, the value of the approaching distance and the code representing the relative direction:

"event": "Working Zone", "distance": 1000, "direction": 1

"Working Zone" is of the type *String* while 1000 and 1 are of the type *int*. The sequence of the name/value pairs does not make a difference. Five different traffic events have been provided for

a demonstration and further modifications are up to the evaluators' requirements.

Chapter 6.

Driving Simulator-based Evaluation

This chapter describes how the evaluation tool is evaluated through a driving simulator-based driving test. The design and procedures of the test are described and the test results are recorded and analyzed in the following sections.

6.1. Driving simulator Test Environment and Setup

The following software-based driving simulator is used:

- *OpenDS*: It is a free and open-source driving simulator for automotive industry or scientific studies research/developement. It has already provided some pre-defined driving tasks and we select one of them to perform our driver warning screen evaluation test[1].

The following force feedback steering wheel is used:

- *Logitech Driving Force GT*: It is a racing wheel peripheral designed for racing games with 900-degree rotation, force feedback and race-ready materials[2].

The combination of *OpenDS*, a desk PC and *Logitech Driving Force GT* forms a compact simulating environment for driving. The driver warning screen is displayed in an additional monitor and the complete built-up testing set is shown in Fig 6.1.

6.2. Participant profiles

8 participants were invited to join in the driving simulator-based driving test. The age as well as the gender information are depicted in Table 6.1. Among the 8 participants 6 never attended such driving test before, and the rest two had some experience in similar driving simulator-based tests.

---

[1]http://www.opends.eu/
[2]http://gaming.logitech.com/en-us/product/driving-force-gt-gaming-wheel

Figure 6.1.: An illustration of the driving simulator system plus an additional warning screen

Table 6.1.: Age & gender information of the participants

Age	24	24	24	25	25	25	27	28
Gender	Female	Male	Male	Male	Male	Male	Male	Male

6.3. Experimental Design & Procedures

The experiment was conducted using the driving-simulator equipment mentioned previously. All the participants followed the same instructions (see Appendix) and were provided with the same testing procedures. Before the actual test, all the participants were allocated with a short time-period of practice drive to get familiar with the driving simulator. The test-driving scenario chosen from *OpenDS* is the so-called *idealtest2*, in which an ideal driving-situation is provided: the car driven by the participant is the only vehicle in a street system (see Fig 6.2). The participants were asked to try to behave like in a real driving situation. They need to obey the traffic lights and the maximum driving speed should not exceed 60 km/h. Additionally, they should follow the route indicated by a blue ideal line (see Fig 6.2).

The experimental session consists of two experimental trials, each designed to evaluate a different warning screen design. In the first experiment trail, 5 traffic event warnings corresponding to the

Figure 6.2.: An illustration of the driving scenario *idealtest2*: the participants were presented with a first person driving scenario where the vehicle controlled by the participants was the only vehicle in it. The blue line indicates the driving route.

first warning screen design (see a sample at Fig 5.6) were shown, namely Electronic Emergency Brake Lights, Approaching Emergency Vehicle Warning, Traffic Jam Ahead Warning, Hazardous Location Notification and Working Area Warning. Each warning screen lasted for 6 seconds. Note those warning screens were remotely controlled by the evaluator in a different machine, using the client side. Once a certain warning screen disappeared, the participants were asked to stop driving and received a tiny interview about the warning screen just shown. The participants needed to recall and describe the details of the warning screen by answering the following questions:

- What was the traffic event you just saw? Please describe it briefly.

- Have you noticed the relative position of the traffic event represented by a red dot? If yes, where is it?

- Have you noticed the approaching distance? If yes, what is it?

After all warning screens had been shown, participants were asked to implement an on-line questionnaire regarding the design of the first warning screen, using the online questionnaire function provided at the server side. The second experiment trail was an exact copy of the first one speaking of the procedures, and the only difference was that the warning screens illustrated followed a different interface design (see a sample at Fig 5.7). Finally a third online questionnaire aiming at the comparison of the two warning designs was presented to the participants. After the whole

experiment, participants were invited to a free discussion and they could express their feelings and opinions about the warning screens.

6.4. Experiment Results & Conclusions

6.4.1. Interview Data Collection & Analysis

In the first experimental trial to evaluate the first warning screen design, participants needed to answer the three questions aforementioned for each warning screen. The final results have been summarized in Table 6.2.

	EEBL	Ambulance Approaching	Traffic Jam	Hazardous location	Working Area
Q1	8/8	8/8	8/8	8/8	8/8
Q2	5/8	7/8	8/8	7/8	8/8
Q3	3/8	6/8	7/8	6/8	7/8

Table 6.2.: Interview results summarization for warning screen design one: Q1, Q2 and Q3 correspond to the traffic event, the relative position and the approaching distance, respectively. EEBL is short for Electronic Emergency Brake Lights. The data contained in the cell reflects how many people answered the corresponding question correctly with regard to a certain event. For instance, the cell value "8/8" in row Q1 and column EEBL indicates that all the 8 participants understood the traffic event Electronic Emergency Brake Lights.

From the table we can see that all participants gave the correct answers for the first question regarding the depicted traffic events. For the second question, their performance is a little bit awkward, see only 5 participants were able to tell the relative position of the first traffic event. A trend is, as they witnessed more warning screens and got familiar with the layout of the information areas, participants tended to show better performance of position recognition. Participants performed the worst in the third question about the approaching distance. This could be well explained by the position and the size of the distance information, as it is put in the foot area and has a relatively small font size. Anyway as participants saw more warning screens and learned what they need to focus on by the interview questions, their performances were getting better gradually.

Similarly the statistics collection of experimental trial 2 is summarized in Table 6.3. As can be observed, the general situation reflected in Table 6.3 is better than in Table 6.2. In short, there are two reasons accounting for it: more participants are in favor of warning screen design two (statistics shown in the later section), and they had been fully aware of all the questions after the first experimental trial.

	EEBL	Ambulance Approaching	Traffic Jam	Hazardous location	Working Area
Q1	8/8	8/8	8/8	8/8	8/8
Q2	8/8	8/8	7/8	8/8	8/8
Q3	7/8	7/8	6/8	7/8	8/8

Table 6.3.: Interview results summarization for warning screen design two: Q1, Q2 and Q3 correspond to the traffic event, the relative position and the approaching distance, respectively. EEBL is short for Electronic Emergency Brake Lights.

6.4.2. Data Collections & Analysis

The First Warning Screen Design

Results of the first questionnaire about warning screen design one are summarized in Table 6.4.

	Statement	TD	D	U	A	TA
1	The layout of the warning screen is organized.	0/8	1/8	1/8	6/8	0/8
2	The background colors look comfortable.	0/8	1/8	3/8	3/8	1/8
3	The font used in the warning screen is easy to read.	0/8	0/8	1/8	4/8	3/8
4	The font size of the warning title is large enough.	0/8	0/8	0/8	3/8	5/8
5	The font size of the approaching distance is large enough.	2/8	5/8	1/8	0/8	0/8
6	The traffic symbols shown fit to the warning titles.	0/8	0/8	2/8	4/8	2/8
7	The direction indication of the traffic event is helpful.	0/8	0/8	3/8	2/8	3/8
8	There are too many elements at the warning screen.	2/8	4/8	2/8	0/8	0/8
9	I quickly understood the warnings shown to me.	0/8	0/8	0/8	7/8	1/8

Table 6.4.: Result summarization: questionnaire of the first warning screen design. Statements are rated from "Totally disagree" (TD), "Disagree" (D), "Undecided" (U), "Agree" (A) to "Totally agree" (TA). The number in the cell indicates how many participants choose this option. For instance, for the first statement "The layout of the warning screen is organized", 6 participants choose the option "Agree" (A).

Several observations based on the questionnaire results:

- Generally, warning screen design one is perceived to be organized in the layout.

- It is divided whether the background colors of design one look comfortable.

- The font used in the warning screen is easy to read.

- The font size of the warning title is large enough and the font size of the approaching distance is too small.

- Generally the traffic symbols shown fit to the warning titles.

- Generally the direction indication of the traffic event is helpful.

- Generally the warning screen design does not create heavy information burden to the participants.

- All participants understood the warnings quickly.

The Second Warning Screen Design

Results of the second questionnaire about warning screen design two are summarized in Table 6.5.

	Statement	TD	D	U	A	TA
1	The layout of the warning screen is organized:	0/8	1/8	0/8	6/8	1/8
2	The background colors look comfortable:	0/8	1/8	1/8	5/8	1/8
3	The font used in the warning screen is easy to read:	0/8	0/8	1/8	4/8	3/8
4	The font size of the warning title is large enough:	0/8	0/8	0/8	3/8	5/8
5	The font size of the approaching distance is large enough:	2/8	5/8	1/8	0/8	0/8
6	The traffic symbols shown fit to the warning titles:	0/8	0/8	2/8	4/8	2/8
7	The direction indication of the traffic event is helpful:	0/8	0/8	3/8	2/8	3/8
8	There are too many elements at the warning screen:	2/8	4/8	2/8	0/8	0/8
9	I quickly understood the warnings shown to me:	0/8	0/8	0/8	5/8	3/8

Table 6.5.: Result summarization: questionnaire of the second warning screen design. Statements are rated from "Totally disagree" (TD), "Disagree" (D), "Undecided" (U), "Agree" (A) to "Totally agree" (TA).

Several observations based on the questionnaire results:

- Generally, warning screen design one is perceived to be organized in the layout.

- Generally, the background colors of design two look comfortable.

- The font used in the warning screen is easy to read.

- The font size of the warning title is large enough and the font size of the approaching distance is too small.

- Generally, the traffic symbols shown fit to the warning titles.

- Generally, the direction indication of the traffic event is helpful.

- Generally, the warning screen design does not create heavy information burden to the participants.

- All participants understood the warnings quickly.

The Comparison of the two designs

Results of the third questionnaire of the two different warning screen designs comparison are summarized in Table 6.6.

	Statement	S1	S2	U
1	Which screen is easier to comprehend?	1/8	5/8	2/8
2	Which screen is more graphically attractive?	2/8	4/8	2/8
3	Which screen makes you better warned?	1/8	3/8	4/8
4	Which screen has a better font?	3/8	5/8	0/8
5	Which screen has a better arrangement of the elements?	2/8	2/8	4/8
6	Generally, which screen would you prefer?	2/8	6/8	0/8

Table 6.6.: Result summarization: questionnaire of the two warning screen designs comparison. S1 is warning screen design 1, S2 is warning screen design 2 and U means "Undecided". For instance, for the first question "Which screen is easier to comprehend?", 5 participants choose screen design 2.

Some conclusions could be drawn from the questionnaire results, combining with the explanations and options of the participants:

- Expel those undecided ones, more participants perceived design two to be easier to comprehend. In the free discussions many participants expressed this was influenced by the position of the traffic symbol image. One participant mentioned her reading habit (reading from left to right) mattered in the warning screen reading process. In the first warning screen design, the traffic symbol indicating the traffic event is put at the left side, therefore she was quicker in recognizing the traffic event. This is why she thought design one is easier to comprehend. Other participants saw it in a different way: in the second design the traffic symbols were put in a position closer to their line of sight, therefore they responded quicker. Consider in the right-hand drive countries the warning screens are more likely to be located at the right side, putting the traffic symbol at the left side of the screen would be the best choice: it is both close the drivers' line of sight and it fits to the reading habit of human beings. For the left-hand drive countries like UK, there seems to be a trade-off between these two factors.

- Speaking of the graphical attractiveness, most participants talked about the difference in the background colors. Half participants liked the light green color adopted in design two (4 of 8), with the remaining half divided by 2 undecided and 2 in favor of design one. There were also more participants thought design two had better fonts and warning effectiveness. Consider the provided key information as well as the font size was the same, it is a matter more about personal preference. In the final statement the majority participants (6 of 8) expressed their support of design two, which hint us it should be picked if we need to use one of them.

- All participants perceived the font size of the approaching distance information was not large enough, and its foot position also made it less viewy. Some participants proposed to enlarge it simply or adopt more viewing-attractive colors like deep red; some suggested to move it to the title area and one even mentioned some special visual effects (say the page turning effect) could be added to the way how the distance information is changed, thus making it more well-marked (though it would probably not be allowed in a car as it could be distractive).

The Comparison of the actual driving track and the ideal driving track

We have mentioned in the *idealtest2* scenario that, there is a blue ideal line indicating the route and the participants were supposed to follow it (see Fig 6.2). *OpenDS* provides an analyzer tool through which we could compare the actual driving track with the ideal one, and we could see whether the warning screens influent the participants' driving behavior in Fig 6.3 and Fig 6.4.

Discussion

Conclusions judging from the previous statistics and results are as the following:

- The warning screens displayed could be quickly understood by the interface operators. After a short period of familiarization, interface operators are able to retrieve the key information like the impending traffic event, the relative position etc. quickly.

- The warning screens do generate some positive influence on the interface operators' driving behavior, which helps avoiding possible traffic accidents.

Participants were asked if the warning screens were distractive to them. 5 participants had remarked the warning screens distracted their attentions in varying degrees. Among them 2 participants said they were only slightly distracted and another 2 participants said they were somewhat distracted, but it could still be handled. Only one had mentioned the warning screen placed a notable distraction on her, if she needed to remember the warning information every time. Consider she has very limited driving experience, we redid the test after giving her some extra time in gaining some experience with the driving simulator. After the retest she expressed that the distracting effect was alleviated as she became more familiar with the driving simulator.

Additionally participants were asked about their general feeling towards the warning system. In general, participants showed a common affirmation towards the warning effect generated by the warning screen. They expressed that a brief glancing at the warning screen would be enough in getting aware of the impending traffic event (detailed information not included), either from the warning title or from the related traffic symbol. 2 participants mentioned they always paid attention
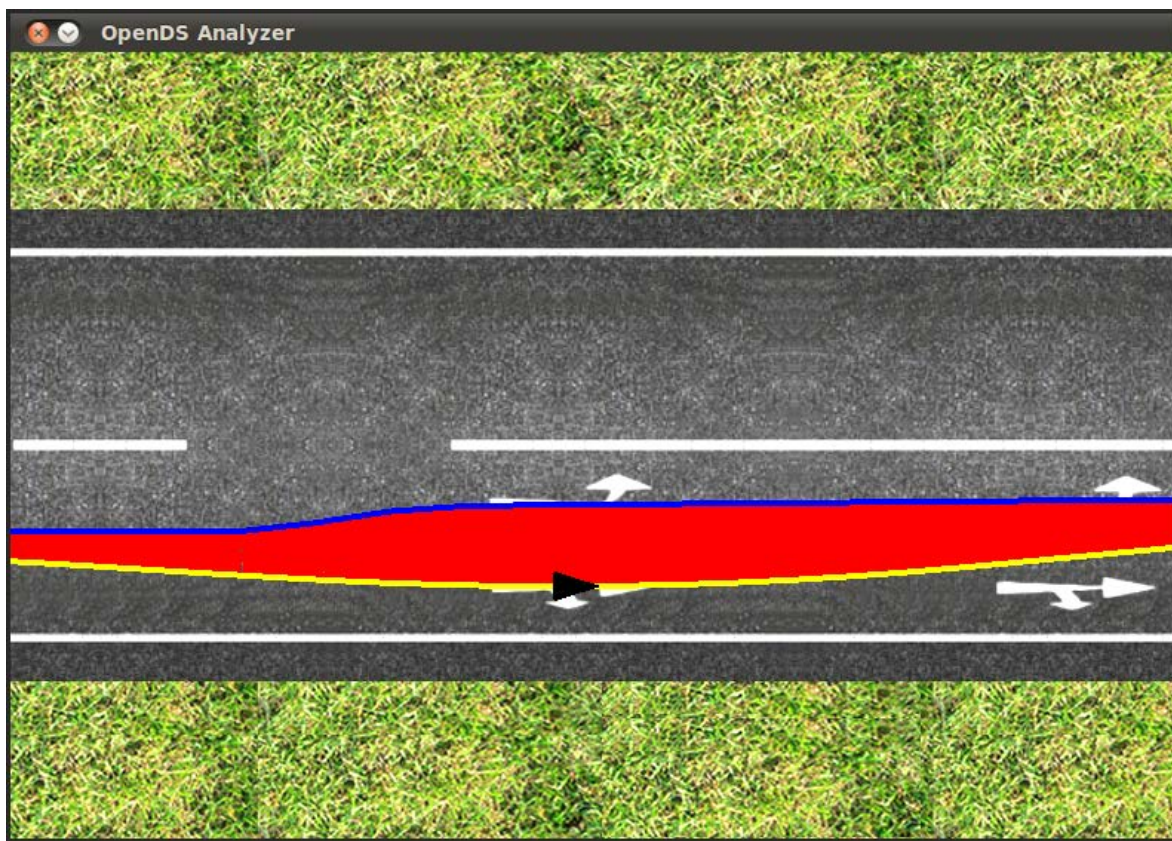
Figure 6.3.: Actual driving track and the ideal driving track comparison of one participant (when the traffic event "Approaching Emergency Vehicle" is shown): the relative position of the traffic event is to the left of the car, and we can see the actual driving track represented by the yellow line deviates to the right to give away to the passing ambulance. The black triangle indicates the heading direction of the car. The ambulance did not really exist in the driving simulator, but remember the participants were asked to behave like in a real driving situation, and they actually did that.

to the warning title first and another 2 participants turned to the traffic symbol first. Once they could not retrieve clear information from the title or the traffic symbol at the first glance (say the title or traffic symbol is bewildering), they would combine both for a better comprehension. If the title or traffic symbol was clear, they would just read one of them (according to their viewing preference). Rest participants did not posses an obvious preference towards the viewing orders. However they also stated it may depend on the specific traffic event shown; sometimes they viewed the title first and sometimes it was the traffic symbol. For those detailed information like the relative position and the approaching distance, participants said they needed more time to find them and this was when the warning screens became distractive. A further remark from them was the distractive degree depended on how long the information finding process lasted.

On the other hand, the following problems have been pointed out by the participants:
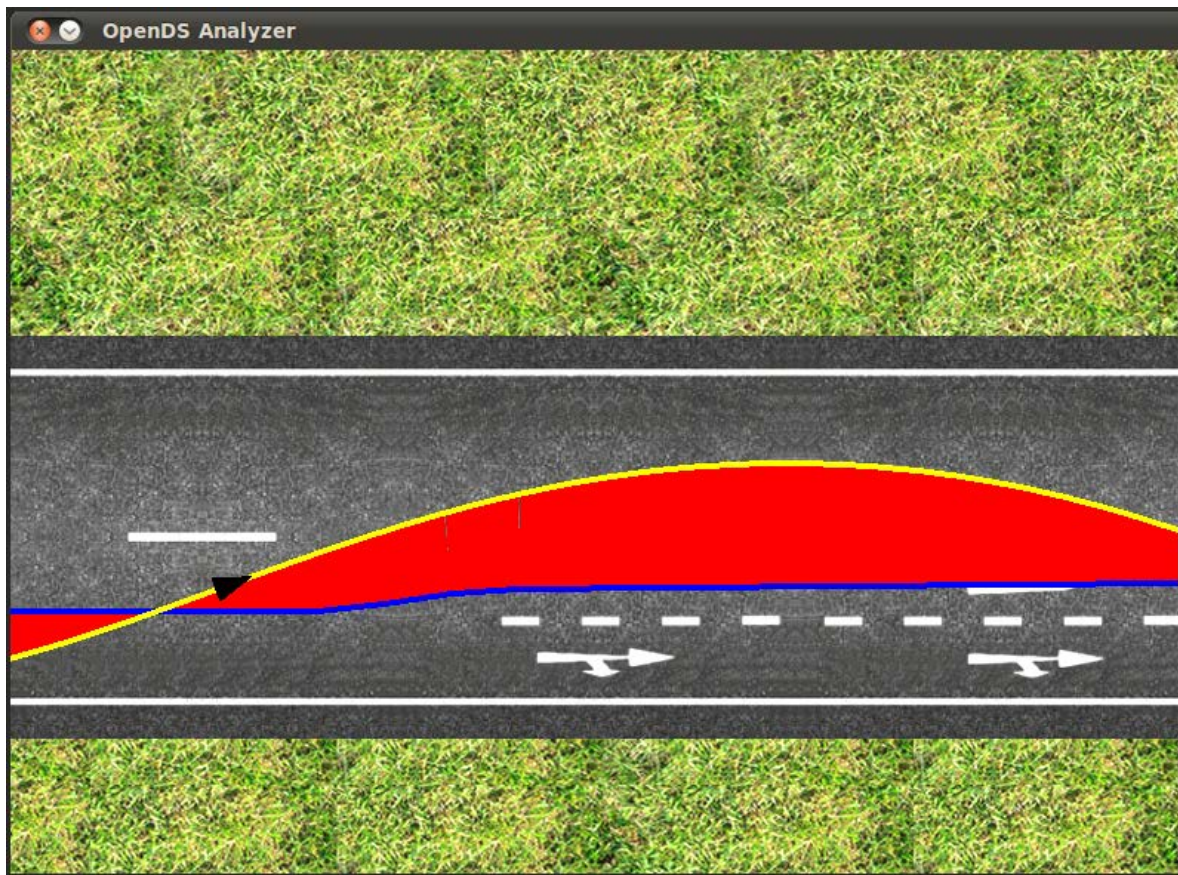
Figure 6.4.: Actual driving track and the ideal driving track comparison (when the traffic event "Working Area Warning" is shown) of one participant: the relative position of the traffic event is to the upper right of the car, and we can see the actual driving track represented by the yellow line deviates to the left to stay away from the working area. The black triangle indicates the heading direction of the car. Again there was not a working area in the driving simulator, but still the participants responded as they received such a warning.

- 4 participants mentioned some traffic symbols are not intuitive, for instance the traffic symbol of the traffic event Dangerous. The dangerous situation could be specified by giving a more detailed traffic symbol portray.

- 3 participants thought the red dot indicating the traffic event position could be enlarged to make it more eye-catching.

6.4.3. Evaluation Conclusion

In this chapter, we implemented a simulator-based driving test to verify the practicability of the warning screen evaluation tool developed. The test emulates how the future users of our

evaluation tool (say the warning screen designers) could evaluate and finally improve their designs by simulated driving tests. A set of sample warning screens with two different interface designs were demonstrated to the test participants, and the detailed statistics and feedback had been successfully collected in the form of online questionnaires and interactive interviews. From the collected data and feedback analysis, we can see the second warning screen design is more popular and there are some common problems in both designs. By selecting the better warning screen designs and solving the revealed problems, more advanced and elaborate warning screens could be created.

Chapter 7.

Summary and Outlook

7.1. Summary

The thesis provides a convenient tool for the evaluation of driver warning screens as well as a comprehensive study of regarding visual driver warning display essentials. It serves as a building block for the further developments and improvements of the warning screens to be integrated into the driving assistant system *DriveAssist*.

Thorough articulations of major driver warning techniques are presented at the beginning of the thesis, namely the visual driver warning display, the auditory driver warning display and the haptic driver warning display. A study of uni-modal and multi-modal driver warnings is also given and it is demonstrated that multi-modal warnings like double-modal warnings which combine visual and auditory warnings are more effective than uni-modal ones. The following part of the thesis introduces the concepts of reaction time including the human reaction time and the device reaction time. An optimal warning time window is portrayed. Then concise and practical advices on the design of the warning screens are presented, which all applied in the demonstration warning screens of the evaluation tool. Then the evaluation tool implementation is given after all these theoretic introductions and preparations. The evaluation tool aims at providing a relatively high degree of evaluation freedom for the evaluators by allowing evaluation GUI customization and remote controlling. Tutorials covering all attention-worthy aspects of both the server side and the client side are also given. Finally we prove the practicability of the evaluation tool by implementing a simulator-based driving test successfully. According to the questionnaire statistics and feedback given by the participants, the warning screens could be evaluated and finally improved.

7.2. Outlook

The adoption of driver warning displays combining with other driving auxiliary techniques like navigation is actually providing us with an easier and safer driving experience. In a word, the

appearances of new theories, new designing concepts as well as new technologies may all lead to the next revolution in the way how the drivers are warned.

Though the evaluation tool we provide here has achieved the established goals, there is still room for further development and perfection. Possible enhancements of the evaluation tool include but are not limited to:

1. Create a more elegant and user-friendly GUI for the evaluation tool. Currently the GUI design of the software is concentrated on providing an organized and practical visual effect, which just fits to the need of the thesis. However the acceptance and attractiveness of the evaluation tool would be further strengthened if the GUI would be prettier.

2. Provide a more powerful client side. Currently the client side provides a dynamic upgrading function and the evaluators are allowed to choose between 5 different warning screens. More functions as well as warning screens could be added in depend on the specific demands raised by the evaluators. It is also wanted that if the client side could be connected and interacted with the driving simulator (say *OpenDS* could receive the message sent by the client side and response).

3. Auditory warning display evaluation extension. Currently the evaluation tool only intends to evaluate visual warning screens. As *DriveAssist* also supports auditory warnings, it could be beneficial to integrate the auditory warning evaluation functions into the evaluation tool, e.g. auditory earcon test, auditory icon test and verbal warning test.

Appendix A.

Appendix

A.1. Driver Warning Screen Evaluation Test Explaination

You are going to participate in a driving-simulator based driving test, which aims at evaluating a driver warning screen evaluation tool.

The driving-simulator system consists of two monitors and a gaming driving wheel. The monitor right in front of you simulates the real driving condition, and the other monitor put aside will show some warning screens for driving assistance, like informing you an ambulance is passing by, etc. The warning screens will show up randomly and each will last for 6 seconds. You should pay attention to the content of the warning screen, try to get the warning information while keep driving normally just like in a real driving experience. Please try to follow the ideal blue line, obey the traffic lights and your maximum speed should not exceed 60 km/h. You will be interviewed about the warning screens presented and there will be some on-line questionnaires afterwards.

Many thanks for your participation!

List of Figures

List of Tables

List of Acronyms

IDE   Integrated Development Environment

JRE   Java Runtime Environment

JSON   JavaScript Object Notation

XML   Extensible Markup Language

SE   Standard Edition

JDK   Java Development Kit

ISO   International Standards Organization

ID   Infotainment Display

CC   Center Column

DB   Dash Board

HUD   Head-Up Display

CTS   Central Traffic Service

V2X   Vehicle-to-X

MT   Mobile Terminals

IVIS   In-Vehicle Information System

LCD   Liquid Crystal Display

GUI   Graphical User Interface

WHO   World Health Organization

DVR   German Road Safety Council

NSF   American National Sleep Foundation

ITS   Intelligent Transportation System

GV   Ghostview

HMI   Human Machine Interface

IEEE   Institute of Electrical and Electronics Engineers

TUM   Technische Universität München

Bibliography

[1] J.-S. Wang, R. Knipling, and M. Goodman, "The role of driver inattention in crashes: new statistics from the 1995 crashworthiness data system," *40th annual proceedings of the Association for the Advancement of Automotive Medicine*, p. 377–392, 1996.

[2] R. Parasuman, P. Hancock, and O. Olofinboba, "Alarm effectiveness in driver-centred collision-warning systems," *Ergonomics, 40*, p. 390–399, 1997.

[3] S. Arun, M. Murugappan, and K. Sundaraj, "Hypovigilance Warning System: A Review on Driver Alerting Techniques," *IEEE Control and System Graduate Research Colloquium*, pp. 65–69, 2011.

[4] S. Diewald, A. Möller, L. Roalter, and M. Kranz, "DriveAssist – A V2X-Based Driver Assistance System for Android," *Mensch and Computer 2012–Workshopband: interaktiv informiertallgegenwärtig und allumfassend*, 2012.

[5] B. Esgro, R. Grayhem, and I. Wilson, "Effects of odorant administration on driving alertness, fatigue, safety, and performance," *Conference of the Society for Psychophysiological Research*, 2005.

[6] C. Ho and C. Spence, "Multisensory warning signals for event perception and safe driving," *Theoretical Issues in Ergonomics Science*, pp. 523–554, 2008.

[7] M. Ganzhorn, J. Diederichs, and H. Widlroither, "Enhancing the reproduction of road signs in automotive HMIs to protect children," *11th International Conference on ITS Telecommunications*, pp. 338–344, 2011.

[8] J. Castellano, "Liquid gold: the story of liquid crystal displays and the creation of an industry," 2005.

[9] S. Diewald, A. Möller, L. Roalter, and M. Kranz, "Mobile Device Integration and Interaction in the Automotive Domain," in *AutoNUI: Automotive Natural User Interfaces Workshop at the 3rd International Conference on Automotive User Interfaces and Interactive Vehicular Applications (AutomotiveUI 2011)*, Nov.–Dec. 2011.

[10] S. Diewald, T. Leinmüller, B. Atanassow, L.-P. Breyer, and M. Kranz, "Mobile Device In-

tegration and Interaction with V2X Communication," in *19th World Congress on Intelligent Transport Systems (ITS)*, Oct. 2012.

[11] S. Diewald, B. Atanassow, T. Leinmüller, L.-P. Breyer, and M. Kranz, "Key Findings from the Development of a V2X Data Visualization Solution," in *Proceedings of the 20th World Congress on Intelligent Transport Systems*, ITS WC '13, Oct. 2013.

[12] M. Blattner, D. Sumikawa, and R. Greenberg, "Earcons and icons: their structure and common design principles," *Human–Computer Interaction, 4*, pp. 11–44, 1989.

[13] P. Green, W. Levison, G. Paelke, and C. Serafin, "Suggested Human Factors Design Guidelines for Driver Information Systems," *Technical Report UMTRI-93-21*, pp. 338–344, 1994.

[14] C. Baber, "Psychological aspects of conventional incar warning devices," *Human Factors in Alarm Design: Taylor and Francis*, pp. 193–205, 1994.

[15] L. Hagenmeyer, "Development of aMultimodal, Universal Human-Machine-Interface for Hypovigilance-Management-Systems," *Mechanical.vol. PhD Stuttgart (Germany): University of Stuttgart*, p. 218, 2007.

[16] S. Belz, G. Robinson, and J. Casali, "A new class of auditory warning signals for complex systems: auditory icons," *The Journal of the Human Factors and Ergonomics Society*, pp. 608–618, 1999.

[17] W. Gaver, "Auditory icons: using sound in computer interfaces," *Human–Computer Interaction, 2*, p. 167–177, 1986.

[18] P. Keller and C. Stevens, "Meaning from environmental sounds: types of signal-referent relations and their effect on recognizing auditory icons," *Journal of Experimental Psychology: Applied, 10*, p. 3–12, 2004.

[19] J. McKeown, "Candidates for within-vehicle auditory displays," *Proceedings of ICAD 05 – eleventh meeting of the international conference on auditory display*, p. 182–189, 2005.

[20] C. Spence and C. Ho, "Multisensory warning signals for event perception and safe driving," *Theoretical Issues in Ergonomics Science*, pp. 523–554, 2013.

[21] S. Belz, G. Robinson, and J. Casali, "Temporal Separation and Self-Rating of Alertness as Indicators of Driver Fatigue in Commercial Motor Vehicle Operators," *Human Factors, 46*, pp. 154–169, 2004.

[22] C. Ho and C. Spence, "Assessing the effectiveness of various auditory cues in capturing a driver's visual attention," *Journal of Experimental Psychology: Applied, 11*, p. 157–174, 2005.

[23] S. Belz, G. Robinson, and J. Casali, "A New Class of Auditory Warning Signals for Complex Systems: Auditory Icons.," *Human Factors, 41*, pp. 608–618, 1999.

[24] S. McAdams, "Recognition of sound sources and events," *In: S. McAdams and E. Bigand, eds. Thinking in sound: the cognitive psychology of human audition.*, pp. 146–198, 1993.

[25] R. Graham, "Use of auditory icons as emergency warnings: evaluation within a vehicle collision avoidance application," *Ergonomics, 42*, p. 1233–1248, 1999.

[26] S. Belz, J. Winters, G. Robinson, and J. Casali, "A Methodology for Selecting Auditory Icons for Use in Commercial Motor Vehicles," *Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 41*, pp. 939–943, 1997.

[27] E. Haas and J. Casali, "Perceived urgency and response time to multi-tone and frequency-modulated warning signals in broadband noise," *Ergonomics, 38*, pp. 2313–2326, 1995.

[28] J. Bliss and S. Acton, "Alarm mistrust in automobiles: how collision alarm reliability affects driving," *Applied Ergonomics, 34*, p. 499–509, 2003.

[29] D. McKeown, S. Isherwood, and G. Conway, "Auditory Displays as Occasion Setters," *Human Factors: The Journal of the Human Factors and Ergonomics Society, 52*, pp. 54–62, 2010.

[30] J. Edworthy and E. Hellier, "Complex nonverbal auditory signals and speech warnings," *From: M.S. Wogalter, ed. Handbook of warnings*, p. 199–220, 2006.

[31] C. Baldwin, "Verbal collision avoidance messages during simulated driving: perceived urgency, alerting effectiveness and annoyance," *Ergonomics, 54*, pp. 328–337, 2010.

[32] E. Hellier and J. Edworthy, "Signal words," *In: M.S.Wogalter, ed. Handbook of warnings*, p. 407–417, 2006.

[33] D. Strayer and W. Johnston, "Driven to distraction: dual-task studies of simulated driving and conversing on a cellular telephone," *Psychological Science, 12*, p. 462–466, 2001.

[34] C. Simpson and D. Williams, "Response time effects of alerting tone and semantic context for synthesized voice cockpit warnings," *Human Factors, 22*, p. 319–330, 1980.

[35] S.-H. Chang, "Driving performance assessment: effects of traffic accident location and alarm content," *Accident Analysis and Prevention, 40*, p. 1637–1643, 2008.

[36] A. Guillaume, L. Pellieux, V. Chastres, and C. Drake, "Judging the urgency of nonvocal auditory warning signals: perceptual and cognitive processes," *Journal of Experimental Psychology: Applied, 9*, p. 196–212, 2003.

[37] H. Lazarus and H. Hoege, "Industrial safety: acoustic signals for danger situations in factories," *Applied Ergonomics, 17*, p. 41–46, 1986.

[38] C. Ho, C. Spence, and Z. Hong, "Warning Signals Go Multisensory," *In: Proceedings of HCI International 2005, Lawrence Erlbaum Associates (2005*, pp. 1–10, 2005.

[39] W. Janssen and H. Thomas, "In-vehicle collision avoidance support under adverse visibility conditions," *In: Y.I. Noy, ed. Ergonomics and safety of intelligent driver interfaces*, pp. 221–229, 1997.

[40] C. Ho, "Haptic Interface for the Distracted Drivers," *SICE Annual Conference 2008*, pp. 338–344, 2008.

[41] M. Makhsous, R. Hendrix, Z. Crowther, E. Nam, and F. Lin, "Reducing whole-body vibration and musculoskeletal injury with a new car seat design," *Ergonomics, 48*, p. 1183–1199, 2005.

[42] F. Beruscha, K. Augsburg, and D. Manstetten, "Haptic warning signals at the steering wheel: a literature survey regarding lane departure warning systems," *The electronic journal of haptic research, 4*, 2011.

[43] A. Horowitz and T. Dingus, "Warning signal design: a key human factors issue in an in-vehicle front-to-rear-end collision warning system," *Proceedings of the Human Factors and Ergonomics Society 36th annual meeting*, pp. 1011–1013, 1992.

[44] J. Schumann, H. Godthelp, and B. Farber, "Breaking up open-loop steering control actions the steering wheel as an active control device," *In: A.G. Gale, I.D. Brown, C.M. Haslegrave, H.W. Kruysse and S.P. Taylor, eds*, pp. 321–332, 1993.

[45] J. Lee, B. Gore, and J. Campbell, "Display alternatives for in-vehicle warning and sign information: message style, location, and modality," *Transportation Human Factors, 1*, p. 347–375, 1999.

[46] C. Spence and J. Driver, "A new approach to the design of multimodal warning signals," *In: D. Harris, ed. Engineering psychology and cognitive ergonomics, Vol. 4: Job design, product design and human–computer interaction*, p. 455–461, 1999.

[47] B. Jan and A. Hendrik, "Vibrotactile in-vehicle navigation system," *Transportation Research Part F: Traffic Psychology and Behavior*, p. 247–256, 2004.

[48] S. Selcon, R. Taylor, and F. McKenna, "Integrating multiple information sources: using redundancy in the design of warnings," *Ergonomics, 38*, p. 2362–2370, 1995.

[49] C. Spence and J. Driver, "Cross-modal links in attention between audition, vision, and touch: implications for interface design," *International Journal of Cognitive Ergonomics, 1*, p. 351–373, 1997.

[50] M. Green, "How Long Does It Take to Stop: Methodological Analysis of Driver Perception-Brake Times," *Transportation Human Factors, 2*, p. 195–216, 2000.

[51] H. Summala, "Brake Reaction Times and Driver Behavior Analysis," *Transportation Human Factors, 2*, p. 217–226, 2000.

[52] T. Liukkonen, "Human Reaction Times as a Response to Delays in Control Systems," *Kajaani Unit of Department of Information Processing Science*, 2009.

[53] F. Von, A. Huhtala, P. Kullberg, and K. Saarl, "Personal tempo and phenomenal time at different age levels," *Reports from the Psychological Institute, 2*, 1956.

[54] A. Welford, "Choice reaction time: Basic concepts," *In: A. T. Welford (Ed.), Reaction Times*, pp. 73–128, 1980.

[55] K. Boff, L. Kaufman, and J. Thomas, "Handbook of Perception and Human Performance: Vol. II," *Cognitive Processes and Performance*, 1986.

[56] D. McGehee, E. Mazzae, and G. Bladwin, "Driver reaction time in crash avoidance research: Validation of a driving simulator study on a test track," *Proceedings of the International Ergonomics Association 2000 Conference*, 2000.

[57] M.-C. Chambrin, "Alarms in the intensive care: how can the number of false alarms be reduced," *Critical Care, 5*, p. 184–188, 2001.

[58] D. McGehee, T. Brown, J. Lee, and T. Wilson, "Effect of warning timing on collision avoidance behavior in a stationary lead vehicle scenario," *Human performance:models, intelligent vehicle initiative, traveller advisory and information systems*, pp. 1–7, 2002.

[59] M. Galer, A. Baines, and G. Simmonds, "Ergonomic Aspects of Electronic Dashboard Instrumentation," *Human Factors in Transport Research, 1*, 1980.

[60] United States Department of Defense, "Human Engineering Design Criteria for Military Systems, Equipment and Facilities," *Military Standard MILSTD-1472D*, 1989.

[61] D. Cornog and F. Rose, "Legibility of Alphanumeric Characters and Other Symbols II: A Reference Handbook," 1967.

[62] P. Green, S. Goldstein, K. Zeltner, and S. Adams, "Legibility of Text on Instrument Panels: A Literature Review," *Technical Report UMTRI-88-34*, 1988.

[63] L. Silverstein and R. Merrifield, "The Development and Evaluation of Color Systems for Airborne Applications," *Report DOT/FAA/PM-85-19, also listed as NADC-81-011-60*, 1985.

[64] M. Williams, E. Hoekstra, and P. Green, "Development and Evaluation of a Vehicle Monitor Driver Interface," *Technical Report UMTRI 93-22*, 1993.

[65] P. Green, "Symbols for Controls and Displays," *Automotive Ergonomics*, pp. 237–268, 1993.