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Human Factors Studies on Automotive Head-Up Display Design

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Abstract

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Head-up display (HUD) systems were introduced into the automobile industry as a means for improving driving safety. They superimpose safety-critical information on top of the driver's forward field of view and thereby help drivers keep their eyes forward while driving. Since the first introduction about three decades ago, automotive HUDs have been available in various commercial vehicles.

Despite the long history and potential benefits of automotive HUDs, however, the design of useful automotive HUDs remains a challenging problem. In an effort to contribute to the design of useful automotive HUDs, this doctoral dissertation research conducted four studies.

In Study 1, the functional requirements of automotive HUDs were investigated by reviewing the major automakers' automotive HUD products, academic research studies that proposed various automotive HUD functions, and previous research studies that surveyed drivers' HUD information needs. The review results indicated that: 1) the existing commercial HUDs perform largely the same

functions as the conventional in-vehicle displays, 2) past research studies proposed various HUD functions for improving driver situation awareness and driving safety, 3) autonomous driving and other new technologies are giving rise to new HUD information, and 4) little research is currently available on HUD users' perceived information needs. Based on the review results, this study provides insights into the functional requirements of automotive HUDs and also suggests some future research directions for automotive HUD design.

In Study 2, the interface design of automotive HUDs for communicating safety-related information was examined by reviewing the existing commercial HUDs and display concepts proposed by academic research studies. Each display was analyzed in terms of its functions, behaviors and structure. Also, related human factors display design principles, and, empirical findings on the effects of interface design decisions were reviewed when information was available. The results indicated that: 1) information characteristics suitable for the contact-analog and unregistered display formats, respectively, are still largely unknown, 2) new types of displays could be developed by combining or mixing existing displays or display elements at both the information and interface element levels, and 3) the human factors display principles need to be used properly according to the situation and only to the extent that the resulting display respects the limitations of the human information processing, and achieving balance among the principles is important to an effective design. On the basis of the review results, this review suggests design possibilities and future research directions on the interface design of safety-related automotive HUD systems.

In Study 3, automotive HUD-based take-over request (TOR) displays were developed and evaluated in terms of drivers' take-over performance and visual scanning behavior in a highly automated driving situation. Four different types of

TOR displays were comparatively evaluated through a driving simulator study - they were: Baseline (an auditory beeping alert), Mini-map, Arrow, and Mini-map-and-Arrow. Baseline simply alerts an imminent take-over, and was always included when the other three displays were provided. Mini-map provides situational information. Arrow presents the action direction information for the take-over. Mini-map-and-Arrow provides the action direction together with the relevant situational information. This study also investigated the relationship between driver's initial trust in the TOR displays and take-over and visual scanning behavior. The results indicated that providing a combination of machine-made decision and situational information, such as Mini-map-and-Arrow, yielded the best results overall in the take-over scenario. Also, drivers' initial trust in the TOR displays was found to have significant associations with the take-over and visual behavior of drivers. The higher trust group primarily relied on the proposed TOR displays, while the lower trust group tended to more check the situational information through the traditional displays, such as side-view or rear-view mirrors.

In Study 4, the effect of interactive HUD imagery location on driving and secondary task performance, driver distraction, preference, and workload associated with use of scrolling list while driving were investigated. A total of nine HUD imagery locations of full-windshield were examined through a driving simulator study. The results indicated the HUD imagery location affected all the dependent measures, that is, driving and task performance, drivers' visual distraction, preference and workload. Considering both objective and subjective evaluations, interactive HUDs should be placed near the driver's line of sight, especially near the left-bottom on the windshield.

Keywords: Automotive head-up displays, Functional requirements, Interface design, Highly automated vehicles, Take-over requests, Interactive head-up displays, Optimal display location

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Chapter 1

Introduction

1.1 Research Background

Head-up display (HUD) systems were introduced into the automobile industry in the 1980s, as a means for improving driving safety. They superimpose information displays on top of the driver's forward field of view (FoV), and, thereby, help drivers keep their eyes forward while driving. Compared to traditional head-down displays (HDDs), automotive HUDs reduce the driver's eye-off-the-road time (EoRT) (Gish et al., 1999; Horrey and Wickens, 2004; Liu et al., 2004; Medenica et al., 2011; Nwakacha et al., 2013; Palinko et al., 2013; Steinfeld and Green, 1995; Weinberg et al., 2011) and reaccommodation demands (Gish and Staplin, 1995) by presenting visual information within the driver's forward FoV, at a focal plane further into the forward scene. With the advantages in information access costs, automotive HUDs are considered to have the potential to improve driving performance and safety. Some studies have empirically demonstrated the positive effects of HUDs over HDDs in terms of performance of primary and secondary driving tasks (Gish et al., 1999; Liu and Wen, 2004; Srinivasan et al., 1994; Steinfeld and Green, 1995; Wittmann et al., 2006), and, driver distraction and workload (Weinberg et al., 2011).

Since the first introduction by General Motors in 1988, commercial automotive HUDs have been available in various production cars. The use of automotive HUDs is expected to increase in the years to come (Future Market Insights, 2015; IHS, 2013; MarketsandMarkets.com, 2016; MarketsandMarkets.com, 2015; Pala, 2012; Zion Market Research, 2016). It is projected that by 2024, almost one-third of all cars will be equipped with a HUD system (ABI Research, 2015).

The projection for increased use of automotive HUDs seems to be partly based on the fact that the range of possible automotive HUD functions is expanding with the advent of new technologies in the areas of photonics, augmented reality, internet-of-things and autonomous systems (Gabbard et al., 2014). Indeed, past research studies have proposed a variety of automotive HUD functions reflecting the technological advances. Some examples include displaying hazard warnings (Charissis and Papanastasiou, 2008; George et al., 2012; Lee et al., 2015; Maag et al., 2015; Park and Kim, 2013; Plavšic et al., 2009; Suzuki and Hashimoto, 2012; Tonnis and Klinker, 2006; Tonnis et al., 2005), traffic sign/signal notifications (Caird et al., 2008; Chang et al., 2015; Lee et al., 2015; Park and Kim, 2013; Yang et al., 2016) and driving instructions (Charissis and Papanastasiou, 2008; Lee et al., 2015; Lin et al., 2011; Maag et al., 2015; Park and Kim, 2013; Riener and Jeon, 2012; Riener and Thaller, 2014; Yoon et al., 2014). These proposed functions reflect the commonly shared idea that the usefulness of automotive HUD lies in enhancing driving performance and safety by supporting the primary and secondary driving tasks. Other studies, on the other hand, have proposed automotive HUD functions pertaining to non-driving-related tasks, such as displaying communication-related information (Charissis et al., 2007; Maurer et al., 2014; Wang et al., 2014; Zimmermann et al., 2014) and outside environment information (Fujimura et al., 2013), and, supporting augmented reality games (Schroeter et al., 2014; Steinberger et al., 2015). These proposals represent the more recent idea that automotive HUDs could be utilized to create new driver experience - they tend to involve displaying new types of information previously non-existent or difficult to display through HUDs.

The current technological feasibility of creating various HUD functions, however, does not mean that an automotive HUD system can be designed to display a wide variety of information without limit. Displaying too much information through HUDs can result in information overload. Also, poor interface design can cause problems, such as visual clutter (Gish and Staplin, 1995; Pauzie, 2015), misaccommodation (Gish and Staplin, 1995; Ward and Parkes, 1994), and cognitive capture/tunneling (Gish and Staplin, 1995; Pauzie, 2015; Tufano, 1997; Ward and Parkes, 1994), and, further aggravate driver information processing. In order to avoid these negative consequences, only the information necessary for the driver should be carefully selected and displayed. In this regard, understanding the drivers' information needs, and, defining the functional requirements of automotive HUDs (what information should be displayed and when) accordingly is crucial for the design of useful HUDs. In addition, the necessary information must be presented in a manner conducive to human information processing. Hence, human factors display design principles should be used as a guide to interface design.

Nielsen's notions of utility, usability and usefulness (Nielsen 1994) may be useful in understanding the roles of functional requirements analysis and interface design mentioned above and their interplay in the design of automotive HUDs. Nielsen defined utility as the degree to which a system addresses the user's needs. Thus, the outcome of functional requirements analysis, that is, the specification of automotive HUD functions, directly affects the system utility perceived by the drivers. Usability is defined as a quality attribute that assesses how easy user interfaces are to use. The usability of the system is, therefore, mainly determined by the HUD interfaces resulting from screen-level interface design. Utility and usability together determine the overall usefulness of a system. As mentioned earlier, previous research studies have portrayed the usefulness of automotive HUDs as improving driving performance and safety, and creating new driver experience. Utility and usability are closely inter-related in the design of automotive HUDs - functional requirements analysis sets the goal and contexts for interface design, and interface design, when informed by the human factors engineering and HCI knowledge, can limit the range of realizable HUD functions. Also, both functional requirements analysis and interface design are informed and/or limited by design inputs, including drivers' characteristics, driving tasks, environments, and available vehicle technologies.

Despite the promising applications of automotive HUDs and the significant previous research efforts, however, the design of useful automotive HUDs remains a challenging problem. While there exist a plethora of research gaps in regard to the design of useful automotive HUDs, the following existing research gaps are considered important in relation to the HUD functional requirements and interface design.

One of the major research gaps is the lack of integrated understanding of the existing knowledge and views concerning the utility (functional requirements) aspects of the automotive HUD design. With the advent of new technologies, the range of possible applications of automotive HUDs seems to be expanding. However, what information automotive HUDs should present to the driver so as to benefit driving is still a question that needs to be addressed. Understanding information needs and wants of automotive HUD users is fundamental to the determination of HUD information set; yet, the current knowledge on them seems rather limited. A few reviews have been carried out on automotive HUDs in the fields of human-vehicle interaction research (Gish and Staplin, 1995; Harrison, 1994; Pauzie, 2015; Tufano, 1997; Ward and Parkes, 1994). However, these studies were mostly concerned with safety and human factors design issues related to the interface design of automotive HUDs. The authors were not aware of literature reviews focusing on the information needs and wants of automotive HUD users. Examining and synthesizing existing ideas and research findings on the information needs and wants of automotive HUD users would be an important first step towards addressing the problem of adequate information choice. Such effort will assist in defining and re-defining the role of automotive HUDs within the rapidly evolving in-vehicle information systems.

There is another research gap, with respect to the usability (interface design) aspects of the automotive HUD design, that the existing knowledge and data appear disjointed and poorly integrated. In recent years, various research studies have proposed different HUDs that present safety-critical information in particular styles. However, it is not well understood what type of display would be most advantageous or adequate for effectively communicating safety information and thus best serve the driver in performing the associated driving task. In terms of the design of HUD interface, a few studies have investigated the impacts of display design variables of HUDs, such as color (Choi et al., 2013; Huang et al., 2013; Moon et al., 1998), display type (analog vs. digital) (Huang et al., 2013; Moon et al., 1998), layout (Park et al., 2012) and display location (Chao et al., 2009; Flannagan et al., 1994; Morita et al., 2007; Horrey et al., 2004; Tangmanee et al., 2012; Tsimhoni et al., 2001; Tretten et al., 2011; Yoo et al., 1999). While a few reviews have been carried out on automotive HUDs in the fields of human-vehicle interaction research (Gish and Staplin, 1995; Harrison, 1994; Pauzie, 2015; Tufano, 1997; Ward and Parkes, 1994), however, these studies were mostly concerned with safety and human factors design issues related to the interface design of automotive HUDs, not the conceptual display design of automotive HUDs. Relatively little research has been conducted to evaluate the available HUDs in the interface design.

There are still knowledge gaps in designing useful automotive HUDs in certain situations, such as autonomous driving, and the usage of full-windshield automotive HUDs. One important knowledge gap lies in the design of automotive HUDs as a visual aid in highly automated vehicles, especially Level 3 and Level 4 vehicles (SAE J3016, 2016). Until reaching the fully autonomous driving, it would be inevitable that drivers have to be able to take the control of the automation system when required. Drivers need to quickly understand their surroundings and make an appropriate decision to ensure a safe response, if a sudden take-over request (TOR) occurs. In-vehicle information display systems should be designed to allow the driver to respond safely in a take-over situation. HUDs are considered highly useful in helping drivers process TORs as they have little information access cost to obtain the necessary information (Wickens et al., 2003). Regarding TOR displays in highly automated vehicles, however, most previous studies have suggested simple visual alerts in the form of simple icons or symbols, or audible alarms such as a high-pitched tone, beep sounds, sinusoidal tone, etc. (Eriksson and Stanton, 2017; Gold et al., 2016; Melcher et al., 2015; Mok et al., 2015; Naujoks et al., 2014; Wandtner et al., 2018; Zeeb et al., 2016). There is a lack of understanding of how drivers' take-over and visual scanning behavior are affected when more information-rich and more automated information displays are presented, such as a display providing the situational information or suggesting decision alternatives. Such visual aids may be needed when a sudden manual intervention is required, such as a take-over situation. In addition, there is little research on how display characteristics of TOR displays affect drivers’ trust, and how driver's trust relates to the actual usage of TOR displays. The actual usage of automation may depend on the user's level of trust (Lee and Moray, 1994). Eriksson et al. (2018) showed that providing visual aids to help drivers understand the current situation and suggesting the decision selection were helpful for the decision-making process in a take-over scenario. However, there is a lack of discussion of the relationship between drivers' trust and their take-over behavior according to the visual information displays. This lack of knowledge hinders ensuring a safe transition to manual control in highly automated vehicles.

Regarding the design of full-windshield automotive HUDs, the location of HUD imagery is one of main design variables that would significantly affect driving as well as HUD information processing performance. Automotive HUD systems must be designed to help drivers focus on the road ahead and at the same time quickly process the information it presents. The recent technological advances, such as the full-windshield AR HUD technologies, enable presenting HUD imagery at various locations outside the vehicle. This capability greatly expands the range of design possibilities. Multiple studies have examined the effects of HUD imagery location on driving performance and driver preference (Tretten et al., 2011; Chao et al., 2009; Morita et al., 2007; Yoo et al., 1999; Flannagan et al., 1994). These previous studies, however, provided different recommendations on HUD imagery locations. Four out of the six studies suggested that the HUD imagery should be presented from 0 to 10 degrees below the line of sight (Tretten et al., 2011; Chao et al., 2009; Morita et al., 2007; Flannagan et al., 1994). Two other studies found that 5 degrees to the right and left of the center, and the central position gave the best performance and were more likely to be preferred (Tsimhoni et al., 2001; Yoo et al., 1999). One study suggested that the HUD imagery location can be 7 degrees or higher above the line of sight (Morita et al., 2007). One limitation of previous research studies on HUD imagery location was that they considered only a simple, non-interactive visual object, such as a static warning symbol. Few studies have investigated more complex visual objects that drivers can manipulate interactively, such as scrolling lists. Also, few studies have considered the full-windshield automotive HUD systems in previous HUD location studies. Consequently, how HUD imagery location affects driving performance and task performance, and driver distraction and preference is not well understood for such interactive visual objects. This lack of understanding hampers optimizing the design of HUD imagery and fully capitalizing on the advantages of HUD.

1.2 Research Objectives and Questions

In an attempt to address the aforementioned research gaps, and, therefore, contribute to the design of useful automotive HUDs, this dissertation research conducted four major studies (Studies 1-4) – two qualitative studies (Studies 1 and 2) and two empirical studies (Studies 3 and 4). Study 1 and 2 examined the functional requirements and safety-related interface design of automotive HUDs through systematic literature reviews. Studies 3 and 4 developed and evaluated the automotive HUD interface designs for specific task contexts through driving simulator experiments, such as processing the take-over requests of Level 3/4 automated vehicles and utilizing interactive HUDs in the full-windshield automotive HUD system – the specific contexts of Study 3 and 4 were determined based on the results of Study 1 that autonomous driving and other new technologies are giving rise to new HUD information. The research objectives and specific research questions of each of the four studies are shown in Table 1.1.

Table 1.1: Research objectives and specific research questions of this dissertation research

Research objective		Research question
Study 1. To investigate the developer, researcher and user perspectives on the functional requirements of automotive HUDs	1)	What types of information are presented by the existing commercial automotive HUD systems and for what situations?
	2)	What types of information have previous studies suggested for automotive HUDs and for what situations?
	3)	What types of information do drivers require for automotive HUDs and for what situations? What is their relative importance?
Study 2. To examine the existing or proposed automotive HUDs communicating safety-related information focusing on the interface design	1)	What types of display designs are presented by the existing commercial automotive HUDs for safety-related functions? What are their behaviors and structures, and also related human factors display design principles?
	2)	What types of display design have been proposed by academic research for automotive HUDs in safety-critical situations? What are their behaviors and structures, and also related human factors display design principles? How effective are the proposed HUD display concepts for users?
Study 3. To develop and evaluate automotive HUDs for take-over requests in highly automated vehicles	1)	How do the proposed TOR displays affect on take-over and visual scanning behavior?
	2)	What are the characteristics of drivers' initial trust in the proposed TOR displays?
	3)	What is the relationship between drivers' initial trust and drivers' take-over and visual scanning behavior?
Study 4. To comparatively evaluate the interactive scrolling list locations of full-windshield automotive HUD system	1)	Does HUD imagery location affect on driving and task performance, driver distraction, workload and preference, during item search and selection while driving?

Figure 1.1 depicts the conceptual framework that informed the four research objectives above; the conceptual framework also guided the entire study (the scope of this study is represented in bold). It shows the relationship between functional requirements analysis and interface design, and the information sources for each aspect of design. It also describes how HUD design affects the utility, usability and usefulness of the resulting system.

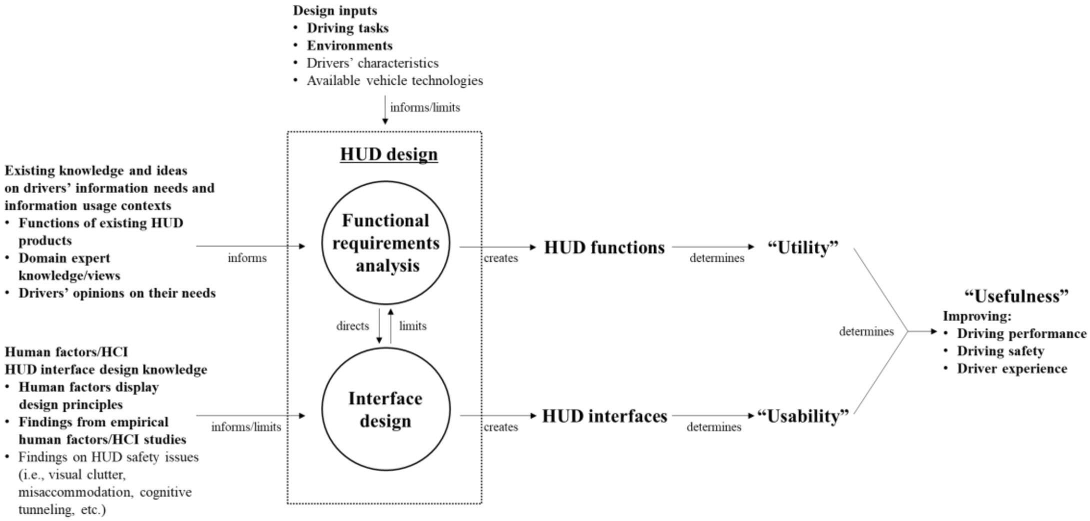


Figure 1.1: Conceptual framework used to inform the research questions and guide the study

1.3 Structure of the Thesis

Brief descriptions of the chapters of the current PhD dissertation are presented in this section. In Chapter 1, research background, research objectives and questions were described. The overall structure of this research is also presented. In Chapter 2, the functional requirements of automotive HUDs were investigated by reviewing the major automakers' automotive HUD products, academic research studies that proposed various automotive HUD functions, and previous research studies that surveyed drivers' HUD information needs. In Chapter 3, the interface design of automotive HUDs for communicating safety-related information were examined by reviewing the existing commercial HUDs and display concepts proposed by academic research studies. Each display was analyzed in terms of its functions, behaviors and structure. Also, related human factors display design principles, and, empirical findings on the effects of interface design decisions were reviewed when information was available. In Chapter 4, automotive HUD-based TOR displays were developed and evaluated in terms of drivers' take-over performance and visual scanning behavior in a highly automated driving situation. The relationship between driver's initial trust in the proposed TOR displays and take-over and visual scanning behavior was also investigated. In Chapter 5, interactive HUD imagery locations associated with use of scrolling list while driving were evaluated in terms of driving and task performance, driver distraction, workload and preference. In Chapter 6, a brief summary and implications of this dissertation research, and future research directions were presented. Figure 1.2 shows the overall structure of this thesis.

Chapter 1.
Introduction

- Research background
- Research objectives and questions
- Structure of the thesis

Chapter 2.
Functional Requirements of Automotive HUDs

- Functions of existing commercial HUD systems
- Domain expert knowledge/views
- Drivers' opinion on their needs

Chapter 3.
Interface Design of Safety-Related Automotive HUDs

- Safety-related displays presented by the existing commercial HUD systems
- Safety-related HUDs proposed by academic research

Systematic review studies

Chapter 4.
Development and Evaluation of Automotive HUDs for Take-Over Requests (TORs) in Highly Automated Vehicles

- Development of automotive HUD-based TOR displays
- Comparison of the proposed TOR displays
- Characteristics of drivers' initial trust in the proposed TOR displays
- Relationship between drivers' initial trust and take-over and visual behavior

Chapter 5.
Human Factors Evaluation of Display Locations of an Interactive Scrolling List in a Full-windshield Automotive Head-Up Display System

- Effects of interactive scrolling list locations of full-windshield automotive HUD system on driving and task performance, driver distraction, preference and workload

Driving simulator studies

Chapter 6.
Conclusion

- Summary and implications
- Future research directions

Figure 1.2: The overall structure of the thesis

Chapter 2

Functional Requirements of Automotive Head-Up Displays: A Systematic Review of Literature from 1994 to Present

2.1 Introduction

HUDs have been available in various production cars since the introduction of the first one by General Motors in 1988. The use of automotive HUDs is expected to increase in the years to come (Future Market Insights, 2015; IHS, 2013; MarketsandMarkets.com, 2016; MarketsandMarkets.com, 2015; Pala, 2012; Zion Market Research, 2016). It is projected that by 2024, almost one-third of all cars will be equipped with HUDs (ABI Research, 2015).

Despite the three decades of automotive HUD use and the significant previous research efforts, however, the design of useful automotive HUDs remains a challenging problem. One of the difficulties developers and researchers are experiencing is the lack of integrated understanding of the existing knowledge and views concerning both the utility (functional requirements) and usability (interface design) aspects of the automotive HUD design. While much work has been conducted, the existing knowledge and data appear disjointed and poorly integrated. Remedying this situation would greatly contribute to the design of useful automotive HUDs. It would also help identify future research directions.

As an attempt to alleviate the aforementioned problem and, therefore, contribute to the design of useful automotive HUDs, the objectives of the current study were to 1) provide an integrated understanding of the existing knowledge and views on the functional requirements (what information should be displayed and when) of automotive HUDs, and, on the basis of such understanding, 2) suggest directions for future automotive HUD design research. The aspect of interface design was not included in this study.

According to the existing literature on the topic of functional requirements analysis, the functional requirements of a product can be largely derived from the following information sources: market research (gathering and analyzing existing product information) (Pahl and Beitz, 2013; Pugh, 1991; Sommerville and Sawyer, 1997; Sudin et al., 2010; Ulrich and Eppinger, 2011), domain expert knowledge (proposals and research results on new applications of technological products found in academic papers) (Pahl and Beitz, 2013; Pugh, 1991), and users' opinions on their needs (Sommerville and Sawyer, 1997; Sudin et al., 2010; Ulrich and Eppinger, 2011). Therefore, the current study entertained the following research questions so as to accomplish the study objectives (shown in Table 2.1).

Table 2.1: Research questions of Study 1

Research question	
Research Question 1)	What types of information are presented by the existing commercial automotive HUD systems and for what situations?
Research Question 2)	What types of information have previous studies suggested for automotive HUDs and for what situations?
Research Question 3)	What types of information do drivers require for automotive HUDs and for what situations? What is their relative importance?

The first research question was addressed by examining the major automakers' automotive HUD products. The second, by reviewing academic research studies that proposed various automotive HUD functions. Finally, the third, by examining previous research studies that surveyed drivers' HUD information needs. For the second and third research questions, the systematic literature review method was employed as it is considered the best method for integrating existing knowledge on a research topic (Cronin et al., 2008; Mulrow, 1994).

2.2 Method

In this study, two separate literature searches were conducted: one for addressing Research Question 1, and, the other, Research Questions 2 and 3.

The literature search for Research Question 1 targeted documents describing HUDs of fifteen automobile manufacturers: Audi, Bentley, BMW Group, Ford, General Motors, Honda, Hyundai/KIA, Jaguar Land Rover, Mazda, Mercedes-Benz, PSA Peugeot Citroen, Renault, SAAB, Toyota, and Volvo. These fifteen manufacturers were the major commercial vehicle manufacturers. This study did not consider HUDs in concept cars or prototype HUDs as they did not necessarily represent the final commercial products and also it was difficult to find product descriptions for them.

For each manufacturer, the HUD systems installed in its models were identified through web searches. Then, other details, including the specifications of the HUD systems and the contexts and purposes of information use, were examined using the vehicle manuals and available YouTube or other video clips on the internet. The commercial HUD systems were searched up to December, 2017.

The literature search for Research Questions 2 and 3 was intended to provide a comprehensive literature review. The search period was from January

1994 to September 2016. Four online databases were utilized: ACM digital Library, Science Direct, Scopus, and Web of Science. Three concepts were initially selected as the keywords for literature search: HUD, automobiles, and information display design. Then, for each initial keyword, interchangeable and topically related terms were further explored to determine more keywords. The final set of search keywords used for the literature search is shown in Table 2.1. The search formula used for the database searches first combined the keywords within each concept (initially chosen keyword) with the Boolean operator 'OR' and, then, linked the resulting expressions corresponding to the three concepts with the Boolean operator 'AND'. The keywords in Table 2.2 were generic, and, allowed identifying a wide range of documents related to the automotive HUD design.

Table 2.2: Search keywords used for literature review

Concept	Search keywords
HUD	Head up display*, Head-up display*, HUD*
Automobiles	Automotive, vehicle*, car*, automobile
Information display design	Interface, augmented reality, information, design, human factors, system

*Note: An asterisk (*) at the end of a keyword indicates that all terms that start with that root were included in the search.

A total of 1378 documents were obtained as a result of the keyword searches in the four databases: 138 from ACM Digital Library, 92 from Science Direct, 297 from Scopus, and 851 from Web of Science, respectively. A wide range of documents, including journal articles, conference papers, and other forms of publication, such as master's and doctoral dissertations, and technical reports were collected. For each of the 1378 documents, its title, abstract and keywords were examined with the following exclusion criteria: (1) studies that are not related to automotive HUDs, (2) duplicate studies, (3) no full-text access supported, and (4) studies that are not written in English or Korean. A total of 165 relevant studies remained after the elimination of unqualified documents. Then, the 165 studies were carefully reviewed to identify the ones relevant to addressing Research Questions 2 and 3 – the studies that were irrelevant or were focused on the hardware design/development were excluded. A total of 27 studies were identified. The studies in the reference lists of the 165 studies were also examined and 17 additional studies were found. As a result, a total of 44 studies were included in this review. 41 studies pertained to Research Question 2, and, three, Research Question 3.

2.3 Results

2.3.1 Information Types Displayed by Existing Commercial Automotive HUD Systems

A total of 27 information types were identified from examining the commercial HUDs of the fifteen automobile manufacturers. The 27 information types were grouped into five categories: vehicle state, safety, navigation, communication/infotainment and outside environment.

The vehicle state category consists of current speed, cruise control-related information, gear shift-related information, RPM, system messages, fuel-related information, high beam status, turn signal status, parking assist status, hybrid system status, race car-related information, electronic stability control status, brake assist status, eco-driving status, and tire pressure status. The safety category is composed of collision warning, road signs notification and warning, lane keeping-related information, and night vision-related warning. The navigation category consists of navigation instructions, remaining distance to destination, and compass heading. The communication/infotainment category includes radio, audio player and phone call information, and voice recognition system status. The outside environment category consists of outside temperature.

Table 2.3 describes the 27 information types along with their usage situations and/or purposes. As can be seen from the table, the 27 HUD information types represent those provided by traditional in-vehicle displays, such as instrument panel and navigation system displays. None of the 27 HUD information types represented novel information types created specifically for HUDs.

Table 2.4 summarizes the information types each manufacturer supports with its HUDs. Note that: for each manufacturer in the first row, the number in the parenthesis denotes the total number of information types that one or more of the manufacturer's HUDs display; and, for each information type in the second column, the number in the parenthesis denotes the total number of manufacturers whose HUDs (one or more) display it.

Examination of the vehicle manuals resulted in the following observations regarding the way information is presented by the commercial HUD systems:

- Each of the commercial HUD systems has a display space allocation scheme, which defines a number of sub-areas within the entire HUD display area and the information types that could be displayed in each display area. Some of the commercial HUD systems, such as Cadillac XTS 2017, Chevrolet Corrvete 2018 and Acura RLX 2014, provide a few optional display layouts among which the driver can select according to the driving situation or driver need. The optional display layouts of each commercial HUD system are all based on its display space allocation scheme.

- For most of the commercial HUD systems, the display layout (or each of the optional display layouts provided) is not static but dynamic in that its content and configuration can change according to the change in situation or the occurrence of a certain event or condition; safety-related warnings and user action feedbacks could be displayed interruptively. Also, in general, for each display layout available, the driver can activate or deactivate any of the information types in it through changing the product settings. This allows for creating individual-specific display layouts.

The display layouts of some commercial HUD systems that the authors were able to find from the vehicle manuals are described in Appendix A - not all vehicle manuals provided information regarding display layouts of the HUD systems. Also, note that for the commercial HUD systems of General Motors, only two are presented since each of the others is similar to either one of the two.

Table 2.3: Information types displayed by commercial HUDs and their usage situations and/or purposes

Information types		Usage situations and/or purposes
Vehicle state information	Current speed	• Supporting driver vehicle longitudinal control, especially in a speed-limit zone
	Cruise control-related information	• Informing driver of cruise control system mode and setting • Preventing driver errors and supporting vehicle longitudinal control • Enhancing driver-automation interaction
	Gear shift-related information	• Informing driver of gear position and vehicle operation mode • Preventing driver errors • Suggesting the optimal gear position to improve manual driving performance
	System messages	• Informing driver of vehicle malfunctions or oncoming problems • Enabling timely vehicle maintenance • Ensuring undisrupted driving and improving driving safety
	RPM/Tachometer	• Informing driver of vehicle's engine status • Helping drivers decide when to shift gears on a manual transmission • Improving driving performance and fuel economy
	Fuel-related information	• Indicating the need to obtain more fuel when fuel is low • Ensuring undisrupted driving
	High beam status	• Informing driver of high beam status • Improving driver perception of outside environment • Useful when visibility is low • Improving safety

(Continued)

Information types		Usage situations and/or purposes
Vehicle state information	Turn signal status	• Informing driver of turn signal status • Providing feedback to driver on his/her own action
	Parking assist system status	• Informing driver of parking assist system status • Reducing human errors • Enhancing driver-automation interaction
	Hybrid system status	• Informing driver of hybrid system status, such as power driving mode, battery status, power/torque distribution status, etc. • Applicable only to hybrid vehicles
	Race car-related information	• Informing driver of car race-related information, such as gear position and lap information • Useful for car race • Improving driving performance
	Brake assist system status	• Informing driver of brake assist system status • Reducing human errors • Enhancing driver-automation interaction
	Electronic stability control status	• Informing driver of electronic stability control status • Helping minimize the loss of control • Improving driving safety
	Eco-driving status	• Informing driver of vehicle eco-driving mode • Helping reduce fuel consumption and carbon dioxide emission
	Tire pressure status	• Enabling early detection of tire problems • Ensuring undisrupted driving • Improving driving safety

(Continued)

Information types		Usage situations and/or purposes
Safety information	Collision warning (including blind spot detection, distance alert)	• Informing driver of an impending collision, and helping to prevent a collision or reduce the severity of a collision • Improving driving safety
	Road signs notification/warning	• Improving driver perception of road signs or warnings • Improving driving safety
	Lane keeping-related information	• Warning the driver of unintentional lane departures • Improving driving safety
	Night vision-related warning	• Increasing driver awareness in a dark environment • Helping detect potential hazards • Improving driving safety
Navigation information	Navigation instructions	• Providing driver with navigation instructions and information on best route • Helping drive in unfamiliar areas • Improving driving performance and safety
	Remaining distance	• Informing driver of remaining distances to the next turn, and, thereby, helping driver to know when to turn • Improving driving performance and safety
	Compass heading	• Providing compass direction to driver • Helping driver drive without navigation instructions

(Continued)

Information types		Usage situations and/or purposes
Communication/ infotainment information	Radio-related information	• Providing driver with radio-related information, such as current radio station, station frequency, etc. • Supporting driver interaction with an in-car entertainment system • Improving driver experience
	Audio player status	• Providing driver with audio player information, such as song title, media type, etc. • Supporting driver interaction with an in-car entertainment system • Improving driver experience
	Phone call-related information	• Providing driver with phone call-related information, such as incoming calls, phone call history, etc. • Supporting driver interaction with an in-car communication system • Improving driver experience.
	Voice recognition system status	• Informing driver of voice recognition system status • Supporting driver-vehicle/driver-AI interaction • Improving driving performance and driver experience.
Outside environment information	Outside temperature	• Informing driver of outside temperature • Improving driver situation awareness (outside environment)

Table 2.4: Information displayed by existing commercial automotive HUDs

Manufacturers		General Motors (21)	Toyota (18)	BMW Group (15)	Honda (14)	SAAB (13)	Hyundai/ KIA (10)	Mercedes-Benz (8)	PSA Peugeot Citroen (8)	Mazda (8)	Audi (8)	Volvo (7)	Jaguar Land Rover (5)	Renault (5)	Bentley (5)	Ford (2)
Vehicle state information	Current speed (14)	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
	Cruise control-related information (14)	●	●	●	●		●	●	●	●	●	●	●	●	●	●
	Gear shift-related information (8)	●	●	●	●	●		●		●			●			
	System messages (7)	●	●	●	●	●			●			●				
	RPM / Tachometer (5)	●	●	●	●	●										
	Fuel-related information (5)	●				●	●	●	●							
	High beam status (3)	●				●			●							
	Turn signal status (2)	●				●										

(Continued)

Manufacturers		General Motors (21)	Toyota (18)	BMW Group (15)	Honda (14)	SAAB (13)	Hyundai / KIA (10)	Mercedes-Benz (8)	PSA Peugeot Citroen (8)	Mazda (8)	Audi (8)	Volvo (7)	Jaguar Land Rover (5)	Renault (5)	Bentley (5)	Ford (2)
Vehicle state information	Parking assist status (2)		●			●										
	Hybrid system status (2)		●		●											
	Race car-related information (2)	●						●								
	Brake assist status (2)		●							●						
	Electronic stability control status (1)	●														
	Eco-driving status (1)		●													
	Tire pressure status (1)	●														

(Continued)

Manufacturers		General Motors (21)	Toyota (18)	BMW Group (15)	Honda (14)	SAAB (13)	Hyundai/ KIA (10)	Mercedes-Benz (8)	PSA Peugeot Citroen (8)	Mazda (8)	Audi (8)	Volvo (7)	Jaguar Land Rover (5)	Renault (5)	Bentley (5)	Ford (2)
Safety information	Collision warning (including blind spot detection, distance alert) (11)	●	●	●	●	●	●		●	●		●		●		●
	Road signs notification / warning (11)	●	●	●			●	●	●	●	●	●	●		●	
	Lane keeping-related information (9)	●	●	●	●		●			●	●			●	●	
	Night vision-related warning (2)			●							●					
Navigation information	Navigation instructions (14)	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
	Remaining distance (7)	●	●	●		●	●	●			●					
	Compass heading (4)	●	●		●	●										

(Continued)

Manufacturers		General Motors (21)	Toyota (18)	BMW Group (15)	Honda (14)	SAAB (13)	Hyundai/ KIA (10)	Mercedes-Benz (8)	PSA Peugeot Citroen (8)	Mazda (8)	Audi (8)	Volvo (7)	Jaguar Land Rover (5)	Renault (5)	Bentley (5)	Ford (2)
Communication/ infotainment information	Radio-related information (6)	●	●	●	●		●				●					
	Audio player status (5)	●	●	●	●		●									
	Phone call-related information (4)	●		●	●							●				
Outside environment information	Outside temperature (3)	●	●			●										

*Note that: for each manufacturer in the first row, the number in the parenthesis denotes the total number of information types that one or more of the manufacturer's HUDs display; and, for each information type in the second column, the number in the parenthesis denotes the total number of manufacturers whose HUDs (one or more) display it.

2.3.2 Information Types Previously Suggested for Automotive HUDs by Research Studies

Forty-one research studies identified from the literature search have proposed prototype HUD systems, each of which displayed particular types of information. They reflect the researchers' views on the functional requirements of automotive HUD. It was found that many of these information types were not supported by existing commercial automotive HUD systems.

The information types displayed by the prototype HUD systems were organized into a hierarchical structure of information categories employing the KJ method (card sorting). The resulting hierarchical structure consists of two main information categories, which are: the conventional driving-related, and the autonomous driving- and non-driving-related information category; each of the two information categories contains multiple information sub-categories, and each sub-category, lowest-level information types.

The conventional driving-related information category includes information types directly relevant to the driver tasks for maneuvering a conventional vehicle which Geiser (1985) referred to as primary driving tasks. The category consists of eight sub-categories: hazard warnings, traffic sign/signal notifications, night vision images, road visibility improvement, future state predictions, driving instructions, route planning information, and driver state/behavior feedback.

The autonomous driving- and non-driving-related information category is composed of six sub-categories: autonomous driving-related information, conventional communication-related information, driver-to-driver communication information, driver-to-passenger/passenger-to-driver communication information, outside environment information, and entertainment contents.

Table 2.5 describes each of the information types examined, within the hierarchical structure of information categories and sub-categories.

Table 2.5: Information types suggested for automotive HUDs by past research studies and their categorization

Main category	Sub-category & purposes	HUD information	References
Conventional driving-related information	Hazard warnings: • Supporting detecting and avoiding hazards in the environment • Improving driver situation awareness (obstacles/objects) • Improving safety	Lead vehicle warnings	Charissis and Papanastasiou (2008); Park and Kim (2013)
		Lane departure warnings	Charissis and Papanastasiou (2008); Lee et al. (2015); Park and Kim (2013)
		Pedestrian warnings	Park and Kim (2013)
		Locations of possible hazards (e.g., upcoming crash)	Tonnis and Klinker (2006); Tonnis et al. (2005)
		Locations of possible hazards (e.g., other vehicles and pedestrians) and their dangerousness levels	George et al. (2012)
		Directions of possible hazards and the recommended steering wheel angle movements	Maag et al. (2015)
		Visually concealed hazards warnings	Plavšic et al. (2009)
		Blind spot image	Suzuki and Hashimoto (2012)
	Traffic sign/signal notifications: • Helping drivers comply with regulations • Improving driver situation awareness (traffic system) • Improving safety	Traffic sign notifications (e.g., speed limit, children, highway exits, etc.)	Lee et al. (2015); Park and Kim (2013)
		Traffic signal-related information presented when approaching an intersection (e.g., 'Prepare to stop' and 'Signals ahead')	Caird et al. (2008)
		Traffic signal-related information in two modes (real-time upcoming traffic signal information and predicted upcoming traffic signal information considering the time to approach)	Yang et al. (2016)

(Continued)

Main category	Sub-category & purposes	HUD information	References
Conventional driving-related information	Night vision images: • Supporting detection and avoidance of hazards in the environment in a dark environment • Improving driver situation awareness (obstacles/objects) • Improving safety	Highlighted infrared image of pedestrian	Tsuji et al. (2002)
		Night vision images of a pedestrian or animal *Note: This night vision system was adaptive as it was only lit up when the system detected potential hazards.	Kovordányi et al. (2006)
		Night vision alerts of possible hazards and their dangerousness levels	Park et al. (2015)
	Road visibility improvement: • Supporting visual road perception and understanding in a low visibility environment • Improving driver situation awareness (road) • Improving safety	Lane marking for improving road visibility	Alexander (2005); Charissis and Papanastasiou (2008)
		Enhanced ego lane information	Biswas and Xu (2015)
		Enhanced-vision images of the road scene	Halmaoui et al. (2014); Tarel et al. (2012)
	Future state predictions: • Supporting driver prediction of future state of the vehicle and the environment • Improving driver situation awareness (prediction) • Improving driving performance and safety	Trajectory curve (the vehicle's future path with the current acceleration) and safety boundary curve (the vehicle's future path with full acceleration) indicator for hard cornering	Kruit et al. (2005)
		Braking distance and drive-path indicator representing the safety boundary area	Tonnis et al. (2007)
		Oncoming vehicle's future virtual projected path of three seconds *Note: This system intended to help the driver make left-turns safely across oncoming traffic without a protected left-turn signal.	Tran et al. (2013)
		Upcoming traffic congestions	Charissis and Papanastasiou (2008)
		Traffic signal-related information in two modes: real-time upcoming traffic signal information and predicted upcoming traffic signal information considering the time to approach	Yang et al. (2016)

(Continued)

Main category	Sub-category & purposes	HUD information	References
Conventional driving-related information	Driving instructions: • Supporting wayfinding and avoiding hazards • Reducing driver workload • Improving driving performance and safety	Navigation instructions	Charissis and Papanastasiou (2008); Park and Kim (2013)
		Navigation instructions using points of interest (POI) *Note: POIs are the places or objects that the driver might be interested in, such as nearby famous restaurants, tourist attractions, notable roadside buildings, etc.	Lin et al. (2011)
		Real scene-based route guidance utilizing photos obtained from the social media	Chang et al. (2015)
		Lane change instructions/recommendations for upcoming intersections or highway exists	Lee et al. (2015); Park and Kim (2013); Yoon et al. (2014)
		Subliminal visual cues enhancing the driver's awareness of traffic signs *Note: The subliminal visual cues were represented as briefly flashed visual stimuli.	Riener and Jeon (2012); Riener and Thaller (2014)
		Directions of possible hazards and the recommended steering wheel angle movements	Maag et al. (2015)
	Route planning information: • Supporting vehicle route planning • Improve driver decision making • Improving driving performance	Estimated times to destination for alternative routes	Chu and Joseph (2008)

(Continued)

Main category	Sub-category & purposes	HUD information	References
Conventional driving-related information	Driver state/behavior feedback: • Supporting detection of driver problems • Improving driver skills • Improving driving performance	Driver's state alert *Note: This system provides implicit and ambient visual feedback on the driver's state (drowsiness and distractions) in the driver's viewing direction	Beyer et al. (2010)
		Verbal corrective advice on driving style for safe and economical driving (e.g., 'Try to avoid sudden movements of the steering wheel.')	Karvonen et al. (2006)
		Real-time, quantitative driving behavior information for encouraging fuel-efficient and safe school bus driving (amount of engine idle time, current acceleration/deceleration rate, and miles per gallon)	Pace et al. (2007)
		Real-time electric vehicle driving advice for promoting efficient driving (energy consumption scales, and coaching advice icons for stabilizing velocity, smoothing out acceleration/deceleration, and avoiding hydraulic brake usage)	Jagiellowicz-Kaufmann et al. (2015)
Autonomous driving- and non-driving-related information	Autonomous driving-related information: • Supporting human interaction with automated systems (automated highway, autonomous vehicles, cooperative driving) • Improving driving performance and safety	Automated highway information (vehicle operation mode, vehicle-to-vehicle gap, and current lane position)	Cha and Park (2006)
		Partially-automated vehicle status information about the longitudinal and lateral control	Wulf et al. (2015)
		Notification of an imminent handover of control for Level 3 autonomous vehicles	Politis et al. (2015)
		Communication information for cooperative driving among highly automated vehicles (e.g., lane change action arrows, gap information, and cooperation partner information)	Zimmermann et al. (2014)
	Conventional communication-related information: • Supporting driver communication with other people • Improving driver experience	Phone call-related information (incoming call notification, remaining time to answer the phone under a suitable situation, and voice message-related information), and SMS and email arrival notifications	Charissis et al. (2007)

(Continued)

Main category	Sub-category & purposes	HUD information	References
Autonomous driving- and non-driving-related information	Driver-to-driver communication information: • Supporting driver communication with other drivers • Improving driving performance and safety • Improving driver experience	Driver's sign of appreciation for another driver's behavior (a thumb-shaped icon) *Note: A gesture-based HUD system was developed.	Wang et al. (2014)
		Communication information for cooperative driving among highly automated vehicles (e.g., lane change action arrows, gap information, and cooperation partner information)	Zimmermann et al. (2014)
	Driver-to-passenger/passenger-to-driver communication information: • Supporting driver-passenger communication • Improving driver and passenger experience	Gaze visualization that indicates where the passenger is looking at (for supporting the driver-passenger collaboration)	Maurer et al. (2014)
	Outside environment information: • Providing driver with information about the things in the environment • Improving driver experience	Location of an outside target that the driver points at while holding the steering wheel *Note: A gesture-based HUD system was developed.	Fujimura et al. (2013)
	Entertainment contents: • Reducing the boredom of driving and improving drive engagement • Improving driving experience (fun)	Video game-related information *Note: Two games, 'rewards of glory' and 'zombies on the road,' were illustrated as examples.	Schroeter et al. (2014); Steinberger et al. (2015)

2.3.3 Information Types Required by Drivers (users) for Automotive HUDs and Their Relative Importance

As mentioned earlier in Method, the literature search identified three studies relevant to Research Question 3. In each of the studies, the study participants were provided with a set of predetermined information types and were instructed to evaluate the information types in perceived importance/preference. Table 2.6 provides a summary of the three studies describing their major findings and study methods. The sets of information types employed in these studies differed much from one another, as shown in Table 2.6. The research studies did not examine the situations, tasks or purposes for which the different information types are used. Detailed descriptions of the studies are provided in what follows.

Moon and Park (1998) examined the relative importance of information employing the analytic hierarchy process (AHP) technique. Prior to the user evaluation, nine different information types were identified by analyzing conventional displays in the dashboards of existing vehicles. Information typically not presented on the dashboards, such as speed limit, pedestrian warnings, email notifications, etc., was not considered in this study. 30 male participants, ranging in age from 25 to 32 years (mean age 28.4 years), participated and all had a driver's license. The study found that fuel level was perceived to be the most important information, followed by engine overheating status, turn signal status, battery level, brake status, current speed, door open status, seat belt status and emergency light status.

Park et al. (2012) conducted a survey to determine the relative importance of various HUD information types. A total of thirty-three types of HUD information were considered and grouped into four categories: vehicle state, vehicle maintenance, navigation and surroundings awareness. The relative importance of information was determined within each information category. 34 participants aged from 20 to 49 years participated in this study. As for the vehicle state category, it was found that current speed, gearshift position and fuel level were of the highest priority, followed by RPM, HVAC system status, temperature, total distance traveled, IT devices connection status and ECO status. Regarding the information types within the vehicle maintenance category, the order of priority was as follows: brake status, tire pressure, coolant level, engine status, battery level, door open status, side mirror status, engine oil level and airbag status. Among the information types within the navigation category, speed limit was found to be the most important information, followed by remaining distance to arrival, remaining time to arrival, current location, traffic condition, turn-by-turn navigation instructions, turn signal status, and the name of destination. As for surroundings awareness, the most important information was collision warnings during parking, followed by pedestrians in the vicinity, traffic lights, locations of nearby gas stations, distances from driving/parking lanes, locations of nearby parking lots, and locations of nearby car washes.

Guo et al. (2014) surveyed 545 Chinese drivers on their attitude to automotive HUD systems. The participants (age range of 25-50 years) having a driver's license evaluated ten types of HUD information. The study found that the HUD information perceived as the most needed was gap, that is, the distance to the lead car. Current speed was ranked second, followed by traffic condition, speed of the lead car, failure notification, turn signal status, navigation, fuel level, engine speed and tire pressure. The authors recommended that the first four types of information, that is, distance to the lead car, current speed, traffic condition, and speed of the lead car, should be considered high-priority for HUDs.

Table 2.6: Information types required by drivers (users) for automotive HUDs and their relative importance

References	HUD information		Research methods
Moon and Park (1998)	Fuel level Engine overheating status Turn signal status Battery level Brake status Current speed Door open status Seat belt status Emergency light status		• 30 participants (25-32 years) were recruited. • Only the information types of conventional HDDs were considered.
Park et al. (2012)	Vehicle state	Current speed, Gearshift position, Fuel level RPM HVAC system status Temperature Total distance traveled IT devices connection status ECO status	• 34 participants (20-49 years) were recruited. • The information types were divided into four categories, and the relative importance of information was determined within each information category.
	Vehicle maintenance	Brake status Tire pressure Coolant level Engine status Battery level Door open status Side mirror status Engine oil level Airbag status	

(Continued)

References	HUD information		Research methods
Park et al. (2012)	Navigation	Speed limit Remaining distance to arrival Remaining time to arrival Current location Traffic condition Turn-by-turn navigation instructions Turn signal status Name of destination	
	Surroundings awareness	Collision warnings during parking Pedestrians in the vicinity Traffic lights Location of nearby gas stations Distances from driving/parking lanes Locations of nearby parking lots Locations of nearby car washes	
Guo et al. (2014)	Distance to the lead car Current speed Traffic condition Speed of the lead car Failure notification Turn signal status Navigation Fuel level Engine speed Tire pressure		• 545 participants (25-50 years) were recruited. • 7.24% of 545 participants had experience of using automotive HUDs.

*Note: The HUD information in each cell of the second column is in the order of importance, and the highest priority information is in bold.

2.4 Discussion

2.4.1 Information Types Displayed by Existing Commercial Automotive HUD Systems

As shown in Table 2.3, the existing commercial HUD systems collectively display a variety of information types to improve driving performance, safety and driver experience – a total of 27 information types were identified. One notable observation from Table 2.3 was that none of the 27 information types were created specifically for automotive HUDs – they represent information types currently provided by conventional in-vehicle displays (dashboard and navigation system displays), and, thus, have identical usage situations and purposes (Table 2.3).

Related to the above observation, it should be noted that in most of the current HUD-equipped vehicles, the information displayed by the HUDs is also displayed by the conventional in-vehicle displays. This redundancy or duplicate presentation seems to suggest that the manufacturers conceptualized their HUD systems as an additional complement for the conventional displays.

The conceptualization of HUDs as a complement for the conventional in-vehicle displays may be reasonable as the information types displayed by the conventional displays represent some of the key information for driving. Allocating them within the easily accessible forward FoV would likely benefit driving as long as the HUD system's interface was designed to achieve a high usability - note that a product's overall usefulness is determined by both its utility and usability (Nielsen, 1994), as depicted in Figure 1.1. However, some questions arise as to the role of automotive HUDs within the continuously evolving in-vehicle displays system:

- Among the various information types of the conventional displays, which ones should be displayed redundantly by both a HUD and a conventional display and which ones, by either one of the two? In other words, what is the best way to allocate the information types of the conventional in-vehicle displays between the two display areas?

- Should HUDs be utilized only as a complement for conventional in-vehicle displays? Could they be utilized to display novel and/or non-conventional information types to enhance driving experience? Also, what are the possible roles of HUDs in future vehicles?

Table 2.4 shows the information types that each manufacturer supports with its HUDs. It was found that some of the 27 information types were commonly supported by majority of the automobile manufacturers - current speed, cruise control, and navigation instructions were supported by 14 out of the 15 manufacturers; also, collision warning and road signs notification/warning were supported by 11 manufacturers. The commonality seems to indicate a view shared by the manufacturers that one major function of automotive HUDs is to support primary driving tasks, such as vehicle longitudinal control, navigation and detection of safety hazards.

Aside from the commonality, Table 2.4 also revealed that the manufacturers varied substantially in the number of vehicle models equipped with a HUD system and in the set of information types their HUDs display. General Motors, which pioneered the adoption of the HUD technology in the automotive industry, offered a HUD to eleven of its vehicle models; and, combined together, their HUDs displayed the most (21) information types. On the other hand, Ford had three HUD-equipped vehicle models, which presented the smallest number (2) of information types. General Motors, Toyota, BMW Group, Honda and SAAB supported relatively many (13-21) information types while Jaguar Land Rover, Renault, Bentley and Ford, a small number of (2-5) information types.

It is not clear what gave rise to the observed differences between the automobile manufacturers in the set of information types supported. It would be interesting to understand how each manufacturer determined the types of information that its HUD systems support; however, gathering information on the manufacturers' in-house research activities and findings is extremely difficult, if not impossible. The observed differences may perhaps reflect the differences in the automobile manufacturers' product differentiation strategies. Another possibility is that the manufacturers have different views on the range of useful HUD functions that benefit driving, that is, the role of automotive HUDs within the in-vehicle displays system.

Related to the differences between the manufacturers described above, it is thought that the range of information types a HUD system displays would affect its utility and usability in a different manner. Increasing the range of information types would tend to enhance a HUD system's utility if the information types indeed addressed the drivers' actual information needs/wants in their driving contexts. However, a design decision to support more information types with a HUD system inevitably leads to increased system complexity, which in turn increases the difficulty of creating a user interface with high usability. It is thought that such a trade-off relationship between utility and usability needs to be taken into account with great care when determining the set of information types to be supported by an automotive HUD system. While multiple previous studies (Gish et al., 1999; Horrey and Wickens, 2004; Liu et al., 2004; Medenica et al., 2011; Nwakacha et al., 2013; Palinko et al., 2013; Steinfeld and Green, 1995; Weinberg et al., 2011) demonstrated the advantages of displaying information in the driver's FoV using HUDs, other studies (Gish and Staplin, 1995; Pauzie, 2015; Tufano, 1997; Ward and Parkes, 1994) reported potential safety concerns associated with the use of HUDs, such as visual clutter and cognitive capture. Therefore, increasing the number of supported information types at the cost of reduced interface usability could become detrimental to driving safety. The impacts of design decision on the utility, usability and overall usefulness must be evaluated.

Good interface design based on the display design principles (Wickens et al., 2003), to some extent, would enable supporting a variety of information types within an automotive HUD system without creating the safety problems mentioned above or exceeding the human information processing capacities. However, how to accomplish that is not well understood. Currently, it is unknown what type of interface is the best for automotive HUD systems and what and how much information can be safely and effectively displayed by automotive HUDs (Gish and Staplin, 1995; Pauzie, 2015; Tufano, 1997; Ward and Parkes, 1994); no detailed interface design standards/guidelines specific to automotive HUDs are currently available. Overall, given the lack of detailed design guidance, it is thought that designing a useful HUD system requires the following efforts: 1) determining the information types that represent actual information needs of the drivers and their usage contexts, and, 2) creating different design alternatives that vary in the number of supported information types (selected among those representing actual driver information needs) and the interface design, and, comparatively evaluating them in terms of utility, usability and overall usefulness.

This study reviewed the way the commercial HUD systems presented different information by examining available vehicle manuals (see Appendix A). Each of the commercial HUD systems utilized a single or multiple display layouts based on a particular HUD display space allocation scheme. For most of the commercial HUD systems, the display layout(s) was not static but dynamic in that its content and configuration could change according to the change in situation or the occurrence of a certain event or condition; safety warnings or user action feedback could be displayed interruptively.

The idea of using a particular display space allocation scheme can be beneficial if it is designed to be compatible with the drivers' expectations or mental models. Also, providing multiple optional display layouts and event-driven, interruptive displays seems to be a solution to the problem of presenting a wide variety of information types within a HUD system.

Again, as described above, the existing commercial HUD systems differed in the range of information types supported and the interface design. Naturally, they would differ in product utility, usability and usefulness. However, such differences are currently not well understood - little research seems to have been conducted to compare existing commercial HUD systems in some measures of HUD utility, usability and/or usefulness. Related to this, it should be pointed out that measures of automotive HUD utility and usefulness currently do not seem available at least in scholarly articles while previous research studies have defined different usability measures focusing on the primary and secondary task performance during driving (Gish et al., 1999; Horrey and Wickens, 2004; Liu et al., 2004; Medenica et al., 2011; Nwakacha et al., 2013; Palinko et al., 2013; Steinfeld and Green, 1995; Weinberg et al., 2011).

The existing commercial HUD systems were also found to enable the drivers to create individual-specific display layouts by allowing them to activate or deactivate any of the information types in a display layout through changing the product settings. This capability seems highly beneficial as it allows maximizing usefulness of HUD systems at the individual driver level and for each particular driving situation, and, thereby, improves the overall usefulness of the product at the population level. One potential problem, however, might be the costs (time and efforts) involved in changing the display setting. Design solutions for minimizing the display setting costs would be needed in order for the drivers to fully utilize the feature.

2.4.2 Information Types Previously Suggested for Automotive HUDs by Research Studies

As summarized in Table 2.5, previous research studies have proposed displaying various information types through HUDs. Two main information categories emerged from them: the conventional driving-related information category, and the autonomous driving- and non-driving-related information category. The conventional driving-related information category included the following sub-categories: hazards warnings, traffic sign/signal notifications, night vision images, road visibility improvement, future state predictions, driving instructions, route planning information, and driver state/behavior feedback. The autonomous driving- and non-driving-related information category consisted of the following sub-categories: autonomous driving-related information, conventional communication-related information, driver-to-driver communication, driver-to-passenger/passenger-to-driver communication information, outside environment information and entertainment contents.

As for the information types in the conventional driving-related information category, a significant portion of them pertained to improving driving safety – for example, see the information types in the 'hazards warnings', 'traffic sign/signal notifications', 'night vision images', 'road visibility improvement', and 'future state predictions' subcategories. The prototype HUD systems displaying these safety-related information types aimed at enhancing the driver's situation awareness (SA) at some or all of the three levels of SA: perception, comprehension, and projection (Endsley, 1995). Level 1 SA, that is, perception of important elements and events in the environment, was improved generally by enlarging the natural human perceptual volume of space and time by presenting information from sensors (Alexander, 2005; Biswas and Xu, 2015; Caird et al., 2008; Charissis and Papanastasiou, 2008; Halmaoui et al., 2014; Kovordányi et al., 2006; Lee et al., 2015; Park and Kim, 2013; Park et al., 2015; Plavšic et al., 2009; Suzuki and Hashimoto, 2012; Tarel et al., 2012; Tonnis and Klinker, 2006; Tonnis et al., 2005; Tsuji et al., 2002); such information could not be acquired by unassisted human sensory organs. Following up with the latest advances in the sensor technologies and linking them with HUDs would likely help designers ideate new automotive HUD functions, since the available technologies could serve as design inputs as shown in Figure 1.1. The prototype HUD systems by George et al. (2012), Maag et al. (2015) and Park et al. (2015) enhanced Level 2 SA (defined as comprehension of the current situation) by providing interpretation of the current situation – they presented dangerousness levels of possible hazards and recommended steering wheel angle movements. HUD designs investigated by Charissis and Papanastasiou (2008), Kruit et al. (2005), Tonnis et al. (2007), Tran et al. (2013) and Yang et al. (2016) improved Level 3 SA (defined as projection of future status) by offering predictions of future states and events. Interestingly, these displays did not offer any interpretations – leaving the interpretation to the human driver may be appropriate unless the machine interpretation is extremely accurate and reliable. Also, too much interpretation of the environment for the driver might reduce the driver's situation awareness.

The view that HUDs are a means for improving driving safety, implied by the above-mentioned safety-related information types, seems to be predicated upon the widely believed advantage of HUDs, that is, reduced EoRT and reaccommodation demands (Gish et al., 1999; Horrey and Wickens, 2004; Liu et al., 2004; Medenica et al., 2011; Nwakacha et al., 2013; Palinko et al., 2013; Steinfeld and Green, 1995; Weinberg et al., 2011). Also, it might be further justified on the basis of human factors display design principles, such as the principles of minimum information access cost and proximity compatibility (Wickens et al., 2003) - HUDs can reduce the information access cost by displaying the information in the driver's FoV, and AR HUDs in particular allow references to be displayed close to the referents affording more efficient information processing. However, as mentioned earlier, the use of HUDs could also create a new set of problems to the drivers, such as masking of external targets, visual clutter, misaccommodation, and cognitive tunneling, and, may adversely affect driving safety in certain situations (Gish and Staplin, 1995; Pauzie, 2015). Thus, newly proposed HUD functions (including those purporting to improve driving safety) and their interfaces must be evaluated in terms of the risks of such potential side-effects.

The information types in the autonomous driving- and non-driving-related information category have been proposed recently, especially during the past five years (2011~2016). These new information types seem to reflect the profound shift in the meaning of automobile and driving that has started to take place at the beginning of the century. Emerging autonomous vehicle and other technological innovations are expected to transform human activities inside a vehicle (Anderson et al., 2014), and, such changes will result in a new set of user information needs and wants (see Figure 1.1). Automotive HUDs may become a key for addressing some of such new needs and wants although predicting what they will eventually display and for what purposes is difficult – despite the uncertainty, however, it is expected that many attempts will be made to utilize automotive HUDs for non-driving activities, such as gaming and socializing.

The information types summarized in Table 2.5, which represent the researchers' point of view, illustrate how the automotive HUD technology can be combined with others to produce potentially useful applications – all of them were the results of combining HUDs with budding and blooming technologies, such as sensors, augmented reality, artificial intelligence, the internet of things, connected cars, etc. Indeed, HUDs possess one characteristic that would make them suitable for bringing the benefits of emerging technologies to the driver: it naturally connects the driver and the technological elements designed to perceive and act upon the physical environment, in the physical environment itself.

Finally, it is perhaps worth pointing out that most of the information types shown in Table 2.5 have not been adopted in commercial HUD systems. While the reasons are not clear, a couple of possible explanations are suggested here: first, for some of the information types presented in Table 2.5, they could not be adopted in commercial HUD systems because they require currently unavailable, immature or prohibitively expensive technologies. For example, presenting oncoming vehicle's future virtual projected path (Tran et al., 2013) or video game-related information (Schroeter et al., 2014; Steinberger et al., 2015) requires the full-windshield HUD technology, which is known to be expensive and technically difficult for the implementation in passenger cars at this time. Second, information types, such as notification of an imminent handover of control (Politis et al., 2015), and communication information for cooperative driving among highly automated vehicles (Zimmermann et al., 2014), are for high-level autonomous driving. However, such high-level autonomous driving is not part of our daily life yet. Third, some of the information types, for example, video game-related information (Schroeter et al., 2014; Steinberger et al., 2015), may not be justified in terms of its costs and benefits - while such features may improve certain aspects of driver experience, they may give rise to serious side effects, such as driver distractions. It would also be extremely difficult to integrate such information into a commercial HUD system without compromising the interface usability.

2.4.3 Information Types Required by Drivers (users) for Automotive HUDs and Their Relative Importance

The literature searches identified only three studies concerning Research Question 3 (Table 2.6). As mentioned earlier, in each of these studies, the study participants were provided with a set of pre-determined information types and were instructed to evaluate them in perceived importance/preference.

The three studies were found to differ substantially in their key findings, that is, the user-perceived high-priority HUD information types (Table 2.6). This is not surprising when considering the differences in the research methods - the studies employed very different sets of predetermined information types, and also differed substantially in the number of study participants. The differences in the sets of predetermined information types seem to reflect each study's unique research context, such as the time of publication and the particular design problem considered.

All in all, it is thought that the three studies have limited value in helping address Research Question 3. Two major limitations of the studies are as follows:

- The studies did not examine the usage situations/contexts of the HUD information types considered ("who needs a particular information type and when or for what purposes?"). Therefore, they provide little information concerning the design of automotive HUD systems that are capable of displaying the right kind of information at the right moment in an individually-tailored manner. The information needs and wants of

HUD users are time-varying and situation-dependent and different individuals have disparate information needs and wants according to their lifestyle, interests and work tasks. The design of useful HUD systems should be therefore aimed at addressing diverse and changing needs in a flexible and intelligent manner. Indeed, currently, many of the commercial HUD systems are, to some extent, reconfigurable/customizable (Selker et al., 2002) or adaptive (Dijksterhuis et al., 2012; George et al., 2012; Kovordányi et al., 2006) (see Appendix A for detailed descriptions).

- While the studies mostly did not describe the characteristics of the study participants in detail, it appears that they did not utilize specific participant inclusion or exclusion criteria related to the prior experience of using automotive HUD systems. Given that fact that automotive HUDs have not been widely available, it is likely that only a small portion of the study participants had had any prior experience of using HUDs – for example, in Guo et al. (2014), only 7.24% of 545 subjects had experience of using automotive HUDs. This may represent a serious limitation – one may not be able to accurately judge what HUD information is important and what is not without actual experience of using automotive HUDs in the real-world driving contexts. A previous literature review by Harrison (1994) also pointed out the possible effects of prior use experience on the perception of HUDs.

Further research studies are needed to address the current lack of knowledge and data concerning Research Question 3.

Chapter 3

A Literature Review on Interface Design of Automotive Head-Up Displays for Communicating Safety-Related Information

3.1 Introduction

HUD systems were introduced into the automobile industry in the 1980s, as a means for improving driving safety. They superimpose safety-critical information on top of the driver's FoV, and, thereby, help drivers keep their eyes forward while driving. Compared with traditional head-down displays (HDDs), HUDs are known to reduce the driver's EoRT (Gish et al., 1999; Horrey and Wickens, 2004; Liu et al., 2004; Medenica et al., 2011; Nwakacha et al., 2013; Palinko et al., 2013; Steinfeld and Green, 1995; Weinberg et al., 2011). Large EoRT is a safety hazard (Dingus et al., 1997), and, thus, reducing EoRT could offer some advantages.

However, simply providing safety-related information in the driver's FOV through HUDs does not guarantee improving driving performance and safety. In order to provide the intended benefits, HUDs must be designed such that they respect the characteristics and capacities of the human information processing system, and, also, conform to the characteristics of the information to be presented and accommodate the specific contexts of information use. Poorly designed HUDs indeed can adversely affect driving safety by creating new sets of problems, including visual clutter, information overload, inattentive blindness and cognitive capture (Gish and Staplin, 1995; Pauzie, 2015; Tufano, 1997; Ward and Parkes, 1994). These problems have a direct impact on the usability and further on the usefulness of the system (Park and Park, 2019). Therefore, how to present the information through HUDs, that is, the interface design of HUDs is crucial for the development of useful automotive HUDs.

Several research efforts have been directed toward the interface design of automotive HUDs from a human factors point of view. For example, there have been some literature reviews on the safety and human factors issues pertinent to the interface design of automotive HUDs (Gish and Staplin, 1995; Harrison, 1994; Tufano, 1997; Ward and Parkes, 1994). A few studies have investigated the impacts of display design variables of HUDs, such as color (Choi et al., 2013; Huang et al., 2013; Moon et al., 1998), display type (analog vs. digital) (Huang et al., 2013; Moon et al., 1998), layout (Park et al., 2012) and display location (Chao et al., 2009; Flannagan et al., 1994; Morita et al., 2007; Horrey et al., 2004; Tangmanee et al., 2012; Tsimhoni et al., 2001; Tretten et al., 2011; Yoo et al., 1999).

Despite previous research efforts, however, research gaps still appear to exist in determining the optimal interface design of automotive HUDs. During the last few decades, and in recent years in particular, various research studies have proposed different HUDs that present safety-critical information in particular styles. However, it is not well understood what type of display would be most advantageous or adequate for effectively communicating safety information and thus best serve the driver in performing the associated driving task. Relatively little research has been conducted to evaluate the available HUDs in the interface design.

As an initial effort towards addressing the knowledge gap, the objective of the current study was to provide a review of the interface design of automotive

HUDs for communicating safety-related information. The research questions to address the study objective are shown in Table 3.1.

Table 3.1: Research questions of Study 2

Research question	
Research Question 1)	What types of display designs are presented by the existing commercial automotive HUDs for safety-related functions? What are their behaviors and structures, and also related human factors display design principles?
Research Question 2)	What types of display design have been proposed by academic research for automotive HUDs in safety-critical situations? What are their behaviors and structures, and also related human factors display design principles? How effective are the proposed HUD display concepts for users?

In order to organize each type of safety-related HUD system systematically, the function-behavior-structure ontology (FBS ontology) was utilized (Rosenman and Gero, 1998). The FBS ontology helps to provide a concrete description of a design object utilizing the following concepts: purpose, function, behavior, and structure. On the basis of the review results, this review suggested design possibilities and future research directions on the interface design of automotive HUD systems related to safety features.

3.2 Method

This study conducted two literature searches, one for documents describing existing safety-related commercial HUD systems, and, the other one for research articles proposing or evaluating automotive HUDs communicating safety-related information.

The literature search for the existing commercial HUD systems examined

HUD systems provided by fifteen major automobile manufacturers: Audi, BMW Group, Ford, General Motors, Honda, Hyundai/KIA, Jaguar Land Rover, Mercedes-Benz, PSA Peugeot Citroen, Renault, SAAB, Toyota, and Volvo. These fifteen manufacturers were the major commercial vehicle manufacturers. This study did not consider HUDs in concept cars or prototype HUDs as they did not necessarily represent the final commercial products and also it was difficult to find product descriptions for them. For each manufacturer, the HUD systems installed in its models were identified through web searches. Then, other details, including the specifications of the HUD systems and the contexts and purposes of information use, were examined using the vehicle manuals and available YouTube or other video clips on the internet. The commercial HUD systems were searched up to October, 2019.

In order to search the research articles proposing or evaluating automotive HUDs communicating safety-related information, four online databases were utilized: ACM digital Library, Science Direct, Scopus, and Web of Science. The search period was from January 1994 to March 2019. Four concepts were initially selected as the keywords for literature search: HUD, automobiles, information display design, and safety. Then, for each initial keyword, interchangeable and topically related terms were further explored to determine more keywords. The final set of search keywords used for the literature search is shown in Table 3.1. The search formula used for the database searches first combined the keywords within each concept (initially chosen keyword) with the Boolean operator 'OR' and, then, linked the resulting expressions corresponding to the three concepts with the Boolean operator 'AND'. The keywords in Table 3.2 were generic, and, allowed identifying a wide range of documents related to the automotive HUD design.

Table 3.2: Search keywords used for literature review

Keywords areas	Search keywords
HUD	Head up display*, Head-up display*, HUD*
Automobiles	Automotive, vehicle*, car*, automobile
Display interface design	Interface, augmented reality, display, design, human factors, system
Safety information	Safety, warning*, alert*

*Note: An asterisk (*) at the end of a keyword indicates that all terms that start with that root were included in the search.

Based on the search strategy, a total of 576 studies were identified: 69 from ACM Digital Library, 64 from Science Direct, 348 from Scopus, and 95 from Web of Science, respectively. A wide range of documents, including journal articles, conference papers, and other forms of publication, such as master's and doctoral dissertations, and technical reports were collected. For each of the 576 documents, its title, abstract and keywords were examined with the following exclusion criteria: (1) studies that are not related to the interface design of automotive HUDs, (2) duplicate studies, (3) no full-text access supported, and (4) studies that are not written in English or Korean. A total of 102 relevant studies remained after the elimination of unqualified documents. Then, the 102 studies were carefully reviewed to identify the ones relevant to the safety-related HUDs, and those studies were excluded in which the description of the proposed display is not sufficient or the display appears in areas other than the windshield. A total of 24 studies were identified as relevant to safety-related HUDs. The studies in the reference lists of the 24 studies were also examined and 7 additional studies were found. As a result, a total of 31 studies were included in this review.

Each type of safety-related HUD system was described based on the FBS ontology. The definitions of the FBS concepts (Rosenman and Gero, 1998) were slightly modified for the current study. They are as follows:

- Purpose: the reason why a display exists or why it is what it is, what it is intended for;
- Function: the thing a display performs;
- Behavior: the manner in which a display acts under specified conditions;
- Structure: what constitutes a display (or defines its constitution).

In this study, the structure of a display is represented in terms of its form or shape, and display attributes. The form or shape of a display refers to the visible shape or configuration of the components of a display. Display attributes denote design variables such as color, dimensionality, frame of reference, location, etc.

In addition to describing the displays using the FBS ontology, related human factors display design principles were examined, and, where possible, empirical findings on the effects of interface design were reviewed.

3.3 Results

The results are divided into two sub-sections: the first section describing the interface design of existing safety-related commercial HUDs, and, the second, the interface design of automotive HUDs proposed by research studies related to safety-related functions.

3.3.1 Commercial Automotive HUDs Presenting Safety-related Information

Safety-related features on the existing commercial HUD systems include road signs notification, collision warning, lane keeping-related warning, and night vision-related warning (Park and Park, 2019).

Many commercial HUD manuals, such as BMW Group (BMW 3/4/5/6/7/X/M, MINI, Rollsroyce Ghost), Honda (Acura RLX, Accord, Clarity), Hyundai/KIA (Hyundai Aslan/Equus/Genesis, KIA K9), Jaguar Land Rover (Jaguar XE/XF), Mercedes-Benz (C, E, S), Toyota (Lexus RX/HS/GS, Prius), and Volvo (XC90), provided descriptions of the interface designs for road signs notifications (e.g., speed limit displays). Road signs notifications in the manuals utilized the actual traffic signs as a warning symbol in an unregistered presentation manner (Figure 3.1a). Unregistered displays are presented at a fixed location on the windshield without spatial relation to an environmental or in-vehicle object, and thus they do not have to resemble or behave like real 3D objects (Tönnis and Plecher, 2011). The road sign notifications appear, when the road signs are detected and needed for the current driving situations.

The descriptions of collision warnings were provided in Ford (Explorer, Mustang, Taurus), Honda (Acura RLX, Accord) and BMW Group (BMW 4/5/6/7) manuals (Figure 3.1b). The collision warning provided in Ford (Explorer, Mustang, Taurus) manuals consists of a red laser beam. When collision risks are detected, the red warning light illuminates. The collision warning provided in Honda (Acura RLX, Accord) manuals consists of an orange oval symbol. When a potential collision is detected, the orange symbol flashes. The collision warning shown in BMW Group (BMW 4/5/6/7) manuals consists of icons depicting the corresponding hazards, such as pedestrians, animals, and vehicles. When the collision risks are detected, the icon lights up red or flashes depending on the risk levels. All collision warnings provided by commercial HUD systems were displayed in the unregistered manner.

The descriptions of lane keeping-related warning was only provided in Honda (Acura RLX, Accord) manuals and the warning display consisted of a lane marking icon. When the vehicle approaches the edge of a lane, the lane marking icon appears with the corresponding lane displayed in orange (Figure 3.1c). The lane marking warning was also an unregistered display.

The descriptions of night vision-related warning were only shown in Audi (A7/8, S7/8) manuals. The night vision warning utilized the pedestrian or animal warning icons in the unregistered manner. If there are pedestrians or wild animals in front of the vehicle, the warning icons are highlighted in red (Figure 3.1d).

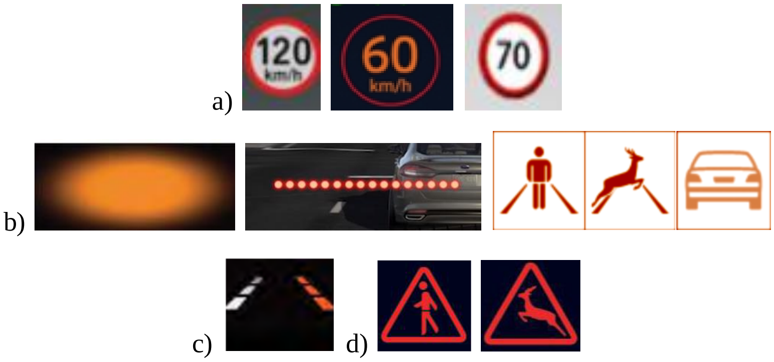


Figure 3.1: Safety-related displays provided by the existing commercial HUDs:
a) speed limit notifications (BMW Group, Mercedes-Benz, Jaguar Land Rover),
b) collision warnings (Honda, Ford, BMW Group),
c) lane keeping-related warning (Honda), and
d) night vision-related warning (Audi)

A summary of safety-related displays provided by the existing commercial HUD systems is presented in Appendix B.

3.3.2 Safety-Related HUDs Proposed by Academic Research

Collision warning (lead vehicle/pedestrian warning)

Alerting collision risks

Kim et al. (2013) proposed three different types of unregistered displays (circle-shaped, slim bar, and thick bar symbols) for lead vehicle warning (Figure 3.2a). The proposed displays were presented at three different locations (top, left side, and right side) on the HUD image plane. A driving simulator-based experiment was conducted to evaluate the utility of the display concepts. Compared with conventional crash warning systems, the display concepts were found to significantly reduce reaction time to front hazard warning when the icons were located at the top. Subjective ranking data showed that the most preferred display was the slim bar. The study participants mentioned that the thick bar display could occlude the outside world and the circle shape display could be confused with other traffic signals or lighting.

Lind (2007) designed a HUD displaying a forward collision warning. The forward collision warning consists of a red laser beam, located at the lower part of the windshield (Figure 3.2b). The effectiveness and preference of the warning was investigated through a driving simulator experiment by comparing four different types of warning systems including HUD: HUD, high HDD, cluster display, and steering wheel display. The result showed that the HUD system was found to be the most effective in terms of reaction time to the warning and the amount of missed warnings. Regarding the preference ratings, the HUD was the highest ranked in the four systems. Barakat et al. (2015) also utilized the same HUD warning concept of the study by Lind (2007) (Figure 3.2c). In an on-road experiment, drivers' eye behavior was analyzed. Two age groups (young and old) were considered. It was found that subjects tended to rarely fixate on the HUD. Also, none of the subjects fixated on the HUD during the warning period or right after the warning; it was suggested the simple HUD design might not distract the driver. In terms of age effects, the older group more glanced at the HUD than the younger group did.

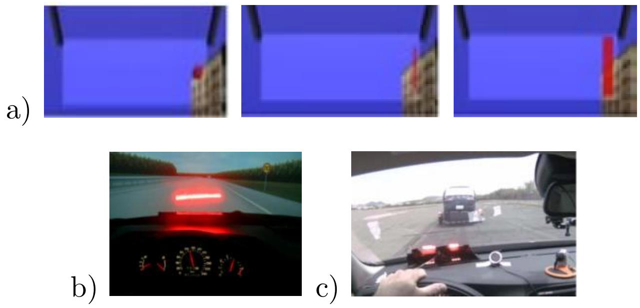


Figure 3.2: Forward collision warnings: a) circle-shaped, slim bar, and thick bar icons, b) a red laser beam (a driving simulator test), and c) a red laser beam (an on-road test)

<u>Alerting collision risks, indicating risk levels of hazards, and identifying the hazards</u>

Politis et al. (2015) compared two types of collision warning displays: an abstract warning, and language-based warning (Figure 3.3). The abstract warning was adaptively displayed with a circle in three colors – red, orange, and yellow. The warning changed from yellow to red according to the urgency levels. The languages-based warning was represented by text messages color-coded in three colors like as the abstract warning. Both unregistered warnings were placed at the top of the windshield. A driving simulator-based experiment was conducted and the abstract warning showed a significantly faster recognition time than the languages-based warning in a low-urgency situation. In a high-urgency situation, however, both displays performed equally in the response task.

a) b)

Figure 3.3: Collision warnings: a) an abstract warning, and b) language-based warning

<u>Alerting collision risks, indicating risk levels of hazards, and identifying the hazards</u>

Kazazi et al. (2015) compared two different warning displays for collision warning: a stop sign and a caution sign (Figure 3.4a). The stop sign induces the immediate reaction to the dangerous situations, whereas the caution sign indirectly warns the drivers indicating the upcoming dangers such as pedestrians, lead vehicle, etc. Both signs were provided in an unregistered presentation manner. Driving behavior was analyzed by age group with several performance measures related to collision avoidance in a driving simulator experiment. The result indicated that in critical situations, the stop sign showed better performance in terms of brake reaction in the older group, while the caution sign, in the younger group. In both groups, the stop sign led to the strongest brake reaction.

Winkler et al. (2015) extended the study by Kazazi et al. (2015) examining more various warning displays. Each warning concept is divided into two styles: generic and specific (Figure 3.4b). In generic style a warning (a red octagon-shaped stop sign or an exclamation mark in a triangle shape) is provided regardless of the situations, whereas in specific style several traffic signs, such as pedestrian sign, bicycle road sign, etc., are selectively provided according to the situations. All but one of the specific warnings (swerving sign) were designed to be familiar since they utilized the traffic signs. The proposed swerving sign was composed of a traffic cone symbol with an arrow indicating the steering direction. Driving performance and eye gaze behavior were analyzed through a driving simulator experiment. The results showed that the swerving sign which was an unfamiliar and less understandable design was the least effective in terms of driving performance and gaze behaviors.

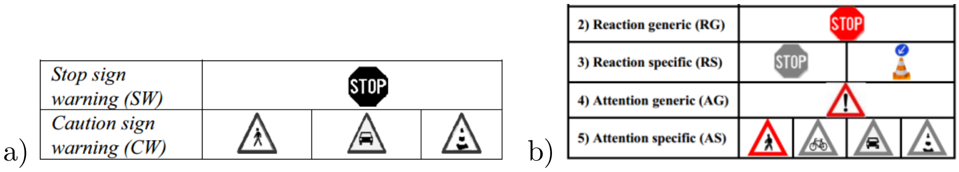


Figure 3.4: Collision warnings: a) a stop sign, and caution sign, b) a generic style, and specific style warning

Alerting collision risks, and indicating the directions/locations of hazards

Chen et al. (2008) developed a bus collision warning system alerting the front and side collisions (Figure 3.5). Three types of unregistered warning symbols consisting of a black crash icon with a red background indicated the directions of potential dangers: left, right, and front side. The symbol was provided with short beep sounds. The proposed concept was evaluated with a bus driving simulator. Four different types of collision warning interfaces were compared: beep sounds, voice, voice with beep sounds, and HUD with beep sounds. The HUD with beep sounds was found to be the best in terms of reaction times to the alerts.

Figure 3.5: Bus collision warning alerting the front and side collisions

Park and Kim (2013) proposed to use a contact-analog green bounding box to alert the vehicle ahead (Figure 3.6a). Contact-analog displays are spatially aligned with the outside world and behave like real objects in the world obeying the same laws of motion perspective (Tönnis, 2008). The proposed concept was prototyped and implemented for real vehicles in an extended study (Yoon et al., 2014). Lubbe (2017) proposed a contact-analog green bounding box to alert suddenly-appearing pedestrians (Figure 3.6b). In order to assess the effectiveness of the proposed display, four different types of interfaces (audio-visual, brake pulse, HUD, audio-HUD) were compared through a driving simulator experiment. The results showed the brake pulse interface was the most effective in terms of brake behavior.

a)  b) 

Figure 3.6: Collision warnings: a) a green bounding box alerting lead vehicles, and b) a green bounding box alerting pedestrians

Park and Kim (2013) proposed using a short arrow-shaped icon to indicate a nearby pedestrian (Figure 3.7). The warning symbol is spatially registered being located right above the head of a real pedestrian in the outside world. This concept was further investigated and tested in the real world by Yoon et al. (2014).

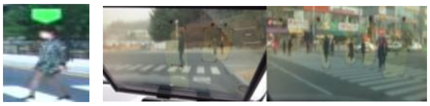


Figure 3.7: Pedestrian warnings: a short arrow-shaped icon located above the head of a real pedestrian

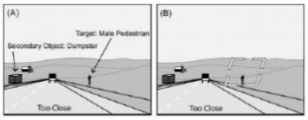
Alerting collision risks, indicating the locations of hazards, identifying the hazards, and indicating the risk levels of hazards

Charissis et al. (2010) also proposed a contact-analog, bounding box style lead vehicle warning display, which alerts the driver to potential collisions under adverse weather conditions (Figure 3.8). The bounding box style display is designed as an actual vehicle icon. The display utilizes a color coding scheme – the color of a lead vehicle changes from green to yellow to red as the distance decreases. A downward triangle is added on top of the display, especially if the lead vehicle is on the same lane. The proposed display was found to significantly reduce the number of collisions in a driving simulator experiment.

Figure 3.8: Lead vehicle warnings: iconic representation of actual vehicles

Rusch et al. (2013) proposed a yellow contact-analog rhombus shaped outline for the pedestrian warning through an AR HUD system (Figure 3.9a). This AR display appears when the distance to the pedestrians is within 350m. The four sides of the rhombus were converging according to the distance to the target. The broken line becomes a solid line as the driver gets closer to the pedestrian. A driving simulator study was conducted and the result indicated near significant response time benefits for AR cued hazards. AR cueing increased response rate for detecting pedestrians and warning signs but not vehicles.

Phan et al. (2016) proposed a yellow squared shaped outline to indicate nearby pedestrians (Figure 3.9b). An unregistered pedestrian sign was added at the bottom-left side on the HUD image plane when the time-to-collision (TTC) is less than 2s (Figure 3.9b). A driving simulator study was conducted and the result showed the proposed display enhanced the drivers' awareness.

a) 

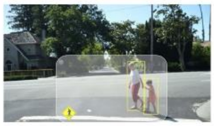
b) 

Figure 3.9: Pedestrian warnings: a) a rhombus shaped outline, and b) squared shaped outline display

George et al. (2012) developed a prototype display adaptively providing information about potential hazards, such as pedestrians and other vehicles, considering the driving situation and driver's eye-gaze. The locations of potential hazards and their dangerousness levels were presented using an arrow-shaped symbol. The symbol was created based on the weather vane metaphor (Figure 3.10). The information was presented only if needed, and the warnings were contact-analog types. A color coding scheme was developed to indicate the dangerousness levels of possible hazards. Vertical position of each arrow-shaped symbol along the virtual pole also indicated the corresponding hazard's dangerousness level. The Highway Code attached to the end of each arrow-shaped symbol indicated the type of danger.

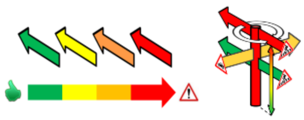
a) 
b) 

Figure 3.10: Pedestrians and other vehicles warning using the weather vane metaphor: a) indication of dangerousness levels and b) indication of the types of dangers

Kim et al. (2016a) proposed an AR pedestrian collision warning by using an ecological interface design (EID) approach. Based on the EID framework, a contact-analog display named virtual shadow was designed. The proposed display consists of a circle and pole, similar to a lollipop icon (Figure 3.11a). The display changes its physical form depending on the situations. For example, the direction and length of the display are determined by an approaching object and the vehicle's speed. An initial usability evaluation found that the virtual shadow display outperformed the baseline (outline in a square) in all aspects such as visibility, attention, situation awareness, and workload.

This virtual shadow concept was also assessed in an on-road situation compared with a traditional warning sign (Kim et al., 2016b) (Figure 3.11b). The traditional warning was represented by text 'BRAKE'. Both warnings improved the driving performance, resulting in larger gaps between the pedestrians and vehicle. In terms of braking behavior, the virtual shadow concept showed smoother braking behavior compared to the traditional warning.

a) b)

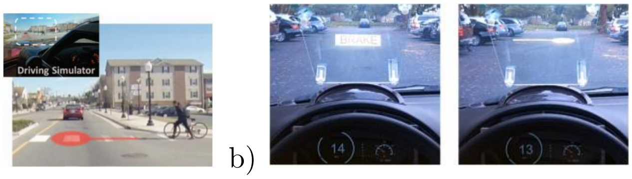


Figure 3.11: Virtual shadow-type pedestrian warnings: a) a driving simulator test, and b) an on-road test

Blind spot detection

<u>Alerting hazards and indicating the locations of hazards</u>

Tonnis et al. (2005) developed an AR-based HUD displaying the locations of potential dangers around the vehicle in two formats: a 2D unregistered bird's eye view and a 3D contact-analog arrow (Figure 3.12a). A 2D unregistered bird's eye view concept consists of a vehicle icon and a small circle indicating the potential hazards. A driving simulator-based experiment was carried out and the 2D unregistered bird's eye view concept resulted in faster mean reaction time to the alert and lowered mean error rates significantly. In terms of the mean lane deviation, however, the 3D contact-analog arrow concept showed significantly better results than the 2D bird's eye view concept. Regarding subjective rating, four criteria (preference, ease of use, speed, and precision) were employed, and the 2D bird's eye view concept was significantly superior to the 3D arrow concept in all aspects.

Figure 3.12: Potential hazard warnings: a) a 2D bird's eye view and 3D arrow, and b) a revised bird's eye view and revised 3D arrow

Tonnis and Klinker (2006) extended the study that was previously conducted by Tonnis et al. (2005). In the extended study, the two concepts were visually improved and auditory cues were added. In order to avoid the ambiguity in directing the potential dangers, the 2D bird's eye view concept used an arrow pointing the location of the dangers, and the 3D arrow concept additionally utilized an arrow pole and three fins at the rear-side (Figure 3.12b). It was found that the improved 3D arrow concept outperformed the 2D bird's eye view concept in driving and task performance. Also, the 3D arrow concept was preferred over the 2D bird's eye view concept.

Alerting hazards, indicating the locations of hazards and identifying the hazards

Plavšic et al. (2009) compared four different displays for alerting visually concealed hazards: a 3D contact-analog bounding box symbol, a 3D contact-analog annotating symbol, a 2D unregistered traffic symbol, and a 2D unregistered bird's eye view symbol (Figure 3.13). The four types of warning displays presented a visually concealed danger's location. The 3D contact-analog displays provided visual warnings in close proximity to the potential hazards; on the other hand, the unregistered displays did not capitalize on such proximity. Driving simulator experiments were conducted and the four displays were evaluated in terms of overall workload, intuitiveness, concentration, safety and attractiveness. It was found that in all criteria, the best display was the 2D unregistered bird's eye view symbol.

Figure 3.13: Concealed hazard warnings: a) a 3D contact-analog bounding box symbol, b) a 3D contact-analog annotating symbol, c) a 2D unregistered traffic symbol, and d) a 2D unregistered bird's eye view symbol

Suzuki and Hashimoto (2012) proposed a driving assistance system alerting a blind spot through a HUD. The proposed system showed the blind spot with a transparent image through the HUD. The image was displayed with the first person point of view so that the driver can easily recognize the situation covered by a forward obstacle.

Safety boundary delineation

Informing the braking distance/driving path

Tonnis et al. (2007) developed a contact-analog visual driving aid, which combined a bar representing the braking distance and line segments depicting the driving path into a single display (Figure 3.15). Since the visual aid presents two different pieces of information using a single combined object, it can be considered a configural display (Sanders and McCormick, 1987). The visual aid was found to improve driving performance in terms of driving speed and lane deviation without increasing overall driver workload.

Figure 3.15: A braking distance and driving path indicator

Informing the oncoming vehicle's future path

Tran et al. (2013) developed a contact-analog left turn aid, which provides oncoming vehicle warnings - it provided information about a vehicle approaching from the opposite direction when the driver needs to make a left turn at an intersection. The proposed display presents the oncoming vehicle's future path of 3 seconds using three different types of virtual projected path: solid, chevron and wireframe types (Figure 3.16). A driving simulator experiment showed that the left-turn aid produced more conservative driver behavior.

Figure 3.16: Virtual oncoming vehicle's future path of 3 seconds: a) solid, b) chevron and c) wireframe types

Road sign notification

<u>Notifying road signs</u>

Doshi et al. (2009) compared three different display concepts for speed limit warning: an exclamation mark warning symbol in a triangle shape, numbers showing the vehicle's current speed and the speed limit, and a vertical status bar showing the current speed and the speed limit (Figure 3.17). All three displays were unregistered types. A speed compliance experiment was conducted in an on-road situation. It was shown that the most effective alert in terms of the average amount of time the driver spent over the speed limit before returning to under the limit was the warning symbol, followed by the status bar and the numbers. However, the 'numbers' display was found to be the best in terms of the eye-on-the-road time with the shortest time for looking down at dashboard. The overall user opinion was that the warning symbol was the most helpful in recognizing the speed limit without experiencing distraction.

Figure 3.17: Speed limit warnings: a) an exclamation mark in a triangle shape, b) numbers showing the vehicle's current speed and the speed limit, and c) a vertical status bar showing the current speed and the speed limit

Caird et al. (2008) proposed that the signal at the intersection be presented in advance through a HUD system. Two signs of ''prepare to stop'' and ''signals ahead'' were considered for the study (Figure 3.18). The ''prepare to stop'' sign consists of an actual traffic sign (a rectangular icon) and the "signals ahead'' sign also consists of an actual traffic sign (a diamond in-vehicle sign). The driving simulator experiment showed that the primary behavioral influence of the proposed signs was to cause the drivers to reduce their velocity in advance of an intersection. Eye movement analyses indicated that younger drivers looked at the proposed signs more often and for longer overall durations than older drivers did.

Figure 3.18: Road signs at the intersection

Notifying road signs and indicating the locations of road signs

Park and Kim (2013) proposed a contact-analog outline HUD highlighting traffic signs such as speed limit warning, traffic enforcement cameras warning, and etc. The proposed display was also utilized for lead vehicle warning.

Lane keeping-related warning

Alerting lane departure

Kozak et al. (2006) proposed a lane departure HUD warning utilizing a red laser beam. This display is the same as that suggested by Lind (2007). The proposed

HUD was evaluated through a driving simulator experiment utilizing four different types of warning interfaces: steering wheel torque, rumble strip sound with steering wheel torque, steering wheel vibration with steering wheel torque, and the HUD with steering wheel torque. It was found that the steering wheel vibration with steering wheel torque was the most effective interface in terms of reaction time to warnings, lane excursions, and subjective assessment.

<u>Alerting lane departure and indicating the vehicle's lane position</u>

Dijksterhuis et al. (2012) proposed an adaptive lane departure HUD warning. The display was of the unregistered type and showed the vehicle's lane position within a top view mini map (Figure 3.19). The study also assessed the effects of the adaptive support system. As such, three modes of lane-keeping support (non-adaptive, adaptive and no support) were compared. Non-adaptive mode continuously displayed the lane position information, whereas adaptive mode presented the warning only when the vehicle approached to the edge of the lanes or the standard deviation of the lateral position indicated poor driving performance. The adaptive support mode was found to improve driving performance (mean and SD of lateral position) over the other, and also the subjects preferred the adaptive support mode most in terms of usefulness and satisfaction.

Figure 3.19: An adaptive lane departure warning

<u>Improving the visibility of lane markings, preventing the lane departure, alerting hazards, indicating the locations of hazards, and indicating the risk levels of hazards</u>

Charissis et al. (2010) developed contact-analog virtual lane markings overlaid on the actual road (Figure 3.20). The lane marking icons were easily noticeable even under the adverse weather conditions helping the driver keep the vehicle within its lane. The icons also gave warnings of possible road hazards utilizing a color coding scheme. The lane marking icon colored in red indicated the existence of potential hazards in that area, whereas the green-colored icon indicated absence of such hazards. A driving simulator experiment was conducted and the proposed concept was found to significantly reduce the number of collisions.

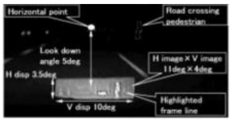
Figure 3.20: Virtual lane markings

Night vision warning

<u>Alerting hazards, indicating the locations of hazards and identifying hazards</u>

Tsuji et al. (2002) developed a night vision HUD system displaying an infrared image of the pedestrians on the road (Figure 3.21a). To evaluate the proposed night vision system, three different interfaces were compared (HUD with voice, conventional night vision display with voice, only voice). The result showed that the HUD with voice interface was the most effective way in terms of reaction time to collision avoidance.

Kovordányi et al. (2006) designed an adaptive, unregistered night vision HUD, which was lit up only when an obstacle on the road ahead was detected (Figure 3.21b). Compared to a conventional night vision system, this discontinuous support improved obstacle detection ability, and resulted in lower workload. Also the proposed display was preferred by all study participants.

a) 

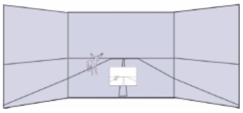
b) 

Figure 3.21: Night vision warning: a) an infrared image of the pedestrians, and b) an adaptive night vision warning

<u>Alerting, identifying hazards and indicating the locations and risk levels of hazards</u>

Park el al. (2015) developed a HUD-based night vision system detecting lead vehicles and pedestrians. Pedestrian warnings are represented by color-coded bounding boxes including a pedestrian road sign in side (Figure 3.22a). A total of four colors (red, orange, yellow, and green) are utilized to indicate the levels of danger. Lead vehicle warnings use a color-coded bounding box with virtual path (Figure 3.22b). Three colors (red, orange, and yellow) are used depending on the levels of danger, and the distance to the lead vehicle is displayed in text on the virtual path only under the most dangerous level. Vehicles and pedestrians are overlaid with the warnings in a contact-analog manner.

a) 

b) 

Figure 3.22: Night vision warning: a) a pedestrian warning, and b) lead vehicle warning

A summary of the interface design of automotive HUDs for safety-related functions described in Section 3.3.2 in Appendix C.

3.4 Discussion

This study examined what types of display exist or have been proposed by the commercial HUDs and academic research in terms of their functions, behaviors, structures and also related human factors display design principles; also, empirical findings on the effects of interface designs were examined.

Based on the review results, it was found that one notable difference between the commercial HUDs and the proposed HUDs by academic research was the presentation method. All of the commercial safety-related HUDs were of the unregistered type and did not utilize the AR technology. On the other hand, safety-related HUDs proposed by academic research studies were mostly AR-based and contact-analog. It is not clear why the existing commercial HUD displays did not adopt the AR technology. Perhaps, it may be due to some technological challenges in incorporating the AR technology into the automotive HUD system, such as requiring a full-windshield display. Alternatively, it may be that the efficacy of the AR HUD technology has not been confirmed for creating safety-related HUD displays.

Given the two display formats, it is not clear under what situations one should be used over the other. Compared with contact-analog displays utilizing the AR technology, unregistered displays provide information at a fixed location, and therefore the driver can expect where the information will be provided. This facilitates the human information processing through top-down processing. Humans respond more quickly or accurately to expected rather than unexpected visual events (Kingstone and Klein, 1991). On the other hand, AR-based contact-analog displays have a high level of proximity, which can help to quickly identify the target locations. Taking into account the different benefits of each display, future research is needed to determine which of the two displays is more suitable for what information or situations.

It seemed that compared with the existing commercial safety-related HUDs, the conceptual or prototype HUDs of the academic research studies were much more diverse in functions, behaviors, and structure of interface design. This likely reflects the exploratory nature of academic research studies and the conservativeness of safety-related commercial products. Another possibility is related to the technological limitations of the AR technology for automotive HUD applications - if the limitations of the current AR HUD technology were the reason for its non-use in the existing commercial products, relevant technological improvements would trigger developing a wide range of new safety-related displays in the commercial automotive HUD systems as suggested by the diversity of creative ideas proposed by academic research studies.

Past studies have presented various interface design ideas to warn or notify about specific external objects, such as lead vehicles or pedestrians. The existing design ideas indicate that there can be multiple pieces of detailed information to be presented about an external object. For example, the lead vehicle warning proposed by Charissis et al. (2010) (shown in Figure 3.8) provides four different pieces of information, that is, hazard occurrence and location with highlighting, hazard type with the vehicle shaped icons, and risk level with color coding. Such interface analysis of display functions suggests that new types of displays can be developed by combining or mixing existing displays or display elements at both the information and interface element levels. Depending on how displays are combined, various displays differing in structure or behavior may be produced. For example, the pedestrian night-vision display suggested by Park et al. (2015) (shown in Figure 3.22a) combined the same pieces of information as the lead vehicle warning mentioned above; however, the two displays differed in the combination scheme – the lead vehicle warning blended the two elemental displays to create a totally new type of display while the pedestrian warning simply juxtaposed the two elemental displays. From a human factors perspective, simply juxtaposing elemental displays for presenting multiple pieces of information may result in increased visual clutter and cause information overload. Future research is needed on how to create displays that provide multiple functions while minimizing problems such as visual clutter and information overload. The application of the EID and the configural display design methods may help address the clutter and the information overload problems. Also, further research on interface analyses of HUD or general automotive displays is warranted as it may help develop a systematic method for creating new displays through combining/blending elemental displays. By exploring the untapped, potentially useful part of the design space, new types of display concepts may be discovered.

This study examined the HUD displays in terms of the human factors display design principles (Wickens et al., 2003). Many of the proposed displays indeed were based on well-known display design principles, such as the principles of proximity compatibility, information access cost minimization, predictive aiding, color coding and consistency. In general, HUDs are thought to be an ideal means for realizing the principles of proximity compatibility and information access cost minimization as they can present information close to the related objects or within the driver's field of view.

While the human factors display design principles can greatly support the design of useful displays, an overuse or poor integration of them could lead to visual clutter and other problems. For example, the display proposed by George et al. (2012) capitalizes on multiple display design principles, such as information access cost minimization, redundancy gain, and consistency; however, despite the utilities of the design principles, the display seems to attempt to present too much information within a very small space. Consequently, the visual complexity increases, and the display has poor legibility and discriminability, leading to difficulties in perceiving information. This would amplify the negative effects on information processing in a safety-critical situation. Thus, the display principles need to be used properly according to the situation and only to the extent that the resulting display respects the limitations of the human information processing, and achieving balance among the principles is important to an effective design. In this regard, future research is needed on how to properly apply the display design principles and how to assess whether they have been applied correctly.

A study of Winkler et al. (2015) used traffic signs already familiar to the drivers as a warning of potential hazards. The results of the study indicated that the familiar and intuitive warning design was more effective in terms of driving performance compared to the unfamiliar and less understandable design. According to the principle of consistency, good displays should be compatible with user expectancies and be consistent across situations (Wickens et al., 2003). Preserving consistency should be taken into account when designing displays especially for the elderly since the elderly might be at a higher risk of experiencing difficulties with unfamiliar designs. The design of visual warnings should also ensure relatively fast reading even for unfamiliar designs. It is, therefore, necessary to investigate whether there is an age effect on user acceptance, driving performance, and eye gaze duration (could be regarded as cognitive tunneling) in terms of display familiarity (e.g., one designed based on well-known knowledge vs. a newly designed one). In addition, there is a need to examine not only age effects but also individual differences depending on the behaviors and structure of interface design.

Chapter 4

Development and Evaluation of Automotive Head-Up Displays for Take-Over Requests (TORs) in Highly Automated Vehicles

4.1 Introduction

With the rapid development of highly automated vehicles, many countries have been putting their efforts on the deployment of automated vehicles to the broader public. However, until employing the fully automated driving, human intervention, that is, a take-over request for a transition of control from the automation to the driver in highly automated vehicles, is inevitable. When a take-over request occurs during highly automated driving, drivers have to be quickly aware of the situation and manually control the vehicle. However, the longer the highly automated driving mode lasts, the less level of attention and situational awareness drivers have. In particular, the human being's possible loss of alertness and awareness of their surroundings, which may become critical if sudden manual intervention is required (National Research Council, 1997). Therefore, in a take-over scenario, it is important to have drivers get back into the control loop as quickly and safely as possible, and it is necessary to design a display system that supports drivers' situation awareness and decision making process to make a safe transition. When using such a support system, furthermore, it is necessary to understand the actual usage behavior of drivers. However, given the uncertainty and complexity of the automation, drivers' actual usage behavior may vary depending on their trust in the display characteristics of the automated system, for example, the information about the system's current intentions, proposed actions, reasoning process, etc. (Chen et al., 2004; Lee and See, 2004). Such information about the automated system pertains to system transparency, and with which operators' trust can be calibrated. Poor calibration of trust may lead to misuse or disuse of the automated system (Lee and See, 2004). Indeed, the efficiency of an automated system often depends on the level of trust of operators in that system (Payre et al., 2016). According to previous studies, trust was an important determinant of system performance (Lee and Moray, 1992) and one of the main predictors of automation use (Parasuraman and Riley, 1997). Therefore, to ensure the appropriate usage of the automated system, appropriate trust calibration must be accompanied (Lee and See, 2004), and in order to achieve the development of appropriate level of trust, the appropriate level of information about the system transparency must be provided (Hoff and Bashir, 2015; Chen et al., 2004). A model proposed by Chen et al. (2004) stated that the system transparency can be achieved according to the three levels: providing information about the system's current state/goals/intentions/proposed actions, providing information about the system's reasoning process, and providing information about the system's projection of the future state. To make the automated system more transparent, information about the system transparency, such as the system's current state, intentions, proposed actions, reasoning process, and etc., should be incorporated in the interface of the automation. In this study, it was defined that the more transparent the system, the higher level of system transparency. A display system that supports take-over requests in highly automated vehicles, denoted as a TOR display, should be designed to support not only drivers' situation awareness and decision making process but also the system transparency.

Despite the need for a TOR display that supports drivers' situation awareness and decision making process for a quick and safe transition, however, TOR displays in previous studies were mostly in the form of simple auditory or visual alarms like traditional in-vehicle warning systems (Eriksson and Stanton, 2017; Gold et al., 2016; Melcher et al., 2015; Mok et al., 2015; Naujoks et al., 2014; Wandtner et al., 2018; Zeeb et al., 2016). In a time-critical situation such as a take-over scenario, these simple warnings may be not enough to help drivers get back into the control loop. In order to effectively assist drivers particularly in such complex and dynamic environments, display design should support drivers' situation awareness directly, leading to an effective decision-making process. According to Endsley (1995), situation awareness (SA) is classified into three levels: perception of the elements in the environment (Level 1 SA), comprehension of the situation (Level 2 SA), and projection of future status (Level 3 SA). Situation awareness increases with the cumulative result of the levels. Considering that a decision must be made in a time-critical situation, TOR displays should also be designed taking into account the level of automation (Parasuraman et al., 2000) and the information quantity. According to Parasuraman et al. (2000), automation is divided into four levels: information acquisition, information analysis, decision and action selection, and action implementation. Time-critical responses may require high levels of automation, such as action selection or implementation, in that a decision can be made faster by automation than by drivers. However, to increase system transparency, it may be needed to provide an appropriate level of information about the automation, without providing too much information. Hence, in a time-critical situation, like a take-over scenario, it is necessary to design a TOR display in consideration of all the following aspects: level of automation, system transparency, situation awareness, and information quantity, and to understand how the TOR display affects the actual usage behavior of drivers in a take-over situation. In addition, it is necessary to investigate how display characteristics of TOR displays affect drivers' trust, and how driver's trust relates to the actual usage of TOR displays. Few studies have been conducted on the impact of display characteristics on operators' trust and the relationship between operators' trust and the actual use of the automated system.

Therefore, the aim of study was to develop TOR displays and evaluate them regarding drivers' take-over performance and visual scanning behavior in a highly automated driving situation. This study also investigated the impact of the proposed TOR displays on drivers' initial trust, and the relationship between drivers' trust and take-over behavior in a take-over scenario. The research questions to address the study objectives are shown in Table 4.1.

Table 4.1: Research questions of Study 3

Research questions	
Research Question 1)	How do the proposed TOR displays affect on take-over and visual scanning behavior?
Research Question 2)	What are the characteristics of drivers' initial trust in the TOR displays?
Research Question 3)	What is the relationship between drivers' initial trust and drivers' take-over and visual scanning behavior?

To address the research questions, a driving simulator experiment was conducted assuming the highly automated driving.

4.2 Method

4.2.1 Participants

A total of 30 participants (20 males, 10 females) participated in this study and their mean age was 28.37 years (SD = 3.72, min = 23, max = 38). An average driving experience was 5.33 years (SD = 4.72, min = 0, max = 15). The total mileage was overs 100,000 km for 8 people, over 10,000 km and less than 100,000km for 12 people, and less than 10,000 km for 10 people. Various levels of driving experience were considered to ensure as much the external validity as possible with regard to subject selection. Two participants had an experience of a limited self-driving automation. The study received ethical approval from Seoul National University Institutional Review Board.

4.2.2 Apparatus

A fixed-base three-channel driving simulator was used in this study. The simulator consisted of adjustable vehicle interior mock-up (seat, steering wheel, gas/brake pedals, gearshift) and three of 42-inch LED monitors. This provided a realistic driving environment with a forward FOV angle of 183.6 degrees. The virtual driving environment was developed using the software (UC-win / Road Ver.10, Forum8) linked with the simulator. During the experiment, the participants' eye movements were tracked and recorded using an eye tracking system (Dikablis Eye Tracking System, Ergoneers).

The participants performed Surrogate Reference Task (SuRT; ISO 14198, 2019) as a non-driving related task during the automated driving. The task was presented on a 10.8-inch screen (Microsoft Surface 3) to the right side of the participant. The participant performed the task using the keypad located on a small table near the SuRT screen. The setup for SuRT was based on ISO 14198. The experimental setup is shown in Figure 4.1.

Figure 4.1: Experimental setup of Study 3

4.2.3 Automotive HUD-based TOR Displays

A total of four TOR displays were developed, taking into account the level of system transparency, automation, information quantity, and drivers' situation awareness that the display can support. All the four TOR displays present an audible beep alarm (every 0.5 seconds, total 2 seconds) as a baseline. The other three displays utilized a multi-modal interface that provides visual displays with an automotive HUD system, along with an audible beep alarm. A description of each TOR display is as follows:

- Baseline: Only an audible beep sound (every 0.5 seconds, total 2 seconds) is provided when a TOR occurs (no visual supported). The information quantity is the lowest among the proposed displays. The level of system transparency, automation and situation awareness of drivers supported are also the lowest, since any information related to the specifics of TORs is not provided.

- Mini-map: Mini-map is a top-view display showing the actual road within approximately 30m in every direction of the driver's vehicle. This display is presented along with an audible beep alarm identical to that of the baseline. Mini-map helps to quickly recognize the current situation, thus supporting the Level 1 of situation awareness of drivers. The top-view display is thought to support recognizing spatial information well (Plavšic et al., 2009; Tönnis et al., 2005), and therefore, it would help the driver perceive spatial relationship between the driver's vehicle and other surrounding objects, even in complex and dynamic driving environments, supporting a bit of Level 2 SA. The level of transparency, situation awareness, and information quantity are relatively high since the display provides situational information. The level of automation is relatively low since this display supports the stage of information acquisition.
- Arrow: Arrow provides action instructions for resolving take-over situations. By indicating lane change directions, Arrow replaces drivers' decision makings and supports Level 3 SA. In-vehicle warnings are recommended to be accompanied by action instructions (ISO 16352). Baber and Wankling (1992) showed that an in-vehicle warning with action instructions was most effective in eliciting appropriate actions. Since only the final decision made by the automation is provided, the situation awareness of drivers, the transparency of the proposed display, and the information quantity are relatively low. The level of automation is the highest since the display supports the stage of decision selection.
- Mini-map-and-Arrow: This display is a combination of the aforementioned Mini-map and Arrow. Arrow is integrated into the Mini-map. By presenting the situation information through the Mini-map

related to the action direction, the display is expected to help develop a comprehensive picture of the current situation, supporting all the levels of SA. The situation awareness of drivers, the transparency of the display, the level of automation and the information quantity are the highest among the proposed displays.

Figure 4.2 shows Mini-map, Arrow, and Mini-map-and-Arrow displays and Table 4.2 presents the characteristics of the displays.

Figure 4.2: a) Mini-map, b) Arrow, and c) Mini-map-and-Arrow

Table 4.2: Characteristics of the proposed displays

Characteristic \ Level	Low	←	→	High
Automation	Baseline	Mini-map	Arrow, Mini-map-and-Arrow	
Situation awareness	Baseline	Arrow	Mini-map	Mini-map-and-Arrow
System transparency	Baseline	Arrow	Mini-map	Mini-map-and-Arrow
Information quantity	Baseline	Arrow	Mini-map	Mini-map-and-Arrow

4.2.4 Driving Scenario

The driving scenario assumed a Level 3 conditional automation situation (SAE J3016, 2016). The automated vehicle drove in the middle lane on a three-lane highway at 100 km/h. The intervals of automated driving ranged from 30 seconds to 2 minutes and were randomized for each trial. Due to the system limit (e.g., road works ahead on the same lane), the participant had to take over the control of the automated vehicle and change to the right or left lane. The participants were instructed to make lane changes considering the safe distance from the oncoming nearby vehicles; they were asked to first determine where to change lanes and then manually operate the vehicle. The take-over time budget was 7 seconds (approximately 194.5m left at 100km/h). The speed of the participant's vehicle was fixed at 100km/h even during the intervals of manual driving and the participants were not allowed to operate the pedals. This was to prevent the participants from braking at any time or accelerating to cut into a lane without perceiving their surroundings when a TOR occurred. In each TOR occurrence, two vehicles approached each in the left and right lanes, from 5m and 15m behind the participant's vehicle. The assignment of the distance to the vehicle of the participant and the lane location was randomized for each trial. In order to prevent learning effects, the speeds of the nearby oncoming vehicles had two conditions. In the first condition, both of the oncoming vehicles were approaching at the same constant speed of 103km/h and therefore the participant had to make a lane change to the lane of the more distant vehicle (15m behind when the TOR occurred). It was approximately 6.8s for the closer vehicle to overtake the participant's vehicle and 18s for the distant vehicle. In the second condition, the vehicle more distant (15m behind) at the TOR occurrence was approaching at 108km/h, and, the vehicle less distant (5m behind), at 92km/h. Thus, the relative positions of the two nearby vehicles reversed during the trial. In order to avoid collision, the participant had to make a lane change to the lane of the closer nearby the vehicle.

4.2.5 Experimental Design and Procedure

Prior to the experimental trials, the participants were provided with a general description of the experiment and an introduction of the Level 3 driving automation. After the explanation, the participants were given a brief demonstration of the TOR displays proposed in this study and were instructed to fill out the questionnaire measuring their initial trust for each of the TOR displays. Multiple training sessions were provided to the participants so that they became familiar with the driving simulator, scenario, non-driving related task (the SuRT task) and each of the four TOR displays. During training sessions, it was confirmed that TOR displays were sufficiently visible to the participants.

A within-subject design was used to compare the four different TOR displays. For each of the four TOR displays, each participant experienced four take-over trials – two repeated trials for each of the two lane change conditions described earlier. Each of the TOR displays was presented in counterbalanced order and the two lane change conditions were presented randomly. During each trial, the participants performed the SuRT for the non-driving related task. The SuRT is a visual-manual demanding task requiring participants to search and select the region in which a target stimulus is located (ISO 14198, 2019). The target stimulus (a larger size circle) is distinguishable from the distractors (smaller circles) based on its size. The display setup and visual demand (moderate level) of the SuRT task used in this study were based on the ISO standard (ISO 14198, 2019). The target size was 5.82mm in diameter (visual angle approximately 0.6 degrees) and the distractors were 4.76mm (visual angle approximately 0.47 degrees). Since the visual demand at this level was rather high, the participants were able to fully engage in the non-driving related task. The participants used a keypad shown in Figure 1 to select the target stimulus area. The participants were informed that they did not need to monitor the performance of the driving automation system during the non-driving related task.

The participants completed subjective ratings after four take-over trials of each of the TOR displays. After the completion of the experiment trials, the participants completed the same questionnaire that they completed before the experiment to rate their trust in the TOR displays.

4.2.6 Experiment Variables

The independent variable was the TOR display type with four levels: Baseline (beep sound), Mini-map, Arrow, and Mini-map-and-Arrow. The dependent variables consisted of objective and subjective measures. The objective measures pertained to take-over performance and eye movement behavior. Take-over performance was measured by reaction time for the onset of the take-over, completion time for the lane change, number of collisions with oncoming vehicles, and standard deviation of lateral lane position. The reaction time was defined as the time in seconds from the onset of the TOR to the moment that steering wheel angle and the angular velocity are over 0. The completion time was computed as the time in seconds from the onset of the TOR to the completion of the lane change. The log data from the driving simulation software program was used to identify the time of the lane change completion. The standard deviation of lateral lane position was defined as the standard deviation of the lateral vehicle distance in meters from the center of the middle lane. Eye movement behavior was measured by glance durations to areas of interests (AOIs), number of glances to AOIs, and number of glances over 2 seconds. The AOIs in this study were the side-view and rear-view mirrors, and, the TOR displays. In terms of the duration and frequency of glances, short fixations less than 120ms were not as glances (ISO 15007-1, 2014). Regarding subjective measures, the ratings of workload, perceived preference, safety, usefulness, desirability, and annoyance were employed. Workload was measured employing the NASA Task Load Index (NASA-TLX) questionnaire (a 100-point scale). Perceived preference, safety, usefulness, desirability, and annoyance were measured with a 10-point scale. The independent and dependent variables were listed in Table 4.3.

Table 4.3: Experimental variables of Study 3

Experimental variables		
Independent variable		TOR displays: Baseline, Mini-map, Arrow, Mini-map-and-Arrow
Dependent variable	Objective measure	1) Take-over performance: Reaction time (s), task completion time (s), collision rate
		2) Driving performance: Standard deviation (SD) of lateral lane position (m)
		3) Eye scanning behavior: Glance duration to AOIs (Areas of interests) (s), number of glances to AOIs, number of glances over 2 seconds (AOIs: TOR displays and side/rear view-mirrors)
	Subjective measure	1) Perceived preference (10-point scale)
		2) Perceived safety (10-point scale)
		3) Perceived usefulness (10-point scale)
		4) Desirability (10-point scale)
		5) Annoyance (10-point scale)
		6) Workload (NASA-TLX) (100-point scale)

To investigate the relationship between drivers' initial trust in the TOR displays and the take-over behaviors, each participant's trust in the TOR displays, as a personal variable, was measured using a questionnaire (a 10-point scale). The questionnaire consisted of eleven items that were selected from the trust-related questionnaires developed by previous studies (Jian et al., 2000; Körber et al., 2018; Lee and Moray, 1994; Muir and Moray, 1996). The eleven items pertained to the major factors that influence trust: personal attitudes and initial belief (overall degree of trust, faith, dependence, and reliance), understanding and prediction of system, and confidence in system. The questionnaire items were thought to be capable of describing the participants' initial trust for the TOR displays. Factors that influence trust and the questionnaire items are provided in Table 4.4.

Table 4.4: Factors that influence trust and the questionnaire items

Factors that influence trust	Questionnaire items
● Personal attitudes and initial belief (overall degree of trust, faith, dependence, and reliance) ● Understanding and prediction of system ● Confidence in system	1. I can trust the system 2. I can depend on the system 3. I am wary of the system 4. The system is reliable 5. I am suspicious of the system's intent, action, or output 6. The system might make sporadic errors 7. I have knowledge of the system 8. I understand how the automation operates, and can predict future system behavior 9. I am familiar with the system 10. I am confident in the system 11. I feel comfortable with the system

4.2.7 Statistical Analyses

Comparison of the four TOR displays

A one-way repeated measures ANOVA was conducted to test the effect of the four TOR displays, if the assumption of normality was met. If the assumption of normality was not met, a Friedman test was conducted. For ANOVAs, Mauchly's test was performed to assess sphericity of data. If data violated the sphericity assumption, the Greenhouse-Geisser correction was used. In case there was a significant effect of the four TOR displays, post-hoc Bonferroni multiple pairwise comparisons were conducted for ANOVAs, and Wilcoxon signed-rank tests, for Friedman tests. A Bonferroni correction was applied to the α-level to control the Type Ⅰ error rates. All statistical tests were conducted at an alpha level of 0.05 using SPSS 25.

Characteristics of drivers' initial trust in the four TOR displays

A cluster analysis was performed on the results of the questionnaire items that assessed the drivers' initial trust in the four TOR displays. The dataset consisted of the mean values of the eleven questionnaire items for each type of TOR display. First, the hierarchical analysis was employed through the Ward's method using the Euclidean distance in order to obtain the approximate range of the clusters. The Ward's method provides guidance for estimating the number of clusters in a dataset. Second, based on the range of the clusters derived from the Ward's method, the K-means clustering was carried out with indices of the cubic clustering criterion (CCC), Calinski-Harabasz (CH), and Pseudo t2 to determine the best number of clusters. All statistical tests were conducted using SPSS 25 and R.

Relationship between the drivers' initial trust and take-over and visual behavior

To examine the relationship between drivers' initial trust and take-over behaviors, the differences between cluster groups for each type of dependent variable mentioned in Section 4.2.6 were examined. Since the number of appropriate clusters derived from the cluster analysis were two, a two-sample t-test was conducted to test whether the group means were different, if the assumption of normality was met. If the assumption of normality was not met, a Mann–Whitney U test was employed. All statistical tests were conducted at an alpha level of 0.05 using SPSS 25.

4.3 Results

4.3.1 Comparison of the Proposed TOR Displays

For each of the dependent variables, the mean and standard deviation values of each TOR display are presented in Figure 4.3-5.17 with asterisks indicating the statistical significance in the post-hoc Bonferroni multiple pairwise comparisons or Wilcoxon signed-rank tests (* < .05, ** < .01, *** < .001).

<u>Objective measures (take-over performance)</u>

The results of the ANOVA and post-hoc Bonferroni multiple comparisons on mean reaction time indicated that the three displays, that is, Mini-map, Arrow, and Mini-map-and-Arrow, resulted in significantly shorter mean reaction time than Baseline, $F(2, 63) = 22.25$, $p = .000$. However, the three displays (Mini-map, Arrow, and Mini-map-and-Arrow) did not significantly differ from each other in the mean reaction time (Figure 4.3).

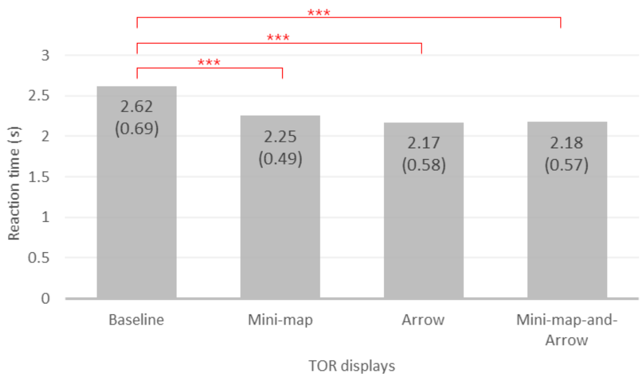


Figure 4.3: Mean and standard deviation (in parentheses) of reaction time with asterisks indicating significance in the multiple pairwise comparisons

As for mean completion time, Arrow, and Mini-map-and-Arrow were significantly shorter than Baseline, F(3, 87) = 9.29, p = .000. However, Mini-map did not significantly differ from any other displays (Figure 4.4).

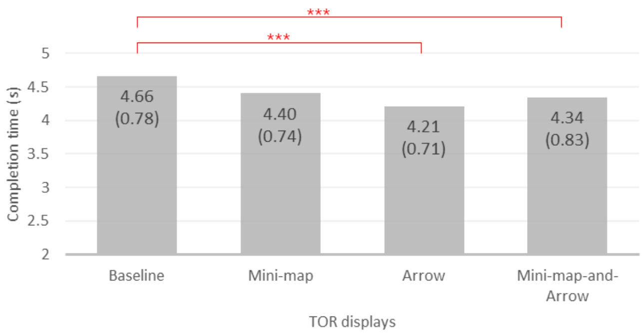


Figure 4.4: Mean and standard deviation (in parentheses) of completion time with asterisks indicating significance in the multiple pairwise comparisons

In terms of mean standard deviation of lateral position, there was no significant difference between the TOR displays (Figure 4.5).

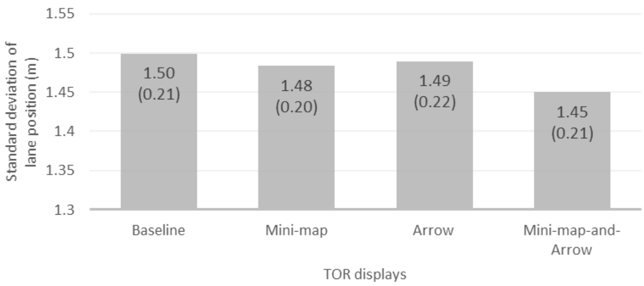


Figure 4.5: Mean and standard deviation (in parentheses) of standard deviation of lateral lane position

As for the number of collisions, Baseline had 5 collisions. Mini-map and Arrow each had one collision. Mini-map-and-Arrow had no collision. No statistical analysis was performed.

Objective measures (eye movement behavior)

The result of the ANOVA test showed that mean total AOI glance duration was not significantly affected by the TOR display type (Figure 4.6).

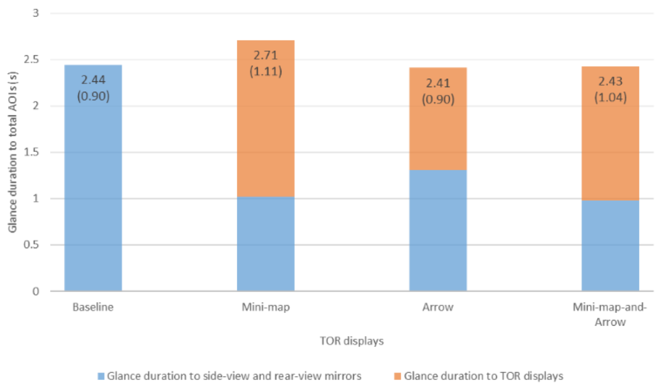


Figure 4.6: Mean and standard deviation (in parentheses) of glance duration to total AOIs

As for mean mirror glance duration, Mini-map-and-Arrow was significantly lower than Arrow, F(2, 58) = 4.65, $p = .013$ (Figure 4.7).

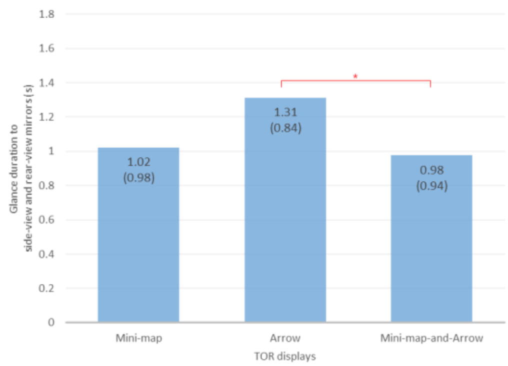


Figure 4.7: Mean and standard deviation (in parentheses) of glance duration to side-view and rear-view mirrors with the asterisk indicating significance in the multiple pairwise comparisons

In terms of mean TOR display glance duration, Arrow resulted in significantly lower than Mini-map, and Mini-map-and-Arrow, $F(2, 48) = 13.62$, $p = .000$. Mini-map-and-Arrow showed significantly lower mean glance duration than Mini-map (Figure 4.8).

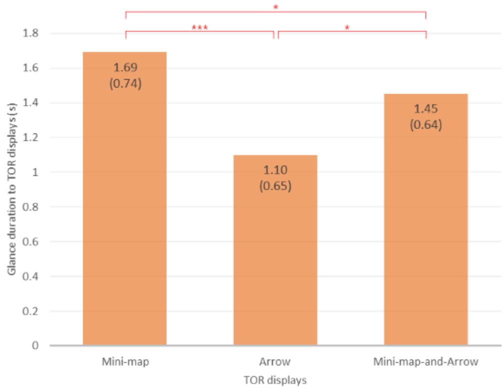


Figure 4.8: Mean and standard deviation (in parentheses) of glance duration to TOR displays with asterisks indicating significance in the multiple pairwise comparisons

Regarding mean number of glances to total AOIs, the result of the Friedman test showed that Mini-map and Mini-map-and-Arrow resulted in significantly lower than Baseline, $\chi 2(3) = 22.63$, $p = .000$. Arrow showed significantly higher mean number of glances to total AOIs than Mini-map and Mini-map-and-Arrow (Figure 4.9).

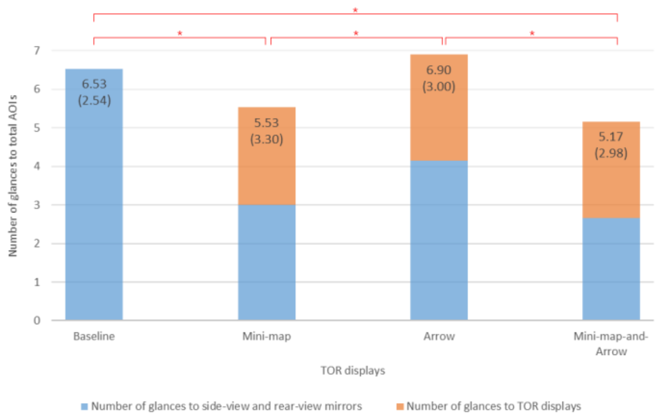


Figure 4.9: Mean and standard deviation (in parentheses) of number of glances to total AOIs with the asterisk indicating significance in the multiple pairwise comparisons

In terms of mean number of glances to mirrors, Arrow showed significantly higher than Mini-map and Mini-map-and-Arrow, $\chi2(2) = 17.41$, $p = .000$ (Figure 4.10).

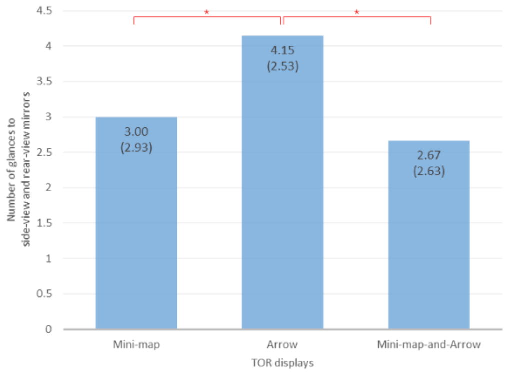


Figure 4.10: Mean and standard deviation (in parentheses) of number of glances to side-view and rear-view mirrors with the asterisk indicating significance in the multiple pairwise comparisons

In terms of mean number of glances to TOR displays, there was no significant difference between Mini-map, Arrow, and Mini-map-and-Arrow (Figure 4.11).

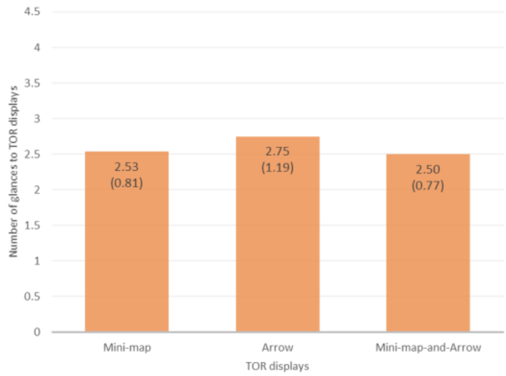


Figure 4.11: Mean and standard deviation (in parentheses) of number of glances to TOR displays

From the eye-tracking data, two glances longer than 2 seconds were found for Mini-map (2.8 seconds and 2.258 seconds). The two glances were performed by two different participants.

<u>Subjective measures</u>

The results of the ANOVA and post-hot Bonferroni multiple comparisons on mean perceived preference indicated that the three TOR displays, that is, Mini-map, Arrow, and Mini-map-and-Arrow, resulted in significantly higher than Baseline, $F(2, 67) = 38.48$, $p = .000$. Mini-map-and-Arrow showed significantly higher mean perceived preference values than Mini-map (Figure 4.12).

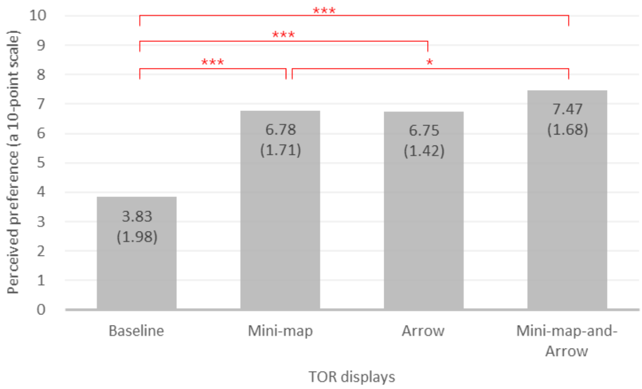


Figure 4.12: Mean and standard deviation (in parentheses) of perceived preference with asterisks indicating significance in the multiple pairwise comparisons

As for mean perceived safety, three TOR displays, Mini-map, Arrow, and Mini-map-and-Arrow, showed significantly higher than Baseline, $F(2, 62) = 29.96$, $p = .000$. Mini-map-and-Arrow showed significantly higher mean perceived safety than Mini-map (Figure 4.13).

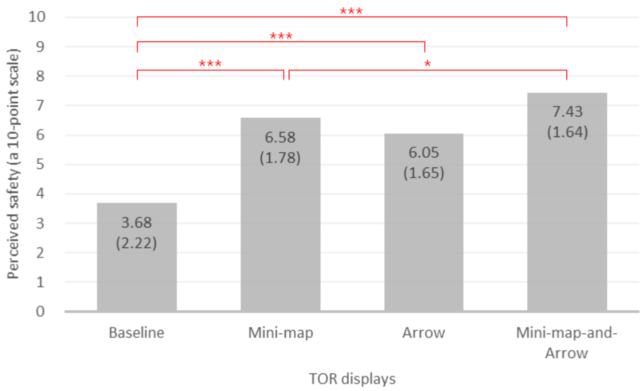


Figure 4.13: Mean and standard deviation (in parentheses) of perceived safety with asterisks indicating significance in the multiple pairwise comparisons

In terms of mean perceived usefulness, the three TOR displays, that is, Mini-map, Arrow, and Mini-map-and-Arrow, resulted in significantly higher than Baseline, $F(2, 69) = 46.31$, $p = .000$. Mini-map-and-Arrow showed significantly higher mean perceived usefulness than Mini-map, and Arrow respectively (Figure 4.14).

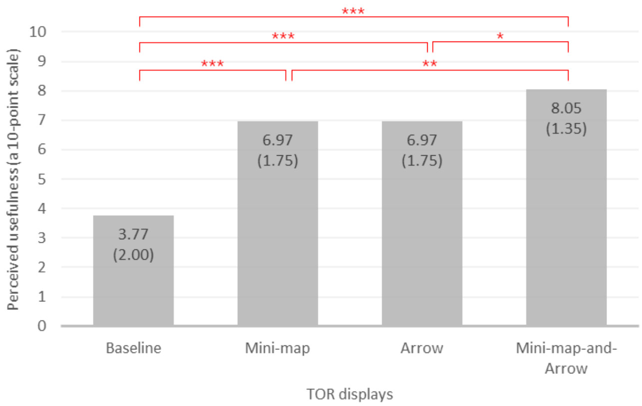


Figure 4.14: Mean and standard deviation (in parentheses) of perceived usefulness with asterisks indicating significance in the multiple pairwise comparisons

As for mean desirability, the three TOR displays, that is, Mini-map, Arrow, and Mini-map-and-Arrow, resulted in significantly higher than Baseline, $F(2, 67) = 24.26$, $p = .000$. Mini-map-and-Arrow display showed significantly higher mean desirability than Mini-map (Figure 4.15).

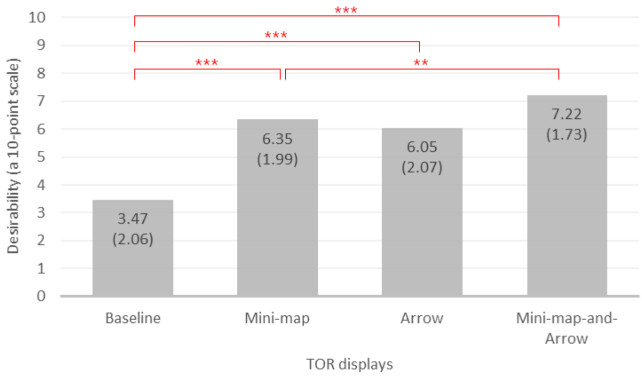


Figure 4.15: Mean and standard deviation (in parentheses) of desirability with asterisks indicating significance in the multiple pairwise comparisons

In terms of mean annoyance, there was no significant difference between the TOR displays (Figure 4.16).

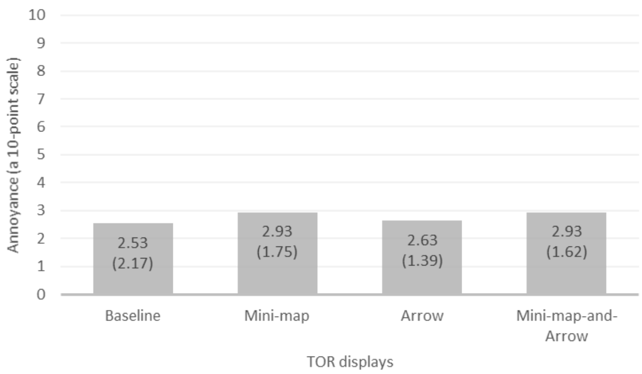


Figure 4.16: Mean and standard deviation (in parentheses) of annoyance

As for mean workload, the three TOR displays, that is, Mini-map, Arrow, and Mini-map-and-Arrow, resulted in significantly lower than Baseline, $F(3, 87) = 37.12$, $p = .000$. Mini-map-and-Arrow showed significantly lower mean workload than Mini-map (Figure 4.17).

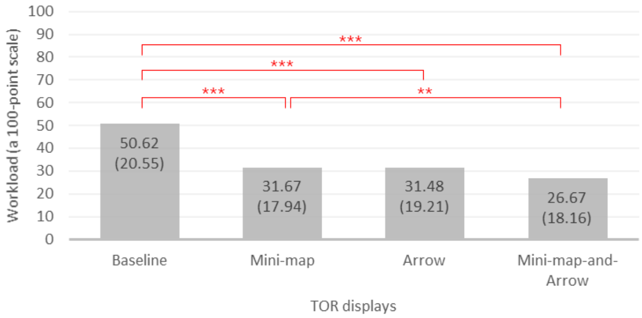


Figure 4.17: Mean and standard deviation (in parentheses) of workload with asterisks indicating significance in the multiple pairwise comparisons

4.3.2 Characteristics of Drivers' Initial Trust in the four TOR Displays

For drivers' initial trust in the four TOR displays, the cluster analysis resulted in identification of two cluster groups; one group included 25 people and the other, 5 people. There was a statistically significant difference between the two cluster groups. The cluster means for each of the four TOR displays were shown in Table 4.5, and Figure 4.18 illustrated the box-and-whiskers plots of the two cluster groups.

Based on the results described in Table 4.5 and Figure 4.18, the two cluster groups of the initial trust in TOR displays had quite different characteristics. Cluster 1 showed the lower initial trust level compared to cluster 2 for all TOR displays. Therefore, cluster 1 and 2 were denoted 'lower trust group' and 'higher trust group', respectively. The largest mean difference between the lower trust and higher trust group was found in Mini-map. The characteristics of the two cluster groups (that is, trust groups) were as follows:

- Trust group 1 (25 people): Group 1 was labelled ‘lower trust group’ as this group showed lower trust level in all TOR displays compared to trust group 2. The cluster means for Baseline was a little above the mid-point, for Mini-map and Mini-map-and-Arrow were a little below the mid-point, and for Arrow was the lowest.
- Trust group 2 (5 people): Group 2 was labelled ‘higher trust group’ as the group showed higher trust level in all TOR displays compared to trust group 1. The cluster means for Mini-map was the highest, followed by Baseline, Mini-map-and-Arrow, and Arrow.

Table 4.5: Cluster means for each of the four TOR displays

Group \ Display	Baseline	Mini-map	Arrow	Mini-map-and-Arrow
Lower trust group (25 people)	5.38	4.96	4.27	4.73
Higher trust group (5 people)	7.87	8.22	6.71	7.58
Differences	2.49	3.26	2.44	2.85

a) b)

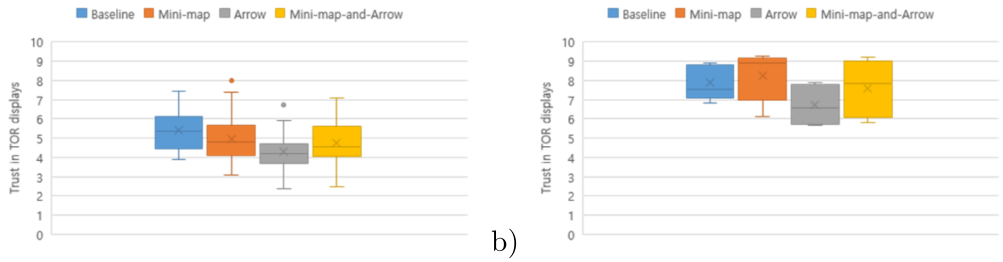


Figure 4.18: Box-and-whiskers plots of two cluster groups: a) the lower trust group and b) the higher trust group

4.3.3 Relationship between Drivers' Initial Trust and Take-over and Visual Behavior

For each of the dependent variables, the mean and standard deviation values of each cluster group are presented in Figure 4.19-5.32 with asterisk indicating the statistical significance between the two trust groups (* $<$ .05, ** $<$ .01, *** $<$ .001).

Objective measures (take-over performance)

The results of two-sample t-test on mean reaction time indicated that the higher trust group resulted in a significantly shorter mean reaction time than the lower trust group when using Mini-map-and-Arrow, $t(24) = 2.67$, $p = .013$ (Figure 4.19).

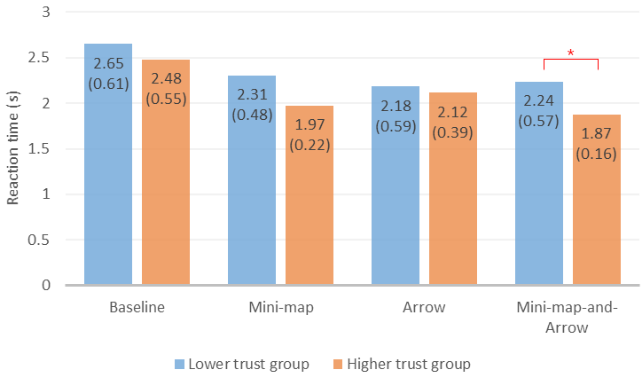


Figure 4.19: Mean and standard deviation (in parentheses) of reaction time of the lower and higher trust groups with the asterisk indicating the significance of the difference between the two trust groups

As for mean completion time and standard deviation of lateral position, there was no significant difference between the two trust groups for any of TOR displays (Figure 4.20).

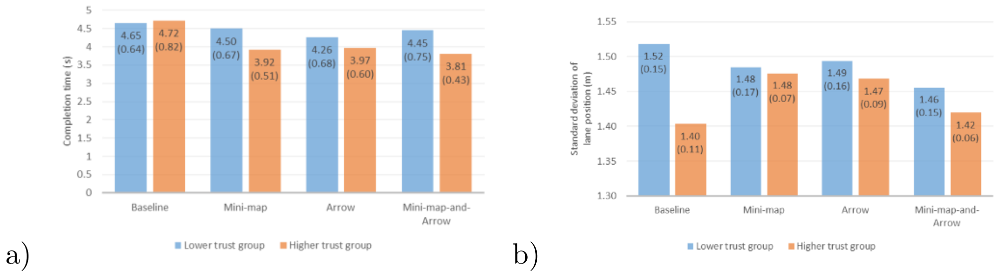


Figure 4.20: Bar graphs for mean and standard deviation (in parentheses) of a) completion time and b) standard deviation of lateral lane position

<u>Objective measures (eye movement behavior)</u>

The Mann-Whitney U test showed that the lower trust group resulted in significantly higher mean total AOI glance duration than the higher trust group for Mini-map, $U = 24$, $p = .032$ and Mini-map-and-Arrow, $U = 25$, $p = .037$ (Figure 4.21).

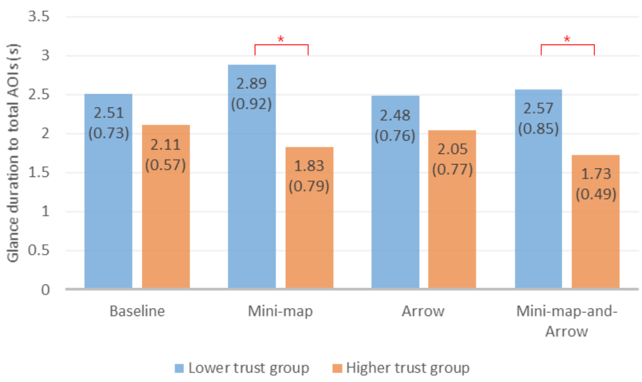


Figure 4.21: Mean and standard deviation (in parentheses) of glance duration to total AOIs of the lower and higher trust groups with asterisks indicating the significance of the differences between the two trust groups

As for mean mirror glance duration, the lower trust group showed significantly higher mean mirror glance duration than the higher trust group for Mini-map, $t(28) = 5.17$, $p = .000$ and Mini-map-and-Arrow, $t(23) = 3.81$, $p = .001$ (Figure 4.22).

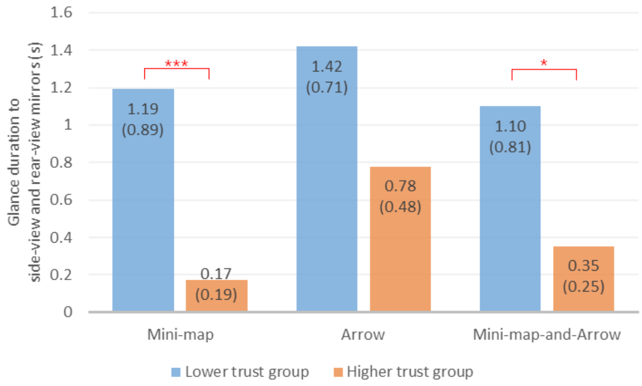


Figure 4.22: Mean and standard deviation (in parentheses) of glance duration to side-view and rear-view mirrors of the lower and higher trust groups with asterisks indicating the significance of the differences between the two trust groups

As for mean TOR display glance duration, there was no significant difference between the two trust groups for the TOR displays (Figure 4.23).

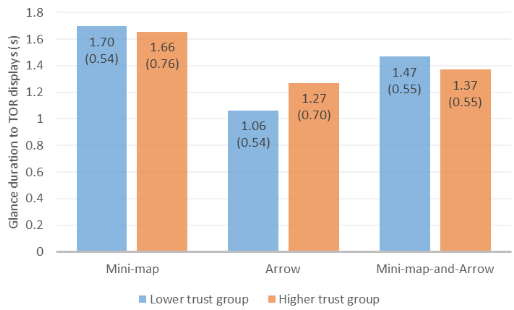


Figure 4.23: Mean and standard deviation (in parentheses) of glance duration of TOR displays of the lower and higher trust groups

The Mann-Whitney U test showed that the lower trust group resulted in significantly higher mean number of glances of total AOIs than the higher trust group for Mini-map, $U = 26.5$, $p = .044$ (Figure 4.24).

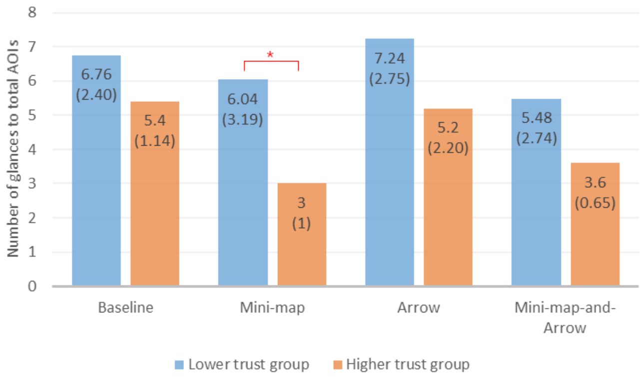


Figure 4.24: Mean and standard deviation (in parentheses) of number of glances to total AOIs of the lower and higher trust groups with the asterisk indicating the significance of the difference between the two trust groups

As for mean number of glances to side-view and rear-view mirrors, the lower trust group showed significantly higher mean number of glances to side-view and rear-view mirrors than the higher trust group for Mini-map, $U = 26$, $p = .041$ (Figure 4.25).

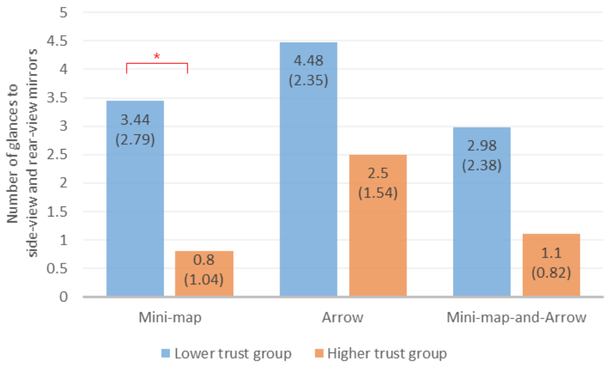


Figure 4.25: Mean and standard deviation (in parentheses) of number of glances to side-view and rear-view mirrors of the lower and higher trust groups with asterisks indicating the significance of the differences between the two trust groups

As for mean number of glances of TOR displays, there was no significant difference between the two trust groups for all the TOR displays (Figure 4.26).

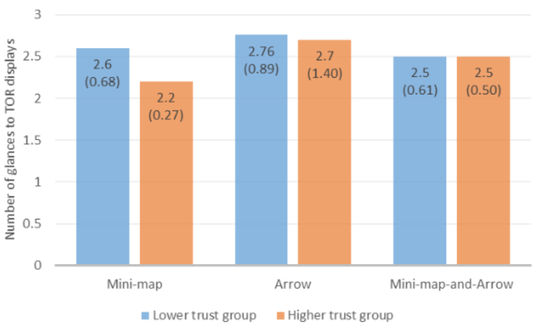


Figure 4.26: Mean and standard deviation (in parentheses) of number of glances of TOR displays of the lower and higher trust groups

Subjective measures

As for mean perceived preference, the higher trust group resulted in significantly higher mean perceived preference than the lower trust group for Mini-map, $t(28)$ = -2.52, p = .018 (Figure 4.27).

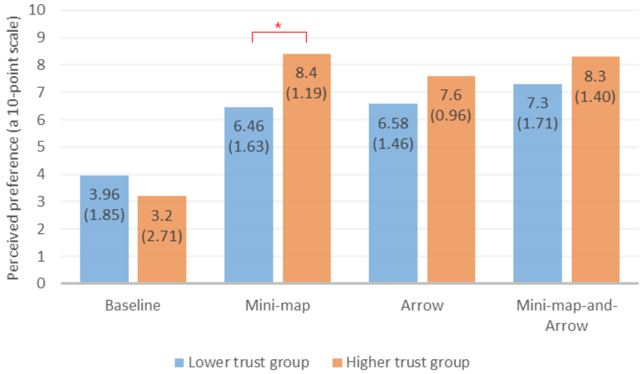


Figure 4.27: Mean and standard deviation (in parentheses) of perceived preference of the lower and higher trust groups with the asterisk indicating the significance of the difference between the two trust groups

In terms of mean perceived safety, the higher trust group resulted in significantly higher mean perceived safety than the lower trust group for Mini-map, $t(28)$ = -2.31, p = .029 and Mini-map-and-Arrow, $t(28)$ = -2.07, p = .048 (Figure 4.28).

Figure 4.28: Mean and standard deviation (in parentheses) of perceived safety of the lower and higher trust groups with asterisks indicating the significance of the differences between the two trust groups

In terms of mean perceived usefulness, the higher trust group resulted in significantly higher mean perceived usefulness than the lower trust group for Mini-map, $t(28) = -3.05$, $p = .005$ (Figure 4.29).

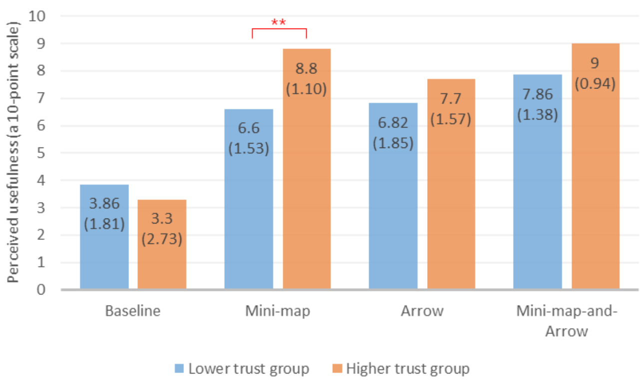


Figure 4.29: Mean and standard deviation (in parentheses) of perceived usefulness of the lower and higher trust groups with asterisks indicating the significance of the difference between the two trust groups

In terms of mean desirability, the higher trust group showed significantly higher mean desirability than the lower trust group for Mini-map, $t(28) = -2.62$, $p = .014$ (Figure 4.30).

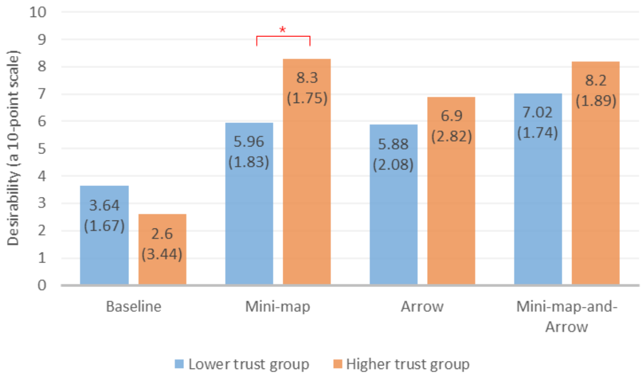


Figure 4.30: Mean and standard deviation (in parentheses) of desirability of the lower and higher trust groups with the asterisk indicating the significance of the difference between the two trust groups

The Mann-Whitney U test showed that the lower trust group showed significantly higher mean annoyance than the higher trust group for Mini-map, $U = 12$, $p = .005$ (Figure 4.31).

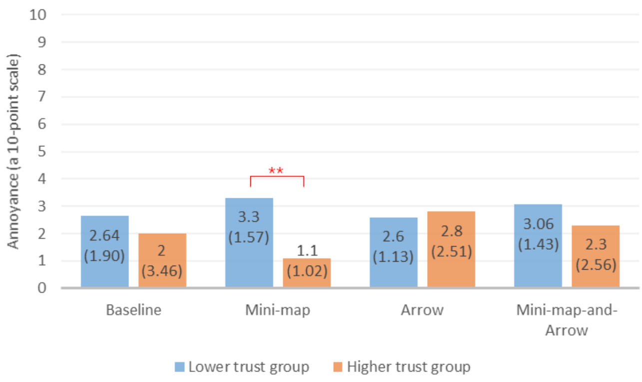


Figure 4.31: Mean and standard deviation (in parentheses) of annoyance of the lower and higher trust groups with asterisks indicating the significance of the difference between the two trust groups

As for mean workload, there was no significant difference between the two trust groups for all the TOR displays (Figure 4.32).

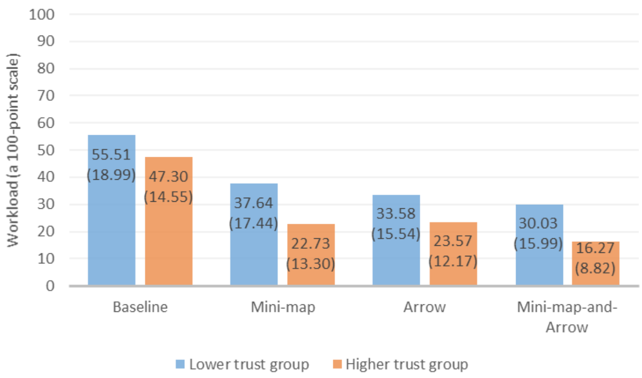


Figure 4.32: Mean and standard deviation (in parentheses) of workload of the lower and higher trust groups

4.4 Discussion

This study developed four different types of automotive HUD-based TOR displays and evaluated them using the driving simulator in terms of drivers' take-over performance and visual scanning behavior in a highly automated driving situation. The study also investigated how the proposed TOR displays affect drivers' initial trust and whether their initial trust affects the take-over behavior in the context of a sudden manual intervention task.

4.4.1 Comparison of the four TOR displays

Based on the results of take-over performance, it was indicated that three TOR displays, that is, Mini-map, Arrow, and Mini-map-and-Arrow, affected the initial response to the take-over. The three TOR displays resulted in significantly faster mean reaction times than Baseline. This may be because presenting the same information (imminent occurrence of take-over) in both the auditory and visual channels would facilitate drivers' detection of take-over requests. Also, the information delivered by the TOR displays seemed to enhance drivers' situation awareness and follow-up decision making. In terms of task completion time, Arrow and Mini-map-and-Arrow showed significantly shorter mean completion times than Baseline. It seems that the displays with arrow indicating an action instruction are believed to help drivers perform quick actions. It is interesting that Mini-map did not significantly differ from Baseline in mean completion time while it did in mean reaction time. It is not clear why the advantage in reaction time did not transfer to that in completion time; it may be related to the fact that Mini-map did not present a clear suggestion or direction on what to do while Arrow and Mini-map-and-Arrow did. Regarding the number of collisions, Mini-map-and-Arrow appeared to be the safest of the four TOR displays.

Some evidence of benefit of using Arrow was also found in mean TOR glance times, one of the eye movement behavior measures. Arrow had significantly shorter mean TOR glance times than Mini-map and Mini-map-and-Arrow; this seems to reflect the differences in the amount of the visual information presented by the TOR displays. Interestingly, Mini-map was found to have a larger mean TOR glance time than Mini-map-and-Arrow; this is despite that Mini-map-and-Arrow provided more visual information than Mini-map. It may be that the arrow symbol in Mini-map-and-arrow supported drivers' human decision making by providing the machine's decision; the arrow may have helped drivers selectively, and, thus, effectively, process the information contained in the mini-map element.

However, when considering some other measures of eye movement behavior, it should be prudent to use only Arrow. The mean mirror glance time and mean number of glances to mirrors were both significantly larger for Arrow than Mini-map or Mini-map-and-Arrow. In other words, drivers actively sampled more visual information from the side-view and rear-view mirrors when using Arrow than Mini-map or Mini-map-and-Arrow. This suggests that receiving only the final machine-made decision without situational information through the HUD system was relatively less sufficient for drivers to make and execute their decision, when compared with receiving situational information or both. Relatedly, in terms of the mean number of glances to all AOIs (side-view and rear-view mirrors, and TOR displays), Arrow had a significantly higher frequency than Mini-map and Mini-map-and-Arrow, and did not significantly differ from Baseline. This also seems to suggest that receiving the machine decision only is less sufficient for drivers than receiving both the machine decision and the situational information; and, it increases drivers' behavior of seeking information from the traditional displays.

The subjective evaluation results were consistent with the results of take-over performance and eye movement behavior. All three audio-visual TOR displays had higher means in perceived preference, safety, usefulness and desirability ratings than Baseline, and reduced perceived workloads in comparison with Baseline. Providing SA-enhancing information or a directive based on machine decision making seems to have a positive effect on the drivers' subjective ratings. In terms of mean perceived preference, safety, usefulness, and desirability, Mini-map-and-Arrow was rated significantly higher than Mini-map, which indicates that on average, the participants preferred to receive a directive in combination with the situation information over receiving the situation information only. Mini-map and Arrow did not significantly differ in mean perceived preference, safety, usefulness, and desirability. This may indicate that the types of information provided by the two displays provide similar benefits despite the differences in them. In terms of mean perceived preference, safety, and desirability, Arrow and Mini-map-and-Arrow did not differ significantly. This may imply possible trade-off between display transparency and ease of information processing. As combining Arrow and Mini-map (Mini-map-and-Arrow) did not increase mean perceived workload, adding Arrow to Mini-map does not much increase the amount of visual information and clutter beyond that of Mini-map, but, improves display transparency and also reduces the information processing costs associated with decision making. In fact, the mean perceived workload was significantly lower for Mini-map-and-Arrow than for Mini-map. Also, Mini-map-and-Arrow and Arrow did not significantly differ. On average, Mini-map-and-Arrow was perceived as more useful than the other two audio-visual TOR displays. This may be due to the fact that Mini-map-and-Arrow provides more information than the other two. No significant difference in mean annoyance rating was found. This suggests that the users may be willing to accept the audio-visual TOR displays, despite the increase in the amount of visual information presented.

To sum up, both objective and subjective results indicated that providing a combination of machine-made decision and situational information, such as Mini-map-and-Arrow, yielded the best results in the take-over scenario. A final decision by the automation, such as Arrow, can facilitate more rapid action decision, and may help drivers' information processing, especially when presented with the situational information simultaneously. However, given the fact that using only the final machine-made decision can cause drivers to actively check more information from the traditional displays, it should be cautious to provide only the machine-made decision in the take-over scenario.

4.4.2 Characteristics of drivers' initial trust in the four TOR displays

The scores of the participants' initial trust were classified into two clusters – the lower trust (25 people) and higher trust (5 people) groups. Given that the number of participants was skewed toward the lower trust group, it was indicated that those who do not trust the information provided by the automation were found to be much more than those who trust. It is not clear why, but one reason might be that the proposed TOR displays in this study has not been commercialized yet.

In the lower trust group, mean trust value of Baseline was the highest followed by Mini-map, Mini-map-and-Arrow, and Arrow (Table 4.5). It is thought that the interface of Baseline is more similar to the traditional in-vehicle displays, and therefore the lower trust group appeared to trust in Baseline more than other TOR displays. Overall, there seems to be a tendency to not trust in information that relies on the automated system.

The higher trust group had the highest mean trust value for Mini-map (Table 4.5). It may be because the higher trust group trusts that Mini-map shows the situation as it is. Considering that the higher trust group showed higher trust level in all the TOR displays compared to the lower trust group, it seems that the higher trust group has a high degree of trust in the information provided by the automated system.

Based on the results of the cluster means for each of the four TOR displays, both trust groups showed Arrow had the lowest mean trust values among the four displays. It may be because, in the case of Arrow, no information is provided as to why the automated system made the decision.

4.4.3 Relationship between drivers' initial trust and take-over and visual behavior

Based on the results of take-over performance (mean reaction time) and eye movement behavior (mean total AOI glance duration, mean mirror glance duration, mean number of glances to AOIs, and mean number of glances to mirrors), the participants' initial trust in the proposed TOR displays was found to have significant associations with their actual take-over and visual behavior in the take-over scenario. The lower trust group had a significantly larger mean reaction time than the higher trust group for Mini-map-and-Arrow (Figure 4.19). Also, mean AOI glance times and mean mirror glance times were significantly higher for the lower trust group than for the higher trust group for Mini-map and Mini-map-and-Arrow (Figure 4.21 and 4.22). The mean number of glances to AOIs and mirrors were significantly higher for the lower trust group than for the higher trust group for Mini-map (Figure 4.24). These results may be because the participants with lower trust in TOR displays spent more time confirming the information from the automation through additional sampling of information and comparison. The three audio-visual TOR displays did not significantly differ in the mean TOR display glance time and mean number of glances to TOR displays. This is consistent with the interpretation that the participants with lower trust in the TOR displays spent more time confirming the information from the automation through additional sampling of information from the traditional displays and comparison.

Interestingly, the results showed that there were significant differences between the two trust groups mainly on Mini-map and/or Mini-map-and-Arrow displays. This may be because the differences between the cluster means are the largest on Mini-map followed by Mini-map-and-Arrow (Table 4.5). The large differences in the trust values resulted in significant differences in take-over performance and eye movement behavior. Another possible explanation for this is that the higher trust group tended to rely entirely on Mini-map believing that it shows the environment as is. On the other hand, it seems that the lower trust group spent more time checking information from both the traditional displays and Mini-map and/or Mini-map-and-Arrow. Mini-map and Mini-map-and-Arrow present a large amount of information. This is thought to have given rise to the prominent differences between the two groups. In case of Arrow, the group mean differences in all dependent variables were not significant. This may be related to the fact that for Arrow, the two groups differed least in the trust score (Table 4.5).

Drivers' initial trust in the TOR displays also had significant associations with the results of subjective ratings. For Mini-map, the mean perceived preference, usefulness, desirability ratings were significantly lower for the lower trust group than for the higher trust group (Figure 4.27, 4.29, and 4.30). For Mini-map and Mini-map-and-Arrow, the mean perceived safety rating was significantly lower for the lower trust group than for the higher trust group (Figure 4.28). These results are thought to be because drivers with low trust would not find the automation useful. In terms of mean perceived annoyance, the rating was significantly higher for the lower trust group than for the higher trust group for Mini-map (Figure 4.31). This maybe because drivers with low trust would not find the automation useful, while the automation consumes attentional resources.

In summary, it was found that the actual take-over and visual behavior of drivers may vary according to their initial trust. The higher trust group primarily relied on the proposed TOR displays while the lower trust group tended to check more information through the traditional in-vehicle displays, such as side-view or rear-view mirrors. Accordingly, the higher trust group responded faster to the TORs by making the most of the proposed TOR displays than the lower trust group, which also influenced the positive evaluation of subjective measures.

4.5 Conclusion

In conclusion, when designing a TOR display, it is useful to provide both situational information and machine-made decisions in a take-over situation. Even if the amount of information increases, drivers seem to want to be informed about the reasoning process for the proposed action suggested by the automated system. In other words, drivers may want to know what the automated system currently collects and understands for the systems' goals, and they seem to find this useful. It is therefore, in take-over scenarios, visual aids with high transparency should be considered.

Regarding drivers' initial trust in the proposed TOR displays, it was found that their trust varied depending on the display characteristics. Also, the take-over and visual behavior of drivers was found to have significant associations with their initial trust in the TOR displays. Therefore, what display characteristics should be provided for the appropriate use of the automated system is an important factor to consider when developing a TOR display.

In this study, only take-over scenarios related to system limit (e.g., road works ahead on the same lane) were considered, but various take-over scenarios, such as adversarial attacks, should be investigated in future studies. Also, different age groups should be taken into account in future studies in order to examine the impacts of the prior experience of using HUD systems.

Chapter 5

Human Factors Evaluation of Display Locations of an Interactive Scrolling List in a Full-windshield Automotive Head-Up Display System

5.1 Introduction

An automotive HUD system must be designed to help the driver focus on the road ahead and at the same time quickly process the information it presents. The location of the HUD imagery is one of many design variables that would significantly affect driving as well as HUD information processing performance. The recent technological advances, such as the full-windshield AR HUD technologies, enable presenting HUD imagery at various locations outside the vehicle. This capability greatly expands the range of design possibilities.

Multiple studies have examined the effects of HUD imagery location on driving performance and driver preference so as to determine the recommended locations (Tretten et al., 2011; Chao et al., 2009; Morita et al., 2007; Tsimhoni et al., 2001; Yoo et al., 1999; Flannagan et al., 1994). Tretten et al. (2011), Chao et al. (2009), and Flannagan et al. (1994) recommended that the HUD imagery should be presented from 0 to 10 degrees below the line of sight. Morita et al. (2007) suggested that the HUD imagery location can be more than 4 degrees in the downward direction or more than 7 degrees in the upward direction. Tsimhoni et al. (2001), and Yoo et al. (1999) stated that 5 degrees to the right and left of the center, and the central position gave the best performance and were more likely to be preferred.

The existing studies, however, considered displaying a simple, non-interactive visual object (e.g., a warning symbol); and, none seem to have examined more complex visual objects that the driver can manipulate interactively - for example, a scrolling list.

Consequently, how HUD imagery location affects driving performance and task performance, and driver distraction and preference is not well understood for interactive visual objects. This lack of understanding hampers optimizing the design of HUD imagery and fully capitalizing on the advantages of HUD.

As an effort towards addressing this problem, the current study investigated the effect of interactive HUD imagery location on driving performance and secondary task performance, driver distraction, preference and workload. The interactive HUD element considered was a single-line interactive scrolling list and the associated task was performing item search and selection.

5.2 Method

5.2.1 Participants

A total of 24 participants (18 males and 6 females) participated in this study and their mean age was 27.04 years (SD = 2.68, min = 24, max = 36). An average driving experience was 3.71 years (SD = 4.12). The study received ethical approval from Seoul National University Institutional Review Board.

5.2.2 Apparatus

A fixed-base three-channel driving simulator was used in this study. The simulator consisted of adjustable vehicle interior mock-up (seat, steering wheel, gas pedal, brake pedal, gearshift) and three 42-inch LED monitors. This provided an immersive driving environment with a forward FOV angle of 183.6 degrees. The virtual driving environment was developed using a driving simulation software (UC-win / Road Ver.10, Forum8) linked with the simulator. During the experiment trials, the participants' eye movements were tracked and recorded using an eye tracking system (Dikablis Eye Tracking System, Ergoneers). The experimental setup is shown in Figure 5.1.

Figure 5.1: Experimental setup of Study 4

5.2.3 Experimental Tasks and Driving Scenario

The primary task was to follow a lead vehicle. The initial speed of the lead vehicle was 60km/h, and the participants were instructed to follow the lead vehicle maintaining a distance of around 40m. In each experiment trial, the lead vehicle randomly slowed down to 20km/h for a short duration and returned to the initial speed four times, and changed lanes two times. When the lead vehicle slowed down, the collision warning display appeared for three seconds located around the 5 degrees below the driver's forward line of vision. The current speed of the participant's vehicle was also presented continuously around the 5 degrees below the driver's forward line of vision, along with the collision warning. The participants were told to drive on a given road about 2km long, which was a highway with two lanes including slight curves.

The secondary task was a music selection task, which required searching for and selecting a target song name with the single-line interactive scrolling list of song names through the HUD. The target song name was auditorily provided to the participants with the visual cue at four random times. The number of the song names in the list was four or six and the scrolling list showed a single-line information at a time. The participants were instructed to manipulate the scrolling list using the buttons on the simulator's steering wheel. The secondary task was performed at a self-paced rate. The participants was told to put top priority on the primary task and were allowed to start the secondary task when they thought they could. An auditory cue signalled the completion of scrolling list manipulation.

5.2.4 Experiment Variables

The independent variable was the HUD imagery location with nine levels (L1-L9) (Figure 5.2). The locations were spaced approximately 10 degrees apart vertically, and 24 degrees apart horizontally from participant's straight ahead line of sight to cover the entire windshield.

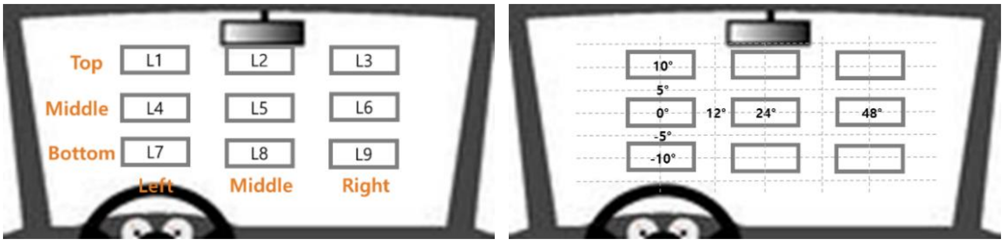


Figure 5.2: Nine HUD imagery locations of the single-line interactive scrolling list

The dependent variables consisted of measurements of driving performance, secondary task performance, driver distraction, perceived preference, and workload. The secondary task performance was measured by task completion time. The task completion time was defined as the time duration from the onset of the manipulation of the music selection task to the moment that the participant selects the correct song. Driving performance was measured by standard deviation of distance headway (longitudinal operation) and standard deviation of lane position (lateral operation). Distance headway was defined as the momentary distance to a lead vehicle (Östlund et al. 2006). Lateral position was defined as the distance between the front wheel center and the road centerline. Driver distraction was measured by EoRT. The EoRT was defined as the total time of eye glance away from the road during each experimental trial. Workload was measured by the NASA-TLX questionnaire. Perceived preference was measured with a 10-point scale. Table 5.1 shows the experimental variables used in this study.

Table 5.1: Experimental variables of Study 4

Experimental variables		
Independent variable	HUD imagery location with nine levels (L1-L9)	
Dependent variable	Objective measure	1) Driving performance: SD of distance headway (m), SD of lane position (m)
		2) Secondary task performance: Task completion time (s)
		3) Driver distraction: EoRT (s)
	Subjective measure	1) Perceived preference (10-point scale)
		2) Workload (NASA-TLX) (10-point scale)

5.2.5 Experimental Design and Procedure

Prior to the start of the experiment trials, training sessions were provided to the participants so that they became familiar with the driving simulator, scenario, primary and secondary tasks and each of nine HUD imagery locations.

Each participant performed a single experiment trial for each of the nine HUD imagery locations. The order of the nine experiment trials was randomized for each subject. In each trial, the scrolling list appeared at the corresponding HUD imagery location four times. After each experiment trial, the participants were asked to fill in the NASA-TLX questionnaire and subjectively rate the level of perceived preference on a 10-point scale.

5.2.6 Statistical Analyses

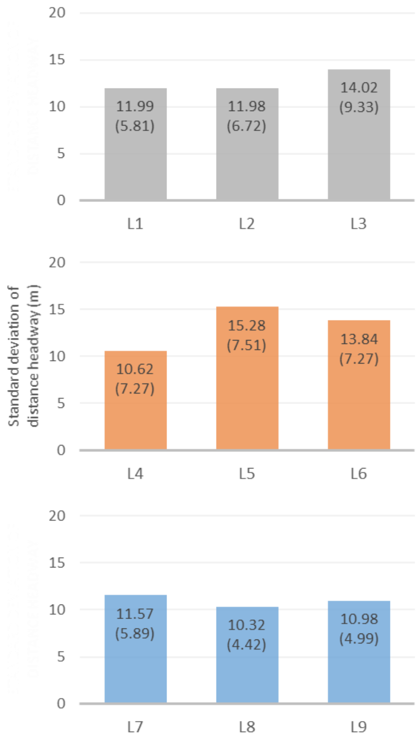
A one-way repeated measures ANOVA was conducted to test the effect of the HUD imagery locations if the assumption of normality was met. If the assumption of normality was not met, a Friedman test was conducted. For ANOVAs, the Mauchly's test was performed to assess sphericity of data. If data violated the sphericity assumption, the Greenhouse-Geisser correction was used. In case there was a significant effect of the nine HUD imagery locations, post-hoc Bonferroni multiple pairwise comparisons were conducted for ANOVAs, and Wilcoxon signed-rank tests, for Friedman tests. A Bonferroni correction was applied to the α-level to control the Type Ⅰ error rates. All statistical tests were conducted at an alpha level of 0.05 using SPSS 25.

5.3 Results

For each of the dependent variables, the mean and standard deviation (in parentheses) values for each of the nine HUD imagery locations are presented in Figure 5.3-5.9.

<u>Driving performance</u>

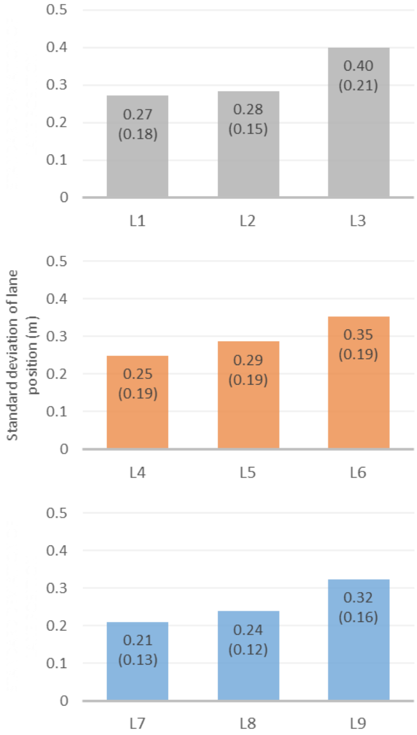
In terms of standard deviation of distance headway, the Friedman test showed that there were significant differences for L5 – L1/4/7/8/9, and L6 – L4/8, $\chi2(8) = 17.02$, $p = .030$ (Figure 5.3).



Locations	Sig.
L5 - L4	0.014
L6 - L4	0.018
L5 - L1	0.021
L7 - L5	0.037
L8 - L5	0.005
L9 - L5	0.024
L8 - L6	0.022

Figure 5.3: Mean and standard deviation (in parentheses) of standard deviation of distance headway

In terms of standard deviation of lane position, there were significant differences for L7 – L1/2/3/5/6/9, and L3 – L1/2/4/5/8, and L4/8 – L6/9, and L1 – L3/6, χ2(8) = 42.37, *p* = .000 (Figure 5.4).

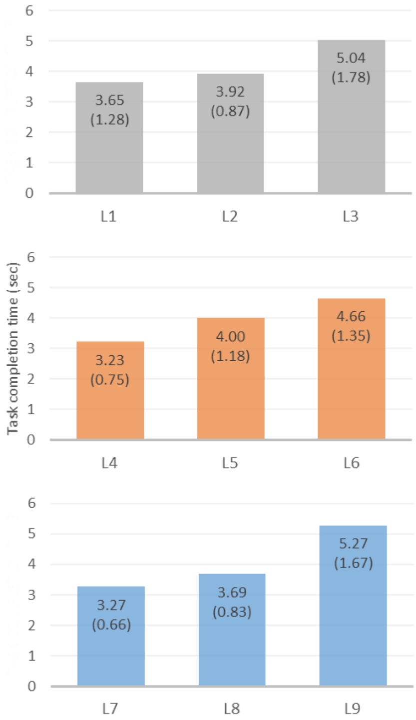


Locations	Sig.
L3 - L1	0.012
L6 - L1	0.013
L7 - L1	0.018
L3 - L2	0.015
L7 - L2	0.003
L4 - L3	0.003
L5 - L3	0.018
L7 - L3	0.000
L8 - L3	0.000
L6 - L4	0.002
L9 - L4	0.022
L7 - L5	0.021
L7 - L6	0.000
L8 - L6	0.007
L9 - L7	0.011
L9 - L8	0.022

Figure 5.4: Mean and standard deviation (in parentheses) of standard deviation of lane position

Secondary task performance

As for completion time for the secondary task, there were significant differences for L3 – L1/2/4/5/7/8, and L6 – L1/2/5/7/8/9, and L9 – L1/2/5/7/8, and L4 – L2/5/6/8/9, and L7 – L2/5/8, χ2(8) = 77.14, *p* = .000 (Figure 5.5).

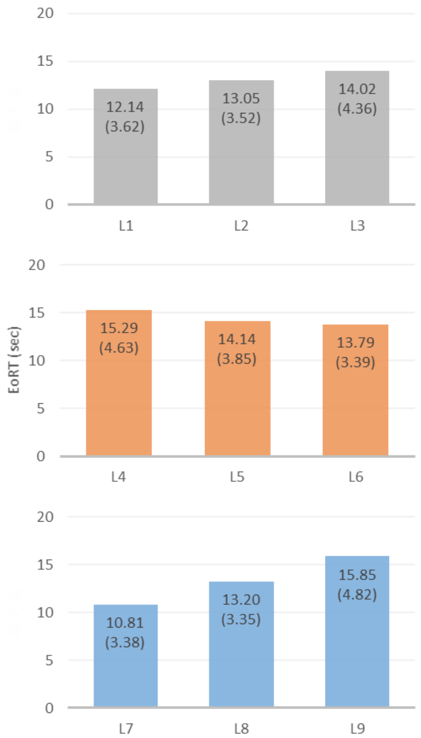


Locations	Sig.
L3 - L1	0.001
L6 - L1	0.006
L9 - L1	0.000
L3 - L2	0.015
L4 - L2	0.001
L6 - L2	0.012
L7 - L2	0.002
L9 - L2	0.000
L4 - L3	0.000
L5 - L3	0.008
L7 - L3	0.000
L8 - L3	0.001
L5 - L4	0.001
L6 - L4	0.000
L8 - L4	0.007
L9 - L4	0.000
L6 - L5	0.007
L7 - L5	0.015
L9 - L5	0.000
L7 - L6	0.000
L8 - L6	0.002
L9 - L6	0.049
L8 - L7	0.046
L9 - L7	0.000
L9 - L8	0.000

Figure 5.5: Mean and standard deviation (in parentheses) of task completion time

Eye movement behavior

In terms of EoRT, there were significant differences for L1 – L3/5/6/9, and L7 – L2/3/4/5/6/8/9, and L9 – L2/8, $\chi 2(8) = 35.80$, $p = .000$ (Figure 5.6).

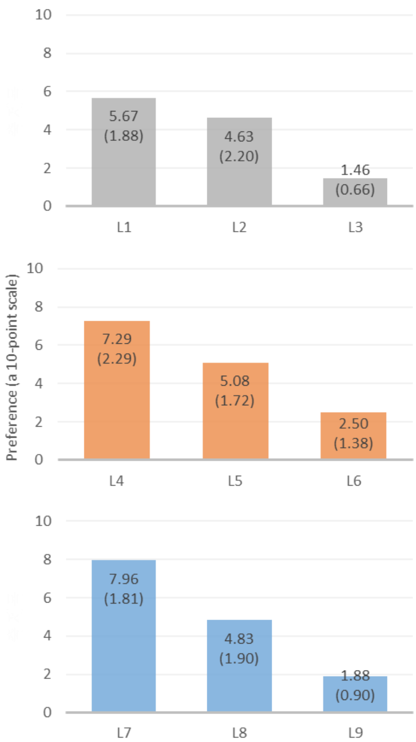


Locations	Sig.
L3 - L1	0.036
L5 - L1	0.039
L6 - L1	0.024
L9 - L1	0.001
L7 - L2	0.005
L9 - L2	0.010
L7 - L3	0.005
L7 - L4	0.000
L7 - L5	0.002
L9 - L5	0.110
L7 - L6	0.002
L8 - L7	0.003
L9 - L7	0.000
L9 - L8	0.002

Figure 5.6: Mean and standard deviation (in parentheses) of EoRT

Perceived preference and workload

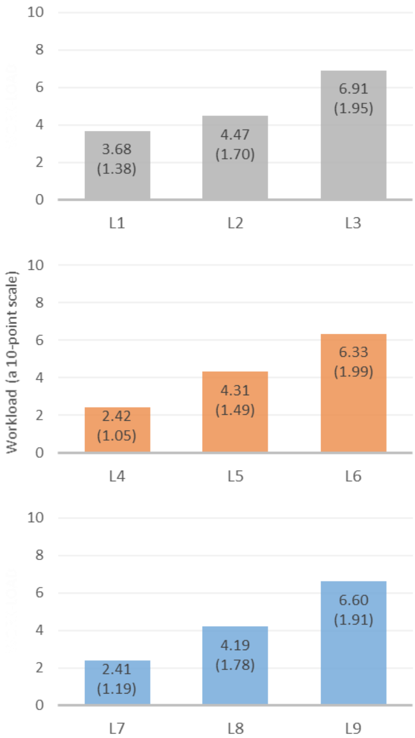
As for perceived preference, there were significant differences for L1 – L2/3/4/6/7/9, and L4 – L2/3/5/6/8/9, and L7 – L2/3/5/6/8/9, and L3 – L2/5/6/7/8, and L6 – L2/8/9, and L9 – L2/5/8, $\chi2(8) = 138.78$, $p = .000$ (Figure 5.7). Overall, perceived preferences increased on the left sides (e.g., L1/4/7), compared to the right side (e.g., L3/6/9).



Locations	Sig.
L2 - L1	0.013
L3 - L1	0.000
L4 - L1	0.004
L6 - L1	0.000
L7 - L1	0.000
L9 - L1	0.000
L3 - L2	0.000
L4 - L2	0.000
L6 - L2	0.002
L7 - L2	0.000
L9 - L2	0.000
L4 - L3	0.000
L5 - L3	0.000
L6 - L3	0.003
L7 - L3	0.000
L8 - L3	0.000
L5 - L4	0.001
L6 - L4	0.000
L8 - L4	0.000
L9 - L4	0.000
L6 - L5	0.000
L7 - L5	0.000
L9 - L5	0.000
L7 - L6	0.000
L8 - L6	0.000
L9 - L6	0.042
L8 - L7	0.000
L9 - L7	0.000
L9 - L8	0.000

Figure 5.7: Mean and standard deviation (in parentheses) of perceived preference

The ANOVA test showed that there were significant differences in many pairwise comparisons, F(3, 80) = 42.48, p = .000 (Figure 5.8). Overall, workload decreased on the left sides (e.g., L1/4/7), compared to the right side (e.g., L3/6/9).



Locations	Sig.
L1-L3	.000
L1-L4	.006
L1-L6	.000
L1-L7	.024
L1-L9	.000
L2-L3	.000
L2-L4	.000
L2-L6	.004
L2-L7	.000
L2-L9	.000
L3-L4	.000
L3-L5	.000
L3-L7	.000
L3-L8	.000
L4-L5	.001
L4-L6	.000
L4-L8	.008
L4-L9	.000
L5-L6	.000
L5-L7	.001
L5-L9	.000
L6-L7	.000
L6-L8	.002
L7-L8	.002
L7-L9	.000
L8-L9	.000

Figure 4.8: Mean and standard deviation (in parentheses) of workload

5.4 Discussion

This study investigated the effects of interactive HUD imagery location associated with the use of interactive scrolling list while driving on driving and task performance, driver distraction, preference and workload.

In terms of driving performance, both measures, that is the mean standard deviation of distance headway and the mean standard deviation of lane position, were affected by the HUD imagery location. The mean standard deviations of distance headway for bottom-left/right positions (L1, L4, L7, L8, L9) were significantly lower than those for middle-right positions (L5, L6) (Figure 5.3). It indicates that the longitudinal control could be negatively affected at the middle-right positions compared to the bottom-left and -right positions. Regarding the standard deviation of lane position, the mean standard deviation of lane position was significantly lower for the bottom-left position (L7) compared to the top-right position (L3) (Figure 5.4). It indicates that the HUD imagery location also significantly affect longitudinal control. Lateral control was found to be negatively affected at the top-right positions compared to the bottom-left positions.

The mean secondary task completion times were, in general, significantly lower for the left positions (L1, L4, L7) compared to the right positions (L3, L6, L9) (Figure 5.5). It indicates that the HUD location for the right positions could negatively affect the task performance compared to the left positions.

As for the EoRT (Figure 5.6), the mean EoRT for the bottom-left (L7) was the lowest except for the mean EoRT of L1 position. The mean EoRT for the bottom-right (L9) was significantly larger than the left-top/bottom positions (L1, L2, L7, L8). The results indicated that the HUD location significantly affects drivers' visual distraction. The participants were visually less distracted when the HUD imagery was located at the bottom-left side of the windshield. An interesting observation was that the EoRT of the middle-left position (L4) was as high as that of the bottom-right position (L9). It may be because when the HUD is located near the driver's forward field of view, it sometimes cannot be clearly distinguished whether drivers look forward or look at the display. When the HUD imagery is near the forward gaze of the driver during driving, the HUD imagery may be processed even if the gaze is not on it, via the peripheral vision.

The study results indicated that the HUD imagery location affects perceived preference and workload. The subjective rating results showed that the participants preferred the left-middle and left-bottom (L4, L7) position the most (Figure 5.7). In general, perceived preference decreased as the HUD location changed from the left to right side of the windshield. In terms of workload, the result showed that the participants had less workload when the HUD imagery was located on the left-bottom (L4) and left-middle (L7) side of the windshield (Figure 5.8). The workload score increased as the HUD location changed from left to right, and from bottom to top. These results are consistent with those of driving performance.

In addition, it was found that the effect of the horizontal HUD imagery position was more pronounced for the bottom level than the other levels. At the bottom level, as the horizontal HUD image position changed from left to right, the perceived preference rating decreased and the workload score increased. For each measure, the rate of change was higher at the bottom level than at the other levels. This is consistent with the previous finding that the horizontal and vertical HUD imagery positions interact significantly in affecting response times to HUD warnings (Yoo et al., 1999).

To sum up, the scrolling list location had effects on driving and task performance, visual distraction, preference and workload. Considering both objective and subjective evaluations, the area enclosing the bottom-left parts of the windshield was considered the most optimal location. It seems that those locations can help drivers focus on the road ahead and at the same time manipulate the HUD system. According to several human factors references, the optimal location of visual displays is usually considered to be about 15 degrees below the horizon (Guastello, 2013; Burgess-Limerick et al., 2000; Ankrum and Nemeth, 1995; McCormick and Sanders, 1982; Kroemer and Hill, 1986; Stokes, 1969). It is consistent with the generally preferred area for visual displays in existing human factors guides and the optimal location derived from this study. It is also consistent with the findings of some past studies suggesting that the locations of 0 to 10 degrees below the forward line of vision were the optimal (Tretten et al., 2011; Chao et al., 2009; Morita et al., 2007; Flannagan et al., 1994). To minimize adverse effects on driving operation, interactive HUDs should be placed near the driver's line of sight, especially near the bottom-left of the full-windshield.

5.5 Conclusion

This study is significant in that it examined the interactive visual object to determine the optimal location of a HUD. In a full-windshield interactive HUD system, the HUD imagery location is an important a key design variable that affects driving and task performance, visual distraction, and perceived preference and workload.

While we believe that the study findings are useful for HUD interface design, they should be interpreted with caution. The recommended locations from this study may be valid only for the type of visual object, task type, driving condition considered in this study. The visual object considered in this study was a single-line scrolling list which takes up only a small part of the windshield and therefore does not block the driver's front view severely. If larger and more complex visual objects were considered, the recommended locations may change. Likewise, different task types with different complexity levels and different driving conditions may lead to different recommendations on visual object location. In addition, the elderly who have prior HUD use experiences should be considered since participants' prior HUD use experience may influence experimental results.

Chapter 6

Conclusion

6.1 Summary and Implications

This PhD dissertation research consists of four major studies. In Study 1, the functional requirements of automotive HUDs were investigated through a systematic literature review. By examining the major automakers' automotive HUD products, academic research studies that proposed various automotive HUD functions, and previous research studies that surveyed drivers' HUD information needs. In Study 2, the interface design of automotive HUDs for communicating safety-related information was examined by reviewing the existing commercial HUDs and display concepts proposed by academic research studies. Each display was analyzed in terms of its functions, behaviors and structure. Also, related human factors display design principles, and, empirical findings on the effects of interface design decisions were reviewed when information was available. In Study 3, automotive HUD-based TOR displays were developed and evaluated in terms of drivers' take-over performance and visual scanning behaviors in a highly automated driving situation. Four different types of TOR displays were comparatively evaluated through a driving simulator study. The relationship between drivers' initial trust in the proposed TOR displays and their take-over and visual scanning behavior was also investigated. In Study 4, the effects of interactive HUD imagery locations associated with use of scrolling list while driving were investigated in terms of driving and secondary task performance, driver distraction, preference, and workload. A total of nine HUD imagery locations of full-windshield were examined through a driving simulator study.

In an effort to address the big questions of what information should be presented to drivers by automotive HUDs and when, and how automotive HUD interface should be designed, a total of four different studies were conducted in this research, consisting of two qualitative studies (Studies 1 and 2) and two empirical studies (Studies 3 and 4). The findings of this research are expected to greatly contribute to the development of useful automotive HUD systems.

Considering the new HUD functions proposed in recent research studies, it is though that automotive HUD systems have a potential to significantly improve the driver experience, especially through integration with other technologies. In order to develop a HUD system that helps in a variety of contexts, including highly automated driving, more human factors studies are needed to design the interface with high usability and transparency, as well as to gain an accurate understanding of the diverse and changing user information needs and usage contexts.

6.2 Future Research Directions

Some future research directions concerning the design of automotive HUD systems were derived from this study. They are provided below:

1. Future research studies should provide an established set of measures and methods for evaluating an automotive HUD system's utility, usability and overall usefulness.
    - Few research studies seem to have investigated how to evaluate the utility of an automotive HUD system.
    - While previous research studies utilized different usability measures for evaluating automotive HUD systems, no established, standard set of usability measures seems to exist at this time.
    - Few studies have investigated how to combine the utility and usability of an automotive HUD system to determine its overall usefulness.
    - Both individual- and population-level measures of utility, usability and usefulness need to be defined.
2. Research studies are needed to comparatively evaluate the existing commercial automotive HUD systems and/or the current dominant designs.
    - Different automotive HUD systems exist in the market; yet, their comparative evaluation in terms of utility, usability and overall usefulness is currently unavailable. Comparative evaluation of existing design alternatives would inform design improvement and innovation.

3. Research should attempt to establish and re-establish the possible roles of HUDs in future vehicles.
    - There is a research need to define the functional requirements of automotive HUD systems for Levels 3 and 4 autonomous driving.
    - Efforts must be continually made to explore possibilities of combining newly emerging technologies (e.g., sensors, artificial intelligence and internet-of-things) with automotive HUDs.
4. Research efforts should be made to understand the actual product use practices and subjective experiences of the existing automotive HUD system users.
    - Future HUD system development must take into account the dynamic, context-sensitive and individual-specific nature of the driver information needs.
    - Little contextual inquiry and analysis research seems currently available concerning the actual automotive HUD system use practices and problems/challenges.
    - HUD information needs and design improvement points perceived by actual HUD users need to be investigated.
    - User studies on automotive HUD systems should recruit participants with a diverse range of prior HUD use experience, spanning novice to more experienced HUD users.

5. Research is needed to better accommodate different HUD users' information needs and preferences.
    - Different individuals would have disparate information needs according to their lifestyle, interests and work tasks. There is a need to examine how various user characteristics, such as lifestyle, interest, gender, age, region, etc., affect user information requirements.
    - The costs (time and efforts) involved in changing the product settings according to an individual user's unique information needs or preferences need to be minimized through good interface design or the use of machine intelligence.
6. Research should attempt to develop design principles/guidelines/processes that help designers identify an appropriate user interface type when given an information characteristic and its usage context.
    - What are the information characteristics suitable for contact-analog and unregistered display formats? Which of the two display formats would be more effective, under various circumstances, especially in situations where nearby hazards must be detected quickly?
7. Research is needed to develop a systematic method for creating new displays through combining/blending elemental displays.
    - How to create displays that provide multiple functions while minimizing problems such as visual clutter and information overload?

8. Research is needed to investigate how to design and evaluate HUDs taking into account the drivers' information processing capabilities under safety-critical driving situations.
    - How many HUD displays can be presented without exceeding the drivers' information processing capabilities under safety-critical driving situations? In this regard, what are the priority levels of different HUD displays and how can they be determined?
    - What is the acceptable level of visual complexity of a single or multiple displays within the drivers' information processing capabilities? What are the individual differences in the acceptance levels of visual complexity?
9. Research is needed to investigate possible effects of age and other personal variables on the user acceptance of different HUD interfaces and the driving performance when using different HUD interfaces in terms of the behaviors and structure of interface design (e.g., display familiarity: one designed based on well-known knowledge vs. a newly designed one).

Bibliography

ABI Research, 2015. Automotive Display Technologies: Touch Screens, HUDs, and Dynamic Clusters. https://www.abiresearch.com/market-research/product/1021371-automotive-display-technologies-touch-scre/ (accessed 1 May 2017).

Alexander, L., 2005. Driver Assistive System Displays for Highway Vehicles. ADEAC, 5, 38-41.

Anderson, J. M., Nidhi, K., Stanley, K. D., Sorensen, P., Samaras, C., Oluwatola, O. A., 2014. Autonomous vehicle technology: A guide for policymakers. Rand Corporation.

Ankrum, D. R., Nemeth, K. J., 1995. Posture, comfort, and monitor placement. *Ergonomics in design*, *3*(2), 7-9.

Baber, C., Wankling, J., 1992. An experimental comparison of test and symbols for in-car reconfigurable displays. *Applied Ergonomics*, *23*(4), 255-262

Beyer, G., Bertolotti, G. M., Cristiani, A., Al Dehni, S., 2010. An adaptive driver alert system making use of implicit sensing and notification techniques. Paper presented at the International Conference on Mobile and Ubiquitous Systems: Computing, Networking, and Services.

Biswas, M., Xu, S., 2015. 47.3: Invited Paper: World Fixed Augmented-Reality

HUD for Smart Notifications. Paper presented at the SID Symposium Digest of Technical Papers.

Burgess-Limerick, R., Mon-Williams, M., Coppard, V. L., 2000. Visual display height. *Human Factors*, *42*(1), 140-150.

Caird, J. K., Chisholm, S. L., Lockhart, J., 2008. Do in-vehicle advanced signs enhance older and younger drivers' intersection performance? Driving simulation and eye movement results. International Journal of Human-Computer Studies, 66(3), 132-144. doi:10.1016/j.ijhcs.2006.07.006

Cha, D., Park, P., 2006. Simulator-based human factors evaluation of automated highway system. International journal of automotive technology, 7(5), 625-635.

Chang, Y.-T., Sun, S.-W., You, C.-W., Cheng, W.-H., Hua, K.-L., 2015. A social media based real scene navigation system with a holographic projection on a HUD. 393-396. doi:10.1145/2800835.2800924

Chao, C. W., Huang, C. H., & Doong, J. L., 2009. See-through head-up display of in-vehicle information systems for vision enhancement. In The International Association of Societies of Design Research Conference.

Charissis, V., Naef, M., Papanastasiou, S., Patera, M., 2007. Designing a direct manipulation HUD interface for in-vehicle infotainment. Paper presented at the International Conference on Human-Computer Interaction.

Charissis, V., Papanastasiou, S., 2008. Human–machine collaboration through vehicle head up display interface. Cognition, Technology & Work, 12(1), 41-50. doi:10.1007/s10111-008-0117-0

Chen, J. Y., Procci, K., Boyce, M., Wright, J., Garcia, A., Barnes, M., 2014. *Situation awareness-based agent transparency* (No. ARL-TR-6905). Army research lab aberdeen proving ground md human research and engineering directorate.

Choi, W. J., Lee, W. J., Lee, S. H., & Park, Y., 2013. Vehicle HUD's cognitive emotional evaluation-Focused on color visibility of driving information. Korean Journal of the Science of Emotion and Sensibility, 16.

Chu, K.-H., Joseph, S., 2008. Using Second Life to demonstrate a concept automobile heads up display (A-HUD). Paper presented at the Proceedings of the 10th international conference on Human computer interaction with mobile devices and services.

Dijksterhuis, C., Stuiver, A., Mulder, B., Brookhuis, K. A., de Waard, D., 2012. An Adaptive Driver Support System: User Experiences and Driving Performance in a Simulator. Human Factors: The Journal of the Hum

Dingus, T. A., McGehee, D. V., Manakkal, N., Jahns, S. K., Carney, C., Hankey, J. M., 1997. Human factors field evaluation of automotive headway maintenance/collision warning devices. *Human factors*, *39*(2), 216-229.

Doshi, A., Cheng, S. Y., Trivedi, M. M., 2008. A novel active heads-up display for driver assistance. *IEEE Transactions on Systems, Man, and Cybernetics, Part B (Cybernetics)*, *39*(1), 85-93.

Endsley, M. R., 1995. Toward a theory of situation awareness in dynamic systems. Human Factors: The Journal of the Human Factors and Ergonomics Society, 37(1), 32-64.

Eriksson, A., Stanton, N. A., 2017. Takeover time in highly automated vehicles: noncritical transitions to and from manual control. *Human factors*, *59*(4), 689-705.

Flannagan, M. J., Harrison, A. K., 1994. The effects of automobile head-up display location for younger and older drivers.

Fujimura, K., Xu, L., Tran, C., Bhandari, R., Ng-Thow-Hing, V., 2013. Driver queries using wheel-constrained finger pointing and 3-D head-up display visual feedback. Paper presented at the Proceedings of the 5th International Conference on Automotive User Interfaces and Interactive Vehicular Applications. doi:10.1145/2516540.2516551

Future Market Insights, 2015. Automotive Head-up Display (HUD) Market: Combiner HUD to Outpace Windshield Systems By 2025: Global Industry Analysis and Opportunity Assessment 2015 – 2025. http://www.futuremarketinsights.com/reports/automotive-hud-market (accessed 1 May 2017).

Gabbard, J. L., Fitch, G. M., Kim, H., 2014. Behind the Glass: Driver challenges and opportunities for AR automotive applications. Proceedings of the IEEE, 102(2), 124-136.

Geiser, G., 1985. Man machine interaction in vehicles. ATZ, 87(74-77), 56.

George, P., Thouvenin, I., Frémont, V., Cherfaoui, V., 2012. DAARIA: Driver assistance by augmented reality for intelligent automobile. Paper presented at the Intelligent Vehicles Symposium (IV), 2012 IEEE.

Gish, K. W., Staplin, L., 1995. Human factors aspects of using head up displays in automobiles: A review of the literature.

Gish, K., Staplin, L., Stewart, J., Perel, M., 1999. Sensory and cognitive factors affecting automotive head-up display effectiveness. Transportation Research Record: Journal of the Transportation Research Board, (1694), 10-19.

Gold, C., Körber, M., Lechner, D., Bengler, K., 2016. Taking over control from highly automated vehicles in complex traffic situations: the role of traffic density. *Human factors*, *58*(4), 642-652.

Guastello, S. J., 2013. *Human factors engineering and ergonomics: A systems approach*. CRC Press.

Guo, H., Zhao, F., Wang, W., Jiang, X., 2014. Analyzing Drivers' Attitude towards HuD system using a stated Preference survey. Advances in Mechanical Engineering, 6, 380647.

Halmaoui, H., Hautière, N., Joulan, K., Brémond, R., Cord, A., 2014. Quantitative model of the driver's reaction time during daytime fog – application to a head up display-based advanced driver assistance system. IET Intelligent Transport Systems, 9(4), 375-381. doi:10.1049/iet-its.2014.0101

Harrison, A., 1994. Head-up displays for automotive applications. (No. UMTRI-94-10).

Hoff, K. A., Bashir, M., 2015. Trust in automation: Integrating empirical evidence on factors that influence trust. *Human factors*, *57*(3), 407-434.

Horrey, W. J., Wickens, C. D., 2004. Driving and side task performance: The effects of display clutter, separation, and modality. Human factors, 46(4), 611-624.

doi: 10.1518/hfes.46.4.611.56805

Huang, C. H., Chao, C. W., Tsai, T., Hung, M. H., 2013. The effects of interface design for head-up display on driver behavior. Life Science Journal, 10(2), 2058-2065.

IHS, 2013. Automotive Head-Up Display Market Goes into High Gear.

ISO 14198., 2019. Road vehicles-Ergonomic aspects of transport information and control systems-Calibration tasks for methods which assess driver demand due to the use of in-vehicle systems.

ISO 15007-1., 2014. Road vehicles-Measurement of driver visual behaviour with respect to transport information and control systems-Part 1: Definitions and parameters.

ISO 16352., 2005. Road vehicles -- Ergonomic aspects of in-vehicle presentation for transport information and control systems -- Warning systems

Jagiellowicz-Kaufmann, M., Hammer, T., Hanig, M., Schmitz, M., 2015. Evaluation of a multi-modal driver coaching function for electric vehicles. IET Intelligent Transport Systems, 9(7), 727-733. doi:10.1049/iet-its.2014.0230

Jian, J. Y., Bisantz, A. M., Drury, C. G., 2000. Foundations for an empirically determined scale of trust in automated systems. *International Journal of Cognitive Ergonomics*, *4*(1), 53-71.

Karvonen, H., Kujala, T., Saariluoma, P., 2006. In-car ubiquitous computing: driver tutoring messages presented on a head-up display. Paper presented at the 2006 IEEE Intelligent Transportation Systems Conference.

Kim, H., Isleib, J. D., Gabbard, J. L., 2016a. Casting shadows: Ecological interface design for augmented reality pedestrian collision warning. Paper presented at the Virtual Reality (VR), 2016 IEEE.

Kim, H., Miranda Anon, A., Misu, T., Li, N., Tawari, A., Fujimura, K., 2016b, March. Look at me: Augmented reality pedestrian warning system using an in-vehicle volumetric head up display. In *Proceedings of the 21st International Conference on Intelligent User Interfaces* (pp. 294-298). ACM.

Kim, H., Wu, X., Gabbard, J. L., Polys, N. F., 2013, October. Exploring head-up augmented reality interfaces for crash warning systems. In Proceedings of the 5th International Conference on Automotive User Interfaces and Interactive Vehicular Applications (pp. 224-227). ACM.

Kovordányi, R., Alm, T., Ohlsson, K., 2006. Night-vision display unlit during uneventful periods may improve traffic safety. Paper presented at the 2006 IEEE Intelligent Vehicles Symposium.

Kozak, K., Pohl, J., Birk, W., Greenberg, J., Artz, B., Blommer, M., ... Curry, R., 2006, October. Evaluation of lane departure warnings for drowsy drivers. In *Proceedings of the human factors and ergonomics society annual meeting* (Vol. 50, No. 22, pp. 2400-2404). Sage CA: Los Angeles, CA: Sage Publications.

Körber, M., Baseler, E., Bengler, K., 2018. Introduction matters: Manipulating trust in automation and reliance in automated driving. *Applied ergonomics*, *66*, 18-31.

Kroemer, K. H., Hill, S. G., 1986. Preferred line of sight angle. *Ergonomics*, *29*(9), 1129-1134.

Kruit, J. D., Amelink, M., Mulder, M., van Paassen, M. M., 2005. Design of a rally driver support system using ecological interface design principles. Paper presented at the 2005 IEEE International Conference on Systems, Man and Cybernetics.

Lee, J. D., Moray, N., 1992. Trust, control strategies and allocation of function in human-machine systems. *Ergonomics*, *35*, 1243–1270.

Lee, J. D., Moray, N., 1994. Trust, self-confidence, and operators' adaptation to automation. *International journal of human-computer studies*, *40*(1), 153-184.

Lee, J. D., See, K. A., 2004. Trust in automation: Designing for appropriate reliance. *Human factors*, *46*(1), 50-80.

Lee, J., Yoon, C., Kang, J., Park, B., Kim, K., 2015. Development of lane-level guidance service in vehicle augmented reality system. Paper presented at the 2015 17th International Conference on Advanced Communication Technology (ICACT).

Lin, J. H., Lin, C. M., Dow, C. R., Wang, C. Q., 2011. Design and implement augmented reality for supporting driving visual guidance. In Innovations in Bio-inspired Computing and Applications (IBICA), 2011 Second International Conference on (pp. 316-319). IEEE.

Lind, H., 2007. An efficient visual forward collision warning display for vehicles (No. 2007-01-1105). SAE Technical Paper.

Liu, Y. C., Wen, M. H., 2004. Comparison of head-up display (HUD) vs. head-down display (HDD): driving performance of commercial vehicle operators in

Taiwan. International Journal of Human-Computer Studies, 61(5), 679-697.

Lubbe, N., 2017. Brake reactions of distracted drivers to pedestrian Forward Collision Warning systems. Journal of safety research, 61, 23-32.

Maag, C., Schneider, N., Lubbeke, T., Weisswange, T. H., Goerick, C., 2015. Car Gestures - Advisory warning using additional steering wheel angles. Accid Anal Prev, 83, 143-153. doi:10.1016/j.aap.2015.07.020

MarketsandMarkets.com, 2015. Head-Up Display Market by Component (Video Generator, Projector, Software, Combiner and Others), Application (Military & Civil Aviation, and Automotive, Premium/Luxury Cars, Sports Cars, and Mid-Segment Cars), and Geography - Global Forecast to 2020. http://www.marketsandmarkets.com/Market-Reports/head-up-display-hud-market-684.html (accessed 1 May 2017).

MarketsandMarkets.com, 2016. Automotive Head-up Display (HUD) Market by HUD Type (Windshield & Combiner), Application (Premium, Luxury & Mid Segment Cars), and by Geography (Asia-Oceania, Europe, North America & RoW) - Industry Trends and Forecast to 2021. http://www.marketsandmarkets.com/Market-Reports/automotive-head-up-display-market-11272971.html (accessed 1 May 2017).

Maurer, B., Trösterer, S., Gärtner, M., Wuchse, M., Baumgartner, A., Meschtscherjakov, A., ... Tscheligi, M., 2014. Shared gaze in the car: towards a better driver-passenger collaboration. In Adjunct Proceedings of the 6th International Conference on Automotive User Interfaces and Interactive Vehicular Applications (pp. 1-6). ACM.

McCormick, E. J., Sanders, M. S., 1982. *Human factors in engineering and design*. McGraw-Hill Companies.

Medenica, Z., Kun, A. L., Paek, T., Palinko, O., 2011. Augmented reality vs. street views: a driving simulator study comparing two emerging navigation aids. In Proceedings of the 13th International Conference on Human Computer Interaction with Mobile Devices and Services (pp. 265-274). ACM.

Melcher, V., Rauh, S., Diederichs, F., Widlroither, H., Bauer, W., 2015. Take-over requests for automated driving. *Procedia Manufacturing*, *3*, 2867-2873.

Miyamoto, T., Kitahara, I., Kameda, Y., Ohta, Y., 2006. Floating virtual mirrors: visualization of the scene behind a vehicle. Advances in Artificial Reality and Tele-Existence, 302-313.

Mok, B., Johns, M., Lee, K. J., Miller, D., Sirkin, D., Ive, P., Ju, W., 2015, September. Emergency, automation off: Unstructured transition timing for distracted drivers of automated vehicles. In *2015 IEEE 18th international conference on intelligent transportation systems* (pp. 2458-2464). IEEE.

Moon, H., Park, B., 1998. Analysis of Ergonomic Design Requirement for Head-Up Display-On the Presented Item and Icon Type & Color. Journal of Korean Society of Transportation, 16(2), 107-114.

Morita, K., Sekine, M., Tsukada, Y., Okada, T., Toyofuku, Y., 2007. Consideration on Appropriate Display Area for Head-Up Displays (No. 2007-01-3512). SAE Technical Paper.

Muir, B. M., Moray, N., 1996. Trust in automation: Part II. Experimental studies of trust and human intervention in a process control simulation.

Ergonomics, *39*(3), 429–460.

National Research Council, 1997. Flight to the future: Human factors in air traffic control. National Academies Press.

Naujoks, F., Mai, C., Neukum, A., 2014. The effect of urgency of take-over requests during highly automated driving under distraction conditions. *Advances in Human Aspects of Transportation*, *7*(Part I), 431.

Nielsen, J., 1994. Usability engineering. Elsevier.

Nwakacha, V., Crabtree, A., Burnett, G., 2013. Evaluating Distraction and Disengagement of Attention from the Road. In International Conference on Virtual, Augmented and Mixed Reality (pp. 261-270). Springer Berlin Heidelberg.

Pace, T., Ramalingam, S., Roedl, D., 2007. Celerometer and idling reminder: persuasive technology for school bus eco-driving. Paper presented at the CHI'07 Extended Abstracts on Human Factors in Computing Systems.

Pahl, G., Beitz, W., 2013. Engineering design: a systematic approach. Springer Science & Business Media.

Pala, S., 2012. HUD Future in the Driverless Vehicle Society: Technology Leadership Brief (No. 2012-01-9022). SAE Technical Paper.

Palinko, O., Kun, A. L., Cook, Z., Downey, A., Lecomte, A., Swanson, M., Tomaszewski, T., 2013. Towards augmented reality navigation using affordable technology. In Proceedings of the 5th International Conference on Automotive User Interfaces and Interactive Vehicular Applications (pp. 238-241). ACM.

Parasuraman, R., Riley, V. A., 1997. Humans and automation: Use, misuse, disuse, abuse, *Human Factors*, *39*, 230–253.

Parasuraman, R., Sheridan, T. B., Wickens, C. D., 2000. A model for types and levels of human interaction with automation. *IEEE Transactions on systems, man, and cybernetics-Part A: Systems and Humans*, *30*(3), 286-297.

Park, B., Lee, J., Yoon, C., Kim, K., 2015. Augmented reality and representation in vehicle for safe driving at night. Paper presented at the Information and Communication Technology Convergence (ICTC), 2015 International Conference on.

Park, H., Kim, K., 2013. Efficient information representation method for driver-centered AR-HUD system. Paper presented at the International Conference of Design, User Experience, and Usability.

Park, M., Kim, H., Chong, C., 2012. Deduction & Weight Analysis of Scenario-based Variable Information Elements for Front Window Display (Head-Up Display) in a Car. Journal of Digital Design, 12 (1), 459-468.

Park, J., Park, W., 2019. Functional requirements of automotive head-up displays: A systematic review of literature from 1994 to present. Applied ergonomics, 76, 130-146

Pauzie, A., 2015. Head Up Display in Automotive: A New Reality for the Driver. Paper presented at the International Conference of Design, User Experience, and Usability.

Payre, W., Cestac, J., Delhomme, P., 2016. Fully automated driving: Impact of trust and practice on manual control recovery. Human factors, 58(2), 229-241.

Phan, M. T., Thouvenin, I., Frémont, V., 2016. Enhancing the driver awareness of pedestrian using augmented reality cues. In *2016 IEEE 19th International Conference on Intelligent Transportation Systems (ITSC)* (pp. 1298-1304). IEEE.

Plavšic, M., Duschl, M., Tönnis, M., Bubb, H., Klinker, G., 2009. Ergonomic design and evaluation of augmented reality based cautionary warnings for driving assistance in urban environments. *Proceedings of Intl. Ergonomics Assoc.*

Politis, I., Brewster, S., Pollick, F., 2015. Language-based multimodal displays for the handover of control in autonomous cars. 3-10. doi:10.1145/2799250.2799262

Pugh, S., 1991. Total design: integrated methods for successful product engineering. Addison-Wesley

Riener, A., Jeon, M., 2012. The role of subliminal perception in vehicular interfaces. Paper presented at the Proceedings of the 2012 ACM Conference on Ubiquitous Computing.

Riener, A., Thaller, H., 2014. Subliminal Visual Information to Enhance Driver Awareness and Induce Behavior Change. 1-9. doi:10.1145/2667317.2667328

Rosenman, M. A., Gero, J. S., 1998. Purpose and function in design: from the socio-cultural to the techno-physical. Design Studies, 19(2), 161-186.

Rusch, M. L., Schall Jr, M. C., Gavin, P., Lee, J. D., Dawson, J. D., Vecera, S., Rizzo, M., 2013. Directing driver attention with augmented reality cues.

Transportation research part F: traffic psychology and behaviour, 16, 127-137.

SAE international., 2016. Taxonomy and definitions for terms related to driving automation systems for on-road motor vehicles. *SAE International,(J3016).*

Schroeter, R., Oxtoby, J., Johnson, D., 2014. AR and Gamification Concepts to Reduce Driver Boredom and Risk Taking Behaviours. 1-8. doi:10.1145/2667317.2667415

Selker, T., Burleson, W., Arroyo, E., 2002. E-windshield: a study of using. Paper presented at the CHI'02 Extended Abstracts on Human Factors in Computing Systems.

Sommerville, I., Sawyer, P., 1997. Requirements engineering: a good practice guide. John Wiley & Sons, Inc..

Srinivasan, R., Yang, C. Z., Jovanis, P. P., Kitamura, R., Anwar, M., 1994. Simulation study of driving performance with selected route guidance systems. Transportation Research Part C: Emerging Technologies, 2(2), 73-90.

Steinberger, F., Schroeter, R., Lindner, V., Fitz-Walter, Z., Hall, J., Johnson, D., 2015. Zombies on the road. 320-327. doi:10.1145/2799250.2799260

Steinfeld, A., Green, P., 1995. Driver response times to full-windshield, head-up displays for navigation and vision enhancement. No. UMTRI-95-29. University of Michigan, Transportation Research Institute.

Stokes, R., 1969. Human factors and appearance design considerations of the mod II PICTUREPHONE® station set. *IEEE Transactions on Communication*

Technology, *17*(2), 318-323.

Sudin, M.N., Ahmed-Kristensen S., Andreasen, M.M., 2010. The role of specification in the design process: a case study. International design conference – design 2010, 17–20 May, Dubrovnik, Croatia.

Suzuki, K., Hashimoto, N., 2012. Semi-transparent vision for driving assistance. Paper presented at the Proceedings of the 11th ACM SIGGRAPH International Conference on Virtual-Reality Continuum and its Applications in Industry.

Tangmanee, K., Teeravarunyou, S., 2012. Effects of guided arrows on head-up display towards the vehicle windshield. In Network of Ergonomics Societies Conference (SEANES), 2012 Southeast Asian (pp. 1-6). IEEE.

Tarel, J. P., Hautiere, N., Caraffa, L., Cord, A., Halmaoui, H., Gruyer, D., 2012. Vision Enhancement in Homogeneous and Heterogeneous Fog. IEEE Intelligent Transportation Systems Magazine, 4(2), 6-20. doi:10.1109/mits.2012.2189969

Tonnis, M., Klinker, G., 2006. Effective control of a car driver's attention for visual and acoustic guidance towards the direction of imminent dangers. Paper presented at the Proceedings of the 5th IEEE and ACM International Symposium on Mixed and Augmented Reality.

Tonnis, M., Lange, C., Klinker, G., 2007. Visual longitudinal and lateral driving assistance in the head-up display of cars. Paper presented at the Mixed and Augmented Reality, 2007. ISMAR 2007. 6th IEEE and ACM International Symposium on.

Tonnis, M., Sandor, C., Lange, C., Bubb, H., 2005. Experimental evaluation of an augmented reality visualization for directing a car driver's attention. Paper presented at the Proceedings of the 4th IEEE/ACM International Symposium on Mixed and Augmented Reality.

Tran, C., Bark, K., Ng-Thow-Hing, V., 2013. A left-turn driving aid using projected oncoming vehicle paths with augmented reality. 300-307. doi:10.1145/2516540.2516581

Tretten, P., Gärling, A., Nilsson, R., Larsson, T. C., 2011. An on-road study of head-up display: preferred location and acceptance levels. In Proceedings of the Human Factors and Ergonomics Society Annual Meeting (Vol. 55, No. 1, pp. 1914-1918). Sage CA: Los Angeles, CA: Sage Publications.

Tsimhoni, O., Green, P., Watanabe, H., 2001. Detecting and reading text on HUDs: effects of driving workload and message location. In 11th Annual ITS America Meeting, Miami, FL, CD-ROM.

Tsuji, T., Hattori, H., Watanabe, M., Nagaoka, N., 2002. Development of night-vision system. IEEE transactions on intelligent transportation systems, 3(3), 203-209.

Tufano, D. R., 1997. Automotive HUDs: The overlooked safety issues. Human Factors: The Journal of the Human Factors and Ergonomics Society, 39(2), 303-311.

Ulrich, K. T., Eppinger, S. D., 2011. Product design and development (5th Edition): Tata McGraw-Hill Education.

Wandtner, B., Schömig, N., Schmidt, G., 2018. Effects of non-driving related task modalities on takeover performance in highly automated driving. *Human factors*, *60*(6), 870-881.

Wang, C., Terken, J., Hu, J., 2014. "Liking" other Drivers' Behavior while Driving. 1-6. doi:10.1145/2667239.2667424

Ward, N. J., Parkes, A., 1994. Head-up displays and their automotive application: An overview of human factors issues affecting safety. Accident Analysis & Prevention, 26(6), 703-717.

Weinberg, G., Harsham, B., Medenica, Z., 2011. Evaluating the usability of a head-up display for selection from choice lists in cars. In Proceedings of the 3rd International Conference on Automotive User Interfaces and Interactive Vehicular Applications (pp. 39-46). ACM.

Wickens, C. D., Lee, J., Liu, Y. D., Gordon-Becker, S., 2003. Introduction to Human Factors Engineering (2nd Edition): Prentice-Hall, Inc.

Winkler, S., Kazazi, J., Vollrath, M., 2015, September. Distractive or Supportive--How Warnings in the Head-up Display Affect Drivers' Gaze and Driving Behavior. In 2015 IEEE 18th International Conference on Intelligent Transportation Systems (pp. 1035-1040). IEEE.

Wittmann, M., Kiss, M., Gugg, P., Steffen, A., Fink, M., Pöppel, E., Kamiya, H., 2006. Effects of display position of a visual in-vehicle task on simulated driving. Applied Ergonomics, 37(2), 187-199.

Wulf, F., Rimini-Doring, M., Arnon, M., Gauterin, F., 2015. Recommendations Supporting Situation Awareness in Partially Automated Driver Assistance Systems. IEEE Transactions on Intelligent Transportation Systems, 16(4), 2290-2296. doi:10.1109/tits.2014.2376572

Yang, B., Zheng, R., Yin, Y., Yamabe, S., Nakano, K., 2016. Analysis of influence on driver behaviour while using in-vehicle traffic lights with application of head-up display. IET Intelligent Transport Systems.

Yoo, H., 1999. Display of HUD warnings to drivers: Determining an optimal location.

Yoon, C., Kim, K., Baek, S., Park, S.-Y., 2014. Development of augmented in-vehicle navigation system for Head-Up Display. Paper presented at the 2014 International Conference on Information and Communication Technology Convergence (ICTC).

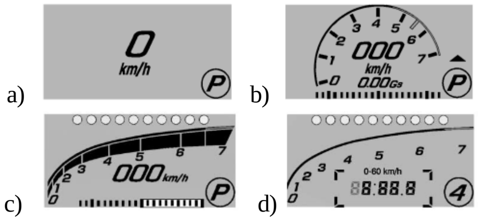
Zeeb, K., Buchner, A., Schrauf, M., 2016. Is take-over time all that matters? The impact of visual-cognitive load on driver take-over quality after conditionally automated driving. *Accident Analysis & Prevention*, *92*, 230-239.

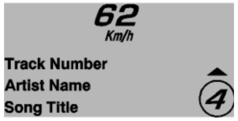
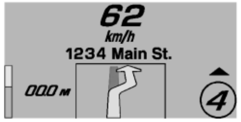
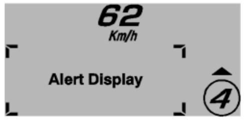
Zimmermann, M., Bauer, S., Lütteken, N., Rothkirch, I. M., Bengler, K. J., 2014. Acting together by mutual control: Evaluation of a multimodal interaction concept for cooperative driving. Paper presented at the Collaboration Technologies and Systems (CTS), 2014 International Conference on.

Zion Market Research, 2016. Automotive Heads-up Display (HUD) Market (Combiner-projected HUD's, Windshield-projected HUD's) for Mid-size Car and Premium Car- Global Industry Perspective, Comprehensive Analysis, Size, Share, Growth, Segment, Trends and Forecast, 2015 – 2021. https://www.zionmarketresearch.com/report/automotive-heads-up-display-market (accessed 1 May 2017).

Appendix A. Display Layouts of Some Commercial HUD Systems

Manufacturers	Brands (Models)	Display layouts	
		Descriptions	Screen image examples
General Motors	Cadillac XTS 2017	The HUD system provides four display layouts from which the driver can select one: a) Speed view: current speed, navigation instructions, remaining distance, speed sign notification/warning, cruise control-related information, fuel-related information, collision warning, lane keeping-related information, audio player status, and phone call-related information b) Audio/phone view: radio-relation information, audio player status, phone call-related information, current speed, navigation instructions, remaining distance, speed sign notification/warning, cruise control-related information, fuel-related information, collision warning, and lane keeping-related information c) Navigation view: navigation instructions, remaining distance, compass heading, current speed, speed sign notification/warning, cruise control-related information, fuel-related information, collision warning, lane keeping-related information, audio player status, and phone call-related information	a)  b)  c)  d) 

		d) Performance view: current speed, RPM/tachometer, navigation instructions, remaining distance, gear shift-related information, fuel-related information, collision warning, lane keeping-related information, audio player status, and phone call-related information	
	Chevrolet Corrvete 2018	The HUD system provides four display layouts from which the driver can select one: a) Tour view: current speed, gear shift-related information, vehicle alerts, navigation instructions, remaining distance, audio player status, and phone call-related information b) Sport view: current speed, RPM/tachometer, gear shift-related information, race car-related information, vehicle alerts, navigation instructions, remaining distance, audio player status, and phone call-related information c) Track view: current speed, RPM/tachometer, gear shift-related information, race car-related information, vehicle alerts, navigation instructions, remaining distance, audio player status, and phone call-related information d) Timing view: RPM/tachometer, gear shift-related information, race car-related information, vehicle alerts, navigation instructions, remaining distance, audio player status, and phone call-related information	

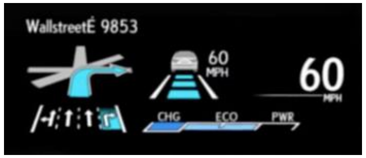
		Vehicle alerts, navigation instructions, remaining distance, audio player status, and phone call-related information are briefly displayed in any HUD view.	 ① When the audio player is activated  ② When the navigation system is activated  ③ When a phone call is connected  ④ When the vehicle alert system is activated

<table>
<tr>
<td rowspan="2">Honda</td>
<td rowspan="2">Acura RLX
2014</td>
<td>The HUD system provides five display layouts from which the driver can select one:
a) Hybid system status (power/torque distribution), and current speed
b) Current speed, RPM/tachometer, and gear shift-related information
c) Current speed, and compass heading or navigation instructions
d) Current speed</td>
<td>a)  b) 
c)  d) 
e) </td>
</tr>
<tr>
<td>When necessary, warning displays appear. Audio changes, voice recognition, and phone information are briefly displayed.</td>
<td>
① When the collision warning system is activated

② When the lane keeping assist system is activated

③ When the vehicle alert system is activated</td>
</tr>
</table>

			 ④ When the audio player is activated  ⑤ When the voice recognition system is activated  ⑥ When the phone call-related system is connected
BMW Group	BMW 3, 4, 5, 6, 7, X	Standard display: current speed, cruise control-related information, gear shift-related information, system messages, collision warning, speed limit notification/warning, lane keeping-related information, night vision-related warning, navigation instructions, remaining distance, radio-relation information, audio player status, phone call-related information, and voice recognition system status	

	BMW M	BMW M display: current speed, RPM/tachometer, gear shift-related information, system messages, road signs notification/warning, navigation instructions, radio-relation information, audio player status, phone call-related information, and voice recognition system status	
Mercedes-Benz	Mercedes-Benz C, S, GLC	Standard display: current speed, cruise control-related information, road signs notification/warning, navigations instructions, and remaining distance	
	Mercedes-AMG	AMG display: current speed, gear shift-related information, and race car-related information	
Toyota	Lexus RX 450h 2017	Lexus: current speed, cruise control-related information, gear shift-related information, RPM/tachometer, system messages, parking assist status, eco-driving status, collision warning, speed limit notification/warning, lane keeping-related information, navigation instructions, remaining distance, compass heading, radio-relation information, audio player status, and outside temperature	
	Prius 2017	Prius: current speed, hybrid system status, collision warning, speed limit notification/warning, lane keeping-related information, system messages, navigation instructions, and remaining distance	

Jaguar Land Rover	Jaguar XE 2017	The HUD system provides one of two display layouts according to the status of the cruise control system: a) When the cruise control system is on: current speed, cruise control-related information, speed limit notification/warning, and navigation instructions b) When the cruise control system is off: current speed, gear shift-related information, speed limit notification/warning, and navigation instructions	a)  b) 

Appendix B. Safety-related Displays Provided by the Existing Commercial HUD Systems

Safety-related HUD systems and purposes	Function	Display visualization			Human factors display design principles	Manufacturers (Models)
		Structure		Behavior		
		Form/shape	Display attributes			
Road sign notification • Improving driver perception of road signs or warnings • Improving driver situation awareness	• Notifying road signs (e.g., speed limit)	Actual road sign	• 2D • Unregistered • First person point of view • Lower part of the windshield • Actual colors of road signs	When the road signs are detected and needed for the current driving situations, the road signs appears.	Consistency	BMW Group (BMW 3/4/5/6/7/X/M, MINI, Rollsroyce Ghost), Honda (Acura RLX, Accord, Clarity), Hyundai/KIA (Hyundai Aslan/Equus/Genesi s, KIA K9), Jaguar Land Rover (Jaguar XE/XF), Mercedes-Benz (C, E, S), Toyota (Lexus RX/HS/GS, Prius),

						Volvo (XC90)
Collision warnings (lead vehicles, pedestrians or animal) • Informing driver of an impending collision, and helping to prevent a collision or reduce the severity of a collision • Improving driver situation awareness (obstacles/objects)	• Alerting collision risks	Laser beam	• 2D • Unregistered • First person point of view • Lower part of the windshield • Red	When collision risks are detected, the red warning light illuminates.	-	Ford (Explorer, Mustang, Taurus)
		Oval	• 2D • Unregistered • First person point of view • Lower part of the windshield • Orange	When collision risks are detected, the orange symbol flashes.	-	Honda (Acura RLX, Accord)
	• Alerting collision risks • Identifying the hazards • Indicating the risk levels	Pedestrian or animal or vehicle icon	• 2D • Unregistered • First person point of view • Lower part of the windshield	When pedestrians or animals or vehicles are detected, the corresponding icon lights up red or flashes depending on the risk	Consistency	BMW Group (BMW 4/5/6/7)

			• Red	levels.		
Lane keeping-related warning • Warning the driver of unintentional lane departures • Improving driver situation awareness	• Alerting lane departures	Lane marking icon	• 2D • Unregistered • First person point of view • Lower part of the windshield • Orange	When the vehicle approaches the edge of a lane, the lane marking icon appears with the corresponding lane displayed in orange.	-	Honda (Acura RLX, Accord)
Night vision-related warning • Increasing driver awareness in a dark environment • Helping detect potential hazards	• Alerting hazards • Identifying the hazards	Pedestrian or animal icon	• 2D • Unregistered • First person point of view • Lower part of the windshield • Red	When pedestrians or wild animals are detected in front of the vehicle, the corresponding icon is highlighted in red.	Consistency	Audi (A7/8, S7/8)

Appendix C. Safety-related HUD displays Proposed by Academic Research

Safety-related HUD systems and purposes	Function	Display visualization			Human factors display design principles	Empirical findings	Authors (Year)
		Structure		Behavior			
		Form/shape	Display attributes				
Collision warnings (lead vehicle/pedestrian warning) • Informing driver of an impending collision, and helping to prevent a collision or reduce the severity of a collision • Improving driver situation awareness	• Alerting collision risks	Circle Slim bar Thick bar	• 2D • Unregistered • First person point of view • Different locations (top, left side, and right side) of the HUD image plane • Red	-	-	• Driving simulator experiment: the HUD significantly reduced reaction time to front hazard warning compared to conventional crash warning systems. • Subjective assessment: slim bar display was the most preferred.	Kim et al. (2013)
		Laser beam	• 2D • Unregistered • First person point of view • Lower part of the windshield • Red	• When lead vehicles at close range detected the display appears. • The display lasted 1.2 second and flashed at a rate of 4 times per second. The on flash lasted 0.15 seconds	-	• Driving simulator experiment: the HUD was found to be the most effective in terms of reaction time to the warning and the amount of missed warnings.	Lind (2007)

(obstacles/objects)				with 0.1 seconds between flashes.		• Subjective assessment: the HUD was the highest ranked in the four systems (HUD, high HDD, cluster display, and steering wheel display).	
						On-road experiment: drivers' eye behavior was analyzed and subjects tended to rarely fixate on the HUD. None of the subjects fixated on the HUD during the warning period or right after the warning. The older group more glanced at the HUD than the younger group did.	Barakat (2015)
	• Alerting collision risks • Indicating the risk levels of hazards	Circle	• 2D • Unregistered • First person point of view	• When a dangerous situation occurs the display appears.	• Color coding scheme	Driving simulator experiment: the abstract warning showed the quicker recognition time than the languages-based warning in	Politis et al. (2015)

		Text indicating the dangerous situation	• Top side of the HUD image plane • Red, orange, yellow	• Color changes according to risk levels of hazards. • Text shows the risk levels (e.g., Collision warning, Left side headlamp out, Call and win free tickets)	• Redundancy gain	a low-urgency situation. In a high-urgency situation, however, both displays performed equally in the response task.	
	• Alerting collision risks • Indicating the risk levels of hazards • Identifying the hazards	Stop sign Pedestrian or vehicle or traffic cone (obstacle) sign	• 2D • Unregistered • First person point of view • Lower part of the windshield • Actual colors of road signs	• When a dangerous situation occurs the display appears. • The stop sign induces the immediate reaction to the dangerous situations, whereas the caution sign indirectly warns the drivers indicating the upcoming dangers.	Consistency	Driving simulator experiment: the stop sign, in critical situations, showed better performance in terms of brake reaction in the older group, while the caution sign, in the younger group. In both groups, the stop sign led to the strongest brake reaction.	Kazazi et al. (2015)
		Stop sign or triangular traffic sign with an exclamation mark	• 2D • Unregistered • First person point of view • Lower part of the windshield	• When a dangerous situation occurs the display appears. • The stop sign and an exclamation mark traffic sign are	Consistency	Driving simulator experiment: the proposed swerving sign which is an unfamiliar and less understandable design was the least effective in terms	Winkler et al. (2015)

		A traffic cone icon with an arrow on top indicating the steering direction (swerving sign) or pedestrian or bicycle or vehicle or traffic cone sign	• Actual colors of road signs	provided regardless of the situations, whereas specific traffic signs, such as pedestrian sign, bicycle road sign, and etc., are selectively provided according to the situations.		of driving performance and eye behaviors.	
	• Alerting collision risks • Indicating the directions/locations of hazards	Vehicle icon with a crash icon on the left or right or front side	• 2D • Unregistered • First person point of view • Lower part of the windshield • Black (icons), Orange (background)	When collision risks are detected the display appears.	-	Driving simulator experiment: the HUD with beep sounds was found to be the best in terms of reaction times to the alerts.	Chen et al. (2008)

		Square shaped outline	• 2D • Contact-analog • First person point of view • Around the target objects • Green	-	-	-	Park and Kim (2013)
				When pedestrians at close range detected the displays appear.	-	Driving simulator experiment: among four different types of interfaces (audio-visual, brake pulse, HUD, audio-HUD), the brake pulse interface was the most effective in terms of brake behavior.	Lubbe (2017)
		Pentagon shaped arrow	• 2D • Contact-analog • First person point of view • Above the target objects • Green	-	-	-	Park and Kim (2013), Yoon et al. (2014)
	• Alerting collision risks • Indicating the locations of hazards	Vehicle icon shaped outline (with or without an inverted	• 2D • Contact-analog • First person point of view	• When lead vehicles at close range detected the displays appear. • Color and size change according to the	• Color coding scheme	Driving simulator experiment: the display significantly decreased the number of collisions.	Charissis et al. (2010)

	• Identifying the hazards • Indicating the risk levels of hazards	triangle)	• Near the target objects • Red, yellow, green	distance to the target (from near to far; red, yellow, and green/bigger to smaller). • An inverted triangle is added on top of the display when the lead vehicle is in the same lane.	• Redundancy gain		
		Rhombus shaped outline	• 2D • Contact-analog • First person point of view • Near the target objects • Yellow	• When the distance to the pedestrians is within 350m the display appears. • Converging line according to the distance to the target (from far to near; broken lines into a solid line)	-	Driving simulator experiment: near significant response time benefits for AR cued hazards. AR cueing increased response rate for detecting pedestrians and warning signs but not vehicles.	Rusch et al. (2013)
		Square shaped outline (with or without a pedestrian sign)	• 2D • Contact-analog • First person point of view • Around the target objects	• When pedestrians at close range detected the display appears. • An unregistered pedestrian sign appears at the	Consistency	Driving simulator experiment: the display enhanced the drivers' awareness	Phan et al. (2016)

			• Yellow	bottom-left side on the HUD image plane when the TTC is less than 2s.			
		Arrows with a virtual pole with traffic signs at the end of the arrows	• 3D • Contact-analog • First person point of view • Bottom side on the HUD image plane • Different colors according to the dangerousness levels	• The display is presented only if needed. • The color of the arrows changes according to the level of risk of hazards. • Arrows are placed from top to bottom on a virtual pole according to the level of risk of hazards.	• Color coding scheme • Redundancy gain • Consistency	-	George et al. (2012)
		Circle with a pole (similar to a lollipop icon)	• 3D • Contact-analog • First person point of view • Around the target objects • Red	The display (e.g., the direction and length of the display) changes its physical form depending on the situations (e.g., an approaching object and the vehicle's speed).	• Ecological interface design (EID)	Usability evaluation: the virtual shadow display outperformed the baseline in all aspects such as visibility, attention, situation awareness, and workload.	Kim et al. (2016a)

					• Predictive aiding	On-road experiment: both warnings improved the driving performance, resulting in larger gaps between the pedestrians and vehicle. In terms of braking behavior, the virtual shadow concept showed smoother braking behavior compared to the traditional warning.	Kim et al. (2016b)
		Text (BRAKE) inside a rectangle	• 2D • Unregistered • First person point of view • Lower part of the windshield • White (background)		-		
Blind spot detection • Increasing driver awareness • Helping detect potential hazards	• Alerting hazards • Indicating the directions/locations of hazards	Vehicle icon with a small circle	• 2D • Unregistered • Third person point of view (Bird's eye view) • Bottom side on the HUD image plane • White inside and red outline	When visual concealed hazards detected the display appears and a small circle indicates the locations of the hazard.	-	Driving simulator experiment: 2D unregistered bird's eye view concept resulted in faster mean reaction time to the alert and lower mean error rates significantly. Regarding subjective rating (preference, ease of use, speed, and precision), the 2D bird's eye view concept was significantly superior to the 3D arrow concept in all aspects.	Tonnis et al. (2005)

		Virtual arrow	• 3D • Contact-analog • First person point of view • Lower part of the windshield • Red	When visual concealed hazards detected the display appears and points the directions of the hazard.	-	Driving simulator experiment: in terms of the mean lane deviation, the 3D contact-analog arrow concept showed significantly better results than the 2D bird's eye view concept.	Tonnis and Klinker (2006)
	• Alerting hazards • Indicating the locations of hazards	Square bracket shaped outline	• 2D • Contact-analog • First person point of view • Around the target objects • Orange	-	-	Driving simulator experiment: the bird's eye view symbol showed the best results in terms of overall workload, intuitiveness, concentration, safety and attractiveness.	Plavšic et al. (2009)
	• Alerting hazards • Indicating the locations of hazards • Identifying the hazards	Vehicle shaped icon with an arrow		Vehicle icons can be changed according to the types of the target object.	-		
		Traffic sign with spatially positioned vehicle icons	• 2D • Unregistered • First person point of view • Bottom side on the HUD image plane	Vehicle icons are spatially positioned according to the actual vehicle locations.	Color coding scheme		

			• Green (driver's vehicle), red (target object)				
		Bird's eye view with triangle shaped icons	• 2D • Unregistered • Third person point of view (Bird's eye view) • Bottom side on the HUD image plane • Green (driver's vehicle), red (target object)	Triangle shaped icons refer to vehicles and spatially positioned according to the actual vehicle locations.	Color coding scheme		
		Semi-transparent real image of the blind spot	• 2D • Contact-analog • First person point of view • The actual location of the blind spot	-	-	-	Suzuki and Hashimoto (2012)

Safety boundary delineation • Increasing driver awareness • Helping to prevent a potential collision	• Informing the braking distance and driving path	a parallel bar connected to the end of the vertical bars	• 2D • Contact-analog • First person point of view • On the road • Green	-	Configural display	Driving simulator experiment: the visual aid was found to improve driving performance in terms of driving speed and lane deviation without increasing overall driver workload.	Tonnis et al. (2007)
	• Informing the oncoming vehicle's future path	Virtual path (solid) Virtual path (chevron) Virtual path (wireframe)	• 2D • Contact-analog • First person point of view • On the road • Red (solid), green (chevron), red (wireframe)	• The display appears when a vehicle approaching from the opposite direction when the driver needs to make a left turn at an intersection. • The display shows the oncoming vehicle's future path of 3 seconds.	Predictive aiding	Driving simulator experiment: a driving simulator experiment showed that the left-turn aid produced more conservative driver behavior.	Tran et al. (2013)
Road sign notification • Improving driver perception of road signs or warnings	• Notifying road signs	Actual road sign	• 2D • Unregistered • First person point of view • Lower part of the windshield	-	• Consistency • Predictive aiding	Driving simulator experiment: the primary behavioral influence of the in-vehicle signs was to cause the drivers' to reduce their velocity in advance of an intersection. Eye movement	Caird et al. (2008)

• Improving driver situation awareness			• Actual colors of road signs			analyses indicated that younger drivers looked at the in-vehicles signs more often and for longer overall durations than older drivers.	
	• Notifying road signs • Indicating the locations of road signs	Square shaped outline	• 2D • Contact-analog • First person point of view • Around the target objects • Red	-	-	-	Park and Kim (2013)
	• Notifying road signs • Notifying exceeding the speed limit	Triangular traffic sign with an exclamation mark Numbers showing the vehicle's current speed and the speed limit	• 2D • Unregistered • First person point of view • Lower part of the windshield • Blue	-	-	On-road study: the most effective alert in terms of the average amount of time the driver spent over the speed limit before returning to under the limit was the warning symbol, followed by the status bar and the numbers. The 'numbers' display was found to be the best in terms of the eye-on-	Doshi et al. (2009)

		Vertical status bar showing the current speed and the speed limit				the-road time with the shortest time for looking down at dashboard	
Lane keeping-related warning • Warning the driver of unintentional lane departures • Improving driver situation awareness	• Alerting lane departure	Laser beam	• 2D • Unregistered • First person point of view • Lower part of the windshield • Red	-	-	Driving simulator experiment: among four types of warning interfaces (steering wheel torque, rumble strip sound with steering wheel torque, steering wheel vibration with steering wheel torque, and the HUD with steering wheel torque), the steering wheel vibration with steering wheel torque was the most effective interface in terms of reaction time to warnings, lane excursions, and subjective assessment.	Kozak et al. (2006)
	• Alerting lane departure	Vehicle icon within a top view mini map	• 2D • Unregistered • Third person point of view	When the vehicle approaches the edge of a lane, the display appears.	-	• Driving simulator experiment: the adaptive support mode was found to improve	Dijksterhuis et al. (2012)

	• Indicating the vehicle's lane position		(Bird's eye view) • Bottom side on the HUD image plane			driving performance (mean and SD of lateral position) over the non-adaptive mode. • Subjective assessment: the subjects preferred the adaptive support mode most in terms of usefulness and satisfaction.	
	• Improving the visibility of lane markings • Preventing lane departure • Alerting hazards • Indicating the locations of hazards • Indicating the risk levels of hazards	Lane marking icon	• 2D • Contact-analog • First person point of view • On the lane markings • Red or green	• The display appears under the adverse weather condition. • The lane marking icon colored in red indicates the existence of potential hazards in that area, whereas the green-colored icon indicates absence of such hazards.	Color coding scheme	Driving simulator experiment: the display significantly decreased the number of collisions.	Charissis et al. (2010)

Night vision-related warning • Increasing driver awareness in a dark environment • Helping detect potential hazards	• Alerting collision risks • Indicating the locations of hazards • Identifying the hazards	Infrared image of the hazards on the road	• 2D • Unregistered • Third person point of view (Bird's eye view) • Bottom side on the HUD image plane	-	-	-	Tsuji et al. (2002)
				• The night vision display is lit up adaptively.		• Driving simulator experiment: compared to a conventional night vision system, this adaptive support improved obstacle detection ability, and resulted in lower workload. • Subjective assessment: the proposed display was preferred by all study participants.	Kovordányi et al. (2006)
	• Alerting collision risks • Indicating the locations of hazards • Identifying the hazards	Square shaped outline including a pedestrian icon in side (pedestrian warning)	• 2D • Contact-analog • First person point of view • Near the target objects • Red/orange/yellow/green	• When pedestrians at close range detected the display appears. • Color changes according to the TTC to the target (from near to far; red,	Color coding scheme	-	Park et al. (2015)

	• Indicating the risk levels of hazards	Square shaped outline with virtual path (vehicle warning)	(pedestrian warning), red/orange/yellow (vehicle warning)	orange, yellow, and green) • In case of the vehicle warning, the distance to the lead vehicle is displayed in text on the virtual path only under the most dangerous level.			

국문초록

자동차 헤드업 디스플레이는 차내 디스플레이 중 하나로 운전자에게 필요한 정보를 전방에 표시함으로써, 운전자가 운전을 하는 동안 전방으로 시선을 유지할 수 있게 도와준다. 이를 통해 운전자의 주의 분산을 줄이고, 안전을 향상시키는데 도움이 될 수 있다. 자동차 헤드업 디스플레이 시스템은 약 30년 전 운전자의 안전을 향상시키기 위한 수단으로 자동차 산업에 처음 도입된 이래로 현재까지 다양한 상용차에서 사용되고 있다. 안전과 편의 측면에서 자동차 헤드업 디스플레이의 사용은 점점 더 증가할 것으로 예상된다.

그러나 이러한 자동차 헤드업 디스플레이의 잠재적 이점과 발전 가능성에도 불구하고, 유용한 자동차 헤드업 디스플레이를 설계하는 것은 여전히 어려운 문제이다. 이에 본 연구는 이러한 문제를 해결하고, 궁극적으로 유용한 자동차 헤드업 디스플레이 설계에 기여하고자 총 4가지 연구를 수행하였다.

첫 번째 연구는 자동차 헤드업 디스플레이의 기능 요구 사항과 관련된 것으로서, 헤드업 디스플레이 시스템을 통해 어떤 정보를 제공할 것인가에 대한 답을 구하고자 하였다. 이에 주요 자동차 제조업체들의 헤드업 디스플레이 제품들과, 자동차 헤드업 디스플레이의 다양한 기능들을 제안한 학술 연구, 그리고 운전자의 정보 요구 사항들을 체계적 문헌 고찰 방법론을 통해 포괄적으로 조사하였다. 자동차 헤드업 디스플레이의 기능적 요구 사항에 대하여 개발자, 연구자, 사용자 측면을 모두 고려한 통합된 지식을 전달하고, 이를 통해 자동차 헤드업 디스플레이의 기능 요구 사항에 대한 향후 연구 방향을 제시하였다.

두 번째 연구는 안전 관련 정보를 제공하는 자동차 헤드업 디스플레이의 인터페이스 설계와 관련된 것으로, 헤드업 디스플레이 시스템을 통해 안전 관련 정보를 어떻게 제공할 것인가에 대한 답을 구하고자 하였다. 실제 자동차들의 헤드업 디스플레이 시스템에서는 어떤 디스플레이 컨셉들이 사용되었는지, 그리고 학계에서 제안된 디스플레이 컨셉들에는 어떤 것들이 있는지 체계적 문헌 고찰 방법론을 통해 검토하였다. 검토된 결과는 각 디스플레이의 기능과 구조, 그리고 작동 방식에 따라 정리되었고, 관련된 인간공학적 디스플레이 설계 원칙과 실험적 연구 결과들을 함께 검토하였다. 검토된 결과를 바탕으로 안전 관련 정보를 제공하는 자동차 헤드업 디스플레이의 인터페이스 설계에 대한 향후 연구 방향을 제시하였다.

세 번째 연구는 자동차 헤드업 디스플레이 기반의 제어권 전환 관련 인터페이스 설계와 평가에 관한 것이다. 제어권 전환이란, 자율주행 상태에서 운전자가 직접 운전을 하는 수동 운전 상태로 전환이 되는 것을 의미한다. 따라서 갑작스런 제어권 전환 요청이 발생하는 경우, 운전자가 안전하게 대처하기 위해서는 빠른 상황 파악과 의사 결정이 필요하게 되고, 이를 효과적으로 도와주기 위한 인터페이스 설계에 대해 연구할 필요성이 있다. 이에 본 연구에서는 자동차 헤드업 디스플레이 기반의 총 4개의 제어권 전환 관련 디스플레이(기준 디스플레이, 미니맵 디스플레이, 화살표 디스플레이, 미니맵과 화살표 디스플레이)를 제안하였고, 제안된 디스플레이 대안들은 주행 시뮬레이터 실험을 통해 제어권 전환 수행 능력과 안구의 움직임 패턴, 그리고 사용자의 주관적 평가 측면에서 평가되었다. 또한 제안된 디스플레이 대안들에 대해 운전자들의 초기 신뢰도 값을 측정하여 각 디스플레이에 따른 운전자들의 평균

신뢰도 점수에 따라 제어권 전환 수행 능력과 안구의 움직임 패턴, 그리고 주관적 평가가 어떻게 달라지는지 분석하였다. 실험 결과, 제어권 전환 상황에서 자동화된 시스템이 제안하는 정보와 그와 관련된 주변 상황 정보를 함께 제시해 주는 디스플레이가 가장 좋은 결과를 보여주었다. 또한 각 디스플레이에 대한 운전자의 초기 신뢰도 점수는 디스플레이의 실제 사용 행태와 밀접한 관련이 있음을 알 수 있었다. 신뢰도 점수에 따라 신뢰도가 높은 그룹과 낮은 그룹으로 분류되었고, 신뢰도가 높은 그룹은 제안된 디스플레이들이 보여주는 정보를 주로 믿고 따르는 경향이 있었던 반면, 신뢰도가 낮은 그룹은 룸 미러나 사이드 미러를 통해 주변 상황 정보를 더 확인 하는 경향을 보였다.

네 번째 연구는 전면 유리창에서의 인터랙티브 헤드업 디스플레이의 최적 위치를 결정하는 것으로서 주행 시뮬레이터 실험을 통해 디스플레이의 위치에 따라 운전자의 주행 수행 능력, 인터랙티브 디스플레이 조작 관련 과업 수행 능력, 시각적 주의 분산, 선호도, 그리고 작업 부하가 평가되었다. 헤드업 디스플레이의 위치는 전면 유리창에서 일정한 간격으로 총 9개의 위치가 고려되었다. 본 연구에서 활용된 인터랙티브 디스플레이는 음악 선택을 위한 스크롤 방식의 단일 디스플레이였고, 운전대에 장착된 버튼을 통해 디스플레이를 조작하였다. 실험 결과, 인터랙티브 헤드업 디스플레이의 위치가 모든 평가 척도, 즉 주행 수행 능력, 디스플레이 조작 과업 수행 능력, 시각적 주의 분산, 선호도, 그리고 작업 부하에 영향을 미침을 알 수 있었다. 모든 평가 지표를 고려했을 때, 인터랙티브 헤드업 디스플레이의 위치는 운전자가 똑바로 전방을 바라볼 때의 시야 구간, 즉 전면 유리창에서의 왼쪽 아래 부근이 가장 최적인 것으로 나타났다.

주요어: 자동차 헤드업 디스플레이, 기능 요구, 인터페이스 디자인, 자율주행차, 제어권 전환, 인터랙티브 헤드업 디스플레이, 최적 디스플레이 위치,

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