Improving the Design of Information Provision for Advanced Driver Assistance Systems in Multi-warning Situations

By

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Publications

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- Fan, B., Jiang, N., Dogan, H., Jianbing, M. and Ali, R., 2018. An Ontological Approach to Inform HMI Designs for Minimizing Driver Distractions with ADAS. In: The 32nd Human Computer Interaction Conference (British HCI'18) 2-6 July 2018 Belfast.
- Fan, B., Jiang, N., Dogan, H., Jianbing, M. and Ali, R., 2018. A rule-based ontological approach for initiating ADAS warnings to avoid driver distraction. In: IEEE SMC 2018, Miyazaki, Japan.

Abstract

Advanced Driver Assistance Systems (ADAS) are applicable to support drivers in making better decisions through warnings. Despite more types of ADAS becoming available within vehicles due to the progress in modern sensor technology such as connected vehicles and vehicular networks, it is still possible for the driver to experience the scenarios where multiple warnings are issued simultaneously. Also, such scenario can distract drivers if the warning is poorly designed.

In order to have a better understanding of ADAS-driving scene, an ontology-based approach is adopted in this thesis. The created ontologies help to determine potential ADAS warnings for the design of multi-warning scenarios that may arise in the future.

For a better understanding of how warnings are designed, initial experiments were performed to explore the effects of driving experience on the response made to multi-warning scenarios, with attention paid to the differences between experienced and inexperienced drivers in the way of responding to multi-warning modes. Compared to experienced drivers, inexperienced drivers showed more potential negative effects in their response to multiple warning modes. Specifically, there were more inappropriate driving behaviours performed by inexperienced drivers in the multi-warning mode, such as directly changing lanes when there is a need to slow down and give way. It is implied that the current warning design is possibly unsuited to inexperienced drivers in multi-warning mode.

Therefore, the warning design is improved by considering two design philosophies. One focuses on the warnings with a higher priority (using a colour or flashing cue), and the other issues a main summary warning to direct the driver. According to the results, the main warning mode reduced the frequency of gaze change. However, it takes time to read the text, which prolongs the reaction, which may be the reason why this warning mode was found unfit for complex and/or urgent situations. Based on this measure, a recommendation is made for future ADAS design.

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I would like to thank my supervisor, Dr. Jiang Nan and Dr. Huseyin Dogan, for their continued support and inspiration in this work. I would also like to thank my external supervisor, Dr. Jianbing Ma and Dr. Rain Ali for his involvement and sincere interest in the research.

I am grateful to those closest to me, my family and friends. I thank my dear father and mother for their care, love and support for me. Thanks to my old and new friends for their unconditional friendship and sincere advice.

Table of Content

List of Figures

List of Tables

Glossary of Acronyms

ADAS	Advanced driver assistance system
ANOVA	Analysis of Variance
BSM	Blind spot monitoring
BRT	Brake reaction time
FCW	Forward collision warning
FF	Fixation frequency
IRT	Initial reaction time
OW	Overspeeding warning
Vehicle-to-everything	V2X

1 Introduction

1.1 Motivation

Driving is a highly dynamic task that requires substantial attentional resources (Endsley 1995; Horrey and Wickens 2003), and drivers make decisions to take actions indispensably based on volatile environmental conditions (Endsley 1995). In order to reduce the workload and ensure the safety of drivers, more and more vehicles are equipped with Advanced Driver Assistance Systems (ADAS). ADAS are in-vehicle systems designed to reduce and even eliminate driver errors, enhance driving safety and efficiency, as well as provide comfort while driving (Tigadi et al. 2016). ADAS can improve road safety by sending warning signals to drivers (Brookhuis et al. 2001; Lindgren and Chen 2006; Shaout et al. 2011; Paul et al. 2016). The car industry has created a number of ADAS in recent years to increase driving security and decrease collisions, such as Forward Collision Warning (FCW) and Blind Spot Monitoring (BSM). By the middle of 2022, all new automobiles sold in the EU must include ADAS (EU-2016/67, 2016) according to the implementation of the EU Vehicle Safety Regulation 2019/2144 (European Parliament and Council).

Early models of ADAS utilise proprioceptors that measure internal vehicle parameters such as wheel velocity or rotational velocity. One of the first active assistance systems is the Anti-lock Braking System (ABS), which began to be mass-produced by Bosch in 1978 (Bengler et al. 2014). The functionality of the current and second generation of driver assistance technologies is built on the application of exteroceptors, and places focus on providing information, warnings, as well as a better driving experience (Bengler et al. 2014). Vehicle-to-everything (V2X) is the newest technology. It is a form of vehicular communication that also includes more specialised forms like V2I (vehicle-to-infrastructure) and V2V (vehicle-to-vehicle) communication (Mosquet et al. 2016). It can be used to warn drivers of road and traffic conditions further away or to monitor traffic lights and other local traffic infrastructure components. It enables drivers to not only have a precise awareness of the current situation but also to receive trustworthy forecasts of unknown events from these technologies, as demonstrated in Figure 1-1. According to the National Highway Traffic Safety Administration (NHTSA), the use of V2X systems is expected to reduce traffic accidents by at least 13% and prevent 439,000 accidents annually (NHTSA 2016)

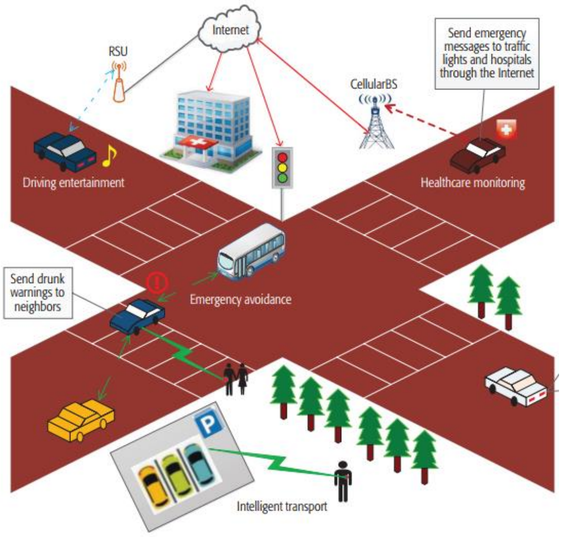


Figure 1-1. Future communication technology in an urban scenario (Sun et al. 2017)

Advanced detection techniques would make it possible for ADAS to monitor more targets, identify potential threats earlier, and possibly produce more warnings. Distracting warnings can result from ADAS if there are too many of them or if they are improperly structured (Biondi et al., 2017). Any second alarm that follows the triggered first alarm may startle, confuse, or interfere with the driver's execution of evasive manoeuvres (Green, 2008). Therefore, studying ways to display warnings when many warnings occur concurrently is a highly worthwhile research direction. In addition, driving performance also depends on driving experience.

The predictive ability of experienced drivers reduces the reaction time by enabling the relatively fast perception and identification of hazardous events (Paxion et al. 2014a). It was confirmed in a study that the reaction of novice drivers to hazards was less and slower compared to experienced drivers (Wallis and Horswill 2007).

Although the use of ADAS can improve driving safety, there is a rise in the complexity of the driving environment as the number of warnings displayed increases. According to some studies where novice and experienced drivers were compared, the subjective mental workload of all drivers increased due to the rise of situational complexity, despite the lower subjective mental workload of experienced drivers (Paxion et al. 2015). This may result from a controlled action that complies with the prescribed rules. Without completely automatized driving routines, novice drivers should feel more nervous than experienced drivers in complex situations (Fuller 2002), which leads to driving impairments. Furthermore, experienced drivers have more mental resources available to detect peripheral information , who are usually more capable of processing the raw information and reducing their levels of cognitive workload (Patten et al. 2006). In the multi-warning mode, experienced and inexperienced drivers may have different reactions as a result.

Therefore, this paper focuses on the impact of multi-warning scenarios on drivers to ensure the acceptability, efficiency, and understandability of ADAS warnings. Additionally, a design scheme for warnings in multi-warning mode is investigated in order to offer suggestions for up-and-coming technologies like V2X.

1.2 Research Aim

This research aims to investigate potential future multiple warning scenarios as well as the influence of driving experience on handling multiple warning scenarios in order to inform the optimal design for ADAS.

1.3 Research Questions

In order to understand how warnings should be designed under multiple warning scenarios, this research will attempt to answer the following main questions:

1. RQ-1: How are ADAS warnings generated and classified?

In order to make ADAS future proof with better information provision strategies, an imperative is to understand possible warnings that can be implemented on ADAS and how to classify them.

2. RQ-2: How to identify multiple warning situations?

In order to propose a general design for dealing with multi-alert situations, the key procedure is to identify possible future multi-warning scenarios and the relationship between warnings.

3. RQ-3: How does driving experience affect driving performance in a multi-warning situation?

As the different levels of driving experience may result in different driving performance, it is necessary to investigate drivers' performance with varied driving experience in a multi-warning situation.

4. RQ-4: How should warnings be designed under multi-warning situations?

The identification of a recommended ADAS design for multi-warning situations is conducive to the reduction of driver distraction.

1.4 Research Objectives

This research is conducted based on the fulfilment of the following objectives:

- Objective 1 (Chapter 2: Literature Review): To explore the possible ADAS warnings and determine their design characteristics by analysing of the reviewed literature and design practices.

  The main purpose of Objective 1 is to fully understand ADAS, which focuses mainly on what can be monitored by ADAS, the design features included in ADAS, and the influencing factors in the response of ADAS.
- Objective 2 (Chapter 4: Ontology for ADAS Driving Environment): To establish a knowledge base of ADAS warnings. Additionally, the created domains of the

knowledge base are expected to facilitate the identification of potential multi-warning scenarios in the future.

The ontology established in the ADAS driving environment is premised on the literature retrieved from the previous objective. A common vocabulary is defined through the established ontology for those researchers needing to share information in the field, and the entities in this ontology are used to support them in creating the comprehensive scenarios of ADAS.

- Objective 3 (Chapter 5: Experiment 1): To investigate the effect of drivers' experience on their driving performance in multi-warning situations.

  To better understand the design of ADAS warning, it is necessary to determine whether the response to the multi-warning mode can be affected by different levels of driving experience. Chapter 5 experiment 1.

- Objective 4 (Chapter 6: Experiment 2): To identify the impact of different multi-warning designs on drivers' driving performance in different multi-warning scenarios.

  This step aims to evaluate the performance of different concepts of multi-warning design in multi-warning scenarios. Based on the results of Objective 4, recommendations can be made for the future practice of ADAS warning design. Chapter 6 experiment 2

1.5 Contributions of the Research

Regarding the suggested research questions and objectives, which are listed below, the key contributions of this research are below:

- Utilizing an ontology-based approach, this study expanded the understanding of the ADAS driving environment by establishing an ADAS-based ontology. This approach identified three potential multi-warning future scenarios, offering valuable guidance for future driving scenario design.

- Investigating the impact of driving experience on responses to multi-warning modes, a relatively unexplored area in ADAS research, revealed that inexperienced drivers were more susceptible to potential negative effects when responding to multiple warning modes compared to experienced drivers. This research aids in tailoring ADAS warning designs, particularly for less experienced drivers, to enhance safety.
- Exploring different warning design options for handling multiple warning scenarios introduced two design philosophies: prioritizing warnings with higher urgency and providing a main summary warning to guide the driver. Findings indicated that the main warning mode, while reducing gaze change frequency, may not be suitable for complex or urgent situations. These insights inform future warning strategies to prevent unintended adverse consequences.

1.6 Structure of the Research

- Chapter 2. Literature Review

Chapter 2 presents a literature review with regard to ADAS. The ADAS and ADAS classifications that currently prevail in the market are discussed. After the design elements shown in the warnings as well as the process model are introduced, this chapter continues with the description of the patterns of ADAS warnings and how they are implemented during driving. Then, the factors that influence the effectiveness of warnings are discussed, before the current problems of ADAS and how the updated techniques are improving ADAS are presented. However, with the rapid development of ADAS sensors, drivers may experience more situations with concurrent warnings, a situation that has scarcely been investigated by existing research. Moreover, whether driving experience will affect multi-warning driving performance is also insufficiently studied.

- Chapter 3. Methodology

Chapter 3 introduces the general experimental methods of this research and discusses the use of driving simulators, driving indicators, and the use of participants. Meanwhile, the overall framework of the research is mentioned. In addition, the composition of this article has experienced the outbreak of COVID-19, so the ethics of this period are stated.

- Chapter 4. Ontology for ADAS Driving Environment

Chapter 4 introduces the establishment of the ADAS-based ontology, the process of the establishment, and the final refined ontology. At the same time, two ADAS examples are provided to explain how the ontology helps to understand the ADAS-based driving situations. Finally, the targets that can be monitored by ADAS are reclassified based on the ontology: combined with driving tasks, three typical multi-warning scenarios are designed. This chapter answers RQ-1 and RQ-2.

- Chapter 5. Experiment 1

Chapter 5 introduces Experiment 1 and answers RQ-3. Experiment 1 analyses multi-warning mode. Driver responses to multiple warning scenarios in the no-warning mode, single-warning mode, and multiple-warning mode are compared. In addition to this, the effect of driving experience on driver responses to multiple warning scenarios is further investigated.

- Chapter 6. Experiment 2

Chapter 5 introduces Experiment 2 and answers RQ-4. Experiment 2 examines different multi-warning designs, including no change, Colour cue, Flash cue and main warning mode. Based on the results of Experiment 1, inexperienced drivers are adopted as the main participants. Eye tracking data have also been introduced. The three typical multiple warning scenarios are also used. This future simulation provides potential guidelines for warning design in multiple warning scenarios.

- Chapter 7. General discussion and recommendation

Chapter 7 synthesizes the findings of this research. Furthermore, this chapter offers integrated recommendations for future multi-warning system design.

- Chapter 8. Conclusion and Future Work

Chapter 8 summarizes the research's key findings related to driving experience and multi-warning scenarios within ADAS. The chapter also outlines promising future research directions, including exploring regional-specific warning designs, incorporating audio and haptic warning modalities, richer scenario designs, and scenarios involving autonomous driving integration.

2 Literature Review

In this chapter, advanced driver assistance system (ADAS) is explained, and the relevant classification defines the domain of this research, i.e., passive ADAS (alerting drivers for a potential hazard). The design elements of ADAS warning and the model of the interaction between driver and warning are investigated. Furthermore, a research gap is proposed by examining the state-of-the-art ADAS and possible solutions.

2.1 Advanced Driver Assistance System (ADAS)

Advanced driver assistance systems (ADAS) provide a driver with required information, automate difficult and repetitive tasks, and lead to an overall increase in the safety of the car for drivers (Tigadi et al. 2016). In the present section, an overview of current ADAS is presented, and the classification of ADAS is also described.

2.1.1 Overview of ADAS

Advanced Driver Assistance Systems (ADAS) are electronic systems designed to support the driver in his/her driving task. ADAS aim to support drivers by providing warning to enhance driver's perception of surrounding environment, or by taking over some driving tasks in a critical situation (Lindgren and Chen 2006). A typical ADAS application incorporates many technologies. Figure 2-1 illustrates the components of ADAS (Choi et al. 2016). In this illustration, sensors collect information regarding the surrounding environment (e.g., pedestrians and vehicle traffic). Algorithms employ the input from the above sensors for real-time synthesis of the detected surroundings besides the processing performed by the sensors. Processors are considered the vital components of most ADAS applications, which consist of electronic control units (ECUs) and microcontroller units (MCUs) to process the algorithms. Subsequently, depending on the results of the above processors and algorithms, the actuator determines whether to control the vehicle or to provide the driver with the information. The mapping system stores geographical data, and it is capable of providing assistance when the GPS is unavailable (e.g., when driving through a tunnel). Connectivity is the ability to communicate with anything else (e.g., the internet) capable of supplementing the on-board sensors.

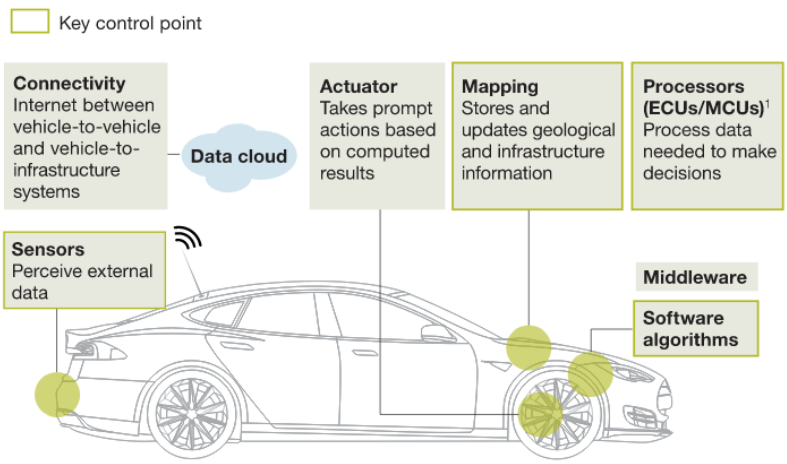


Figure 2-1 Examples of ADAS components (Choi et al. 2016)

The technical functions of a wide variety of systems have been presented in existing research (Shaout et al. 2011; Paul et al. 2016) and are listed in Table 2-1, including their safety benefits.

Table 2-1 Overview of typical ADAS functions

Function	Description
Adaptive High Beam (AHB)	A headlight control strategy.
Autonomous Cruise Control System (ACCS)	Automatically maintains the speed of the vehicle.
Navigation System (NS)	Helps drivers to find their destination.
Autonomous Parking Assistance Systems (APAS)	Performs parallel, perpendicular, or angular parking.
Blind Spot Monitor (BSM)	Detects vehicles, obstacles, and people that the driver cannot see through the mirrors and provides a warning.
Electronic Stability Control (ECS)	Applies the brakes if needed to help steer the vehicle.
Collision Avoidance System (CAS)	An automobile safety system designed to reduce the severity of an accident.
Crosswind Stabilisation (CS)	Compensates for strong winds.
Driver Drowsiness Detection (DDD)	Helps to prevent accidents due to drowsiness.

Driver Monitoring System (DMS)	Monitors the driver’s attentiveness.
Emergency Driver Assistant (EDA)	Monitors the driver’s behaviour. The car takes the control of the brakes and the steering until a complete stop if a driver is not able to drive.
Forward Collision Systems (FCS)	Detect and alert the driver to imminent accidents
Intelligent Speed Adaption (ISA)	Monitors vehicle speed and the local road traffic and takes action (warning or intervention) when the vehicle is detected to be exceeding the speed limit.
Intersection Assistance (IA)	Identifies critical situation at intersections and alerts the driver of red-light infringements or hazardous turnoff situations. The system can even recommend the required speed for a green traffic light wave or approach to the red traffic light.
Lane Departure Warning System (LDWS)	Monitor unintended lane changes by drivers and provide an alert.
Night Vision (NV)	Increase a driver's perception and seeing distance in darkness or poor weather beyond the reach of the vehicle's headlights.
Hill Descent Control System (HDCS)	Allows a smooth and controlled descent in hilly terrain without requiring the driver to touch the brake pedal.
Turning Assistant (TA)	Checks for opposing traffic when turning at low speeds.
Wrong-Way Driving Warning (WWDW)	Prevents driving in the opposing lane.

Previous research has presented many of such systems that may provide different functions to drivers to increase safety. Reviewing the current classifications of such systems can provide more insights into the above functions of ADAS.

2.1.2 Classification of ADAS

Figure 2-2 The ADAS types and its effect (Troppmann 2006b)

Figure 2-2 gives an overview of ADAS, which is divided into **passive** ADAS and **active** ADAS. Passive ADAS technology (e.g., "lane departure warning" and "blind spot detection") is capable of detecting the surrounding environment and alerting the drivers when a potential accident is detected. In contrast, active ADAS technology is silent for most of the driving. When activated, active ADAS technology can take action (e.g., steering and/or braking the vehicle) to prevent collision. An example is the "collision avoidance system" that automatically brings the vehicle to a full stop if a collision is imminent, and the driver does not act fast enough. The above analyses reveal that passive ADAS is a system that increases drivers' awareness of surrounding environment. This research focuses on passive ADAS because of their great demands for the human-machine interaction (HCI) design, especially the design of warnings/information.

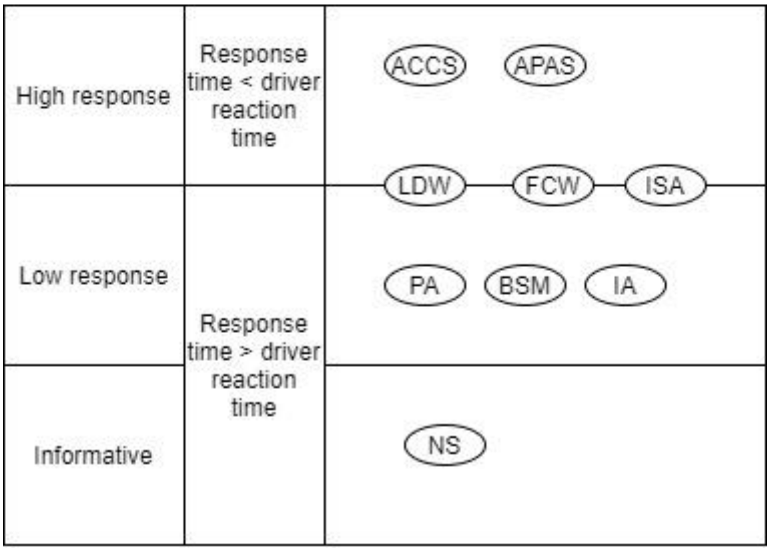


Figure 2-3 Overview of common ADAS classified by the typical system response time and driving processing, based on (Freymann 2006).

ADAS is classified by a distinction between “low response” and “high response” in accordance with the response time (Freymann 2006). "Low response" suggests that the driver is allowed to override the actions/reactions of the ADAS at any time. The "high response" system has a characteristic that the output of its control system will not be override by the driver due to the short response time. For the drivers, they can take in information and make the right decisions through passive ADAS, such as the forward collision warning issued when the set threshold is reached by the distance between the subject vehicle and the vehicle in front. In this case, the driver must increase distance by releasing the accelerator or stepping on the brake. Comparatively, a faster response than drivers is required by active ADAS which is usually automated to prevent an impending collision by correcting the drivers’ action, such as the collision avoidance system. It will take action (emergency braking) to avoid accidents when a collision may occur due to the distance between the vehicle and the vehicle in front reaching the set threshold. In summary, the former inform drivers for the surrounding hazard by warnings, and the latter focuses on the direct intervention of the system. Freymann (2006) presented a good understanding of ADAS, but there is a lack of important factors for the ADAS safety effect.

Understanding safety effect will be beneficial to build an ADAS cluster under different orientations (e.g., what type of drivers' behaviour does ADAS help).

The possible safety benefits of ADAS can be defined as avoidance of inappropriate speed (intelligent speed adaption), maintenance of appropriate longitudinal and lateral distances (forward collision system and lane departure warning system), as well as support of driver awareness (driver monitoring system) (Golias et al. 2002). To be specific, lateral control, longitudinal control, reversing, vision enhancement, driver monitoring, pre-crash system and road surface warning system (Lindgren and Chen 2006). Reviewing the above safety effects, some of the benefits are overlapped. For instance, the pre-crash system can be implemented by longitudinal or lateral control. In this research, the safety effects are classified into four categories:

- Longitudinal task
- Lateral task
- Driver monitoring
- Vision enhancement

Longitudinal means to prevent inappropriate the distance and speed in longitudinal task. Likewise, lateral means to ensure appropriate distance in lateral task. Driver monitoring aims to deal with the driver status. Furthermore, vision enhancement supports the driver in driving conditions with low visibility. Furthermore, Pollard et al. (2013) established a more detailed ontology of a driving situation assessment. Table 2-2 illustrates six levels, including environment, driver state, ego-vehicle, free zone, moving obstacles and communication. This ontology is an object-oriented classification indicating the exact situation/purpose of ADAS.

Table 2-2 Driving situation assessment

Data fusion	Definition
Environment	Contains any element which can be provided by a map as well as elements which must be assessed or broadcast.
Driver state	The driver's ability to drive.
Ego-vehicle	Vehicle's current state, including velocity, orientation, and acceleration.

Free zone	The stated estimation of both unmoving obstacles and navigable space.
Moving obstacles	1) 'Road vehicles' with positions and 2) 'vulnerable people'.
Communication	The quality of service (i.e., ability to broadcast data in good condition).

This research will not consider about driver status warning, because unlike dynamic longitudinal or lateral warning, such situation is largely based on drivers themselves not environment or predictable situation. The passive ADAS presents information/warning through HMI devices, the possible ADAS output modalities are discussed in the next section.

2.2 Understand ADAS Warning

As warning is the main function of passive ADAS, a definition of 'warning' is presented in the present section with relevant design elements under a driver-warning context.

2.2.1 Definition of Warning and Relevant Design Elements

A warning is defined as a rated information (ISO/TR:16352 2005). Perceived information should be processed and weighted to deliver a warning to the recipient. In accordance with the ISO/TR:16352 (2005), a good warning should consist of:

- An element which attracts attention
- A reason for the warning (e.g., cause)
- The consequence if the warning is not observed
- Instruction for action

First, the warning message is triggered by a specific reason, which can originate from the vehicle itself or the surrounding environment. The reason for the warning is to alert the driver about a potential hazard, such as a crossing pedestrian or a slippery road. One way to categorize warning content is based on the sensors involved. For instance, consider the example of a vehicle equipped with a forward collision warning system. When the vehicle ahead starts to decelerate while the driver's vehicle maintains its current speed, the forward collision warning system will provide a verbal warning saying, ‘decreased vehicle ahead’. In this scenario, audio feedback is used to capture the driver's attention and provide the reason for the warning. The warning does not necessarily include information about the potential consequences of not heeding the warning or instructions for specific actions. However, it may imply the potential consequence, such as a rear-end collision, and the driver may respond by releasing the gas pedal or applying the brakes. Therefore, a warning message may not always explicitly state the consequence or provide instructions for appropriate actions. However, in critical situations like an impending crash, including a ‘brake’ or ‘stop’ signal in the warning message may facilitate a faster braking response, highlighting the importance of considering specific elements of the hazard when designing warning systems.

Zarife (2014) presented a list of warning elements adapted from ISO/TR:16352 (table 2-3) to provide more insights into how to design a warning. Urgency is the fundamental element, arousing the driver's attention to the warning and promoting the driver's response. Furthermore, for dynamic driving environments, possible collisions always have a location that may change over time. However, in ISO/TR 16352 (2005), the effectiveness of space warning prompts is discussed, whereas it is not defined as an essential element of warnings. The elements of the action instruction are suitable for the driver to respond in an urgent situation (e.g., emergency braking or steering). In addition, warning elements of dangerous consequences may not be required in numerous critical driving situations, especially in the case of warning elements containing hazard directions and warning causes. By providing the above elements to the driver (e.g., conveying the warning that the vehicle in front is decelerating), the drivers should be able to anticipate the possible consequences. Besides, they can integrate the environmental information to estimate the urgency of the situation and perform corrective actions.

Table 2-3 Warning elements adapted from ISO/TR:16352 (2005) based on Zarife (2014)

Warning element according to ISO	Adapted warning elements
Element which attracts attention	Urgency
Reason	Hazard direction
Consequence	Hazard cause
Instruction for actions	Instruction for action
	Consequences (optional)

2.2.2 Warning Process Model

A warning process model is beneficial to deepen the understanding of warning interact with driving environment. Zarife (2014) built an integrative warning process model based on Communication-Human Information Processing (C-HIP) model (Wogalter et al. 1999). The integrative warning process model includes warning (properties) and ADAS (sender) since C-HIP model does not specify the processing steps on the warning communication or design warning.

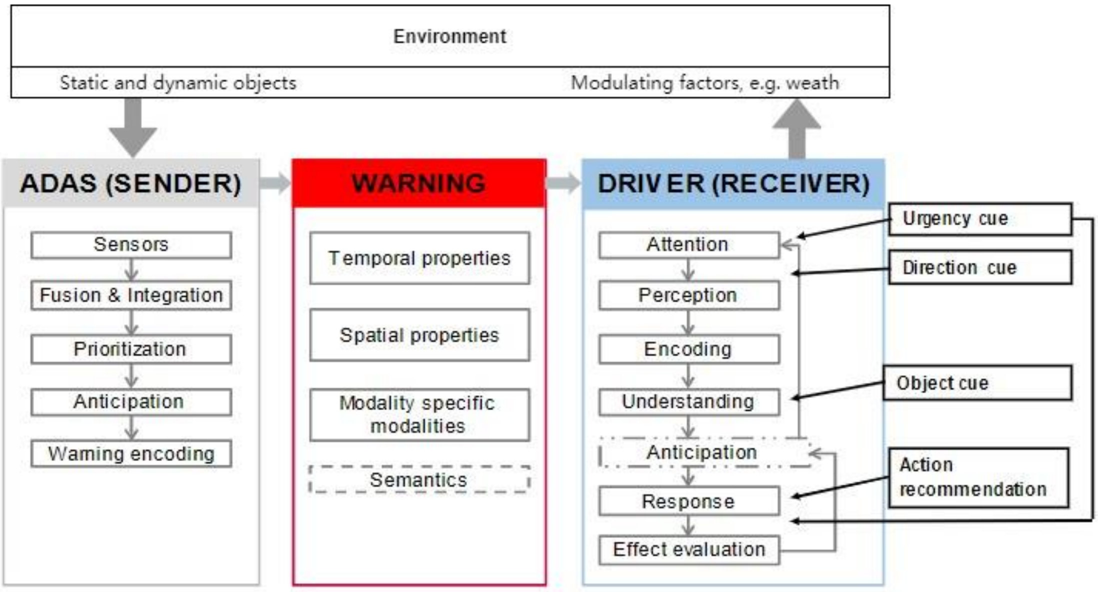


Figure 2-4 An integration model of driver-warning process with warning elements (Zarife 2014)

Figure 2-4 defines the sender as ADAS, the message as the warning, and the receiver is defined as the driver. ADAS uses multiple sensors to acquire environmental data. By fusing and integrating sensory data, the algorithm is capable of "anticipating" the risks of different identified objects with a certain likelihood ratio and quantifying and prioritizing related hazard candidates (objects) based on predefined criteria. Warnings are coded as objects with high priority. This step takes on a critical significance since it can determine which environmental information is encoded into the warning message. For the sender (ADAS), high quality of detection and an optimal warning design is imperative to alert drivers reliably and appropriately. Warning consists of a modality (e.g., visual, audio), temporal properties (e.g., onset, duration) and spatial properties (e.g., location, direction). The combination with the specific elements of different modalities represents warning semantics for communicating with drivers. For the drivers, the first step is to attend to the warning. Assisted by attention resources, the drivers notice the warning and encode its semantics into their own semantic space. The semantics of warnings can be understood by associating with information from long-term memory (or experience) and the environment. After understanding the warning message, drivers should be capable of anticipating the potential impact of a new hazard and their own reactions. Such anticipations can be more accurate, particularly in situations that complement the warning elements. By anticipating, drivers become empowered to respond to the warning and select appropriate measures for the hazardous situation. Once drivers have responded, they evaluate the outcome of their performance and update the association between their actions and their effects in their memory (based on their experience), which includes considering the possibility of employing specific response measures. Moreover, drivers function within a feedback loop with the environment, where their actions bring about changes in the environment and receive novel inputs from the sender (ADAS) and themselves.

Furthermore, the effect of warning element (section 1.2.1) is investigated in the warning process. The urgency cue is the main element to alert drivers and draw their attention to the warning. High urgency cue (e.g., with rapid beep sound) has the potential to reduce drivers' response time. Directional cues can direct the driver 's attention to the relevant locations of a potential hazard, thus facilitating perception and subsequent processing steps. The warning contains directional cues that can effectively guide the driver's attention and facilitate the driver's reaction. Object cue can help the driver gain insights into the cause of the warning and predict the possible consequences. Lastly, the action cue will help the driver to choose the correct action for the hazard response, which is usually under an impending collision.

This model indicates the process of how drivers receive the warning and warning elements helps drivers' perception. As revealed by this model, warnings can be presented under different HMI modalities. In the following sections, how different modalities are designed in the vehicle is presented, and their advantages are compared in different scenarios.

2.2.3 ADAS Warning Modalities

Modality is the first element to design an ADAS warning and different modality can affect the efficiency of warning. Relevant research has demonstrated the potential benefits related to the presentation of ADAS with different modalities or even multisensory warnings to achieve a fast respond and rapidly orient the driver's spatial attention in the direction of potential danger. Passive ADAS related to HMI devices can be grouped in accordance with their output modalities. There are three main types of modalities: visual, audio, and haptic. Visual and auditory warnings have been used extensively in the design of ADAS warnings. Several researchers have considered the possibility of using olfactory warnings. For instance, Raudenbush et al. (2009) suggested that cinnamon and peppermint odour can improve alertness while driving. However, the biggest issue with olfactory warning is it is difficult to perceive it in a timely manner compared with traditional modality (Spence and Ho 2008). Hence, olfactory modality is not reviewed in the present section.

2.2.3.1 Visual Modality

Visual warnings are intuitional and can be used to convey various signals by symbolic information and colour (Braun and Silver 1995). Visual modality is the fundamental strategy for information delivery. Presentation of information in the visual modality should enable the user to perform tasks (e.g., search for information on the display) effectively, efficiently and with satisfaction (ISO:9241-125 2017). Figure 2-5 and Table 2-5 show an overview of possible in-vehicle locations to present visual information to the driver.

Figure 2-5 Possible in-vehicle position to present information (adapt from Wittmann et al. (2006) and Drüke et al. (2018))

Table 2-4 Possible position to present information

Code	Location	Example
A	Dashboard	Vehicle status, navigation
B	Central Console	Navigation, Infotainment
C, E	Windshield	HUD, warning for object in front
D	Nomadic mobile devices	Smartphone or tablet for navigation or entertainment
F	Rear mirror	Rear view
G	A- and B- Pillar	Lane departure warning or blind spot warning
H	Door Mirror	Blind spot warning

The dashboard is the main position for presenting vehicle status. In recent years, fully configurable cluster displays have been developed that can switch between visual themes that display elements like the speedometer and navigation. The central console display can show more detailed information like navigation or infotainment applications (e.g., navigation routes, music, and the rear camera view). A heads-up display (HUD) can be implemented through the full windscreen or just above the dashboard that can assist the driver while performing a primary task (e.g., navigation or visual warning). The door and rear mirror can be adopted to display warnings (e.g., blind spot warnings with symbol on the above mirrors). Also, A- and B-pillars can be employed to show blind spot warnings or lane departure warnings (e.g., red lights indicate the vehicle is moving out of the lane). Furthermore, drivers may mount nomadic devices (e.g., smartphones or tablets) above the central console for navigation, communication, or entertainment.

2.2.3.2 Audio Modality

Audio warning are excellent at attracting attention and do not require visual processing (ISO/TR:16352 2005). A significant factor for an auditory warning is that it has a gaze-free characteristic (Graham 1999). As a result, auditory warnings usually produce faster responses instead of presenting visual warnings. Moreover, verbal warnings can convey spatial information of the direction of a potential hazard, which reduces the perception and response time (Chang et al. 2008). Audio modality can be classified as follows (ISO/TR:16352 2005).

Table 2-5 The type of audio warning

Audio type	Description
Simple Tone	Single or grouped frequencies presented simultaneously
Auditory icons	Auditory icons are familiar environmental sounds that intuitively convey information of the object or action they represent.
Earcon	Earcons can be expressed as musical tones that can be employed in structured combinations to generate auditory messages.
Speech (verbal) message	Speech messages are voice messages adding information beyond pure sound

In general, audio warnings are classified into non-speech warnings and speech warnings (Noyes et al. 2006). As for the former, both simple and complex sounds are included. A classic example of a simple sound is "beep". When immediate attention is needed, simple voices are recommended (Wogalter and Young 1991). As for non-speech warnings, learning is required due to the frequent use of those abstract sounds (e.g., tones, bells, buzzers, etc.) that are not related to the sounds or auditory icons represented by them (Noyes et al. 2006). Speech warnings provide the users with more meaningful (i.e. representative) information as their attention can be brought to the nature of the hazard (Bertone 1982). However, the considerable time cost is one of the disadvantages associated with speech warnings (Noyes et al. 2006). In general, audio warning indicates a level of urgency consistent with the urgency of the hazard (ISO/TR:16352 2005).

2.2.3.3 Haptic Modality

Another modality is a haptic warning. Haptic warnings are beneficial to alert the driver to critical situations and help the driver take corrective action (Enriquez and MacLean 2004; Lee et al. 2004). Moreover, a haptic modality can present warnings to drivers without necessarily increasing their visual or auditory workload (Spence and Gallace 2007; Prewett et al. 2012). Additionally, tactile warning signals are easier to locate than audible ones in confined spaces inside a car. (Spence and Ho 2008). For instance, a system twisting the steering wheel can tell the driver to steer back into the proper lane. Since haptic warnings are capable of facilitating driver responses and initiating a reflexive response to a hazard, they should be evaluated carefully to identify possible unintended reactions. Table 2-6 lists the possible application of haptic modes. Counter-torques are have been commonly implemented in systems helping drivers keep in their lane, or prevent them from leaving the road (Suzuki and Jansson 2003). The haptic seat has been demonstrated as a solution to provide spatial cues to the driver through the vibration of multiple haptic zones (Fitch et al. 2007). A haptic pedal can be adopted to provide an action recommendation to drivers through counter pressures (e.g., reducing speed or braking) (De Rosario et al. 2010).

A haptic seatbelt can use short tensions of the strap to warn of danger (e.g., a possible forward collision) (Chun et al. 2012).

Table 2-6 Types of haptic warnings

Position	Example
Counter-torques	A counter-twist on the steering wheel keeps the drivers in the correct lane
Haptic seat	Alerts the driver by vibrating segments corresponding to the direction of the hazard
Haptic pedal	Accelerator pedal applies counter pressure if the driver reduces speed
Haptic seatbelt	Briefly tensions the seatbelt to alert the driver of a frontal hazard

2.3 The Effectiveness of Warning

The previous section introduced the basic elements for designing ADAS warnings. However, it is necessary to understand how drivers' behaviour interact with the vehicle and traffic environment and how warnings assist the driving process/tasks. The present section will introduce driver model.

2.3.1 Situation Awareness

ADAS warning is a method that help drivers enhance their awareness of surrounding environment to make a better decision. Situation awareness (SA) is the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future (Endsley 1995). Figure 2-6 describes the model proposed by Endsley, in which the state of the environment is used as input to SA, which will lead to decisions and actions.

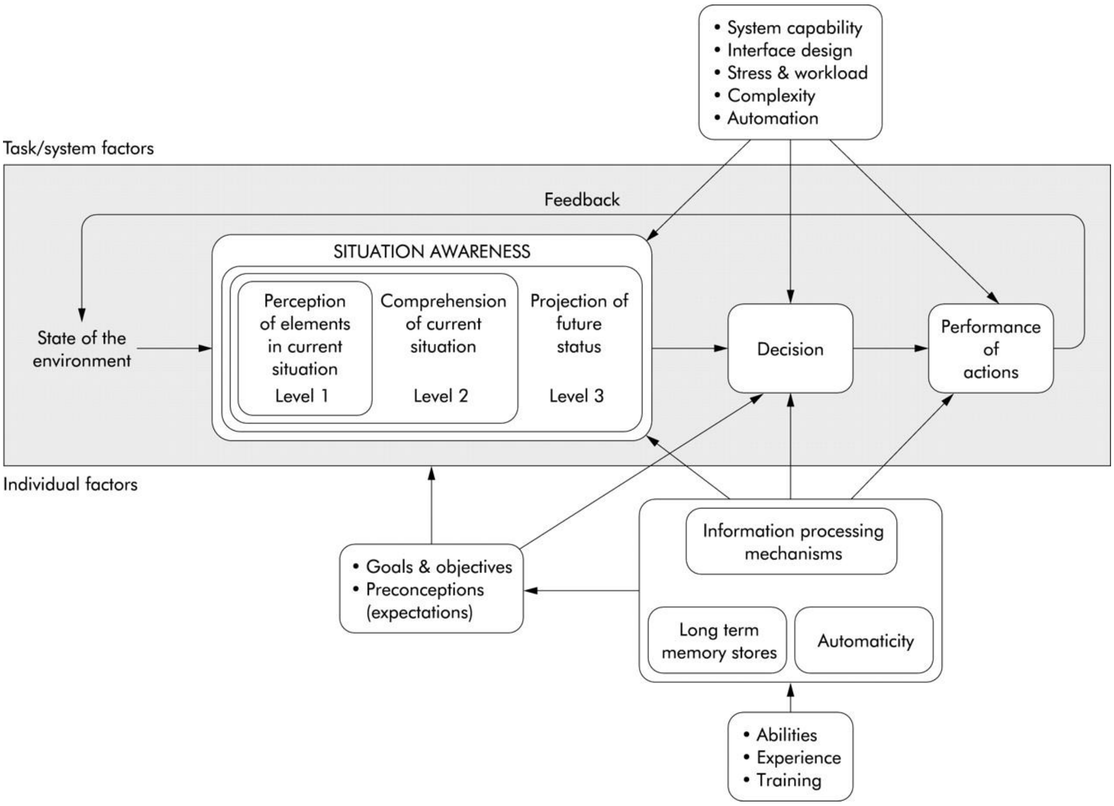


Figure 2-6 Situation awareness model (Endsley 1995)

The first stage of SA (Level 1 SA) is drivers' perception of their current environment. When driving, drivers should be aware of the position of other vehicles, obstacles, and the motion of the ego-vehicle. Comprehending the situation (level 2 SA) is the next essential stage for decision-making. Forming a holistic understanding of the environment and the significance of objects and events are part of this stage. Lastly, projecting the future state of environmental elements (level 3 SA). Drivers should perceive the possible hazard and perform corresponding reaction. A poor SA may lead to a poor response to the hazard situation.

As Endsley (1995) suggested above, individual factors and the capabilities of the systems and tasks are two factors for SA. For individual factors, SA requires drivers to have a goal and expectation for the current situation. Moreover, factors relating to personal ability and experience will affect the information processing and the response to the situation. The capabilities of systems and tasks are reflected in the interface design of the system, as well as the complexity, pressure, and level of automation related to specific tasks. Accordingly, the interface of interface design takes on a great significance when the complexity of the situation increases. Since driving is a highly dynamic task, the drivers should constantly interact with the environment to update the current situation, and it is essential to maintain SA through the warning cues. However, in a complex and dynamic environment, the decisions and execution responses made using SA may be affected by highly attentional demand. The next section will introduce a popular attention resource theory: Multi-Resource Theory.

2.3.2 Multi-Resource Theory (MRT)

Under multitasking scenarios, there is an increase in the human workload required to perform additional tasks than under single-tasking scenarios (Xie and Salvendy 2000). Also, multitasking performance may be affected by the increased workload in multitasking modes. Multiple Resources Theory is a theoretical framework applied to describe how attentional resources are allocated across different cognitive processes and task demands (Wickens 2002). The Four-Dimensional Multiple Resource Model involves four additional dimensions of information processing as required to understand the allocation of attentional resources during task performance (Wickens 2008)：

- In perceptual and cognitive (e.g., working memory) tasks, various resources obtained from those needed to select and execute actions are exercised, as indicated by the stages of processing dimension.
- The resources used in spatial activity differ from those used in verbal/linguistic activity, which is reflected in perception, working memory and action, as indicated by the codes of processing dimension.

- The resources used in auditory perception differ than those used in visual perception, as indicated by the modalities dimension (embedded within perception and not reflected in cognition or response).
- Visual channels, different between focal and ambient visions. A dimension embedded within visual resources. Focal vision, mainly foveal, is supportive of object recognition and especially the high acuity perception related to the reading of text and the recognition of symbols. Distributed throughout the visual field (unlike focal vision) to preserve its competency in peripheral vision, ambient vision is relied on to perceive orientation and movement, so that various tasks can be performed, like walking upright in the target direction or occupying a lane on the highway.

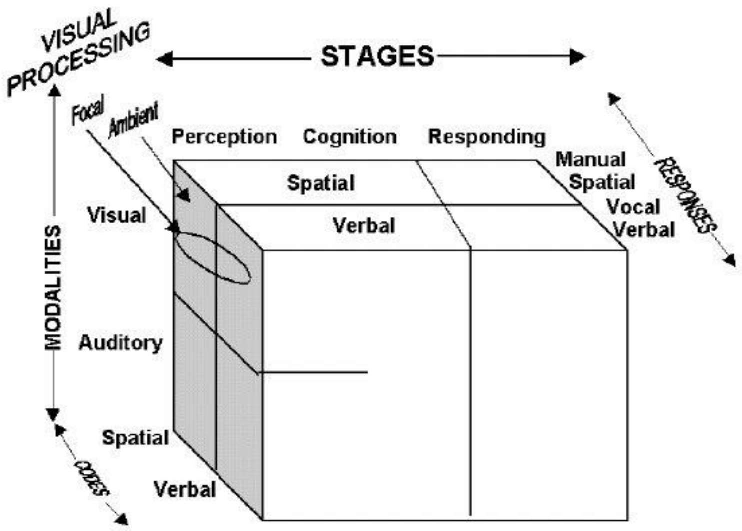


Figure 2-7 Multiple resource model (Wickens 2008)

The Four-Dimensional MRT provides a comprehensive framework for understanding how attentional resources are allocated during task performance, taking into account different dimensions of task demand and information processing. By considering the demands of each dimension, researchers and designers can optimize task design and reduce interference to improve task performance and safety.

However, driving experience plays an important role in the ability to allocate attentional resources during driving. Experienced drivers do not have as much difficulty performing multiple driving-related tasks because they have developed a more efficient allocation of attentional resources. With experience, drivers have learned to automate some driving tasks, such as shifting gears or braking, which require less conscious attention (Patten et al. 2006). This allows experienced drivers to shift their attention to other aspects of the driving environment, such as scanning for potential hazards or navigating unfamiliar roads. In addition, novices scan the road less and tend to focus on the road ahead than experienced drivers, putting them at a disadvantage in the event of a dangerous event (Underwood 2007). Pammer et al. (2018) argued expertise allows drivers to calibrate a hierarchy of attentional filtering to not only direct attentional resources to locations of interest, but also to explicitly prioritise objects of interest when driving. Therefore, experienced drivers may be better able to simultaneously monitor the speedometer, check the rearview mirror, and anticipate the behaviour of driving-related task, without becoming overloaded or distracted. To further investigate the human factor for the performance, the next section will introduce skill-, rule-, knowledge- based model.

2.3.3 Skill-, Rule-, Knowledge- based Model (SRK model)

Everyone has limited processing ability because mental activities share the same resources. As described by Endsley (1995), personal ability, experience and training may affect the capability of SA. As a result, how such factors affect driving performance should be explained. As a cognitive framework proposed by Rasmussen (1983), the Skill-, Rule-, Knowledge- based (SRK) model describes how individuals learn and execute complex tasks, such as driving.

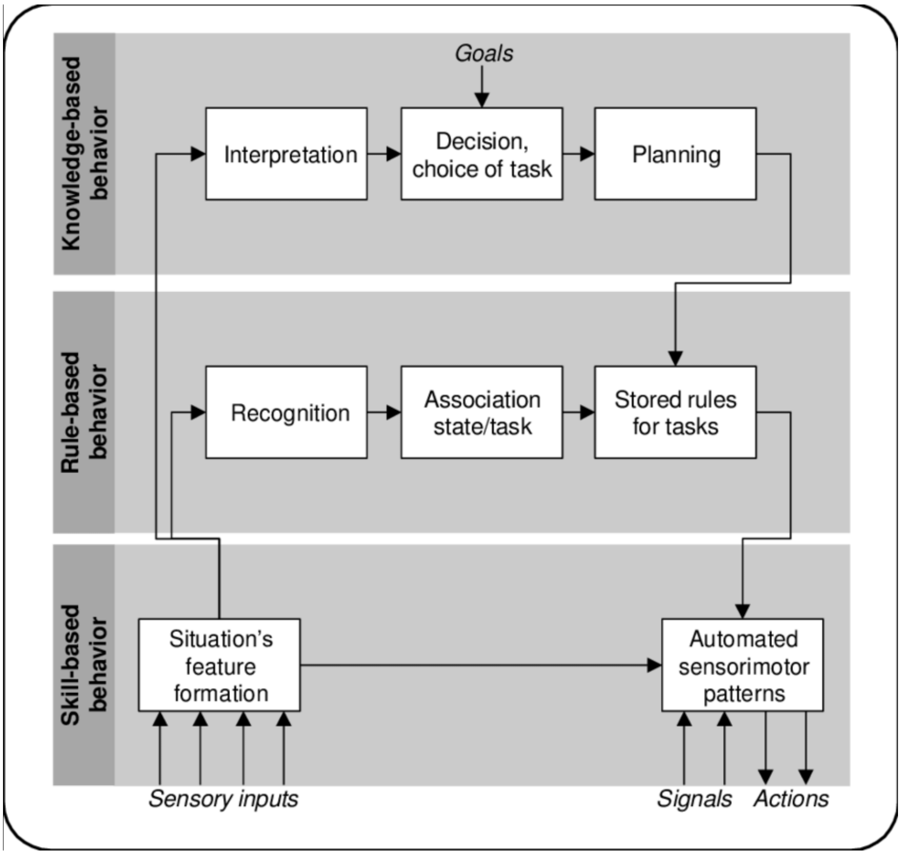


Figure 2-8 SRK model adapted from Rasmussen (1983)

As illustrated in Figure 2-8, there are three levels of determining a performance.

- Skill-Based Stage: The skill-based stage is the first one of cognitive processing in which an individual has learned a set of motor or cognitive skills automated through practice and repetition. When it comes to driving, this stage revolves around the development of various basic driving skills such as accelerating, braking, and steering. In this stage, the heavy reliance of novice drivers on visual and auditory cues to guide their actions makes their driving slower and more deliberate than that of experienced drivers in many cases.
- Rule-Based Stage: The rule-based stage is the second one of cognitive processing in which the actions of an individual are guided by rules or procedures. In the context of driving, this stage focuses on the development of more complex driving skills such as anticipating and responding to traffic signals and signs and following the rules of the road. In this stage, drivers base their

decisions on learned rules and procedures. In spite of this, they may still struggle with more complex situations.

- Knowledge-Based Stage: The knowledge-based stage is the third and last one of cognitive processing in which the actions of an individual are guided by their general knowledge and problem-solving skills. When it comes to driving, this stage revolves around the development of expert driving skills, such as the capability to anticipate and respond to the potential hazards on the road, and the ability to drive in various challenging circumstances such as bad weather. Those drivers in this stage can make complex decisions in a fast and accurate way, which is often based on their overall understanding of the task rather than the specific rules or procedures.

According to the SRK model, novice drivers, who are in the skill-based stage of cognitive processing, rely heavily on visual and auditory cues to guide their actions. Therefore, novice drivers may improve their driving performance and ensure driving safety with the help of multiple driving-related warnings. Multiple warnings can improve the decision-making skills of novice drivers by making them more aware of the potential hazards on the road. For example, to avoid accidents, novice drivers can be alerted to the potential dangers on the road by various warning systems such as lane departure warning, forward collision warning, and blind spot monitoring. These warning systems provide novice drivers with feedback on their driving performance and help them learn from their mistakes, thus promoting the development of their rule-based and knowledge-based skills. However, it is worth noting that the effectiveness of warning systems may be determined by the experience level, cognitive workload, and situational awareness of an individual driver. Multiple warnings may make it more likely for novice drivers to experience cognitive overload, thus affecting their driving performance.

2.4 Challenges with ADAS

As sensor technology has been leaping forward, drivers are facing increasing information reception and processing requirements. There are concerns about driver information overload with automotive HMI which can lead to a concomitant increase in driver distraction (Harbluk et al. 2002). Interacting with more ADAS will be one of the numerous activities that constitutes driving, where the driver should process considerable information regarding the primary driving task (e.g., vehicle control and situation awareness). As a result, drivers are easy to be distracted when they are exposed to additional information sources requesting for the secondary tasks (Harbluk et al. 2002; Vahidi and Eskandarian 2003). Accordingly, passive ADAS can negatively affect the driving safety if the warnings are poorly designed, located, or used inappropriately.

It is generally recognized that driver distraction is a subset of inattentions where an explicit activity other than driving (e.g., operating a cell phone) competes for the attention of the driver (Streff 2000; Cohen and Graham 2003; Lee et al. 2008; Young et al. 2008). Driving is a relatively high-visual-workload task, and it has been estimated that as much as 90% of the information received while driving is visual (Sivak 1996). It is imperative for the passive ADAS warning to attract the driver's attention to be perceived. Thus, it may induce an unintentional shift away from activities required for safe driving. For example, the driver's scanning behaviour may be disrupted if an ADAS warning appears on the dashboard and arouses the driver's attention. As a result, they fail to look where they should for the desired duration and may make the wrong decision.

The potential benefits of ADAS can be negated by poorly designed warning signals that can jeopardize the driver's safety by frightening them. For instance, Rossi et al. (2013) observed participants' behaviours when the participants were driving a simulated vehicle on a dangerous road section. The participants were presented with auditory warnings whenever the speed was overly high. Although the result showed a reduction in speed, a further study by Biondi et al. (2014) reveals that this is a consequence of a startle reaction attributed to the abrupt onset warning signal. In another similar experiment, participants drove a simulated vehicle that gave an audible warning when the speed reached over a given threshold (Adell et al. 2008). The results indicated that auditory reduced driving speed but increase annoyance ratings; this aspect could potentially lead to drivers discontinuing the use of ADAS. Accordingly, warning may interrupt with drivers' current activity and decrease their willingness for continuing the use of such warning (Jamson et al. 2008).

Moreover, existing research has suggested that when facing multiple warnings, any alarm occurring after the first triggered alarm may startle, confuse, or interfere with the driver's evasive actions (Green 2008). This research also reveals that alerts preceding and following a lane change-lane change (LCM) alert can delay drivers' response to the LCM by 0.5 seconds. Drivers are also likely to completely miss the second alert due to their limited ability to process information under high stress (Hancock 1989). The delayed response may be attributed to a mismatch between the demanded and devoted attention to the road under an overload of resources (Hurts et al. 2011). Some research has considered excessive workload and limited attentional resources as contributing factors to distraction (Hurts et al. 2011). Multi-resource theory (section 1.3.2) indicates that if the two tasks compete for the same stage resources, the workload may become overloaded. Although non-visual ADAS output modalities can reduce visual workload, drivers still need a certain demand of mental workload for encoding. As a consequence, it is generally related to a recognition or processing delay (Pettitt et al. 2005) or a deterioration of driving performance (Regan et al. 2011). For example, drivers have delayed responses to a collision warning when the collision warning follows an e-mail alert by 300 ms (Wiese and Lee 2004). Drivers may also miss the second alarm due to the limited ability to process information rapidly under high pressure (Hancock 1989). Thus, a separate alert notifying the driver of the occurrence of the respective conflict can guide the driver to the correct location and sequence to implement appropriate avoidance strategies (Fitch et al. 2007; Green 2008).

2.5 Current Development of Improving ADAS

The above problems can be solved using an optimized human machine interface (HMI) design.

In existing studies, a HUD has been widely employed to present visual warnings/information to keep drivers' eye on the road. Liu (2003) investigated the difference in driving performance between drivers' attention to the HUD and road under two road conditions (low and high). As revealed by the results, drivers paying attention to the HUD, under low and high driving load conditions, reacted faster to speed limit sign changes than when paying attention to the road. Furthermore, HUD has been compared with head-down display (HDD) (Liu and Wen 2004). In their study, displays in commercial vehicles were employed to provide information during cargo delivery, navigation, and speed-related information, as well as to provide warnings about road or vehicle conditions that require immediate attention. A faster response to visual warnings and better compliance with speed-related information were observed when HUD was used. The use of HUD is recommended under high-load road conditions. HUD reduces the number and duration of driver gazes off the road by projecting desired information directly into the driver's line of sight, which allows the drivers to receive information without degrading his eyesight. As a result, the drivers can avoid looking down at the HDD when their eyes are off the road. HUD has already been deployed in some car models (BMW, Mercedes, and Volvo). Figure 2-9 presents an example of commercial HUD in Volvo. Full colour images are now available on newer Volvo models. The Volvo HUD can project driving-related information (e.g., example collision warning, speed limits, and navigation).

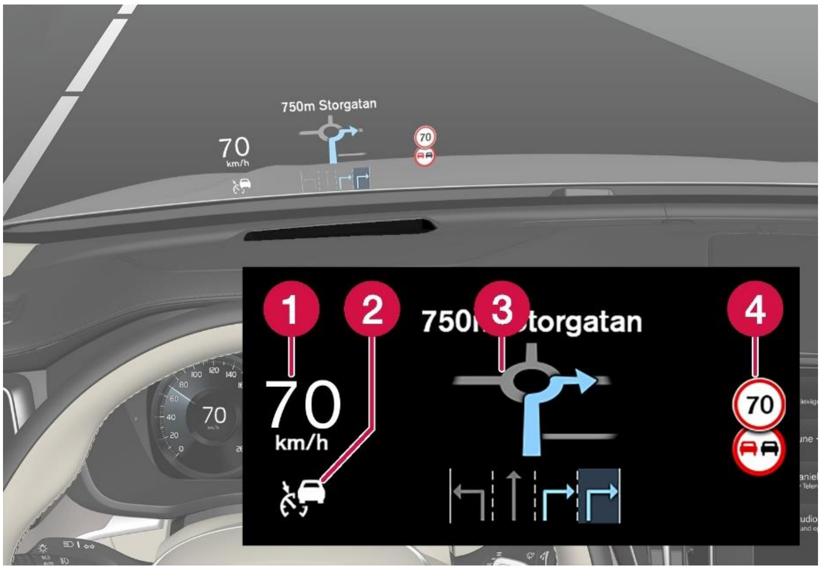


Figure 2-9 Example of commercial HUD (Volvo)

Another route for keeping drivers' eyes on the road is to use a 'gaze-free' modality (i.e., audio and haptic feedback) to present warnings. For instance, Suzuki and Jansson (2003) investigated two modalities (auditory and vibration) for lane departure warnings. They concluded that vibration feedback can effectively reduce the reaction time when drivers are not aware of the meaning of the warning. Notably, monaural or stereo beeps can effectively reduce reaction time after drivers learn the meaning of the warning. Sayer et al. (2005) investigated audio feedback and vibration seats applied in lane departure warnings and curve speed warnings and found a similar result. The results suggest that compared with haptic feedback, audio feedback gains a better recognition result. In other words, drivers gain more insights into the meaning and the required response.

In addition, to maximize the effectiveness and subjective usefulness of warning systems, many studies have investigated the optimized design for warning elements (e.g., modality and specificity).

For example, Kaufmann et al. (2008) proposed a set of guidelines for the use of audio, haptic and visual warnings for three priority levels. The authors defined high-priority warnings as requiring immediate action, while medium-priority warnings do not require immediate response, and low-priority warnings have no direct relevance to driving tasks. Audio and haptic modes are proven suitable for high-priority messages, visual and haptic for medium-priority messages, and audio and visual for low-priority messages. Furthermore, different combinations of modality were investigated. Politis et al. (2014) presented a similar three priority level scenario to evaluate all unimodal, bimodal and trimodal combinations of audio, visual and tactile warnings to alert drivers. The results indicated that as the number of warning signal modalities (visual, auditory, and tactile) increases, the level of annoyance experienced by drivers also increases. However, the level of annoyance caused by using multiple modalities is lower than the level of urgency that is created by the warning signals. This suggests that while multiple modalities may cause some annoyance to drivers, they are still effective in creating a sense of urgency and promoting safe driving behaviours. A further study conducted by Politis et al. (2015) compared abstract warning and language-based warnings under various modalities. The study found that the recognition time for urgency warnings was shorter when presented as abstract warnings, particularly those with high urgency and visual feedback, in non-critical driving situations. On the other hand, warnings accompanied by audio resulted in faster response times in critical situations. Based on these findings, it was suggested to provide abstract visual feedback to drivers in non-critical situations and utilize audio warnings in highly critical situations.

Warnings can also contain different amounts of specific information about the hazard (e.g., its location, direction, or type). Based on warning processing model, the use of more specific warnings can help the driver gain more insights into the cause of the warning while leading to or accelerating the allocation of attention to the hazard. Early research has found that visual collision warnings with specific icons were more acceptable than generic icons (Nakata et al. 2002). Ho and Spence (2005) suggested that responses to a critical event are more rapid when naturalistic audio cues (car horn sounds) originate from the direction of the event (front or back). In-depth research has revealed that the object cues show only a few effects, and the directional cues significantly optimized gaze reactions, braking responses, and collision frequencies (Naujoks and Neukum 2014; Zarife 2014). The above finding suggests that spatial information significantly affects the subjective evaluation of the potential hazard. In another experiment, verbal information regarding the direction of a red-light intersection leads to faster braking responses, more adaptive deceleration, as well as better subjective ratings (Zhang et al. 2015). However, subsequent effects of specificity were moderated by the modality of the warnings (Schwarz and Fastenmeier 2017). They conducted an experiment to investigate the interaction effects of modality (audio and visual) and specificity. The pattern of the interaction effect was a negative impact of specificity for auditory warnings but a positive impact of specificity for visual warnings. This may be due to the fact that a specific visual warning is presented directly on the road (argument reality display), making its presence clearly perceived and aiding its detection. The particular audio warning of an approaching sound causes a fade-in effect, the smooth onset of the sound, which may have been delayed or even mask its detection.

In brief, current researchers have investigated different warning design elements to minimize distraction/overload due to ADAS. However, there is still a gap whether the driver is enabled to recognize accurately and rapidly if multiple warnings are presented simultaneously/almost simultaneously.

2.6 Remaining and Emerging Challenges: Multi-warning Situation

Currently, connected technology is applied by more vehicles to assist drivers in using the data collected by various sensors fitted in other vehicles or infrastructure. In the future, accidents can be significantly reduced worldwide by deploying futuristic technologies based on cooperative systems. Capable to sense their surroundings and display appropriate information, connected vehicles can be used to compensate for the weaknesses of drivers. A typical example is the European Intelligent Road

Safety Cooperative System Integration Project (COOPERS) (Böhm et al. 2007), which focuses on infrastructure-to-vehicle (I2V) communication systems. By sending traffic information to motor vehicles on expressways, it is intended to improve road safety through communication technology in road infrastructure. For the drivers, they can receive, communicate and view various safety warning messages about accidents, weather, road works, traffic jams and so on simultaneously. However, the capacity of human brain is limited, which may hinder drivers from performing multiple tasks simultaneously with the same level of quality. Therefore, a rise in the amount of information resources in the vehicle may distract the driver from the main driving task, which significantly reduces driving performance. However, the human-computer interaction tends to be neglected by most researchers in this field as they still focus on technicality. Thus, it is essential to visualize the important and safety-critical information for the driver, which is a determinant in an effective driver awareness and warning system. However, when these two warnings are related to driving, it is highly important that the driver is allowed to distinguish the priority of the warning and make the right decision promptly.

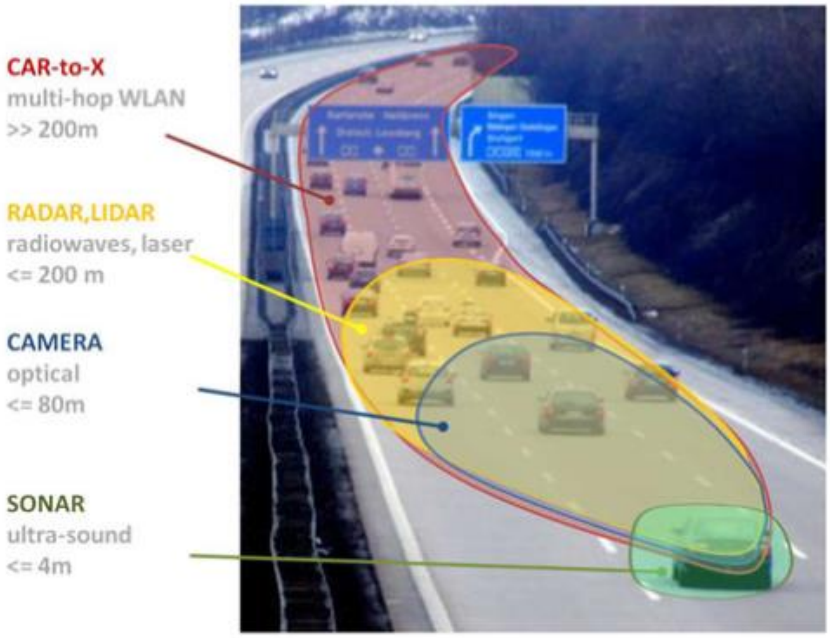


Figure 2-10 Vehicle sensor range (Stübing 2013)

Some researchers focused on drivers' performance under a multi-warning situation. For instance, drivers will perform avoidance manoeuvre accordingly if the individualizing alerts to notify the driver of each conflict with the correct position and the correct order (Shiki et al. 2004). Furthermore, drivers benefit from, and feel it is appropriate to generate multiple unique warnings for a multi-conflict situation (when the warning interval is more than 2 sec) (Fitch et al. 2014). As revealed by the findings, multi-warning may be beneficial to drivers by making them aware of a conflict. In the above two studies, the warning was audio.

The warnings issued by ADAS are visual, audible and tactile in some cases (Meng et al. 2015). In comparison with visual warnings, the driver makes response to audible and tactile warnings faster. Therefore, when the prompt response of drivers is required (rear-end collision), the modalities of this type are suitable (Pfannmüller et al. 2015). However, the effectiveness of auditory warning signals can be affected for some drivers in practice by hearing impairment (McKeown and Isherwood 2007). Furthermore, it is easy for some auditory warning signals to cause confusion with background noise in the context of everyday driving. Although tactile plays a role in the perception of vehicle acceleration and vibration, its modality is often far less important to driving than sight or hearing (Hogema et al. 2009). However, some practical issues has been noted by such modality, for example, some drivers may be insensitive to tactile stimuli (Thornbury and Mistretta 1981), or a masking effect is caused by the whole body vibration experienced by the driver on the road (Ryu et al. 2010) and any insensitivity that results from the driver wearing thick clothing/gloves as tactile cues cannot be perceived by them (Spence and Ho 2008). Also, for some of the frequent early warnings, the modality of audio and tactile may be unavailable. For example, drivers can be the distracted by the prolonged exposure to a continuous acoustic stimulus, which has a negative effect on driving (Adell et al. 2008; Biondi et al. 2014). As a result, the rating of annoyance increases, which causes the driver to stop using ADAS (Jamson et al. 2008). Also, a "cry wolf" type of false alarm rate can be caused by frequent tactile warning signals (Spence and Ho 2008). Complex information can be conveyed by visual warning in a concise and easily understandable manner (Stevens et al. 2002), with low annoyance perceived (Politis et al. 2013). However, there is still a lack of clarity on the design of visual warning in multi-warning situation. Furthermore, priority is the premise to decide whether the warnings should be presented in different ways from the single warning mode when there are multiple warnings issued simultaneously or almost simultaneously. Accordingly, it remains unclear whether the multi-warning mode is also beneficial to other multi-warning scenarios.

Meanwhile, driving performance still depends on other aspects (e.g., age, gender, and experience). For example, female drivers are now over-represented, compared with males, in crashes caused by errors in yielding, gap acceptance and speed regulations (Classen et al. 2013), and age-related deficits in attention and executive control may affect the consistency of driving performance in older drivers (Bunce et al. 2012). The effect of age and gender is not considered in this research. Although the above two factors may influence driving performance or driving style, driving experience determines the overall driving workload. In other word, the level of experience can modulate the influence of the driving tasks on the mode of information processing (Paxion et al. 2014b). For instance, older drivers may benefit from their experience and accurate self-estimation of driving to compensate for cognitive decline due to age influence (Anstey et al. 2005). SRK model (section 1.3.3) explains that performance is dependent on the degree of familiarity with the task and the environment. Accordingly, driving activity may induce a high level of mental workload for inexperienced drivers since they have a low level of task automation (e.g., when driving with an unfamiliar situation). Furthermore, driving experience is related to increased driver SA (Lee et al. 2006). The visual scanning strategy of inexperienced drivers is less efficient and flexible than experienced drivers (Falkmer and Gregersen 2001). Indeed, inexperienced drivers are inclined to focus more on the road directly ahead (Underwood 2007). As a result, spatial arrangement for designing multi-warning may not be suitable for the inexperienced drivers. In contrast, even experienced drivers will cause a great cognitive workload when encountering with a novel situation (Patten et al. 2006). Moreover, they are more sensitive to the situational cue (Xu et al. 2014). The above finding may suggest that although the experienced drivers may be familiar with the current driving situation, additional warning may increase the complexity of situation, thus affecting driving performance. Notably, a study found that experienced drivers adapt ADAS, i.e., not performing a brake operation until ADAS raise (or are close to raising) an alarm (Lyu et al. 2017). Thus, this may indirectly increase the criticality of the situation. As a result, the effects of multiple warning modes on drivers should be investigated based on different levels of driving experience.

3 Methodology

The previous chapter reviewed the research on existing ADAS and identified the limitations of current designs. The aim of this research is to identify possible future multi-warning scenarios. Another goal involves understanding the impact of driving experience on responding to multi-warning modes and proposing an ADAS design to overcome the practicality issues of ADAS in multi-warning modes and increase driving safety. This chapter outlines the scope of this study and describes an ontology-based approach to understanding the field of ADAS driving environments. The experimental environment used in this study, including the equipment and types of data collection, is also described. Ethical considerations related to the outbreak of COVID-19 in the United Kingdom at the beginning of Experiment 2 are described at the end of this chapter.

3.1 Research Methodology

The research methodology used in this study consisted of four main phases: In Phase 1, the existing ADAS-related literature was reviewed and an ADAS-based ontology was established (see Section 3.2.1 and Chapter 4 for details). Although this study focused on passive ADAS, an ontology was established to expand knowledge and clarify defined terms in the ADAS field. Therefore, the established ADAS-based ontology includes the entire ADAS domain, such as related ADAS functions. According to the collected literature, an ontology was initially established. The designed ontology included three levels: ADAS, driving tasks and driving distractions. A focus group was conducted to validate and refine the initial ontology. The final refined ontology helped to better understand the ADAS driving environment, especially future multi-warning scenarios. The established multi-warning scenario was used in this study's experiments. In Phase 2, experimental scenarios were constructed based on driving simulators, the established multi-warning scenario was encoded into a driving simulator and the pilot study was conducted. The data were collected using driving simulator software (see Section 3.2.2.1 for details). In Phase 3, participants were recruited for the study. The most important inclusion criterion was having a valid driving licence (see Section 3.2.2.2). After data collection was completed, participants were pre-processed, including data cleaning and data transformation (see Section 3.2.2.2 for details on the collected data). Finally, in Phase 4, the results were interpreted and recommendations were made for future ADAS designs.

It should be noted that this study was exploratory in nature. Exploratory research is a type of research conducted on a problem that has not been clearly defined (Goundar 2012). To generate suggestions for future ADAS designs, the influence of driving experience on the multi-warning mode (Experiment 1) and the design scheme of the multi-warning mode (Experiment 2) were investigated, as neither of these issues has been well studied. The design of Experiment 2 was based on the results of Experiment 1. Therefore, Phases 3 and 4 were carried out twice – once in Experiment 1 and once in Experiment 2 – to generate more comprehensive suggestions for future designs.

3.2 Application of Research Methods

The methods used in this research are elucidated in the following section.

3.2.1 Ontology-based Data Integration

In this research, an ontological method was adopted to contextualize potential distractions, driving tasks, and user interactions relating to the use of ADAS.

Ontology refers to the representation, naming, and definition of categories, attributes, and relationships between concepts, data, and entities constituting one, many, or all domains of discourse (Gruber 1993). Moreover, ontology is defined as a formal, explicit specification of a shared conceptualization (Studer et al. 1998). To be specific, it can be considered a formal description of concepts within a class/concept, descriptions of the features and attributes (slots) of the class/concept and restrictions on the slots (Noy and McGuinness 2001). Thus, ontology defines a common vocabulary for researchers who need to share information in a domain and includes machine-interpretable definitions of basic concepts in the domain and their relationships. The purpose of established ontology can be defined as (Noy and McGuinness 2001):

- To share common understanding of the structure of information among people or software agents
- To enable reuse of domain knowledge
- To make domain assumptions explicit
- To separate domain knowledge from the operational knowledge
- To analyse domain knowledge

Ontology is capable of defining the relationship between automation levels and algorithm requirements (e.g., ontology of intelligent transportation system (ITS) automation level and scenario assessment for co-driving) (Pollard et al. 2013). Zhao et al. (2015) presented an ontology-based knowledgebase containing maps and traffic rules. With access to a knowledgebase, smart vehicles can gain insights into speeding scenarios and make traffic-compliant decisions at intersections. Furthermore, ontological methods can be adopted to personalize human-machine interaction (HMI) elements in ADAS systems (Lilis et al. 2017).

3.2.2 Driver Behaviour Experiments

The experimental method is a systematic and scientific method of research, allowing the researcher to manipulate one or more variables and control and measure any change in other variables (Kothari 2004). Driving behaviour refers to the actions and decisions made by drivers while operating a vehicle (Fuller 2005).

Driver behaviour experiments can help research investigating how drivers respond to various factors and stimuli while driving. These experiments typically involve observing drivers in a controlled environment, such as a driving simulator, or on a closed course, and manipulating different variables to see how they affect driver behaviour (de Winter et al. 2009). The following section discussed the experimental environment and possible driving behavioural data.

3.2.2.1 Driving Simulator

Experiments have been extensively conducted to assess driving performance. The main experimental environments are presented as follows:

- Naturalistic driving.
- On-road experiment.
- In-depth accident investigation.
- Driving simulator (Papantoniou et al. 2017).

In this research, a driving simulator was adopted to collect data (Figure 3-1). The driving simulator usually consists of a PC or graphics workstation, a monitor, and a simple cab with controls (Kaptein et al. 1996). Based on the driver's actions, the simulator system continuously calculates the position of the simulated vehicle (virtual vehicle). The experiment took place in a dedicated room, where the participants sat on a padded chair in front of a desk with 49-inch monitor (Samsung C49HG90DMC, 144hz, 3840X1080). Logitech G29 was used for the driving steering wheel and pedal. MSI GP65 (i7 2.59Ghz, 16G memory, GeForce RTX 2060) was used to run the driving simulator software. OpenDS is the driving simulator software that used in this research for collecting data. The development of the software has been driven by the EU project GetHomeSafe (Math et al. 2013). The simulator has been previously used in many driving-warning studies, for example Walch et al. (2015), Meschtscherjakov et al. (2015).

Figure 3-1 shows the setup of driving simulator. The participants were required to sit in front of the middle screen, thus eliminating the distance effect of location arrangement. For example, the left mirror is far from the drivers' line of sight, as a result of which the participants can miss a warning easily.

Figure 3-1. Driving simulator

The main benefit of driving simulators is that all the environmental conditions are controllable, and researchers are able to completely restore the pre-defined scenario with all relevant elements in a virtual environment. Critical scenarios have been rare in real driving environments, and the reproduction on the road may be impossible or illegal, such that using a simulator allows researchers to investigate the above scenarios in depth. However, there are some limitations of a driving simulator (De Winter and Happee 2012). The first is that participants may get uncomfortable with the simulator. A 10-to-15-minute training session was conducted to prevent simulator sickness. If participants feel uncomfortable with the simulator, they can leave at any time. Second, there may be limited perceptual and behavioural fidelity. However, this can be overcome by improving the software or hardware of the simulator. For instance, the control of the car's speed and direction through control input can be in accordance with real driving scenarios. The main problem facing a driving simulator is that its positive effect may not be transferred to a real driving environment.

However driving simulators can offer a safe and relatively low cost solution as long as the policy makers and road safety administrators are aware of the limitations of simulator research, especially the accurate prediction of the actual number of collisions (Rudin-Brown et al. 2009).

3.2.2.2 Participants

The recruitment of participants for this research involved two distinct phases: the refinement and validation phase of the ontology, and the experimental phase. Each phase had specific requirements tailored to its objectives.

During the ontology refinement and validation phase, participants with prior experience using ADAS were encouraged to participate. Their familiarity with ADAS systems facilitated more effective refinement of the ontology. Furthermore, participants did not need to be qualified drivers during this phase, as even learner drivers were welcome to contribute their insights and potentially offer novel ideas. However, for the experimental phase, participants were required to be qualified drivers. This was necessary because the experimental stage involved collecting driving data, and learner drivers may not possess the necessary skills and experience to adequately fulfil the data collection requirements.

By implementing these distinct requirements for each phase, the research aimed to optimize the quality of data collected during the experimental phase while benefiting from the diverse perspectives and ideas contributed by participants in the ontology refinement and validation phase. It is important to ensure that qualified drivers were involved in the experimental phase to ensure reliable and accurate driving data, while still allowing learner drivers to contribute during the ontology refinement phase where their insights could be valuable.

3.2.2.3 Driver Behaviours and Attitude Measures

In the context of evaluating driving performance and driver distraction that there are many different methods and measures available. Driving performance data can be divided into two broad categories: objective data and subjective data (Lee et al. 2008). Objective measurement data, such as physiological measures or vehicle control measures, can provide an objective assessment of driver performance and workload. subjective measurement data, such as self-reported ratings of workload or distraction, can provide valuable information about the driver's perception of their own performance and the driving environment. By combining both types of data, researchers and practitioners can gain a more complete picture of the driver's situation, including both their objective performance and their subjective experience.

The selection of specific measures for evaluating driving performance and driver distraction should be guided by a consideration of the nature of the driving task being examined as well as the specific research questions being addressed (Papantoniou et al. 2017). The aim of this thesis is to investigate whether the driver can accurately and quickly respond to the multi-warning mode. Therefore, reaction type, reaction time, as well as eye movement data were chose as objective data. In addition, driver workloads were measured through NASA Task Load Index.

- Reaction type (RT): “Performance may be roughly defined as the effectiveness in accomplishing a particular task” (Paas and Van Merriënboer 1993). In this study, reaction type was selected as a measure of performance. Reaction type refers to the initial action of participants when responding to a warning or event, and it can reflect the correct behaviour of drivers in different scenarios. By measuring reaction type, the number and rate of incorrect responses can be calculated, allowing for the determination of the correct rate of driver responses to warning modes and proving the efficiency of the warning mode.
- Reaction time: Measuring reaction time has become increasingly popular as it is closely related to the risk of accidents (Papantoniou et al. 2017). This measure

evaluates how quickly participants respond to a warning or an event. In the experiments of this research, it was the time passed from the onset of a warning or an event to the first response of the participant. The time required for response time is an absolute value measured in units of time (usually seconds). Moreover, various studies have investigated the impact of driver demographics, such as age and gender, on reaction times under distracted conditions. For instance, Nilsson and Alm (1991) observed that elderly drivers' reaction times were approximately 0.40 seconds slower than those of younger drivers when distracted by a cell phone conversation in response to an unexpected event. Caird et al. (2008) found that distracted older and younger drivers exhibited reaction times that were 0.46 seconds and 0.19 seconds slower, respectively.

- Eye movement measure: fixation and saccade are two types of eye movements that can be adopted to identify driving performance (Papantoniou et al. 2017). Fixations refer to the moments when an observer's eyes remain almost motionless, indicating a focus of attention. The duration and position of fixations can provide insights into the observer's attention orientation and the amount of information being extracted from the fixated location, respectively (Hayhoe 2004). Saccades are very rapid movements that occur when the eye moves from one fixation point to another. More saccades may reveal that the warning is unclear, thus causing the driver to confirm the warning multiple times.

Subjective measures are based on the use of rankings or scales to measure how a participant feels (i.e., acceptance measures). The Technology Acceptance Model (TAM) was used to construct the questionnaire. TAM (Davis 1989) is a widely used theoretical framework for understanding how people adopt and use new technologies. This framework posits that perceived usefulness and perceived ease of use are the primary determinants of an individual's intention to use a technology.

This type of measure is summarized as follows:

- Perceived usefulness, for instance, using the warning system while I am driving will be useless – useful
- Perceived ease of use, for instance, I find the warning system difficult to use totally disagree – totally agree
- Attitude toward behaviour for example, using the system in driving increases my safety totally disagree – totally agree
- Behavioural intention, for example, I would like to purchase the warning system if the system is available in the market.

In this section, the measurement data involved in this research are summarized. Not every measurement data will be collected in the respective experiment. The relevant measurement data should be collected in accordance with the purpose of the experiment. For details, please refer to Chapters 5 and 6.

3.3 Research Framework

The following process shows the framework of this research related to the question and objectives of this research:

Figure 3-2 Research framework

The study plan aimed to narrow the research focus and identify the study question through a literature review. The second chapter presents a literature review of related work and domains, and research gaps were identified. Google Scholar, Springer, IEEEXplore, among others, were utilized as tools and databases in the literature review. Keywords such as ADAS, driving performance, user interface, and driving distraction were used in this research.

The initial establishment of an ADAS-based ontology was based on the literature review, and subsequently improved and validated through focus group research. The ontology provided insight into possible ADAS warnings that may arise in the future.

Multi-warning scenarios were established based on the ontology and applied in subsequent experiments.

The main goal of Experiment 1 was to investigate the impact of driving experience on the response to multiple warning modes. The warning display design used in the experiment was the current warning design available in the market. The aim was to explore whether the current warning design is suitable for multiple warning scenarios. The findings from Experiment 1 guided the approach for Experiment 2, particularly with respect to the requirements for recruiting participants. The main purpose of Experiment 2 is to investigate different designs for the warning display under the multi-warning scenarios established in the ontology, in order to enable drivers to respond more accurately and quickly to multiple warning modes. Lastly, based on the results of the two experiments, recommendations were made for the future design of ADAS.

3.4 Ethical Approval of the Covid-19 Pandemic

All experiments were ethically approved (ethical approval number: 12331). However, the Covid-19 pandemic broke out in the UK just as the second experiment was about to collect data. The second experiment was suspended due to involving face-to-face contact with participants are unlikely to be permitted during this lockdown period. Therefore, the second experiment used a remote study, and the data collection site for the second experiment was located in China. An external funding agency (Huaying company) assisted in the collection of data for Experiment 2, such that further clarification of ethical approval was required.

The data of Experiment 2 all need to be collected remotely. Participants should be informed how data will be collected (with a participant information form) and give consent to the collection of their data (via a consent form). It is always important to be fully transparent with participants, such that they know when, how and with whom data are collected. Collecting research data remotely raises some additional ethical considerations.

The first ethical consideration is Covid-19 concerns. China has developed a mobile phone app (called the health code) that serves as an electronic passport, reporting health status in real time and clearly confirming a person's trajectory within 14 days. The app generates a QR code that identifies the individual's risk level as red, yellow or green. Only green QR codes will be allowed to participate in the experiment. Additionally, any participating personnel (participant and external experimenters) must wear a mask throughout the experimental phase. Finally, after each participant completed the experimental data collection, all experimental instruments (e.g., steering wheel and eye tracker) they touched were sterilized.

A second ethical consideration is privacy concerns and how researchers can ensure that privacy is maintained during data collection. First, the data collection type of Experiment 2 was based on the method in Experiment 1. Only basic information (e.g., driving experience, age, ADAS-related experience and driving data) in the experiment was collected, whereas personal privacy (e.g., personal names) was not involved. Regardless of the data collection method used, it is important that the information was securely transmitted from the participant to the researcher. The collaborators uploaded the data through a secure platform (e.g., dropbox), and the permissions of the network disk were only authorized by the researchers.

A third ethical consideration is that Experiment 2 was based on a driving simulator, such that participants may experience simulator sickness in the experimental phase. In Experiment 1, participants can withdraw from the experiment at any point in time if they felt unwell. Experiment 2 was a remote study, where researchers monitored the entire experiment using cameras, and in some cases, it might be difficult to identify signs of discomfort. Accordingly, participants were reminded before the start of the experiment that they felt uncomfortable, and they can withdraw from the experiment at any point. Furthermore, their status was repeatedly confirmed after each experimental scenario to ensure that possible distress was kept to a minimum.

Fourth, it is imperative for sometimes externally assisted researchers to complete data collection alone due to the time difference between China and the UK. Experimental protocol documentation was established to avoid ethical issues that may arise in the experimental data collection. A remote experimenter moderated the experimental process in the first 10 experiments. The following five experiments were performed by external experimenters who were responsible for monitoring and guiding the process. On that basis, the security and privacy of participants can be ensured when there are no remote researchers.

3.5 Summary

In this chapter, the research methods described in Section 3.1 are adopted to achieve the research objectives, and the research questions mentioned in Section 1.3 are respectively validated. One is to achieve a deeper understanding of the field of ADAS. Secondly, the results of Experiment 1 can illustrate the influence of the multi-warning mode on the driver and the driving experience on the multi-warning. The results of Experiment 2 can guide the design of future ADAS information provision to ensure that ADAS can affect driving behaviour in the least negative way.

4 Ontology for ADAS Driving Environment

To better understand the ADAS driving environment and clarify the defined terms in ADAS filed, this research established an ADAS-based ontology approach.

Fensel and Brodie (2003) established a classification in an ontology:

- Generic or common-sense ontologies: these capture all of the general knowledge. They offer fundamental concepts and concepts of time, space, states, events, and other things, and they can be used in many other domains.
- Representational ontologies: They are not a part of any certain field. Without establishing what they might stand for, they offer entities. As a result, they give a definition of the idea of object- or framework-oriented knowledge expression.
- Domain ontologies: they capture knowledge that is valid for a specific type of domain (e.g., electronics, medicine, etc.).
- Method and task ontologies: While the latter offers terminology for specific activities, the former offers terminology specific to problem solving techniques. Both offer a reasonable perspective on domain knowledge.

In this study, a domain ontology was created specifically for the ADAS domain. As increasingly sophisticated sensor technology is integrated into cars, more warning systems will be created. The established ontologies can provide reasonable and useful definitions of terms used in the domain. In addition, the instances of the ontology were conducive to the analysis of ADAS-based driving scenarios and the establishment of related reasoning systems. A further classification system of ADAS detectable objects was established based on the ontology, in which three typical multi-warning scenarios were designed. These three scenarios depicted the relationship between warnings and presented insights into the design of future multi-warning scenarios.

4.1 Ontology-Based Approach

In the realm of artificial intelligence (AI), ontologies are frequently used to create targeted knowledge structures. A formal, clear specification of a common conceptualization is called an ontology (Studer et al. 1998). It can be thought of as a formal definition of the concepts included within a class or concept, a description of the characteristics and attributes (slots) of the class or concept, and restrictions on the values that can be assigned to the slots (Noy and McGuinness 2001). Identifying the purpose, acquiring and formalizing knowledge, conceptualizing, modelling, and assessing are typically the steps involved in ontology development.

According to Jones et al. (1998), there are four basic approaches to ontology development: TOVE, ENTERPRISE, METHONTOLOGY, and IDEF5. In conducting this research, this research used the IDEF5 approach. The principal defence is that the lack of benchmarks and uniqueness of the proposal made the purpose and requirements of the project unclear from the start. Because of this, a stage-based strategy like TOVE or ENTERPRISE would not be appropriate (Jones et al., 1998). Additionally, ADAS development is constantly evolving due to the rapid adoption of new sensor and communication technologies, resulting in an evolving domain of interest. Because IDEF5 emphasizes iterative ontology refinement and validation when new knowledge is discovered, it is more applicable than METHONTOLOGY.

The general procedure of IDEF5 includes:

1. Organising and scoping: define the purpose and context of the ontology
2. Data collection: extract the raw data for developing the ontology
3. Data analysis: analyse the extracted data for establishing the ontology
4. Initial ontology development: establish a preliminary ontology
5. Ontology refinement and validation: the preliminary ontology will be iteratively refined and tested.

4.1.1 Organising and Scoping

This phase's primary purpose was to establish the ontology's domain and range of application based on an understanding of the research's objectives. The purpose of the research was to provide a comprehensive conceptualization of how drivers interact with and perceive ADAS warnings, as well as how these perceptions and interactions may cause distraction while driving. In more detail, an ADAS with a passive safety focus can detect the driving environment, produce data fusion as an input, and require the driver to take appropriate action (Troppmann 2006a). Considering that responding to ADAS to take the necessary actions is referred to as a secondary activity (Häuslschmid et al. 2017), distraction may develop and impair the driver's ability to focus on the main task of driving (Klauer et al. 2006; Lee et al. 2008). Consequently, the following goals were established as "complete criteria":

- **OBJ1.** Identify the objects that can be detected by ADAS
- **OBJ2.** Identify the possible interaction between a driver and ADAS
- **OBJ3.** Identify the functions that can be provided by ADAS
- **OBJ4.** Define the primary driving tasks
- **OBJ5.** Define the types of distraction
- **OBJ6.** Identify the impact of different distraction on driving performance

4.1.2 Data Collection

A literature review was conducted to gather raw data using 16 sources, including 6 conference papers, 8 journal papers, and 2 websites. The selection of the source materials was based on both their quality and relevance to the goals (e.g., rigor and transparency in the method followed, expertise of the research team, impact factor and reputation of the publisher). As a consequence, a total of 134 different instances were recovered, of which 74 instances were collected for ADAS (Obj. 1 - 3), 43 instances for driving tasks (Obj. 4), and 17 instances for distraction (Obj. 5 - 6). Check table 4-1.

4.1.3 Data Analysis

An initial set of classes was created for each notion after the instances collected were analysed. Note that several classes and initial linkages for ADAS and driving jobs were also chosen by looking at the existing classifications/ontologies found through the literature review. An ADAS classification based on data fusion is described in detail. The core model to derive classes was chosen as Pollard et al. (2013) because it gave a considerably higher level of technical granularity (i.e., the capabilities of sensors used by ADAS instead of the safety features offered by ADAS). Two additional classes, namely user interface and vehicle control, were added to the classification because this classification does not take into account the full provision of ADAS warnings. Additionally, the initial classification utilized to determine classes was a driving task classification that was generated from both the conditions of road traffic and the information processing of drivers (Fastenmeier and Gstalter 2007; Pollard et al. 2013). By taking into account the driving task criticality as indicated by McKnight and Adams (1970), this classification was further improved.

Three classes were created based on the distraction instances: duration, impact, and type. This is because the impact of driving distraction is defined by its duration (Baker and Spina 2007) and type (Ranney et al. 2000; Young et al. 2007). Table 4-1 details every class ever created along with any references to instances that have been gathered.

Table 4-1 Classes and definitions with references

Group	Class	Definition	Reference
ADAS	Environment detection	Driving context or condition (e.g. speed limit) as well as weather condition	(Fu and Huang 2010) (Pollard et al. 2013)
	Driver state detection	Defined as the drivers' ability to drive	(Daza et al. 2014) (Koesdwiady et al. 2016)
	Ego-vehicle detection	Estimated the vehicles' current state	(Pollard et al. 2013)
	Free zone	Combined the state estimation of both unmoving obstacles and navigable space	(Pollard et al. 2013)
	Moving obstacles	Estimated the moving	(Pollard et al. 2013)

		objects on road.	
	Communication	Vehicular communication (e.g. vehicle to vehicle)	(Pollard et al. 2013; Chen et al. 2017)
	User interface	The interface required for ADAS-driver interaction and information delivery	(Adell et al. 2008) (Lu et al. 2005) (Damiani et al. 2009) (May et al. 2014) (Jefferson 2015; Kim et al. 2016)
	Vehicle control	How ADAS take over driving task to prevent collision	(Paul et al. 2016)
Driving Task	Longitudinal driving	Intersection-free driving following the traffic flow	(Fastenmeier and Gstalter 2007)
	Intersection driving	Intersection driving (e.g., turn right)	(Fastenmeier and Gstalter 2007)
	Manoeuvre	Reversing and repositioning a vehicle	(Mylicense.sa.go.au 2018)
	Road character	Type of the road	(Fastenmeier and Gstalter 2007)
Distraction	Type	the Type of distraction that a driver may experience while driving	(Young et al. 2007)
	Duration	The length of time that a distraction lasts	(Papantoniou et al. 2017)
	Impact	The effect that a distraction has on driving performance	(Papantoniou et al. 2017)

4.1.4 Initial Ontology Development

A tentative ontology was created using the data from the literature that was gathered and based. The classes and references taken from various works of literature are displayed in Table 4-1. Three groups are identified based on the extracted classes' domains: ADAS, Driving Task, and Driving Distraction. The preliminary ontology's dimensions are similarly divided into these three groups.

User engagement, sensor data fusion, and vehicle control are the three basic divisions of ADAS. "Environment Detection," "Moving Obstacles," "Free Zone," "Driver State Detection," and "Ego Vehicle Detection" are among the sensor data fusion features. The transmission of information between vehicles or with traffic infrastructure (such as traffic signals) for the purpose of early warning is known as "vehicle communication," and it can be viewed as a development of sensor detection, such as in the "Internet of Vehicles." Using this method, ADAS can identify potential threats early. Therefore, "vehicle communication" will not be taken into account in this research. This research generates two new subclasses for the "User Interaction" class: "User Input" and "ADAS Output". "User Input" refers to how the driver interacts with the ADAS, such as pressing a button to activate or deactivate it or adjusting its settings. The subset "ADAS output" refers to the output of two different ADAS, specifically "vehicle control" (also known as active ADAS) and "warning" (also known as passive ADAS). Active ADAS immediately avoids potential vehicle hazards by regulating steering, braking, or acceleration. However, the ultimate manipulation is still carried out by the driver. Passive ADAS improves the driver's awareness of the immediate environment through alerts. Content, Modality, and Position are all part of the warning subset. The way the warning is presented is its "content." The warning could be beeping, abstract, or informative, such as "action cue," "direction cue," and "object cue." The most popular system of informational warning is the navigation system, which includes a sentence to direct the driver's subsequent actions. The warning is represented by "Modality," which includes "Visual," "Voice," and "Haptic." "Position" refers to the location where the warning is displayed.

Driving tasks were divided into four classes: "driving straight," "turning," "slow manoeuvre," and "road character." Based on earlier research, the first two were condensed from "tasks in longitudinal driving" and "tasks in junctions" (Fastenmeier and Gstalter 2007).

Driver distraction was divided into three classes: "kind of distraction" (such as visual distraction, physical distraction, auditory distraction, and cognitive distraction), "duration" (such as momentary distraction, short-duration distraction and long-duration distraction), and "impact" (such as eye-off road, slower reaction times, lane deviations and collisions) on driving behaviour. The "distraction kind," "duration," and "effect" on the behaviour of the driver are the classes of the driving distraction ontology. "Distraction kinds" refer to the different sorts of driving distractions, including cognitive, physical, auditory, and visual ones. The term "Duration" refers to the period of distraction. Because distraction when driving is unavoidable, the class of duration might reveal the level of distraction. The last "impact" refers to an outcome brought about by distracted driving (e.g., eye off road or cognitive overload).

4.1.5 Ontology Refinement and Validation

The suggested ontology was improved and validated using focus group research (Kitzinger 1995). In a classroom setting, 11 participants were selected (age M = 37.6, SD = 8.37; 2 females and 8 males), all of whom had driving experience and were PhD candidates. Six participants had been driving for more than 10 years, three had been driving for 5 to 10 years, and two were receiving driving lessons and did not have a full driving license at the time of the study. The participants were presented with the initial ontology, which included a complete list of classes, subclasses, and instances, and were asked to thoroughly examine the ontology and discuss the names, meanings, and connections between the classes. They were encouraged to make changes to the ontology based on their own driving experiences by adding or removing specific cases and suggesting class modifications. Notes were taken during the session, and a facilitator was present to guide the discussion. Audio recordings of the group discussions were also made to aid in the understanding of the revisions. The session was followed by the collection of final results, and the main changes are discussed below.

The ADAS ontology, Driving Task ontology, and Driving Distraction ontology are still part of the broader ontology. In contrast, the focus group has refined the class.

Data fusion, user interface, and vehicle control were the three key classes in the initial ADAS ontology, representing "what ADAS can detect" and "how ADAS interacts with the driver." 8 participants suggested that "data fusion" might overlap with "user input" if treated as an ADAS input source. As a result, "Sensor Data Fusion," "Interaction," and "Effects" were added as new ADAS classes. "Sensor Data Fusion" refers to the data that ADAS can detect, including the capabilities of existing sensors and those that may be utilized in ADAS in the future (such as the Internet of Vehicles).

"Interaction" refers to how the driver engages with the ADAS, including standard means of interaction, such as voice input and hand input (such as buttons, knobs, etc.). "Effect" refers to the outcomes that ADAS offers to the driver, such as "warning" and "vehicle control." "Vehicle control" refers to how active ADAS functions for driving safety, such as braking, steering, and acceleration. "Warning" refers to passive ADAS, or warnings that raise the driver's awareness of their immediate driving environment. The initial warning class included content, modality, and position, but participants found the term "position" too vague and believed that there was no appropriate position for the sound of the warning. Therefore, "position" was changed to "urgent level" in the refined ontology, as the design of warnings is constrained for different levels of urgency. The driver should experience the urgency of the design and display in a more prominent position, for example, by receiving more urgent warnings.

The initial driving task ontology consists of three driving tasks plus a class of "road characteristics." However, some participants did not consider the "road feature" being monitored by the ADAS sensor as a driving task. As a result, the driving task ontology was refined to only include "driving straight," "turning," and "slow manoeuvring."

Participants reported satisfaction with the organizational structure of the subclasses, and the original distraction ontology remained unchanged.

The finalized ontologies were established and visualized in Protégé. Figure 4-1, 4-2 and 4-3 shows the finalized ontology of ADAS, Driving Task and Driving Distraction.

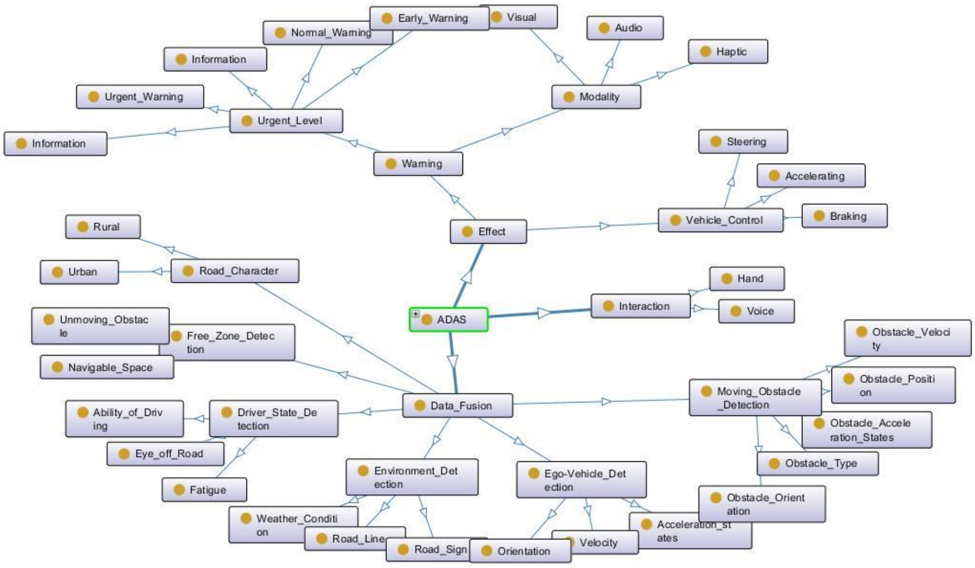


Figure 4-1 Finalized ontology of ADAS

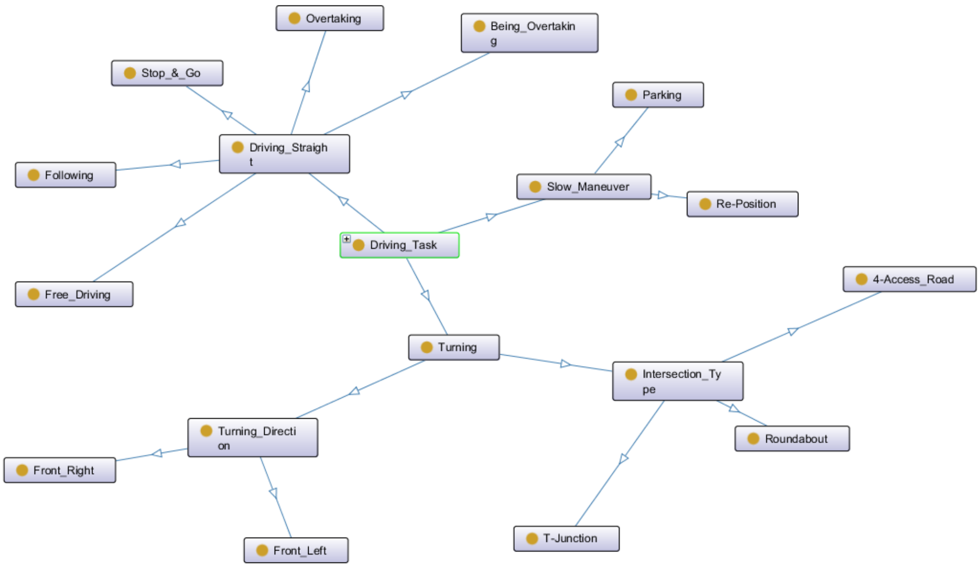


Figure 4-2 Finalized ontology of driving task

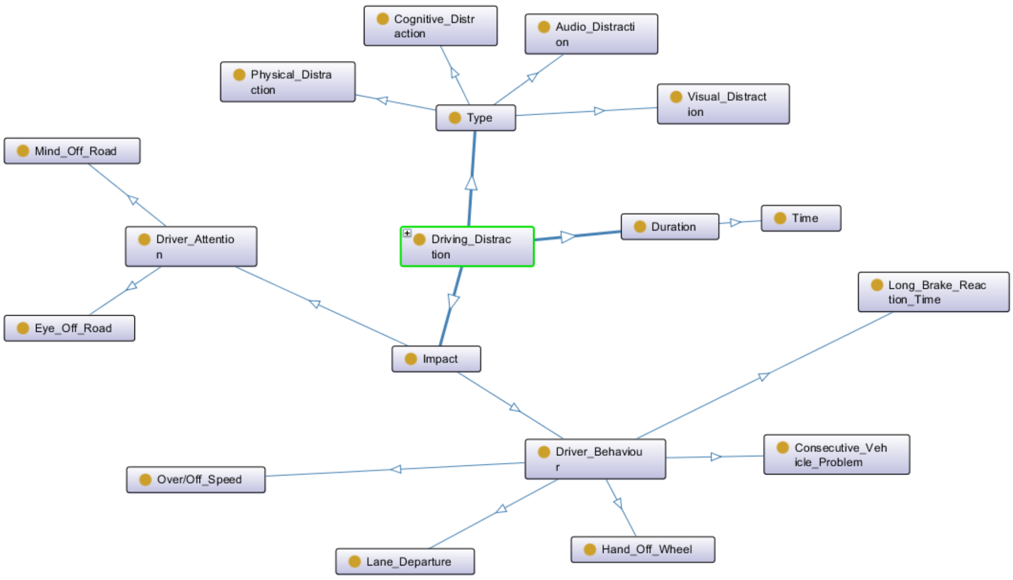


Figure 4-3 Finalized ontology of driving distraction

4.2 Application

This ontology is intended to assist in identifying probable ADAS and potential driver distractions brought on by ADAS while driving. Two hypothetical situations are provided to illustrate how this ontology might be utilized to spot potential disturbances. Both scenarios are based on rules and regulations for UK traffic. A state transition diagram was also created to help people understand the distraction process. Additionally, three multi-warning scenarios were developed for use in later experimental scenarios based on the ontology.

4.2.1 Single-warning Scenario

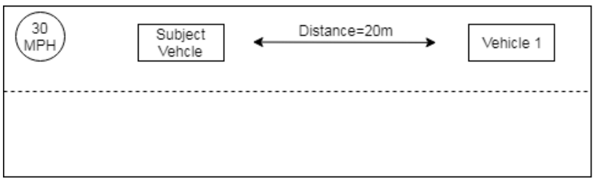


Figure 4-4 Single warning scenario

In a hypothetical driving situation depicted in Figure 4-2, a single ADAS alert can be activated when a particular object is spotted. Here, the subject vehicle (Vehicle 2) is following a fast-moving vehicle (Vehicle 1) in the same lane in a congested region. Vehicle 1 slows down without using its brake indicator, indicating that the driver has stopped pressing the gas pedal to maintain speed and hasn't applied the brake to reduce speed. When the space between the two vehicles decreases below a set threshold, a forward collision warning is activated, and the appropriate indicator appears on the dashboard to alert the driver.

The created ontology can extract the following driving-relevant parameters, with initial values set by the scenarios as shown in Table 4-2. These parameters and values can be supplied to a reasoning system to determine when an ADAS should be activated and what contextual information is relevant.

Table 4-2 Parameters with assumed values under single-warning scenario (created by the author)

Parameter	Value	Type (from created ontology)
Road line	2	Environment detection
Road type	urban	Environment detection
Road sign	Speed limit sign (30mph)	Environment detection
Vehicle 1 position	front at same lane	Moving obstacle
Vehicle 1 velocity	25 mph	Moving obstacle
Vehicle 1 orientation	East	Moving obstacle
Vehicle 1 acceleration	Decelerating	Moving obstacle
Subject vehicle velocity	30 mph	Ego-vehicle detection
Subject vehicle orientation	East	Ego-vehicle detection
Subject vehicle acceleration	0	Ego-vehicle detection
Subject vehicle steering angle	0	Ego-vehicle detection
Driving task	Following	Driving Straight
Content	Flashlight	Warning
Modality	Visual	Warning
Position	Dashboard	Warning

The parameters taken from the distraction ontology and their actual values recorded in the scenario are shown in Table 4-3. If a driver looks at the dashboard for an extended period of time, it may be assumed that the driver is now distracted by the visual alert because the visual warning will divert the driver's focus from the road to the dashboard. This information can be used in conjunction with the contextual data from Table 4-3 to determine when a potential distraction might occur.

Table 4-3 Distraction parameters with assumed value under single-warning scenario (created by the author)

Parameter	Value	Type (from created ontology)
Eye off road	> 3s	Duration
Decrease acceptable gap	Gap less than 3 meters	Impact
Distraction Type	Visual distraction	Type

Figure 4-3 shows the state transition schematic diagram of the single warning process.

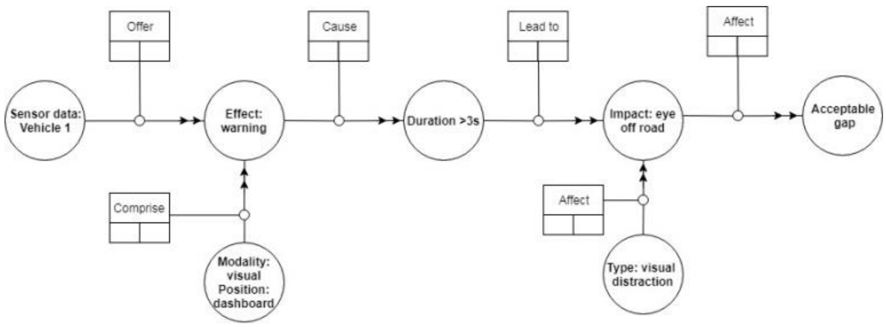


Figure 4-5 Example of driving distraction transition of single warning schematic diagram

4.2.2 Multi-warning Scenario

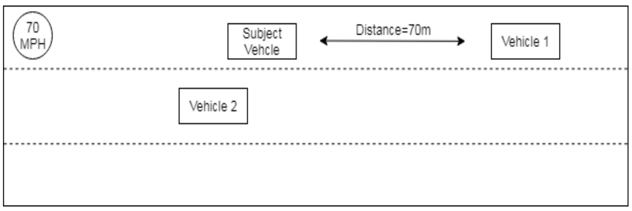


Figure 4-6 Example of multi-warning scenario

In some driving situations, multiple ADAS warnings may be triggered if all relevant ADAS are installed and activated. Figure 4-6 depicts a driving scenario where the subject vehicle is attempting to overtake a slow-moving vehicle in the same lane on a motorway (i.e., Vehicle 1), and there is another vehicle in the overtaking lane (i.e., Vehicle 2) that is running close to the subject vehicle. In this case, a blind spot alert will be triggered to warn the driver that Vehicle 2 is obstructing the overtaking manoeuvre. Simultaneously, with Vehicle 1's deceleration, a forward collision warning may also be activated to alert the driver of a potential rear-end collision if the subject vehicle is too close to Vehicle 1.

When using the values from the scenario, the following parameters can be directly extracted from the ontology. The warning parameters were adapted from the previous multi-conflict study conducted by Fitch et al. (2014).

Table 4-4 Parameters with assumed value under multi-warning scenario (created by the author)

Parameter	Value	Type (from created ontology)
Road line	3	Environment detection
Road type	Highway	Environment detection
Road sign	Speed limit sign (70mph)	Environment detection
Vehicle 1 position	front at same lane	Moving obstacle
Vehicle 1 velocity	60 mph	Moving obstacle
Vehicle 1 orientation	East	Moving obstacle
Vehicle 1 acceleration	Decelerating	Moving obstacle
Vehicle 2 position	Right front not on same lane	Moving obstacle
Vehicle 2 velocity	72 mph	Moving obstacle
Vehicle 2 orientation	East	Moving obstacle
Vehicle 2 acceleration	0	Moving obstacle
Subject vehicle velocity	70 mph	Ego-vehicle detection
Subject vehicle orientation	East	Ego-vehicle detection
Subject vehicle acceleration	0	Ego-vehicle detection
Subject vehicle steering angle	Right	Ego-vehicle detection
Driving task	Overtaking	Driving Straight
Forward collision warning content	Beep 1	Warning
Forward collision warning modality	Audio	Warning
Forward collision warning position	Headset	Warning
Blind spot warning content	Beep 2	Warning
Blind spot warning modality	Audio	Warning
Blind spot warning position	Headset	Warning

The parameters extracted from the distraction ontology and the recorded values in the scenario are displayed in Table 4-4. If a driver spends an extended amount of time looking in the side mirror, the auditory warning of the blind spot alert may be considered a distraction since it will divert their attention from the road to the side mirror. The driver is then alerted to slow down with another audible warning. However, a sudden warning may startle the driver and affect their ability to control the vehicle's speed. The state transition diagram for the multi-warning process was shown in

Figure 4-7.

Table 4-5 Distraction parameters with assumed value under multi-warning scenario (created by the author)

Parameter	Value	Type (from created ontology)
Eye off road	> 3s	Duration
Overlook	Vehicle 1	Impact
Type	Visual distraction	Type
Startle effect	> 2s	Duration
Unnecessary brake	Harsh brake	Impact
Distraction Type	Cognitive distraction	Type

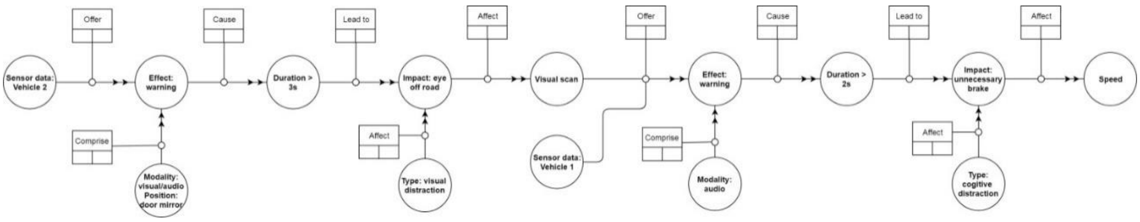


Figure 4-7 Example of driving distraction transition of multi-warning schematic diagram

4.2.3 Creating Multi-Warning Scenario for Experiment

Although a multi-warning scenario is established in 4.2.2, it may be determined that there may be further multi-warning scenarios in the future by looking at data fusion, a subset of the ADAS ontology. The study reclassified ADAS detected objects in order to more thoroughly investigate this scenario. Based on the Driving Task ontology and the ADAS ontology, this classification. Two categories were identified:

- **Dynamic traffic flow detection** Ensure the driving safety in accordance with the surrounding changing traffic situation (mainly based on driving task).
- **Status detection**: This type of detected object conveys information relating to the non-driving task monitoring.

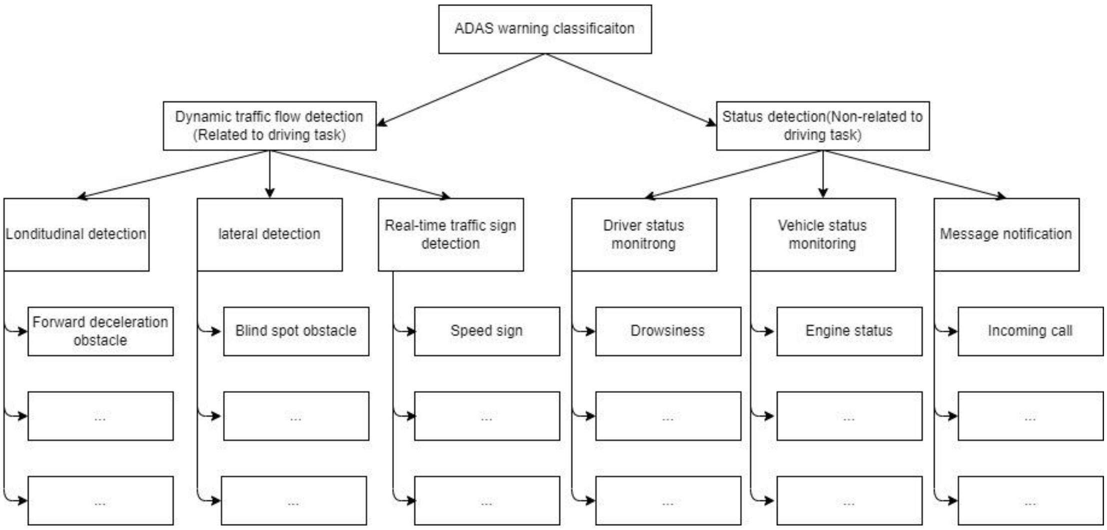


Figure. 4-8 A classification of ADAS-detectable objects based on driving task (created by the author)

The purpose of warnings is to increase the driver's awareness of their surroundings, and it is crucial to prioritize warnings properly. In the case of multiple warnings, there will always be one with the highest priority, depending on the driver's current driving task. For example, in the multiple warning scenario described in section 4.2.2, if the driver intends to overtake, the priority of BSM is higher than that of the FCW, while if the driver is simply following the car, the priority of the FCW is higher than that of the BSM. Therefore, when designing multi-warning scenarios, it is important to consider the driver's current or expected driving tasks in order to effectively prioritize warnings.

This research also takes into account the relationship between warnings and constructs three typical multi-warning situations in order to investigate the influence and design of warnings in multi-warning scenarios. The following shows the three determined multi-warning scenarios:

- Non-conflict and non-cooperation scenario
- Conflict scenario
- Cooperation scenario

The first multi-warning scenario is called the non-conflict and non-cooperation scenario. When two warnings are unrelated to each other and one warning has no bearing on the driver's current task, such as with speeding warnings and message reminders when the driver is speeding, the situation is said to be conflict-free. This scenario requires minimal driving workload as drivers only need to consider one warning, and they have enough time to react.

The second situation is called a conflicting situation, where two warnings actually conflict with each other. For example, a navigation system can notify drivers to change lanes, while blind spot warning alerts drivers to vehicles in the blind spots of the lane they are turning into. Both warnings guide the driver to the next driving task, but the two results of the warnings are contradictory (turn and no turn). It is recommended to avoid situations where warnings conflict, as they increase the driver's cognitive load. However, there is a need to investigate this situation because if future ADAS does not have a prioritization system, figuring out how this system is presented so that drivers can effectively use its warnings to ensure driving safety will be critical.

The final scenario is called cooperation scenario involves two warnings that work together to provide drivers with a better understanding of their driving situation. This type of scenario is particularly helpful in multi-conflict events, where the driver needs to process multiple warnings simultaneously. The FCW and BSM are an excellent example of two warnings that complement each other. The FCW warns the driver of an impending collision with a vehicle ahead, while the BSM warns the driver to be aware of any vehicles in their blind spot when changing lanes. These two warnings work together to provide the driver with a complete picture of their surroundings, allowing them to make informed decisions based on the information provided. The combination of these warnings has the potential to significantly reduce the driver's cognitive load, making driving a less stressful experience.

4.3 Summary

In this section, Ontology-based approach was used in research to create an ADAS-based driving environment that includes ADAS, driving tasks, and driving distractions. An ontology can be created to define the concepts and relationships within each of these areas, such as the different types of ADAS systems, the effects and interactions between them, the types of driving tasks, and the impact and duration of different driving distractions. The benefits of using an ontology-based approach in this research include the ability to create a standardized and consistent understanding of the complex driving environment, which can improve the accuracy and reliability of data analysis and decision-making. It can also enable interoperability between different systems and data sources, allowing for easier sharing and integration of information. However, there are also some disadvantages to this approach. Creating a comprehensive ontology can be a time-consuming and complex process, and it requires a high level of expertise in the domain being studied. Additionally, maintaining and updating the ontology as new information/technology becomes available can be challenging. Overall, an ontology-based approach can be a useful tool for creating a structured and consistent understanding of a complex system such as an ADAS-based driving environment. Additionally, as more warnings are introduced, drivers may become overwhelmed and distracted by concurrent warnings, leading to potentially dangerous situations. The 3 types of multi-warning scenarios established by the ontology are critical to understanding the different scenarios that can occur to improve driver safety and ensure that drivers can use these systems effectively to make informed decisions. By taking these factors into account, ADAS can provide drivers with valuable information while reducing the risk of cognitive overload and distraction, ultimately improving driver safety and reducing the number of accidents on the road.

5 Experiment 1

5.1 Experiment 1 Motivation

As sensor technology advances constantly, there have been more advanced driver assistance system warnings made available to assist drivers. A warning can help drivers make informed decision rapidly by enhancing their perception about the surrounding environment. However, it may be difficult for drivers to make response if the warning system is not well-developed, especially under the context of multiple warnings. In a few studies, the driving behaviour related to the concurrent use of multiple warnings is assessed (Shiki et al. 2004; Fitch et al. 2014; Souders et al. 2019). According to their results, multiple warnings are potentially beneficial in a multi-conflict event. However, most of these warnings are designed as an auditory warning or incorporated with an auditory cue (e.g., a beep sound). According to research, any warning with an auditory modality can trigger a faster reaction (Politis et al. 2015). However, the driver may consider it annoying and irritable to receive two sound warnings simultaneously (Visvikis et al. 2008).

At present, the commercially available ADAS is often designed into two stages: warning and urgent warning. For example, the forward collision warning system issues a visual warning to the driver, informing that the ego-vehicle must keep the distance (or slow down) if the vehicle ahead is too close. In case of no reaction from the driver, the warning will be upgraded to an urgent warning which is frequently a combination of visual and auditory warnings to alert the driver to the urgency in the current environment. According to Naujoks and Neukum (2014) the first-stage warning (early warning) is designed to shift the driver's expectations and attention towards potential hazards, allowing them to prepare for the situation and adjust their driving behaviour. This can include slowing down, increasing following distance, or being more vigilant for sudden stops or changes in traffic patterns The second-stage (urgent warning) is intended to drivers prompt a quick and effective response

(Petermann-Stock and Rhede 2013). This might include braking, swerving, or taking other evasive manoeuvres to avoid a collision. Werneke and Vollrath (2013) examining the effectiveness of these two types of warnings at intersections, early warnings were found to have a more positive impact on driver behaviour compared to late warnings. Specifically, drivers who received early warnings of an upcoming intersection were better able to adapt their driving behaviour, slowing down and increasing their vigilance for potential hazards. Naujoks and Neukum (2013) suggest to initially inform drivers very early about an oncoming critical situation in a first stage (*information*) in order to increase their attention and shift awareness toward the situation without demanding an immediate action like braking but rendering them ready to do so. However, drivers may get confused if it is under a multi-conflict situation. Therefore, it is essential to consider the design of multi-warning mode carefully and ensure that they are clear, concise, and easy to understand to avoid confusion for the driver. Therefore, this experiment is aimed to design a multi-conflict scenario, with the corresponding warnings issued to assess whether the driver can respond correctly and promptly.

In addition, the driving experience is taken into consideration in this study. For example, when two early warnings are issued simultaneously, it is possible that a more experienced driver reacts more quickly and accurately. However, it is uncertain whether the driver can respond correctly by distinguishing the urgency of the warning when two early warnings exist at the same time.

5.2 Method

5.2.1 Warning Design

Blind spot warning (BSM) and Forward collision warning (FCW) were adopted for this experiment. The presentation of these two warnings was designed using current commercial product design concepts (e.g., from Volve and Mercedes-Benz). BSM[1] is single-stage and can be triggered whenever a vehicle is detected in a blind spot. FCW[2] is two-staged, including early warning, which is issued if the subject vehicle approaches the vehicle ahead rapidly, and urgent warning, which is issued when the distance maintained to the vehicle ahead is insufficient. An important goal of using this design concept is to investigate the suitability of current ADAS warning designs for a multi-warning mode, in which multiple warning types are presented to the driver simultaneously or in quick succession. The result can help to better understand the impact of warning design on driver behaviour and how such warning situations can be improved to support safety.

- **Forward collision warning (FCW).** The FCW is shown in a HUD in the middle screen. The FCW is presented as stable red dots (early warning) near the centre of the middle screen when the time-to-collision (TTC) decreases to 4 s. After the TTC drops to 2 s or below, the red dots will blink and be accompanied by an auditory alert (urgent warning intended to prevent collision). Figure 5-3 screenshot of the simulator displaying.

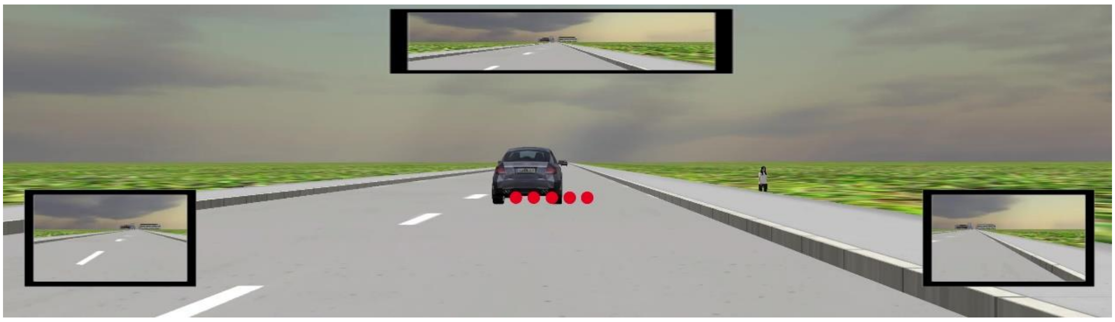


Figure 5-1 Screenshot of the simulator displaying FCW

[1]Mercedes-Benz, (2014). CLA-Class Blind Spot Assist https://www.youtube.com/watch?v=Z5Ee6ZUYx8Q&list=RDCMUCfRUa1Z5gTknsMMaKLthZIg&start_radio=1&rv=Z5Ee6ZUYx8Q&t=66

[2] Mercedes-Benz, (2014). CLA-Class Collision Prevention Assist https://www.youtube.com/watch?v=iZmnmPZ5ww4.

- **Blind spot monitoring (BSM)**. The BSM is visualized as a yellow icon shown in the door mirrors. This system will be triggered when another vehicle in the adjacent lane moves within 8 meters behind the subject vehicle. Figure 5-4 shows the screenshot of the simulator displaying BSM.

Figure 5-2 Screenshot of the simulator displaying FCW

Furthermore, two icons were designed in the dashboard to indicate the status of the two warning systems in real time. In this way, the drivers can know which system is active according to the icon on display.

Figure 5-3 Screenshot of the simulator displaying dashboard (red arrow did not display in real driving simulator)

5.2.2 Scenario Design

The experiment only adopts the cooperation scenario mentioned in Section 4.2.3. The reason for using only the cooperation scenario in the experiments is that it is the most relevant and practical scenario for studying the effectiveness of multiple warnings in multi-conflict events. Multiple conflicting events require the driver to simultaneously process multiple warnings related to the driving environment, which may increase the driver's cognitive load and lead to a higher accident risk. However, the two warnings in the cooperation scenario complement each other and provide the driver with a complete picture of their surroundings. The combination of these two warnings also has the potential to significantly reduce the driver's cognitive load and make the driving experience easier. Therefore, it is necessary to investigate this type of multi-warning situation.

The experimental road is a single carriageway with two lanes (no incoming vehicles). Driving as they would in a real-world situation, the participants are required to strictly follow the traffic signs. Equipped with a cruise control, the subject vehicle has been set to 50 mph. The system will be deactivated in case of the participants stepping on the brake pedal. To instruct the participants to stay at a certain lane, a traffic sign called “lane keep sign” is designed. The participants are not permitted to change lane, accelerate, or brake until the “road work ahead” sign is in sight. After 100 m, another sign (two in total, 100 m apart) will show up to inform the participants about the closure of the lane. The participants may need to change lane or not.

After roughly 20 s of driving, a leading vehicle emerges. The participants should then follow the lead vehicle, with an adjacent lane vehicle trailing about a three-car length behind the subject vehicle. Under the multi-conflict scenario, two hazards emerge at the lateral and longitudinal directions. An adjacent vehicle keeps accelerating when the participants pass the road work sign, which triggers the BSM warning. Meanwhile, the leading vehicle starts deceleration. The FCW will be triggered about 2.6s after the issuance of BSM warning, if the participants take no action in response (i.e., step on the brake).

5.2.3 Experimental Procedure

In total, each participant spent about 1 hour in the experiment. Upon arrival, a consent form was issued to the participants, informing them about the experimental procedure, the usage of data and experimental risks. If they agree to the relevant declaration, the consent form will be signed.

Next, the participants completed a short training drive for familiarity with the driving simulator (around 10 minutes). The experiment can be terminated whenever the participants feel uncomfortable (e.g., simulator sickness). During the process of simulator familiarization, it was assessed whether these signs are understandable by showing all own-designed traffic signs. Also, the experimenter provided instruction to the participants if they failed to follow the signs. With the simulator familiarization complete, the participants received a brief orientation on FCW and BSM, which was followed by warning familiarization (around 10 minutes). During the stage of FCW familiarization, the experimenter first ran the driving simulator, demonstrating how the FCW is displayed on the simulator to ensure the FCW will be triggered. Then, the participants experienced the FCW by driving on the simulator. Under the hazard scenario in the FCW, the leading vehicle decelerated abruptly with no brake light. In the experiment, there is no change to the deceleration rate of the leading vehicle. During the course of BSM familiarization, the participants drove on the middle lane of a one-way three-lane road. Since the simulator vehicle was equipped with a cruise control, the participants were instructed to stay in their current lane. There are vehicles overtaking the subject vehicle from either lane (i.e., right and left). During the experiment, the participants were instructed to pay attention to the door mirrors when there is an approaching vehicle. Also, it was kept asked in the experiment whether they caught sight of the vehicle and the BSM warning. Notably, the participants were not asked to change their lane.

Finally, the participants started on the experimental scenarios (around 30 minutes). The scenarios were assigned at random to the participants. During the experiment, the experimenter stayed in the room, providing no instruction to the participants. Once complete, the aim of this experiment was explained to participants and they filled in a questionnaire intended to assess their subjective attitudes toward the warnings (around 5 minutes).

5.2.4 Measurement and Assessment Criteria

5.2.4.1 Reaction Type (RT)

Reaction type refers to the initial action of participants when responding to a warning or event, and it can reflect the correct behaviour of drivers in different scenarios. By measuring reaction type, the number and rate of incorrect responses can be calculated, allowing for the determination of the correct rate of driver responses to warning modes and proving the efficiency of the warning mode. In this scenario, the two main initial activities were braking and lane changing. Braking is considered a safe reaction, while lane changing is seen as a risky activity. A further analysis was conducted to show the change in activity between the warning modes. The shift from lane changing activity to braking activity is considered a positive impact, whereas the shift from braking activity to lane changing activity is deemed an adverse impact. If there is no change to the initial activities in different warning modes, there will be no impact. If the number of lane change activities and adverse effects increases, it may indicate that drivers are struggling with their response to one warning mode.

5.2.4.2 Initial Reaction Time (IRT)

As assumed, the drivers will react in two ways: braking or changing lanes directly. Therefore, it is necessary to collect initial reaction time data for assessing whether the warning system is effective in improving their reaction speed (although they may respond inappropriately). The measure of initial reaction time is the time counted from when the leading vehicle started to brake to when the subject starts to press the brake pedal or steering. The one-way analysis of variance (ANOVA) was used to analysis the percentage difference of IRT in each warning mode.

The IRT was calculated by using the following formula:

$$\textbf{Mean reaction time} = \boldsymbol{T_{Driver\ starts\ to\ react}} - \boldsymbol{T_{Leading\ Vehicle\ slowing\ down}}$$

$\boldsymbol{T_{Leading\ Vehicle\ slowing\ down}}$ represents the time point the leading vehicle starts to decelerate and $T_{Driver\ starts\ to\ react}$ refers to the time point the subject vehicle starts to react.

5.2.4.3 Brake Reaction Time (BRT)

BRT will be measured in the braking behaviour data to further evaluate each warning mode. Brake reaction time is the time elapsed between the instant a driver recognizes the need to stop the vehicle and the moment they apply pressure to the brake pedal. In this experiment, the brake reaction time was defined as the time elapsed between the moment the leading vehicle starts to slow down and the moment the participant applies pressure to the brake pedal. The ANOVA was used to analysis the percentage difference of BRT in each warning mode.

The following formula was used to calculate the individual BRT:

$$\mathbf{Mean\ reaction\ time} = \boldsymbol{T_{Driver\ starts\ to\ brake}} - \boldsymbol{T_{Leading\ Vehicle\ slowing\ down}}$$

$T_{Leading\ Vehicle}$ represents the time point the leading vehicle starts to decelerate and $T_{Driver\ starts\ to\ brake}$ refers to the time point the subject vehicle starts to brake.

5.2.4.4 Questionnaire

Prior to performing the driving task, the participants filled out a questionnaire used to assess their driving experience and health condition. After the experiment was completed, the participants filled out the questionnaire purposed mainly to assess the evaluation of scenarios, implemented warnings and their preference. A 5-point Likert scale questionnaire was adopted from Section 3.2.2.2 (Subjective measures) to evaluate the following subjective variables (translated from Chinese):

1. Timeliness of blind spot warning (from very untimely to very timely)
2. Timeliness of forward collision warning (from very untimely to very timely)
3. The usefulness of blind spot warning (from not useful to very useful).
4. The usefulness of forward collision warning (from not useful to very useful).

5. I would prefer having two warnings if they both can be presented (from totally disagree to totally agree).
6. I found it difficult to respond in a two-warning scenario (from totally disagree to totally agree).
7. Blind spot monitoring was distracting to me under multi-warning mode (from totally disagree to totally agree).
8. Forward collision warning was distracting to me under multi-warning mode (from totally disagree to totally agree).

Open questions were raised to the participants and interview was conducted with them about the predictability of warning scenarios, the evaluation of the warning system and the explanation of driving behaviour.

5.3 Experiment Design

To investigate whether drivers could perform correctly and promptly under a multi-warning situation, this experiment used within subject design. Four warning modes were run under the multi-conflict scenario: no warning mode (control group), single BSM mode (the subject vehicle only active BSM), single FCW mode (the subject vehicle only active FCW), and multi-warning mode (both warning systems were active). To reduce the driver's prediction of the scene, the adjacent vehicle appeared on either the left or on the right in some cases. Meanwhile, two single collision scenarios were created, with the participants' lane not under construction in the BSM only mode (i.e., they did not need to change lane). Alternatively, the vehicle in front did not decelerate or the approaching vehicle did not accelerate under the FCW only mode. Therefore, participants ran 6 trials but only collected 4 multi-conflict situation data. Data analysis will employ chi-square for the difference in reaction types and ANOVA to analyse initial reaction time and brake reaction time, with alpha set at 0.05.

5.4 Experiment 1 Hypothesis

It was expected that the participants would benefit from the use of the multi-warning mode. Unlike no- and single-warning modes, multi-warning mode allows a driver to better understand the surrounding environment. Therefore, the driver's response in multi-warning mode should be different from their response in single-warning mode. In addition, the participants' response in multi-warning mode may be affected by the amount of driving experience they have.

- H1: Drivers' response in multi-warning mode is different from single-warning mode. This hypothesis suggests that the use of multi-warning mode would result in a different response from drivers compared to single-warning mode. The expectation is that drivers would better understand the surrounding environment in multi-warning mode, leading to a different response, possibly in terms of improved driving behaviour or decision-making.
- H2: Drivers' response in multi-warning mode is different based on their driving experience. This hypothesis suggests that the response of drivers in multi-warning mode would vary based on their level of driving experience. It is possible that inexperienced drivers may find the information from multi-warning mode more difficult to comprehend compared to experienced drivers, leading to different driving behaviours or decision-making.

5.5 Result of Experiment 1

5.5.1 Participants

A total of 34 healthy drivers participated in the experiment. One participant was excluded from data analysis due to the lack of braking response, while one participant was excluded from data analysis due to simulator sickness. The result sample was comprised of 32 participants (30 males) with different occupations and education levels (aged M = 38.03, SD = 10.81, 21 to 56 years old; driving experience M=8.97, SD= 5.95, 1 to 21 years). The participants were divided into two groups depending on the median driving experience (9 years):

- 18 inexperienced driver (Age M = 31, SD = 7.65，driving experience M = 4.62, SD = 3)
- 14 experienced driver group (Age M=47.1 SD = 6.76, driving experience M = 14.8, SD = 3.39)

The statistical result indicated that there is a significant between these two group in driving experience, $F(1, 32) = 74.239$ $p = 0.001 < 0.05$.

5.5.2 Reaction Type

No collision occurred in 128 collision situations either with the decelerating leading vehicle or with the approaching vehicle. When the subject vehicle would cut into its lane, the approaching vehicle would perform an emergency brake. In most multi-conflict scenarios, the subject vehicle would brake whether to wait for the approaching vehicle to pass or due to the deceleration of the leading vehicle. However, in some cases, the subject vehicle changed lane even prior to the passage of the approaching vehicle. A total of 11 drivers (34.4%) in the control group were observed to perform a lane changing activity, as were another 12 drivers (37.5%) in multi-warning mode. Besides, 5 drivers (15.6%) were observed to perform a lane changing activity in the FCW only mode. In comparison, only 2 drivers (6.3%) performed lane change activity in the BSM only mode.

Table 5-1 Crosstabulation of warning mode and initial reaction type with adjusted residuals in overall data

Initial reaction type		Warning mode			
		Control group	BSM only	FCW only	Multi-Warning
Brake	Count	21_a	30_b	$27_{a, b}$	20_a
	Expected count	24.5	24.5	24.5	24.5
	Adjusted residual	-1.7	2.7	1.2	-2.2
Lane change	Count	11_a	2_b	$5_{a, b}$	12_a
	Expected count	7.5	7.5	7.5	7.5
	Adjusted residual	1.7	-2.7	-1.2	2.2

A Chi-Square test was performed to assess the relationship between warning mode and initial reaction type, with a significance level (alpha) set at 0.05. There was a signification relationship between the two variables, χ^2 (3, N=128) = 12.016, p = 0.007 < 0.05). A post-hoc test was conducted to compare two modes at a time, resulting in a total of 6 comparisons. After applying Bonferroni correction for multiple comparisons, the adjusted significance level was set at 0.008 (calculated by dividing the original significance level of 0.05 by the number of comparisons, which was 6). The post-hoc test result indicates that there was a significant difference in the initial behavioural choices of drivers between BSM only and the multiple-warning modes, χ^2 (1, N=32) = 9.143, p = 0.002 < 0.008; but no difference between FCW only and multi-warning, χ^2 (1, N=32) = 3.925, p = 0.048). No differences were observed between these two single-warning models (BSM only vs FCW only, χ^2 = 1.444, p = 0.213). Additionally, the control group was found no different from the FCW only mode (Control Group vs FCW only, χ^2 = 3, p = 0.074) and multi-warning mode (χ^2 =.068, p = 0.5). However, a significant difference was observed between control group and BSM only mode (χ^2 = 7.819, p = 0.005). Based on crosstabulation table, drivers under BSM only mode was more likely to brake than control group and multi-warning mode.

Figure 5-5 list the activity changes between these four-warning schema. These four behavioural changes represent four behavioural definitions respectively:

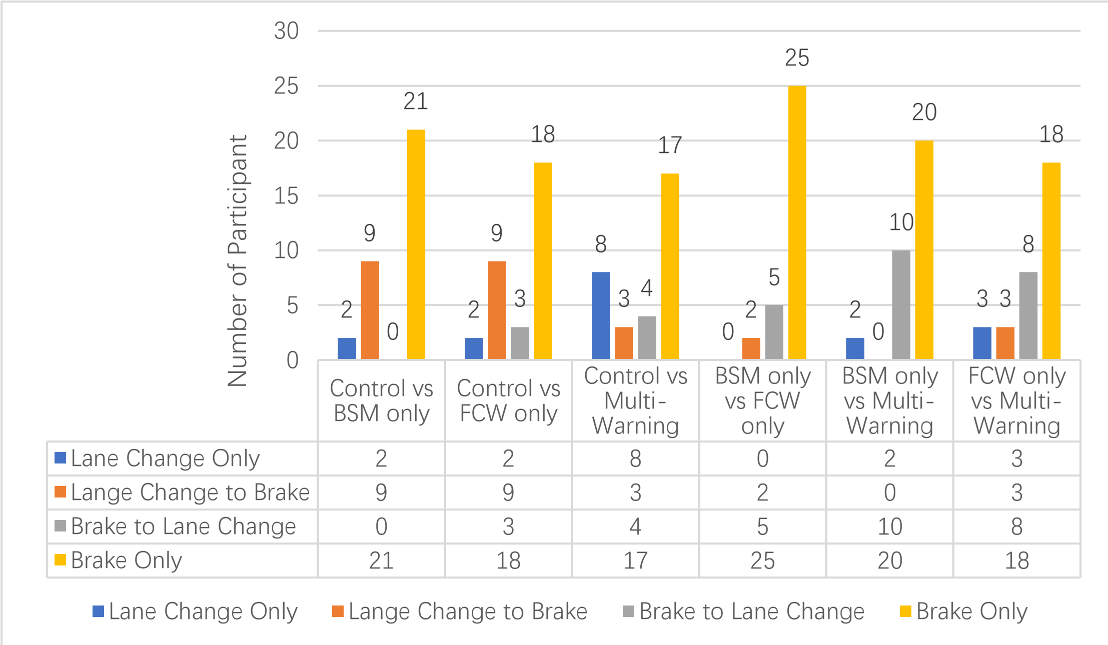
1. **Lane change only** indicates that the presence of the warning may play no role in improving the behavioural choices of the driver.

2. **Lane change to brake** indicates that the warning may improves the behavioural choice of the driver (since braking was defined as the correct choice in the test situation).

3. **Brake to lane change** indicates that the presence of the warning may have a negative effect on the judgment made by the driver on the choice of correct behaviour.

4. **Brake only** indicates that the presence of the warning may or may be of no help to

the driver with behavioural choices.



	Control vs BSM only	Control vs FCW only	Control vs Multi-Warning	BSM only vs FCW only	BSM only vs Multi-Warning	FCW only vs Multi-Warning
Lane Change Only	2	2	8	0	2	3
Lange Change to Brake	9	9	3	2	0	3
Brake to Lane Change	0	3	4	5	10	8
Brake Only	21	18	17	25	20	18

Figure 5-4 Activity change based on different warning schema

Upon further analysis, BSM only mode was observed that a total of 9 drivers (28.1%) transitioned from lane changing to braking behaviour in comparison to the no warning mode. The FCW only mode is same, with 9 drivers (28.1%) transitioned from lane changing behaviour to braking behaviour. In contrast, the multiple warning mode showed the least significant improvement with only 3 drivers (9.38%) shifting from lane changing to braking behaviour while 8 drivers (25%) exhibited no change in their lane changing behaviour. In addition, 4 drivers (12.5%) were observed to change their driving behaviour from braking to changing lanes. A comparison between the single warning mode and multi-warning mode demonstrated that drivers exhibited better performance in the single warning mode. The results from comparing the BSM only mode and multi-warning mode indicated that up to 10 drivers (31.3%) transitioned from braking behaviour in the single-warning mode to lane changing behaviour in the multi-warning mode. Although the behaviour of 3 drivers (9.4%) improved in the FCW only mode in the multi-warning mode, 8 drivers (25%) still demonstrated a shift in their behaviour from braking to lane changing.

5.5.2.1 Effect of Driving Experience

Both groups of drivers exhibit a similar trend in which their initial behavioural choices are more effective under the single-warning scenario. Specifically, the BSM only mode showed that 1 inexperienced driver (5.6%) and 1 experienced driver (7.1%) changed lanes, while under the FCW only mode, 3 inexperienced drivers (16.7%) and 2 experienced drivers (14.3%) changed lanes. Additionally, the behavioural choice in the control group, with 8 inexperienced drivers (44.4%) and 3 experienced drivers (21.4%) changing lanes, demonstrated a similar trend to that of the multi-warning mode, with 8 inexperienced drivers (44.4%) and 4 experienced drivers (28.6%) changing lanes.

Table 5-2 Crosstabulation of warning mode and initial reaction type with adjusted residuals in inexperienced driver group

Initial reaction type		Warning mode			
		Control group	BSM only	FCW only	Multi-Warning
Brake	Count	10_{a}	17_{b}	$15_{a, b}$	10_{a}
	Expected count	13.0	13.0	13.0	13.0
	Adjusted residual	-1.8	2.4	1.2	-1.8
Lane change	Count	8_{a}	1_{b}	$3_{a, b}$	8_{a}
	Expected count	5.0	5.0	5.0	5.0
	Adjusted residual	1.8	-2.4	-1.2	1.8

There was a signification relationship between the two variables in inexperienced driver group, χ^2 (3, N=128) = 10.523, $p = 0.015 < 0.05$. After applying Bonferroni correction for multiple comparisons, the adjusted significance level was set at 0.008. The post-hoc test reveals a significant difference between the control group and the BSM only mode regarding the initial behavioural choice of inexperienced drivers, χ^2 (1, N=36) = 7.259, $p = 0.007 < 0.008$. Moreover, a significant difference was observed between the BSM only mode and the multi-warning mode, χ^2 (1, N=36) = 7.259, $p = 0.007$. However, no significant differences were observed among the remaining warning modes, including the Control Group vs FCW only, χ^2 (1, N=36) = 3.273, $p = 0.07$; Control Group vs multi-warning mode, χ^2 (1, N=36)= 0, $p = 1$; BSM only vs FCW only χ^2 (1, N=36) = 1.125, $p = 0.286$; FCW only vs multi-warning mode

χ^2 (1, N=36) = 3.273, p = 0.07.

Table 5-3 Crosstabulation of warning mode and initial reaction type with adjusted residuals in experienced driver group

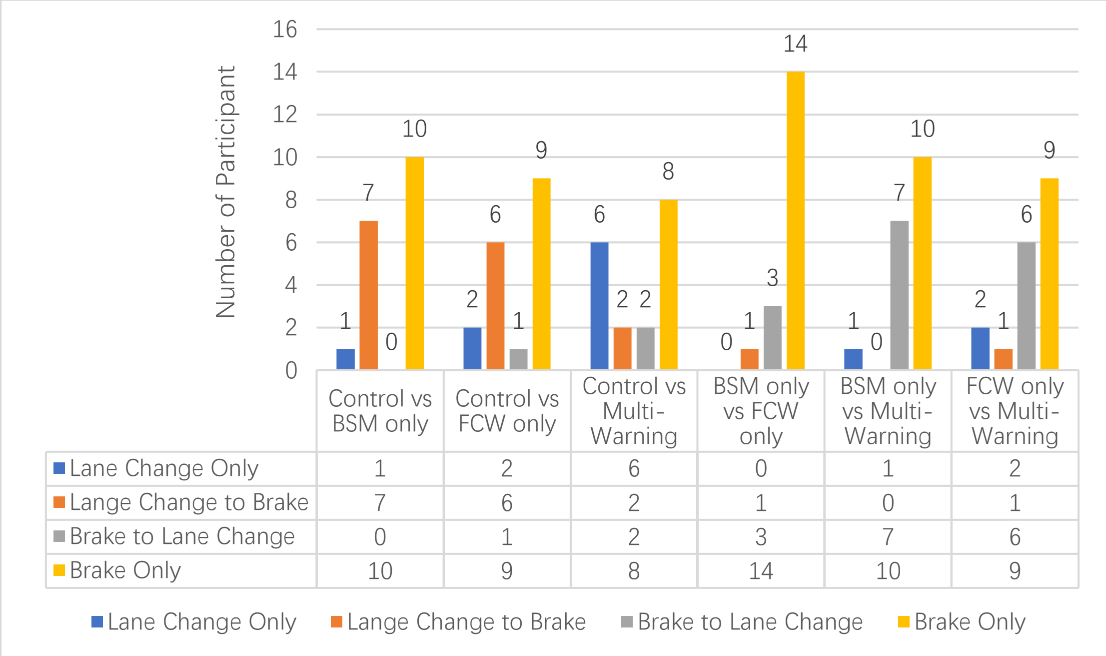
Initial reaction type		Warning mode			
		Control group	BSM only	FCW only	Multi-Warning
Brake	Count	11_a	13_a	12_a	10_a
	Expected count	11.5	11.5	11.5	11.5
	Adjusted residual	-.4	1.2	.4	-1.2
Lane change	Count	3_a	1_a	2_a	4_a
	Expected count	2.5	2.5	2.5	2.5
	Adjusted residual	.4	-1.2	-.4	1.2

For the experienced drivers, no significant differences were observed in the initial behavioural choices, $\chi2$ (3, N=128) = 2.435, p = 0.487 > 0.05. The post-hoc test revealed no significant differences between the Control Group and BSM only mode, $\chi2$ (1, N=28) = 1.167, p = 0.28 > 0.008, Control Group and FCW only mode, $\chi2$ (1, N=28) = 0.243, p = 0.622, and Control Group and Multi-Warning mode, $\chi2$ (1, N=28) = 0.19, p = 0.663. Similarly, no significant differences were observed between the BSM-only mode and FCW only mode $\chi2$ (1, N=28) = 0.373, p = 0.541, BSM only mode and multi-warning mode $\chi2$ (1, N=28) = 2.191, p = 0.139, and FCW only mode and multi-warning mode $\chi2$ (1, N=28) = 0.848, p = 0.357.

In the group of inexperienced drivers, the single-warning mode demonstrated superior behavioural change when compared to the no-warning mode. Specifically, 7 drivers (38.9%) in the BSM only mode and 6 drivers (33.3%) in the FCW only mode switched from lane changing behaviour to braking behaviour. Additionally, only 1 driver (5.6%) in the BSM only mode and 2 drivers (11.1%) in the FCW only mode maintained their lane changing behaviour. In the multi-warning mode, 6 inexperienced drivers (33.3%) retained their lane-changing behaviour, and only 2 drivers (11.1%) exhibited improved driving behaviour. Furthermore, a comparison of the single warning mode and multi-warning mode revealed that 7 (38.9%) and 6 drivers (33.3%), respectively, changed from lane changing behaviour to braking behaviour in the BSM only mode and FCW only mode, while only 1 driver (5.6%) and

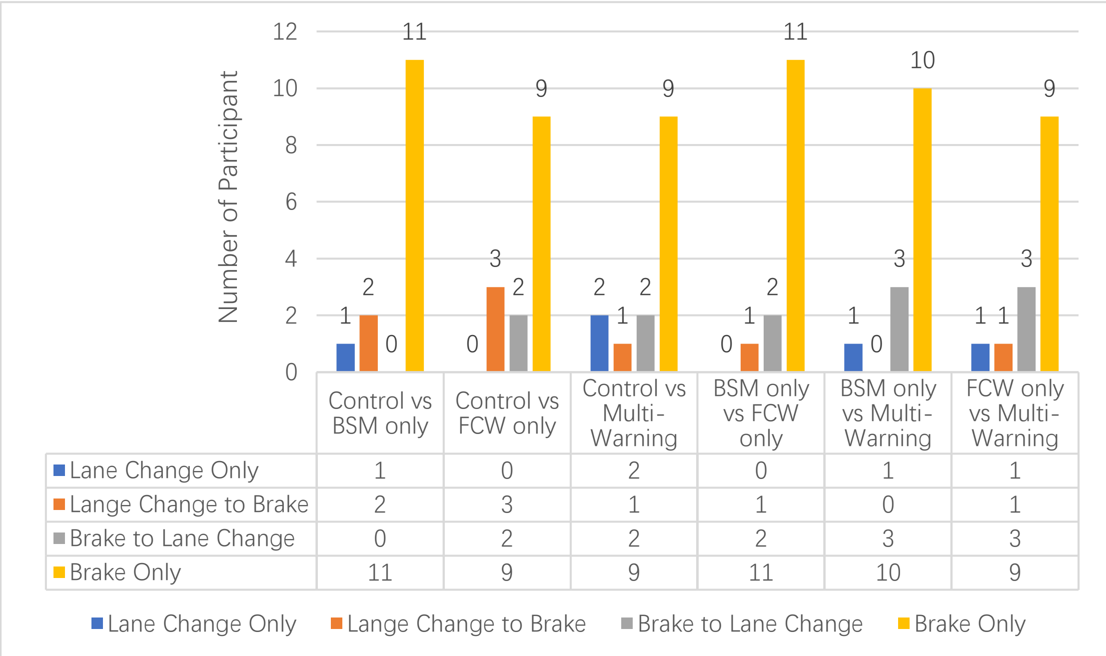
2 drivers (11.1%), respectively, maintained their lane changing behaviour. And, in comparison to the FCW only mode and multi-warning mode, only 1 driver (5.6%) was observed to switch from lane changing behaviour to braking behaviour, but it was not observed in BSM only mode.

Among the experienced drivers, a total of 14 drivers were observed. 2 drivers (14.3%) in BSM only mode and 3 drivers (21.4%) in FCW only mode shifted from lane changing behaviour to braking behaviour compared to the no warning mode. Additionally, only 1 driver (7.1%) in BSM only mode did not change their lane-changing behaviour. The transition from braking behaviour to lane changing behaviour was observed for 2 drivers (14.3%) in FCW only mode, while it was not observed in BSM only mode. In the multi-warning mode, 2 drivers (14.3%) did not change their lane-changing behaviour, and 1 driver (7.1%) was observed to change from lane-changing behaviour to braking behaviour, while 2 drivers (14.3%) were observed to change from braking behaviour to lane-changing behaviour. Comparing the single warning mode and the multi-warning mode, FCW only mode had 1 driver (7.1%) changing from lane changing behaviour to braking behaviour, while it was not observed in BSM only mode. Compared with the single warning mode of the two groups, one driver (7.1%) maintained the lane-changing behaviour, and all 3 drivers (21.4%) were observed to change from braking behaviour to lane-changing behaviour.



	Control vs BSM only	Control vs FCW only	Control vs Multi-Warning	BSM only vs FCW only	BSM only vs Multi-Warning	FCW only vs Multi-Warning
Lane Change Only	1	2	6	0	1	2
Lange Change to Brake	7	6	2	1	0	1
Brake to Lane Change	0	1	2	3	7	6
Brake Only	10	9	8	14	10	9

Figure 5-5 Activity change based on different warning schema in inexperienced driver



	Control vs BSM only	Control vs FCW only	Control vs Multi-Warning	BSM only vs FCW only	BSM only vs Multi-Warning	FCW only vs Multi-Warning
Lane Change Only	1	0	2	0	1	1
Lange Change to Brake	2	3	1	1	0	1
Brake to Lane Change	0	2	2	2	3	3
Brake Only	11	9	9	11	10	9

Figure 5-6 Activity change based on different warning schema in experienced driver

5.5.3 Initial Reaction Time

In total, 128 pieces of data were collected during the experiments. The IRT for the control group was 4.67 seconds (SD = 0.83), while the BSM only mode and the FCW only mode had IRTs of 4.92 seconds (SD = 0.74) and 4.62 seconds (SD = 0.68), respectively. In the multi-warning mode, the IRT was significantly shorter, with a mean of 4.15 seconds (SD = 0.75). These findings suggest that the multi-warning mode led to faster reaction times compared to the other modes tested in the experiment.

The ANOVA analysis results show that there is a significant difference between at least one pair of modes for the dependent variable IRT, F (3, 124) = 5.799, p = 0.001 <0.05. Post hoc analysis using the Least Significant Difference (LSD) test revealed significant mean differences between each mode. Specifically, the control group had a significantly different mean IRT compared to the multi-warning mode (M = 0.52, SE = 0.19, p = 0.007), while the BSM only mode had a significantly different mean reaction time compared to the multi-warning mode (M = 0.77, SE = 0.19, p = 0.001). Additionally, the FCW only mode showed a significantly different mean reaction time compared to the multi-warning mode (M = 0.46, SE = 0.19, p = 0.016). It is worth noting that there were no significant differences in mean reaction time between any other pairs of modes. These results suggest that the multi-warning mode may lead to faster reaction times compared to other warning modes.

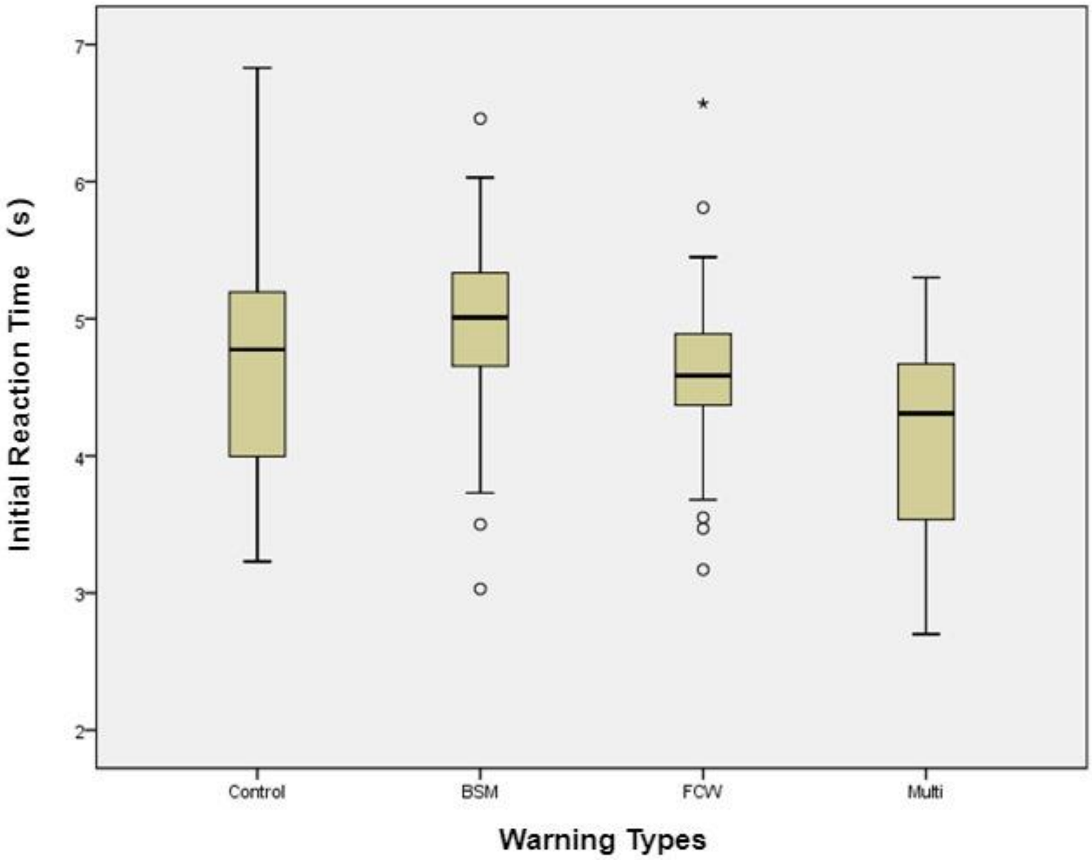


Figure 5-7 Initial reaction time between four warning mode

5.5.3.1 Effect of Driving Experience

The inexperienced driver group had mean reaction times of 4.48 s (SD = 0.82), 4.7s (SD=0.86), 4.53 s (SD = 0.64), and 3.87 s (SD=0.84) under the control group, BSM only mode, FCW only mode, and multi-warning modes, respectively. The experienced driver group had mean reaction times of 4.92 s (SD = 0.80), 5.21 s (SD = 0.43), 4.73 s (SD = 0.74), and 4.52 s (SD=0.42) under the same modes, respectively. And no difference was found between two driver groups.

Table 5-4 Initial reaction time for two driving groups

	Inexperienced Driver	Experienced Driver
Control Group	4.48 s	4.92 s
BSM Only	4.7 s	5.21 s
FCW Only	4.53s	4.73 s
Multi-Warning	3.87 s	4.52 s

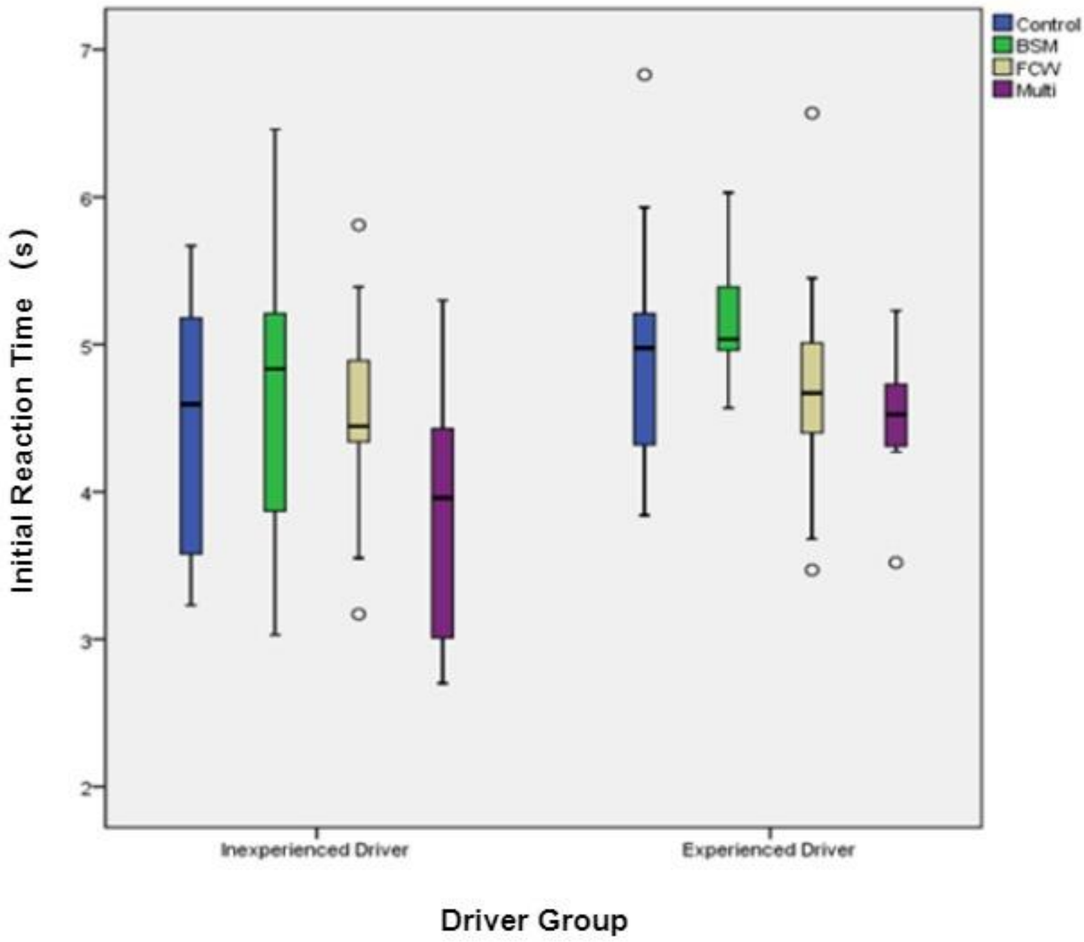


Figure 5-8 Initial reaction time for two driving groups

The results of the ANOVA revealed a significant difference in mean reaction time among the four warning modes for inexperienced drivers, F (3, 68) = 3.775, p = 0.014 < 0.05). Post hoc analysis test showed that multi-warning mode had a significantly faster mean IRT than other 4 groups: control group (M = 0.61, SE = 0.26, p = 0.024), BSM only mode (M = 0.83, SE = 0.26, p = 0.002) and FCW only mode (M = 0.66, SE = 0.26, p = 0.015). No differences found between other groups.

In experienced driver group, the results showed a significant main effect of warning mode on IRT (F (3, 52) = 3.073, p = 0.036). Further comparisons revealed that IRT in the FCW only mode (M = 0.48, SE = 0.24, p = 0.045) and multi-warning mode conditions (M = 0.67, SE = 0.24, p = 0.005) was significantly faster compared to the BSM only mode condition. No other significant differences were found between the warning mode conditions.

5.5.4 Brake Reaction Time

Based on the report, the mean BRT for control group is 4.87 s (SD = 0.65), 5.11 s (SD = 0.84) for BSM only mode, 4.59 s (SD = 0.71) for FCW only mode, and 3.73 s (SD = 0.93) for multi-warning mode. The statistical results show a significant effect of the warning mode on the BRT, F (3, 52) = 6.169, p = 0.001 < 0.05. Further analysis indicated that multi-warning mode are significant for other modes control group (M= 1.14, SE = 0.33, p = 0.001), BSM only mode (M= 1.38, SE = 0.33, p = 0.001), FCW only mode (M= 0.855, SE = 0.33, p = 0.013). The mean difference between other warning modes were not significant.

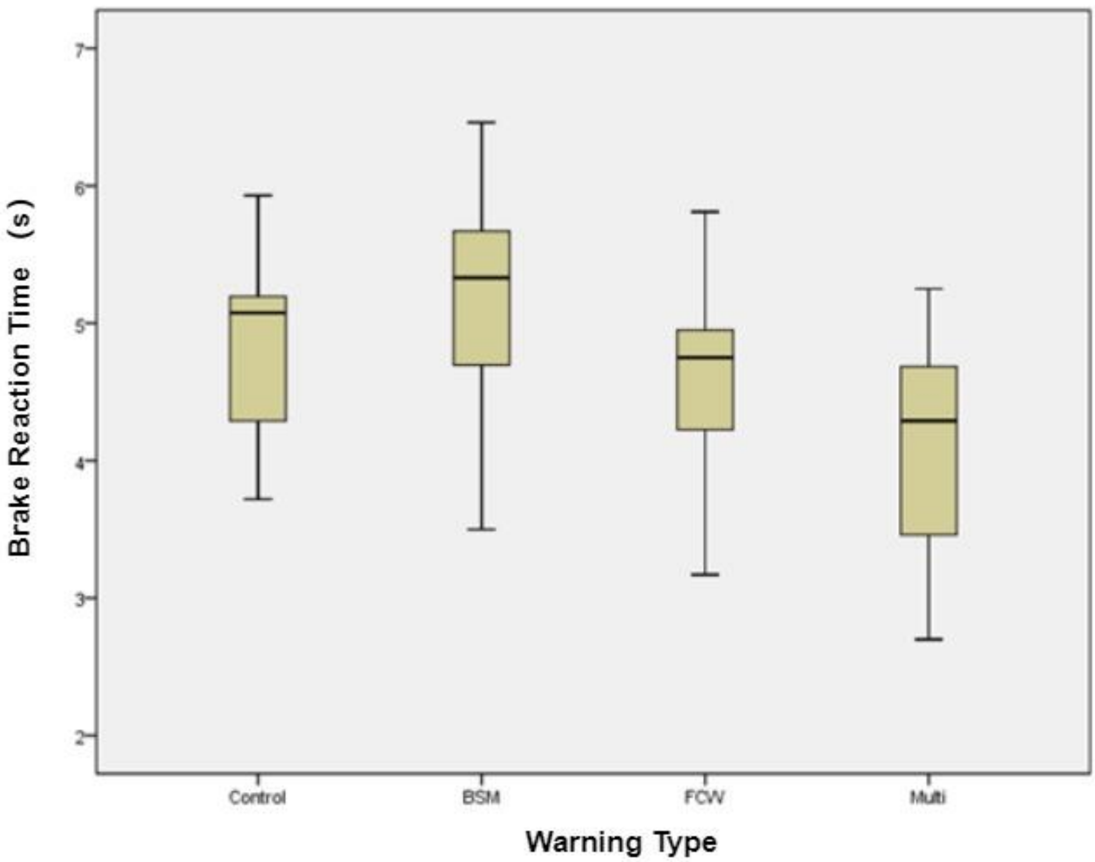


Figure 5-9 Brake reaction time between four warning modes

5.5.4.1 Effect of Driving Experience

In experienced driver group, the mean BRT values for control group, BSM only mode, FCW only mode and multi-warning mode were 4.89 s (SD = 0.66), 4.94 s (SD = 0.96), 4.53 s (SD = 0.89), and 3.73 s (SD = 0.93), respectively.

Table 5-5 Brake reaction time for two driving groups

	Inexperienced Driver	Experienced Driver
Control Group	4.89 s	4.84 s
BSM Only	4.93 s	5.29 s
FCW Only	4.52 s	4.65 s
Multi-Warning	3.73 s	4.48 s

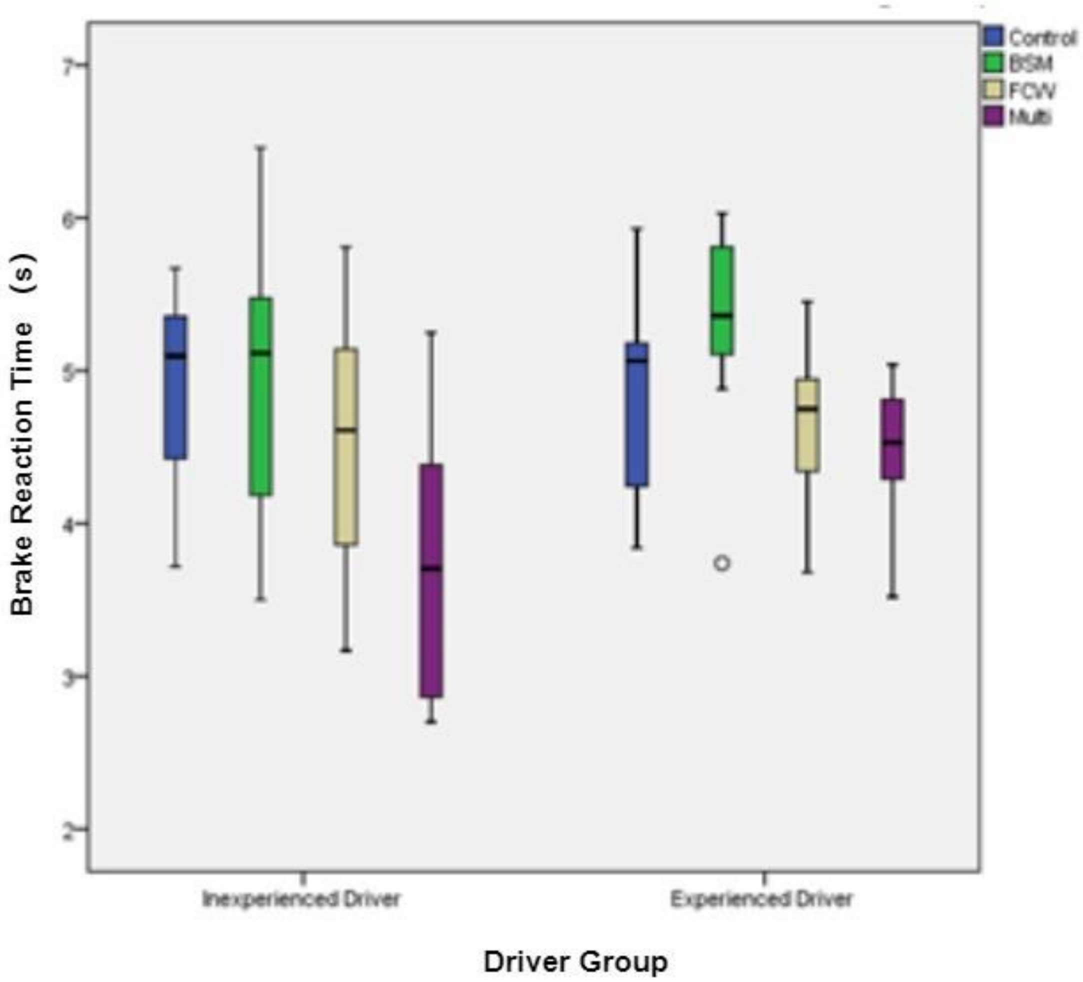


Figure 5-10 Brake reaction time for two driving groups

Based on the ANOVA results for BRT of inexperienced drivers, there was a statistically significant difference in BRT among the four experimental conditions, $F(3, 28) = 3.306$, $p = 0.035 < 0.05$. The multiple comparisons results indicated that the BRT in the multi-warning mode was significantly faster than control group (M = 1.16, SE= 0.43, p = 0.012), BSM only mode (M = 1.21, SE= 0.43, p = 0.01) and the FCW only mode (M = 1.21, SE= 0.43, p = 0.01). There were no significant differences between other modes. Therefore, it can be concluded that the multi-warning mode improved the BRT in inexperienced drivers compared to other warning mode.

The mean reaction times for the experienced driver group were 4.84s (SD=0.68), 5.29 s (SD = 0.73), 4.65s (SD = 0.53), and 4.48 s (SD = 0.47) under the control group, BSM only mode, FCW only mode, and multi-warning modes, respectively. Based on the ANOVA results for BRT of experienced drivers, there was no statistically significant difference in BRT among the four experimental conditions, F (3, 28) = 2.614, p = 0.071.

5.5.5 Driver Preference

The average rating for the FCW system was 4.3 out of 5 (SD = 0.865), indicating that participants found it to be timely. Additionally, participants believed that this system enhanced driving safety, with an average rating of 4.1 out of 5 (SD = 0.995). In contrast, BSM had a lower average rating, with participants rating its timeliness as 3.3 out of 5 (SD = 0.865). Participants rated the extent to which BSM contributed to enhancing driving safety as an average of 2.8 out of 5 (SD = 1.167). The participants did not find the display design for FCW to be distracting, with an average rating of 2 out of 5 (SD = 0.933). However, they believed that the BSM warning was more distracting than FCW, with an average rating of 3.1 out of 5 (SD = 1.238). Participants showed a moderately positive preference for the multi-warning mode with an average rating of 3.8 out of 5 (SD = 0.95), but there was a possibility of confusion, as indicated by an average rating of 3 out of 5 (SD = 1.257).

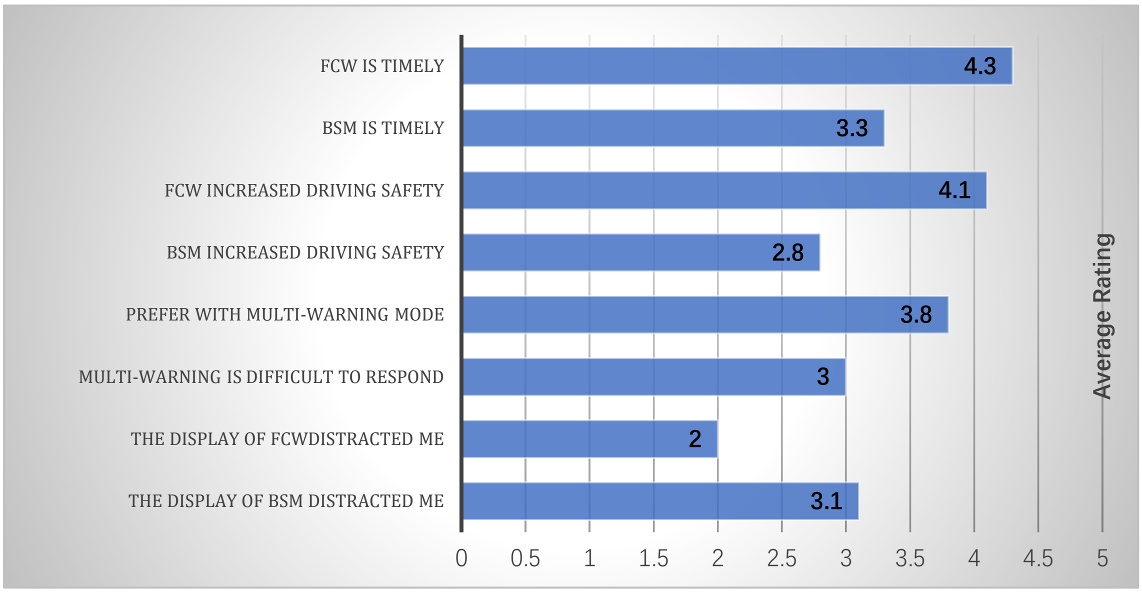


Figure 5-11 Median rating for the parameters assessed in the questionnaire

5.5.5.1 Effect of Driving Experience.

Both the inexperienced and experienced driver groups rated the timing of the BSM warning as adequate, with a mean rating of 3.3 (SD = 0.767) and 3.3 (SD = 1.008) respectively. Similarly, both groups found the FCW warning to be timely, with mean ratings of 4.4 (SD = 0.8556) for the inexperienced group and 4.2 (SD = 0.893) for the experienced group. Regarding usefulness, the experienced group had a moderately positive rating of 3.1 (SD = 1.328) for BSM usefulness compared to the inexperienced group's rating of 2.7 (SD = 1.029). However, both groups found FCW to be useful, with mean ratings of 4.2 (SD = 1.0431) for the inexperienced group and 4 (SD = 0.961) for the experienced group. Both driver groups showed a positive trend towards multi-warning situations, with inexperienced drivers rating the preference for multi-warning at 3.8 (SD = 0.926) and experienced drivers rating it at 3.6 (SD = 1.001). However, the inexperienced group had more difficulty responding to multi-warnings, with a mean rating of 3.3 (SD = 1.274) compared to the experienced group's rating of 2.7 (SD = 1.204). Under multi-warning scenarios, the inexperienced drivers found BSM to be more distracting than FCW, with a mean rating of 3.5 (SD = 1.249) for BSM distraction compared to 2.2 (SD = 1.06) for FCW distraction. In contrast, experienced drivers had lower distraction ratings, with a rating of 2.6 (SD = 1.082) for BSM and 1.6 (SD = 0.633) for FCW. This may suggest that experienced drivers view warnings as support tools and rely more on their driving skills, and thus did not consider warnings to be as distracting as inexperienced drivers.

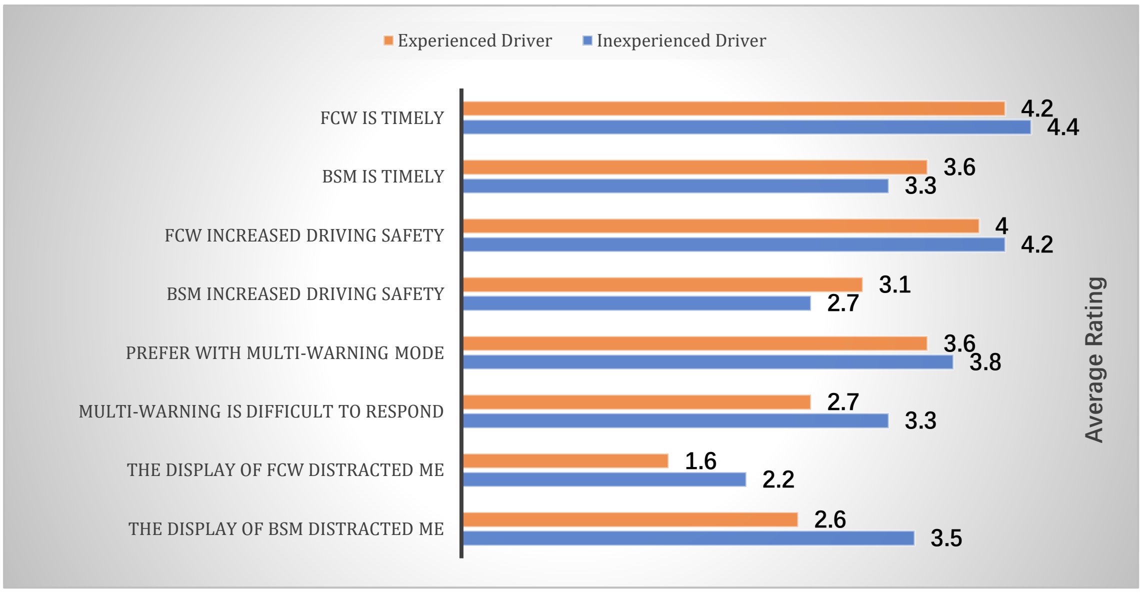


Figure 5-12 Median rating for the parameters assessed in the questionnaire by the two driver groups

5.6 Discussion

In Experiment 1, the effects of different warning modes (no warning, single warning mode, and multi-warning mode) on drivers' responses in a multi-conflict situation were compared. A total of 32 drivers were assigned to two groups based on their driving experience, in order to further analyse the impact of driving experience on responding to multi-warning situations.

According to Hypothesis 1, drivers' responses in multi-warning mode are different from single-warning mode was observed. In the initial reaction type, no significant difference was found between multi-warning mode and the control group (no warning mode). And BSM only mode showed a significant difference compared to multi-warning mode. When comparing BSM only mode and multi-warning mode, it was observed that up to 10 drivers transitioned from braking behaviour in single-warning mode to lane changing behaviour in multi-warning mode. This result indicates that drivers under BSM only mode (with 30 brake activities) performed more appropriately than those under multi-warning mode (with 20 brake activities). According to the multi-resource theory, individuals have limited cognitive resources that they allocate to different tasks (Wickens 1984). Therefore, if both warnings were presented simultaneously, they may compete for the limited cognitive resources, leading to a negative impact on driver behaviour. Moreover, multi-warning mode was found a significant difference compared with other warning modes in both IRT and BRT. This indicated that drivers under multi-warning mode reacted faster than other warning modes. This may be because driving performance can be improved in complex situations with more information (Steyvers and De Waard 2000; Horberry et al. 2006). However, this improvement was only partial as driving behaviour did not improve compared to single-warning mode. Such effect could be due to the fact that any warning presented subsequently to the first alert could startle, confuse, or interfere with drivers' execution of the avoidance manoeuvre (Green 2008). In this experiment, FCW was designed in red colour based on current market warning design, and BSM was a pre-triggered warning that may potentially draw drivers' eyes off the road. FCW, as the post-triggered warning, may suddenly startle drivers and interfere with their reaction.

H2 was also confirmed in this experiment. Driving experience show an effect on respond multi-warning mode. The results of initial reaction type showed that driving experience has an effect on responding to multi-warning mode. In the group of inexperienced drivers, BSM only mode demonstrated a significant difference from both the control group and multi-warning mode. This indicated that inexperienced drivers under BSM only mode (with 17 brake activities) performed more brake activity compared to the control group (with 10 brake activities) and multi-warning mode (with 10 brake activities). Furthermore, multi-warning mode resulted in faster reaction times for both IRT and BRT in the inexperienced driver group. However, no such effect was observed in the group of experienced drivers. The results of the initial reaction type showed that there was no significant difference among the warning modes, indicating that the warning mode did not affect the reaction choice of experienced drivers. Although the IRT results indicated that multi-warning mode and FCW only mode resulted in faster reactions, there was no difference in BRT between each warning mode. According to the SRK model proposed by Rasmussen (1983), experienced drivers can acquire driving skills through practice, resulting in reduced cognitive load and diminished impact of warnings. More experience could lead drivers with a good control and manoeuvring level, such as lateral-position control and mirror looking. The inexperienced driver may not be able to automatically complete all control-level tasks, and the workload in vehicle control is heavy (De Waard 1996). This can cause higher level tasks such as mirror checks to be ignored. Moreover, experienced drivers developed a greater ability to anticipate potential hazards and prepare cognitively for known situations on the road, which allowed them to make more effective decisions in complex driving situations (Cegarra and van Wezel 2012). They were able to quickly and accurately identify and respond to potential hazards, and they were better able to manage their cognitive load while driving. As proposed by Falkmer and Gregersen (2001), inexperienced drivers may exhibit less efficient and flexible visual strategies compared to experienced drivers, and their peripheral vision capabilities may decline as processing demands increase. Indeed, they tended to focus more on the road immediately in front of their vehicle. Regardless of how complex the driving situation was, they continued to rely on this narrow focus. Experienced drivers were able to scan horizontally and be aware of potential hazards or changes in the driving environment, even in complex driving situations (Crundall et al. 1999; Patten et al. 2006). In complex driving situations, such as multi-conflict events, manoeuvre-level tasks can place high demands on both visual and central resources, resulting in decreased performance for inexperienced drivers. Additionally, the design of the selected warnings themselves is individual and did not have a clear priority under the scenario. In this experiment, both warnings were issued visually, with a trigger order that can be interpreted as the priority of the warnings, namely the potential hazard followed by the warning. However, inexperienced drivers may struggle when two warnings are presented simultaneously, as they need to further judge the priority of the warnings, leading to increased cognitive workload and negative impacts in multiple warning modes. Therefore, the experiment observed a strong correlation between warning mode and reaction type in the inexperienced driver group, but less so in the experienced driver group. The subjective measures revealed that inexperienced drivers found it more difficult to perform in multiple warning situations compared to experienced drivers. However, both groups showed a preference for the multiple warning modes. In addition, in terms of the degree of warning distraction, the ratings provided by inexperienced drivers were generally higher than experienced drivers. The distraction score for the BSM was relatively high among inexperienced drivers, with a rating of 3.5 out of 5. This could have been attributed to the fact that the BSM was designed to appear in the side mirror, causing the driver to take their eyes off the road when the warning was triggered. Since inexperienced drivers may not have had a flexible visual strategy caused them found it difficult to correctly understand and respond to subsequent warnings.

The grouping of participants based on the median split method will be discussed in this section. While the UK defines new drivers as those within the first two years after passing a driving test, this research has chosen to use the median split method to divide the sample into two groups based on their driving experience. This decision was made for several reasons. Firstly, the median split method is widely accepted as an effective approach for dividing a sample into two equal groups based on a continuous variable (MacCallum et al. 2002). Moreover, applying the UK definition of a new driver may not be appropriate for this particular experiment. Given the size of participant sample, utilizing the UK definition would have resulted in a very small inexperienced group. This could have limited the statistical power and generalizability of the findings. Furthermore, it is important to highlight that the two groups formed based on driving experience exhibited a statistically significant difference, confirming that the levels of driving experience between the groups are distinct. The primary focus of this study is to investigate the impact of driving experience on driving behaviour and decision-making in specific scenarios. Therefore, the variation in driving experience observed within the sample reflects the diverse levels of experience among the driver population in this research area.

5.7 Conclusion

This chapter provide the answer to the research question of "*RQ-3: How does driving experience affect driving performance in a multi-warning situation?*" the scenario was used a cooperation scenario and the selected warning presentation design was based on current market product. The findings from Experiment 1 suggest that inexperienced drivers are easily negatively impacted by multi-warning situations compared to experienced drivers. Although multi-warning mode improved the driver's reaction time, their behavioural decision-making judgment of the scene did not improve, and more inappropriate response behaviours were observed. This could be because there is no priority between the two warnings when they exist simultaneously, and further judgment is required based on the current driving scene. For experienced drivers, this process may increase their cognitive workload, but they put in less effort to control the vehicle than inexperienced drivers. Therefore, additional judgment on the warning may easily lead to confusion and interfere with inexperienced drivers' decision-making. Moreover, both driver groups showed a preference for the multi-warning mode, indicated that this type of warning could enhance driving awareness and safety. Therefore, it is necessary to investigate how to design such warning situations. Experiment 1 indicated that inexperienced drivers were more easily affected by multi-warning situations. Therefore, the main focus of participants recruited for Experiment 2 was inexperienced drivers. Additionally, Experiment 2 did not only focus on one type of multi-warning scenario, but three types of multi-warning scenarios were tested in Experiment 2.

6 Experiment 2

6.1 Experiment 2 Motivation

Experiment 1 investigated the impact of driving experience on responses to a multiple warning scenario. Participants were divided into two groups based on their driving experience: 18 novice drivers and 14 experienced drivers. They were presented with four warning options, including no warning, two single warning modes, and a multiple warning mode, during a multi-conflict event. The study results showed that driving experience influenced driver performance in various warning mode. Additionally, the occurrence of two warnings simultaneously, even if both were relevant to the current driving scenario, could impair a driver's ability to decision-making. This effect was particularly significant for inexperienced drivers. This may be due to the fact that inexperienced drivers do not have flexible visual strategies and they tended to focus more on the road immediately in front of their vehicle (Falkmer and Gregersen 2001). Regardless of how complex the driving situation was, they may not have been able to effectively adjust their visual attention to changing driving conditions, which could have potentially limited their ability to perceive and respond to hazards on the road. And, when two warnings are presented simultaneously, inexperienced driver may not be able to attend to the warning in a timely manner, leading to difficulty in correctly understanding and responding to subsequent warnings. Furthermore, since there is no displayed priority among ADAS warnings, the driver needs to judge the priority between warnings, which may increase the driver's cognitive load and lead to negative effects.

First of all, to compensate for the inexperienced driver's lack of driving visual retrieval ability, displaying all driving information on the HUD could potentially shorten the display glance time, improve driving performance and response speed, and reduce workload. For example, displaying BSM on the HUD could help drivers retrieve warnings faster. However, this is not the main approach used in this experiment to improve driver understanding of multi-warning. The main objective of Experiment 2 is to investigate which display method can help drivers better comprehend the urgency between warnings in a multi-warning situation, i.e., to better distinguish priorities.

Using colour to code visual warnings is a common way for people to differentiate urgency in everyday life. Design guidelines in ANSI Z535 recommend using red for hazards, orange for warnings, and yellow for caution. Chapanis (1994) studied how colour cue affects people's ability to differentiate between urgency and found that red and orange shades evoke a greater sense of danger than yellow and white. Similarly, Braun and Silver (1995) found that red and orange hues evoke a greater sense of urgency than green. In addition, Chan and Ng (2009) observed that red flashing lights induce a higher sense of urgency compared to yellow and blue flashing lights.

Another effective visual coding method for indicating a sense of urgency is through flashing. Flashlights have been utilized for a long time as a signal encoding technique in the marine, air, and road transportation industries and have been shown to attract attention from a distance (Solomon 2002). Previous research has indicated that flashing lights, as a redundant cue, are more effective at drawing people's attention to a display screen than colour alone (Kiefer 1991). Flashing lights can be used to warn drivers to slow down and give way at railway crossings. Flashing brake lights have been shown to significantly speed up driver reaction times during emergency braking when compared to standard brake lights (Unselt and Beier 2003). Current ADAS use flashing cues, such as two-stage forward collision warning. When the warning is in the early stage, the FCW is displayed on the HUD to remind the driver that the distance between their vehicle and the vehicle ahead is close; when it is upgraded to an urgent warning, the warning starts to flash to warn of an impending collision.

The final method for displaying multiple warning modes is called the "main warning mode". The above approaches use visual codes such as different colours or flashes to mark higher priority warnings, thus focusing the driver's attention on the more urgent warnings. According to ISO/TR 16352:2005, a warning can contain elements that call attention and/or provide operating instructions. In other words, warnings can also provide instructions for action. When two warnings exist at the same time, drivers need additional cognitive workload to judge their relationship due to a lack of prioritization. The main warning mode judges the driving measures that need to be taken by evaluating the priority between the two warnings, and directly guides the behaviour that the driver needs to take with a textual message. For example, in the multiple warning scene of Experiment 1, when BSM and FCW exist simultaneously, the two warnings disappear, and the explanatory text "Slow down, don't change lanes" appears on the HUD. This reduces the steps for the driver to judge the relationship between warnings. This alert design benefits the driver by minimizing the need for the driver to further assess the alert and the current environment, thereby reducing inappropriate behaviour and reaction times due to cognitive overload or misjudgement.

The aim of Experiment 2 is to examine the effects of three warning designs (colour-cue, flashing-cue, and main warning mode) on drivers in multiple warning scenarios, using three types of multiple warning scenarios.

6.2 Method

6.2.1 Warning Design

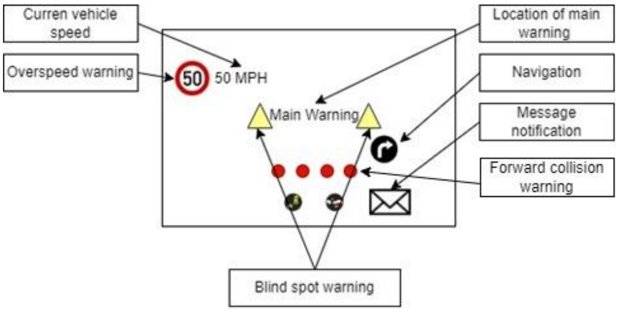
5 warnings were implemented in this experiment:

- Forward collision warning (FCW), as in Experiment 1.
- Blind spot warning (BSM), as in Experiment 1, though the location of BSM was modified and transferred into the HUD (Figure 6-1)
- Message notification, independent from the driving task, to which the participants did not need to make any reaction.

- Overspeed warning (OW), which appeared in the current road section when the current vehicle speed exceeded the limit.
- Navigation, an indicator icon that informed the participants of the next driving task (turn left or turn right).

Furthermore, an automotive HUD graphical interface was integrated into the driving simulator. The initial information display structure design was followed by the real BMW HUD presentation. Figure 6-1 compares the BMW HUD and the designed HUD (cf. Section 6.4 for details of the displayed warnings).

Source: BMWUX[3]



Source: Own authorship

Figure 6-1 Comparison between the BMW HUD and the self-designed HUD in Experiment 2

6.2.2 Apparatus

This experiment inherited the apparatus of Experiment 1. In addition, an eye tracker was also adopted in this experiment in order to collect eye movement data. The eye tracker used is Pupil Core, a wearable eye tracking headset. Participants with corrected sight were asked to wear contact lenses.

3 https://www.bmwux.com/bmw-performance-technology/bmw-technology/bmw-head-up-display-explained/

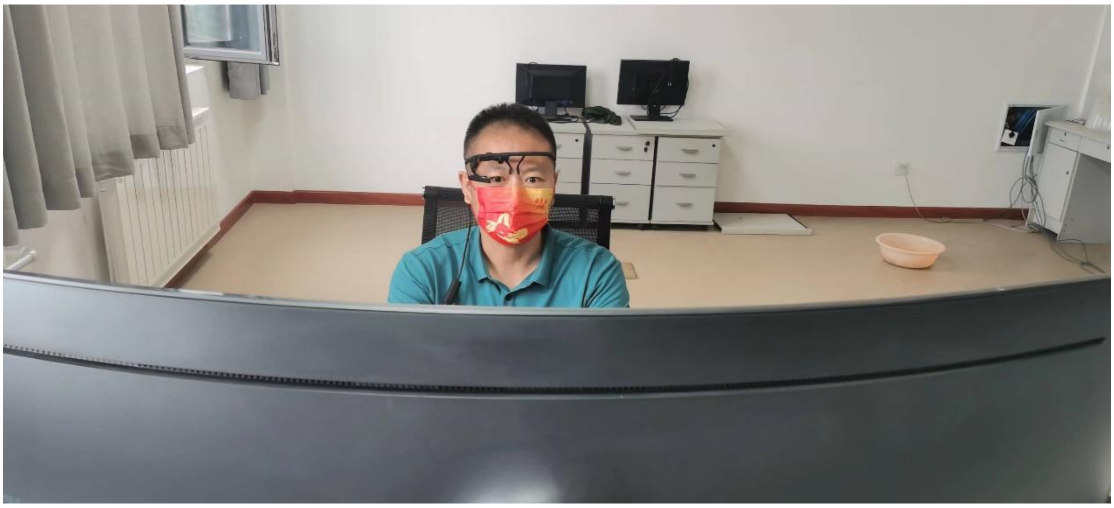


Figure 6-2 A participant with an eye tracker (photo taken with participant's permission)

6.2.3 Scenario Design

In this experiment, three different scenarios were designed: non-conflict and non-cooperation scenario, conflict scenario, and cooperation scenario. The road environment and driving requirements were the same for all scenarios. The road used in the experiment was a one-way dual lane with no oncoming traffic, and participants were instructed to strictly follow traffic signs. The speed of the participant's vehicle was set to 50 mph using cruise control, but the system would be deactivated if the participant pressed the brake pedal. To keep participants within their designated lane, a "maintain the lane" traffic sign was designed, and participants were instructed to maintain their driving within the current lane unless instructed otherwise by warnings or traffic signs.

After approximately 20 seconds of driving, a leading vehicle would appear, and participants were asked to follow it. Another vehicle would be present in the adjacent lane behind the participant's vehicle, with a distance of about three cars, as in Experiment 1.

A multi-warning scenario was then introduced, with a trigger time interval of approximately 2.67 seconds between the two warnings. This interval was selected based on previous research (Fitch et al. 2014) and real-world applications of similar warnings.

- Non-conflict and non-cooperation scenario

A message notification was first presented, followed by an overspeed warning. Vehicles in the environment (the leading vehicle and the adjacent lane vehicle) showed no changes in behaviour and kept moving at a constant speed.

- Conflict scenario

After following the leading vehicle for about 7s, the adjacent lane vehicle started to accelerate uniformly. The BSM was triggered after about 3 seconds. After about 2.67s, the navigation system was presented to inform the participants to change to the lane with vehicles in the blind spot.

- Cooperation scenario

The Cooperation scenario is the same as that in Experiment 1 (cf. Section 5.4.2 for details).

6.2.4 Experimental Procedures

Similar to the procedures in Experiment 1, the procedures of Experiment 2 required around one hour for each participant. As a preliminary measure, all participants were asked to present their Health Code and the results of their body temperature measurement upon arrival to meet COVID-19 prevention requirements. After that, they were given a consent form to review and sign, which informed them of the experimental procedures, data usage, and the risks of the experiment. Participants were then asked to complete a questionnaire designed to collect their demographic data, such as age and driving experience. Contact information was also collected so that participants could be notified in a timely manner if a previous participant was found to be COVID-19 positive. Additionally, the road sign design was explained to the participants before the experiment began.

The next procedure was simulator familiarization (around 10 minutes), during which participants were free to terminate the session immediately if they felt unwell, such as experiencing simulator sickness. During this phase, participants became familiar with the simulator and were asked to provide their own versions of the designed traffic signs to assess whether they were easy to understand. Additionally, if participants failed to follow the signs, the researcher would provide them with instructions.

After the simulator familiarization was completed, the participants received a brief introduction to the warnings that would appear during the experiment, before they underwent warning familiarization (around 10 minutes). In this phase, all warnings that were involved in multi-warning scenarios appeared individually. The display of FCW and BSM followed the procedures in Experiment 1. As for the display of the overspeed warning, the researcher prompted the participants to notice the speed sign and told them to slow down when the warning appeared. When the navigation warning was displayed, the researcher prompted the participants to notice the direction, as pointed out by the icon, and told them to change the lane when the warning appeared. During the display of the information notification, the researcher prompted the participants to notice the envelope-like icon and told them that no action was to be taken when the warning appeared. Additionally, the participants were asked to wear an eye tracker during this phase. Before the eye-tracking recording started, the participants were required to pass a calibration procedure, it allows the eye tracker to accurately track a participant's eye movements. The calibration process helps the eye tracker learn and adjust for the unique characteristics of an individual's eyes, such as the size, shape, and position of the pupils and corneas. During the calibration procedure (around 5 minutes), the participant is instructed to sit in front of the computer screen and position their head in a fixed position relative to the screen. Eye tracker device displays a series of points or stimuli on the screen, and the participant is asked to look at each point or stimulus in turn. Once the calibration points have been viewed, the Pupil eye tracker device analyses the recorded eye movement data to determine the characteristics of the participant's eye movements. Based on the analysis of the recorded data, the Pupil eye tracker device adjusts its tracking algorithms to account for any individual differences in the participant's eye movements. The calibration process is typically repeated two or three times to ensure accuracy.

After a 10-minute break, the participants began the experiment scenarios. They needed to complete a total of 3 scenarios. During the experiment (around 25 minutes), the researcher remained in the room without giving any instructions to the participants. After the scenarios were completed and before they were leaving, the participants were required to complete another questionnaire designed to assess their subjective attitudes towards the warnings. After the participants left, all the instruments that the participants touched were sanitized.

6.2.5 Measurement and Assessment Criteria

6.2.5.1 Reaction Type (RT)

This measurement was conducted for both conflict scenarios and cooperation scenarios. In a conflict scenario, a direct lane change would result in a potential collision due to the presence of vehicles in the blind spot. In the cooperation scenario, similar to Experiment 1, the tested vehicle has low priority on the road, requiring the correct response of braking and waiting for vehicles in the blind spot to pass before changing lanes. However, the non-conflict and non-cooperative scenario does not measure this aspect, as the driver in this scenario only needs to slow down through the braking reaction.

6.2.5.2 Initial Reaction Time (IRT)

Different from Experiment 1, Experiment 2 defined the initial reaction time (IRT) as the duration from the appearance of the multi-alarm mode to the moment when the participant started pressing the brake pedal or rotating the steering wheel. An ANOVA was used to analyse the percentage differences of IRT in each warning mode.

IRT is calculated using the following formula:

$$\textbf{Mean reaction time} = T_{Driver\ starts\ to\ react} - T_{when\ multi-warning\ displayed}$$

6.2.5.3 Eye Movement Data

Two gaze areas were defined: the HUD area and the Environment area. Their definitions are illustrated in Figure 6-3. Subsequently, gaze frequencies (also known as fixation rates) were captured in this experiment. Gaze frequency refers to the frequency of changes in the participant's gaze positions, specifically the number of gaze positional changes from the HUD area to the Environment area. In the non-conflict and non-cooperative scenario, the measurement of gaze frequencies was not conducted for specific reasons. Firstly, in this scenario, there were no road signs indicating the speed limit, eliminating the need for participants to shift their gaze between the HUD area and the Environment area to gather speed-related information. Secondly, since both the warning and informational displays were located in the HUD area, there was no need for participants to switch their gaze between the HUD area and the Environment area. Therefore, the measurement of gaze frequencies was deemed unnecessary for the non-conflict and non-cooperative scenario, as there were no relevant visual cues that required attention diversion.

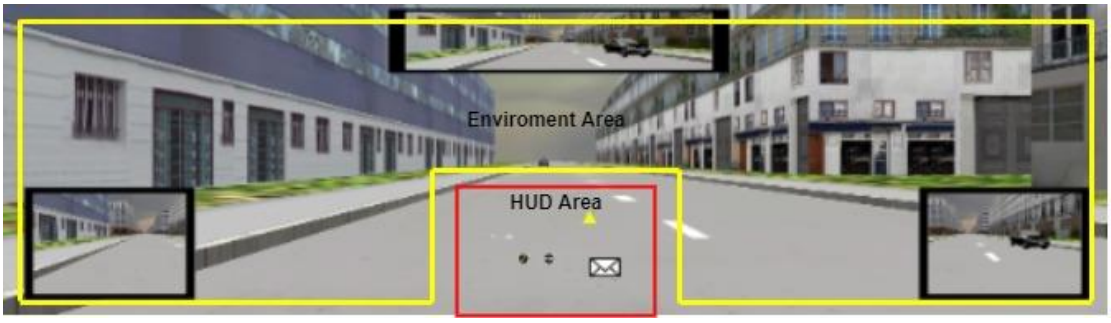


Figure 6-3 A screenshot of defined gaze areas. Inside the yellow box is Environment area and inside the red box is HUD area.

6.3 Experiment 2 Hypothesis

The main warning method is expected to provide advantages to participants overall. This method effectively condenses the meaning of the warning, enhancing participants' comprehension and directly influencing their decision-making in terms of driving behaviour. Consequently, it is anticipated that drivers' shift in focus between the surrounding environment and the warning will be minimized. However, it is hypothesized that the response time for the main warning method may be slower compared to other warning designs. This could be attributed to the additional time required for participants to read and process the content of the warning.

H1: Drivers’ reaction time in the main warning mode is expected to be different from that of other warning designs.

This hypothesis predicts that there will be a difference in drivers' reaction times between the main warning mode and the other warning designs. The main warning mode requires drivers to read and comprehend the warning message, which may take longer than simply noticing a change in abstract warning cues. Therefore, this hypothesize that drivers' reaction times will be slower for the main warning mode compared to the other warning designs.

H2: Drivers’ fixation change in the main warning mode is expected to be less than that of other warning designs.

This hypothesis predicts that there will be a difference in drivers' fixation change between the main warning mode and the other warning designs. Fixation change refers to how often drivers shift their gaze between the warning and the surrounding environment. The main warning mode presents a more explicit and direct warning message, which may reduce the need for drivers to frequently check the abstract warning cues or their surroundings. Therefore, this hypothesize that drivers' fixation change will be less for the main warning mode compared to the other warning designs.

6.4 Experiment Design

To investigate the most suitable warning display design for various warning scenarios, 4 sets of warning schemes are applied to 3 different types of warning scenarios. There are 4 warning modes studied in this experiment:

- No change mode (control group): when multiple warnings are present at the same time, the displayed warning remains unchanged.
- Colour-cue mode: when multiple warnings are present at the same time, the warning with the highest priority is displayed in red.
- Flashing-cue mode: when multiple warnings are present at the same time, the warning with higher priority flashes at a frequency of 1hz.
- Main warning mode: when multiple warnings are present at the same time, the triggered warning disappears, and a main warning in one language is displayed, summarizing the meaning of the triggered warning.

Moreover, a between-group design will be used in this experiment to differentiate driving behaviour under different warnings. A between-group design means that different participants are assigned to different groups, with each group receiving a different warning display design. In this case, the participants will be divided into groups based on the warning display design they receive. This design allows the researchers to directly compare the performance of the different groups on the various warning scenarios. On the other hand, a within subject design means that the same participants are exposed to all of the different warning display designs, and their performance is compared across these designs. This design is useful when the researcher wants to control for individual differences between participants and focus on the effects of the manipulation. However, it may not be appropriate for this study, as it could introduce confounding variables, such as learning effects, order effects, or fatigue. Data analysis will employ chi-square for the difference in reaction types and ANOVA to analyse initial reaction time and brake reaction time, with alpha set at 0.05.

Table 6-1, 6-2 and 6-3 show the icons of the warning design in the driving simulator.

Table 6-1 Icons used in the non-conflict and non-cooperation scenario

Non-conflict and non-cooperation scenario		
	Speeding warning (High priority)	Message notification (low priority)
Control group		
Colour mode		
Flashing mode	 Flashing (frequency: 1Hz)	
Main warning mode	"Overspeeding, Speed limit is 40" (translated from Chinese)	

Table 6-2 Icons used in the conflict scenario

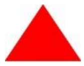
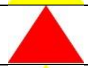
Conflict scenario		
	BSM (High priority)	Navigation indicator (low priority)
Control group		
Colour mode		
Flashing mode	Flashing (frequency: 1Hz)	
Main warning mode	"Turn Left, be careful about the blind spot" (translated from Chinese)	

Table 6-3 Icons used in the cooperation scenario

Cooperation scenario		
	BSM (High priority)	FCW (low priority)
Control group		
Colour mode		
Flashing mode	Flashing (frequency: 1Hz)	
Main warning mode	"Slow down, do not change the lane" (translated from Chinese)	

6.5 Results of Experiment 2

6.5.1 Participants

A total of 32 healthy drivers participated in the experiment. No participants dropped out of the experiment, so the final sample consisted of 25 men and 8 women with different occupations and educational levels.

Participants were divided into 4 groups, each with 8 persons:

1. Control Group: age M = 28.1, SD = 7.89，driving experience M = 4, SD = 1.83
2. Colour-cue group: age M = 29.5, SD = 7.26，driving experience M = 4.1, SD = 2.23
3. Flashing-cue group: age M =33, SD = 5.27，driving experience M = 4.6, SD = 1.9
4. Main warning group: age M = 30.05, SD = 6.998，driving experience M = 4.35, SD = 2.04

Further analyses of the experiment to examine its between-group design showed statistically insignificant differences in age (F=0.442, p = 0.14 > 0.05) and driving experience (F=0.55, p = 0.23 > 0.05) among the 4 groups of participants.

6.5.2 Reaction Type

6.5.2.1 Conflict Scenario

No collisions occurred for all 32 participants. 2 participants in the control group and 1 participant in the colour-cue group performed a lane change, which was not detected in the flashing-cue group and the main warning group. A Chi-Square test was performed to assess the relationship between multi-warning display and initial reaction type. There was no signification relationship between the two variables, χ^2 (3, N=32) = 4.046, p = 0.257 > 0.05).

6.5.2.2 Cooperation Scenario

No collisions occurred for all 32 participants. 2 participants in the control group and colour-cue mode performed a lane change, which was not detected in other two groups. No signification relationship was found between the multi-warning display and initial reaction type, χ^2 (3, N=32) = 4.315, p = 0 .229 > 0.05).

6.5.3 Initial Reaction Time

6.5.3.1 Non-conflict and Non-cooperation Scenario

A total of 32 data points were collected during the experiment. The mean reaction time (IRT) for the control group was 1.62 s (SD = 0.46), for the colour-cue group was 1.6 s (SD = 0.28), and for the main warning group was 1.58 s (SD = 0.44). In comparison, the flashing-cue group exhibited the shortest reaction time, with a mean of 1.41 s (SD = 0.37).

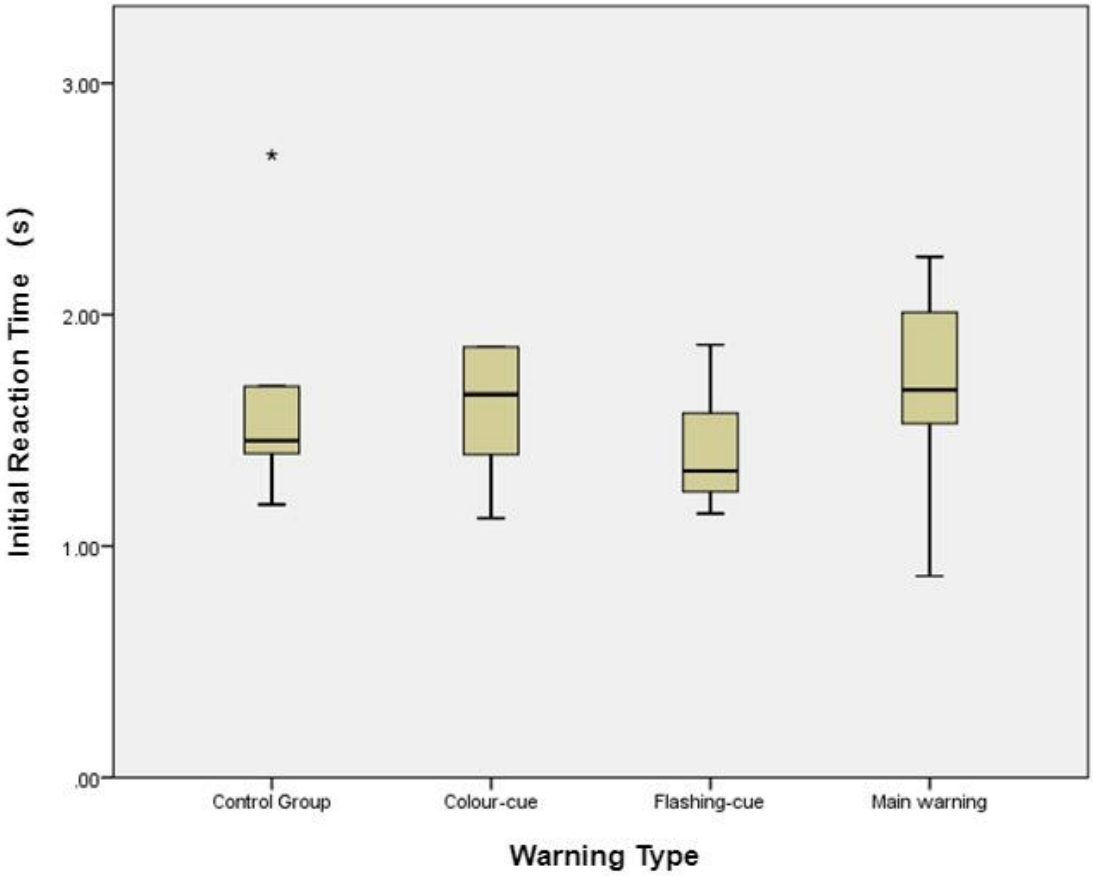


Figure 6-4 Initial reaction time of the four experimental groups in the non-conflict and non-cooperation scenario

No statistically significant differences were observed between the four groups, F (3, 32) = 0.844, p = 0.481 > 0.05).

6.5.3.2 Conflict Scenario

A total of 32 data points were collected during the experiment and no collisions were observed. The mean reaction time (IRT) for the control group was 3.17 s (SD = 0.53), for the colour-cue group was 3.2 s (SD = 0.8), and for the flashing-cue group was 2.8 s (SD = 0.72). In comparison, the main warning group exhibited the shortest reaction time, with a mean of 2.31 s (SD = 0.3).

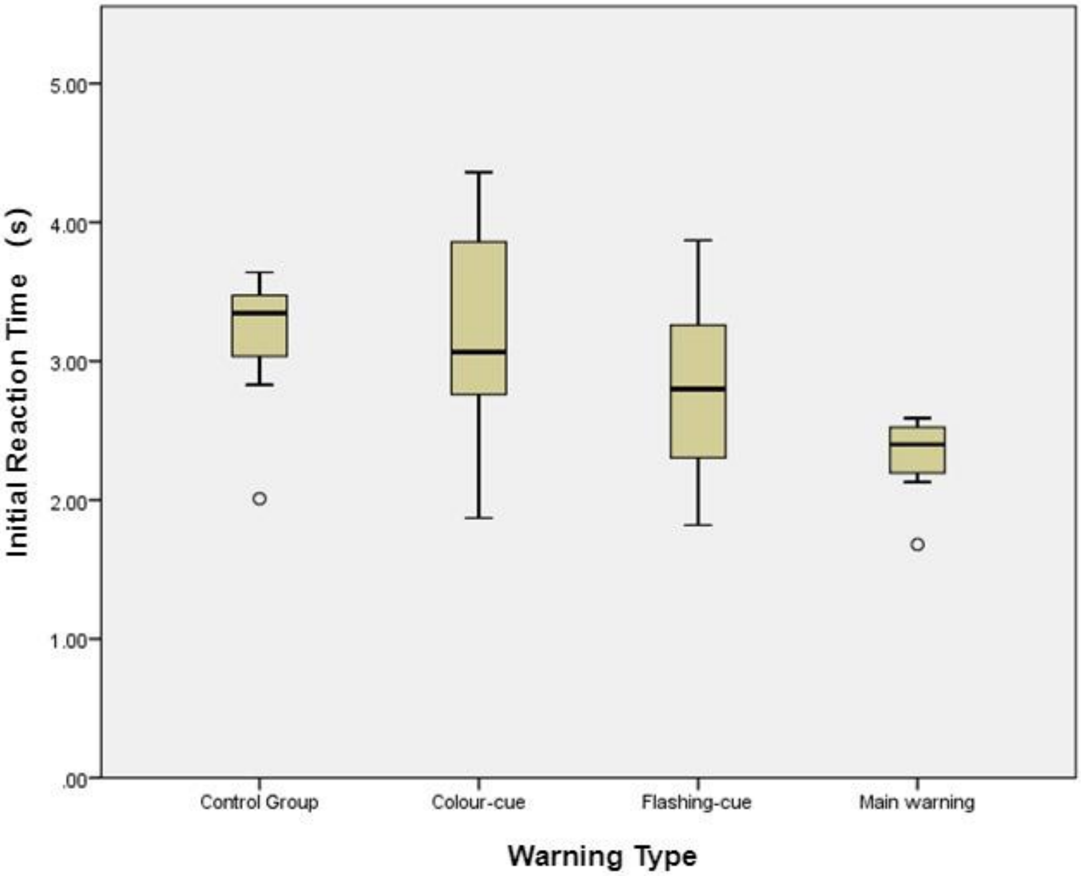


Figure 6-5 Initial reaction time of the four experimental groups in the conflict scenario

Statistically significant differences were observed in the IRT results in the conflict scenario, F (3, 32) = 3.61, p = 0.025 < 0.05. Further analysis only revealed that the IRT of the main warning mode showed significant differences from that of the control group (M = 0.86, SD = 0.31, p = 0.01) and that of the colour-cue group (M = 0.89, SD = 0.31, p = 0.008). In other words, the reaction time of the main warning mode is significantly shorter than that of the no change mode and the colour-cue mode in the conflict scenario. However, no difference was found between flashing-cue mode and main warning mode (M = 0.49, SD = 0.31, p = 0.123). And no difference has found in control group and colour-cue mode, M = .3, SD = .31, p = 0.923; control group and flashing-cue mode, M = 0.37, SD = 0.31, p = 0.242; colour-cue mode and flashing-cue mode, M = 0.4, SD = 0.31, p = 0.207.

6.5.3.3 Cooperation Scenario

No collisions were observed under cooperation scenario. The mean reaction time (IRT) for the control group, colour-cue group, and flashing-cue group was 1.33 s (SD = 0.53), 1.34 s (SD = 0.39), and 1.36 s (SD = 0.43), respectively. In contrast, the main warning group exhibited the longest reaction time, with a mean of 2.04 s (SD = 0.61).

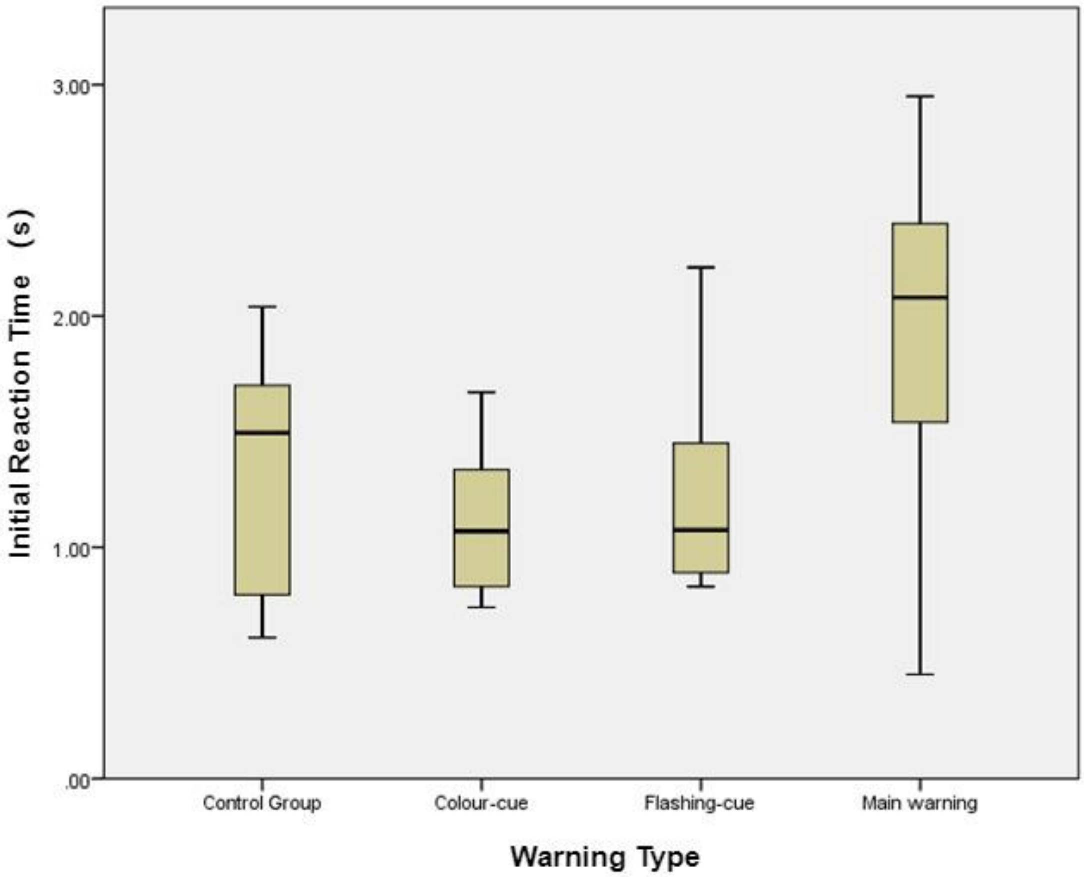


Figure 6-6 Initial reaction time of the four experimental groups in the cooperation scenario

Statistically significant differences were observed in the reaction time (IRT) results in the cooperation scenario, $F(3, 32) = 2.896$, $p = 0.019 < 0.05$. Further analysis revealed that the IRT of the main warning mode showed significant differences compared to other warning modes: control group (M = 0.71, SD = 0.25, p = 0.008), colour-cue mode (M = 0.69, SD = 0.25, p = 0.009), and flashing-cue mode (M = 0.68, SD = 0.25, p = 0.011). However, no significant differences were found between the other warning modes: control group and colour-cue mode (M = 0.02, SD = 0.25, p = 0.94), control group and flashing-cue mode (M = 0.04, SD = 0.25, p = 0.885), and colour-cue mode and flashing-cue mode (M = 0.02, SD = .25, p = 0.944).

6.5.4 Fixation frequency (FF)

6.5.4.1 Conflict Scenario

A total of 32 pieces of data were collected during the experiment. The fixation frequencies of the control group, the colour-cue group, the flashing-cue group, and the main warning group were 4.87 times (SD = 1.81), 4 times (SD = 1.85), 2.5 times (SD = 0.93), and 1.87 times (SD = 0.64), respectively.

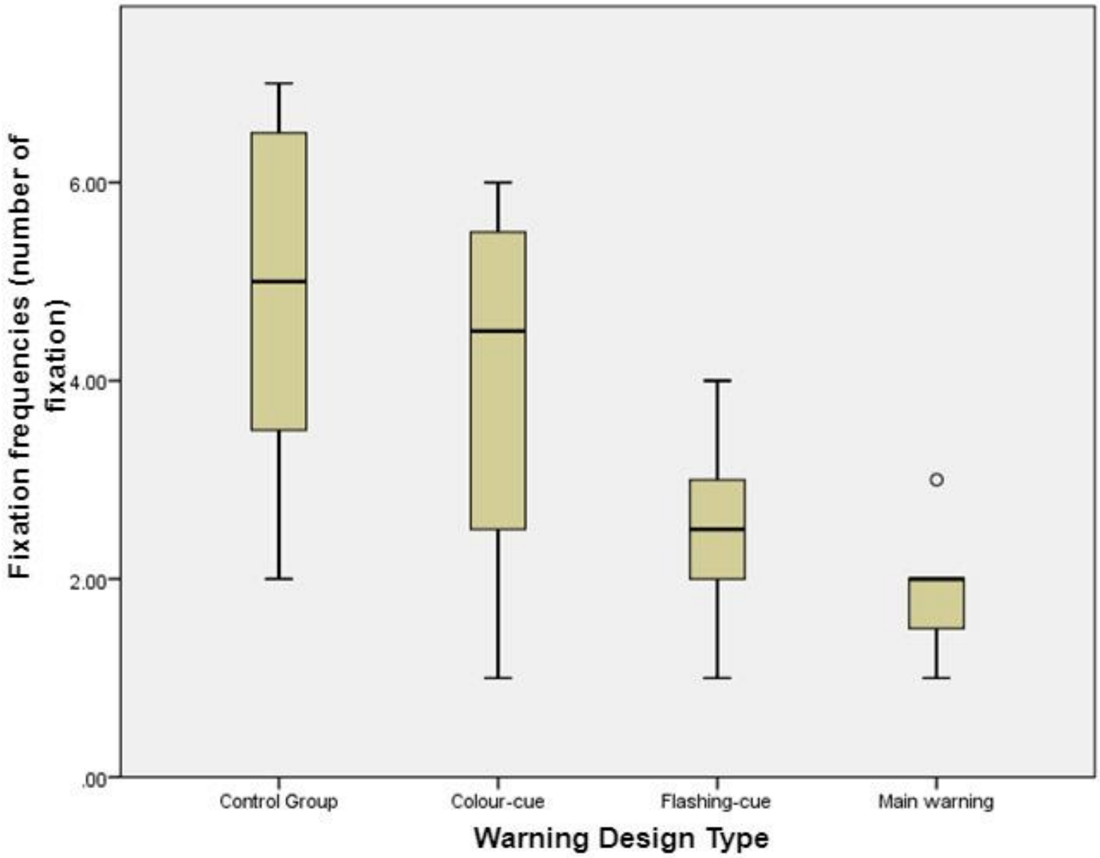


Figure 6-7 Fixation frequencies of the four experimental groups in the conflict scenario

Statistically significant differences were found in the FF results of the conflict scenario, F (3, 32) = 45.125, p = 0.001 < 0.05. Further analysis revealed that the control group had significantly different FF compared to the flashing-cue group (M = 2.38, SE = 0.71, p = 0.002) and the main warning group (M = 3, SE = 0.71, p = 0.001). Additionally, the colour-cue group showed significant differences in FF compared to the flashing-cue group (M = 1.5, SE = 0.71, p = 0.042) and the main warning group (M = 2.13, SE = 0.71, p = 0.005). No significant differences were observed between the control group and the colour-cue mode (M = 0.88, SE = 0.71, p = 0.225), as well as between the flashing-cue mode and the main warning mode (M = 0.63, SE = 0.71, p = 0.383).

6.5.4.2 Cooperation Scenario

A total of 32 pieces of data were collected during the experiment. The fixation frequencies of the control group, colour-cue group, flashing-cue group, and main warning group were 1.75 (SD = 0.71), 2.13 (SD = 0.99) (the second most frequent), 1.88 (SD = 0.83), and 1.75 (SD = 0.46) times, respectively. In the cooperation scenario, no statistically significant differences were observed in the FF results, as indicated by the ANOVA analysis ($F(3, 32) = 45.125$, $p = 0.742 > 0.05$).

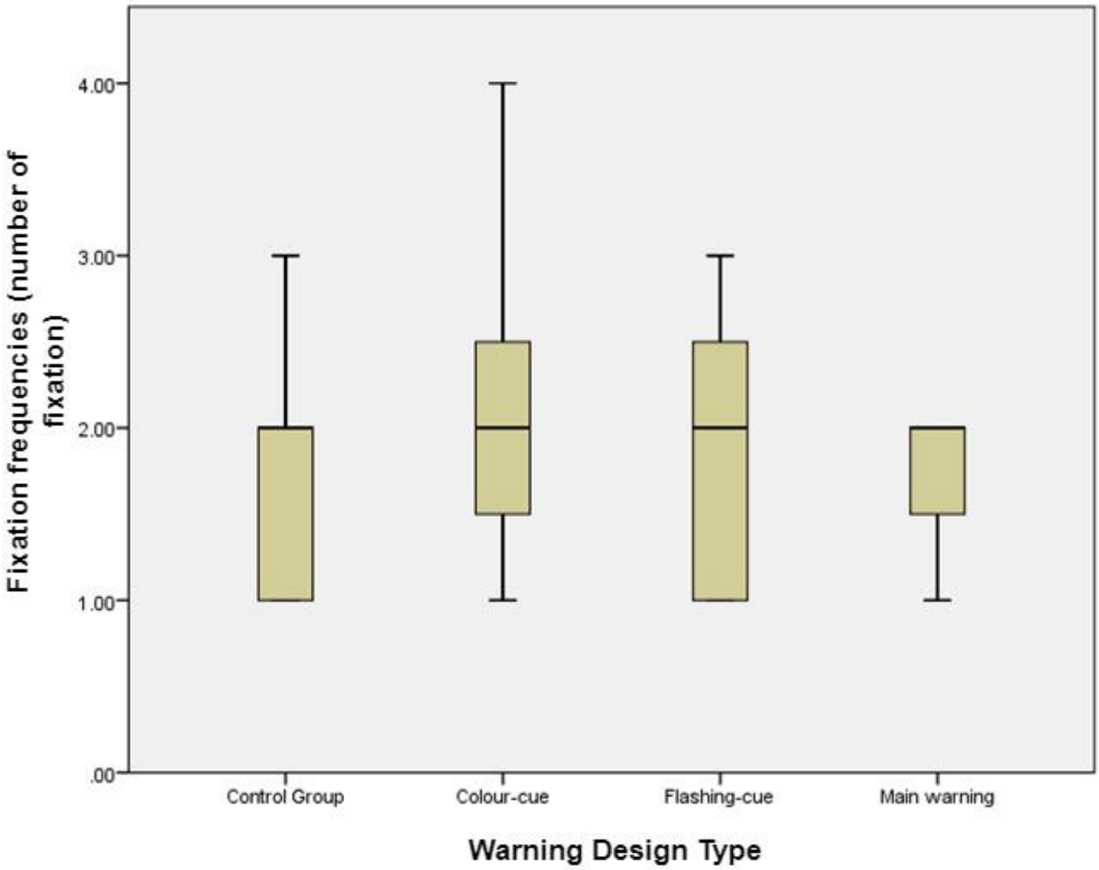


Figure 6-8 Fixation frequencies of the four experimental groups in the cooperation scenario

6.6 Discussion

In Experiment 2, a total of 32 drivers were assigned to four groups to investigate the effects of different warning designs in various multi-warning scenarios. Experiment 2 aimed to identify the most suitable design method for the multiple-warning model by examining three potential future multiple-warning scenarios based on the ontology developed in this study. The participants consisted mainly of drivers with approximately 4 years of driving experience.

Regarding H1, it was observed to be applicable only in certain scenarios. Firstly, the results based on the initial reaction time indicated no differences in reaction time among the four warning mode groups in non-conflict and non-cooperative scenarios. This can be attributed to the relatively lower cognitive load in these driving scenarios. Despite the presence of two warnings simultaneously, they did not interfere with each other, and there was minimal interaction between the driver and the driving environment. Consequently, different display designs did not significantly impact the drivers' reactions under such scenario. However, H1 was partially observed in conflict scenarios. Although there were no differences in the type of initial reaction across the 4 groups of drivers, the analysis of IRT results revealed that the main warning group exhibited the shortest reaction time among all warning modes. Further analysis indicated significantly shorter reaction times for the main warning mode compared to the control group and colour-cue mode. It is worth noting that no significant differences were found between control group and colour-cue mode, as well as between the control group and flashing-cue mode. These marked differences in reaction times observed in conflict scenarios provide evidence supporting the hypothesis that the main warning mode elicits different reaction times compared to other warning designs. In contrast, the positive effect of the main warning mode on reaction times was not observed in the cooperation scenario. In this scenario, there were no differences in the initial reaction types among the four warning mode groups. However, the main warning mode exhibited the longest reaction time compared to the other warning modes. This suggests that the additional time required for participants to read and process the content of the warning message contributed to the longer reaction times. On the other hand, the control, colour-cue, and flashing-cue groups demonstrated relatively shorter reaction times. Further analysis revealed significant differences in reaction times between the main warning mode and the other warning modes. Participants in the main warning mode exhibited significantly longer reaction times compared to the control group, colour-cue mode, and flashing-cue mode. This implies that although the main warning mode provides more information and enhances comprehension, it leads to delayed responses compared to the other warning modes.

H2 was also only observed in conflict scenarios. The FF results in conflict scenarios showed statistically significant differences among the control, colour-cue, flashing-cue, and main warning groups. Further analysis of pairwise comparisons revealed specific differences between the groups. The control group exhibited significantly different FFs compared to the flashing cue and main warning groups. This indicates that the control group, which did not receive any specific warning design, had a higher frequency of fixation. Additionally, there was a significant difference in FF in the colour-cue group compared to the flashing-cue group and the main warning group. This suggests that the colour-cue mode has different effects on participants' FF compared to the flashing-cue mode and the main warning mode, resulting in a higher frequency of fixation. Furthermore, no significant differences were observed between the control group and the colour-cue mode, indicating that both conditions had similar effects on participants' FF. Similarly, no significant difference was found between the flashing-cue mode and the main warning mode. In contrast, H2 was not observed in the cooperative scenario, as no significant difference in FF was found. This suggests that drivers maintained a relatively consistent level of attention to warning and the driving environment, regardless of the warning mode to which they were exposed. In the cooperative scenario, the different warning designs did not significantly influence the frequency of gaze shifts between the warning and the surrounding environment. This may be attributed to the collaborative nature of the scenario, where drivers were more focused on cooperative driving tasks and interactions with other drivers, leading to a similar allocation of attention across the warning designs.

In the established multi-warning scenario, conflicting warnings can be considered as a form of complexity, but this complexity specifically pertains to the interactions between the warnings themselves. It is important to note that in such driving scenarios, there is typically only one potential hazard to be addressed. Conversely, the cooperation scenario represents a different form of complexity, which involves the complexity of the driving environment. In this scenario, multiple conflicts arise as there are two potential hazards that need to be managed simultaneously. The findings from the experiment suggest that the main warning mode may be more suitable when dealing with complexity arising from the interactions between warnings. However, when the driving scene becomes more complex due to the presence of multiple hazards, it may be more appropriate to apply cues that prioritize the more urgent warning.

6.7 Conclusion

In conclusion, the second experiment aimed to address the research question of "RQ-4: How should warnings be designed under multi-warning situations?" The findings provide valuable insights into the design of warnings for multi-warning scenarios, with a focus on the effects of different warning modes on driving performance. The results showed that the impact of warning designs varied depending on the driving scenario. In non-conflict and non-cooperative scenarios, where the cognitive load was relatively low, the different warning modes did not significantly affect drivers' reaction times. This suggests that the simultaneous presence of two warnings did not interfere with each other, and drivers were able to effectively process the warnings without major performance differences among the warning modes. However, in conflict scenarios, the main warning mode demonstrated the shortest reaction times compared to other warning designs. This indicates that emphasizing the main warning can lead to quicker responses from drivers. On the other hand, in the cooperation scenario, the main warning mode resulted in longer reaction times compared to other modes. This suggests that the additional information provided by the main warning, while enhancing comprehension, also led to delayed responses. Therefore, the design of warnings should consider the specific scenario and strike a balance between providing necessary information and maintaining prompt reaction times. Regarding the FF, the results showed that in conflict scenarios, the control group had a higher frequency of fixations compared to the flashing-cue and main warning groups. This suggests that specific warning designs can influence drivers' attention allocation. However, in the cooperative scenario, no significant differences in FF were observed among the warning modes, indicating a consistent level of attention allocation across designs.

7 General Discussion and Recommendation

This chapter synthesizes the research findings and offers recommendations derived from the study's investigations into the effects of various warning modes and designs within multi-warning scenarios in the context of ADAS.

To augment the foundation of this research, recent insights in the ADAS field have underscored the necessity of understanding the intricate interactions between ADAS technologies, driving tasks, and potential sources of distraction. This research embraced an ontology-based approach, combining driving task ontology and driving distraction ontology. This approach has emerged as an increasingly relevant framework for comprehensively delineating ADAS's role within the complex landscape of driving contexts. The fusion of driving task ontology and driving distraction ontology enabled a holistic exploration of how ADAS interfaces with driving tasks and potential distractions, thereby fostering a comprehensive understanding. This holistic understanding not only aligns with contemporary developments in ADAS but also forms a robust foundation for well-informed ADAS warning system design and countermeasures to mitigate distractions.

This research further extended these insights by methodically creating multi-warning scenarios, underpinned by ontological constructs. This innovative and systematic approach enabled the generation of actionable insights into the multifaceted domain of multi-warning system design. By subjecting a diverse array of warning designs to rigorous scrutiny within these meticulously constructed scenarios, this research unveiled discernible pathways to enhance the efficacy of multiple warnings within the context of evolving ADAS technologies. This knowledge, firmly rooted in the latest developments in the field, plays an instrumental role in shaping the future of ADAS technology. It serves as a critical guide for the development of intuitive interfaces, thereby enhancing driver comprehension and response to simultaneous warnings, aligning with the ever-evolving landscape of ADAS technologies.

Furthermore, recent research in the ADAS domain has shed light on the critical influence of driving experience on responses hazard and ADAS (Pammer et al. 2018; Muttart 2020; Deng et al. 2021). The findings resonate with these recent insights, as the result observed distinct responses between novice and experienced drivers under multi-warning scenarios. These observations emphasize the imperative need for personalized considerations in warning system design. Notably, the provision of guidance and support for less experienced drivers has emerged as a crucial requirement, aligning with the evolving emphasis on safety and effectiveness in ADAS systems.

Recent investigations in ADAS have also revealed that the efficacy of warning designs is contingent upon specific driving scenarios (Reinmueller et al. 2018; Azevedo-Sa et al. 2021; Currano et al. 2021). In light of these insights, this research delved into conflict and cooperation scenarios, where certain designs exhibited efficacy in eliciting rapid responses, while trade-offs between comprehensibility and response times were evident. The relevance of tailoring warning designs to suit particular scenarios has been reaffirmed in this research, aligning with the evolving trends in ADAS. Furthermore, the critical consideration of warning priorities and their impact on driver responses and attention allocation resonates with contemporary discussions. Striking a balance between providing comprehensive information and facilitating timely responses has emerged as a prominent design challenge, necessitating the careful curation of warning content and visual cues.

By anchoring the recommendations in the latest insights and developments within the ADAS field, this research aims to contribute to the ongoing discourse on ADAS design, thereby enhancing the safety and efficacy of these systems in the context of evolving driving environments.

One potential guideline is the potential benefits of structured training and guidance for drivers in utilizing and responding to diverse warning designs. The provision of clear instructions and didactic resources can augment driver comprehension and utilization of ADAS warning systems.

To build on these findings, integrated recommendations are proposed for future research and practical implementations:

1. Individualized Considerations:

In the realm of multi-warning system design, it is imperative to recognize the profound impact of individual factors such as driving experience, age, and cognitive abilities on how drivers respond to warnings. To address this, future warning systems should be adaptive, acknowledging and accommodating these individual differences. For instance, customizable settings can empower drivers to tailor warning preferences, aligning with their comfort levels and experience. Additionally, offering enhanced support and guidance within the warning system, particularly for less experienced drivers, can prove beneficial. This support might encompass interactive tutorials, real-time feedback mechanisms, and adaptive adjustments based on individual responses, fostering a safer and more effective driving experience for all.

2. Scenario-Adaptive Design:

The adaptive nature of warning systems should extend to different driving scenarios, each of which presents varying demands in terms of attention and response times. By recognizing these variances, future designs can tailor warnings to align with specific scenarios. For high-risk situations like heavy traffic or adverse weather conditions, warning designs that prioritize immediate and concise alerts can ensure swift driver responses. In contrast, in less critical scenarios characterized by lower cognitive load, warning designs can offer comprehensive information without the need for immediate action. This approach promotes driver comprehension and decision-making without causing undue distraction.

3. Discerning Prioritization:

Within the multi-warning landscape, prioritization of warning content and visual cues plays a pivotal role. Future warning systems should be deliberate in their prioritization efforts, considering the relevance and urgency of each warning. Employing a tiered approach to prioritization, where critical warnings take precedence over less critical ones, can help streamline driver responses. Furthermore, visual cues should be adjusted to match the level of urgency, ensuring that the driver's attention is directed appropriately. Dynamic and adaptive prioritization, which takes into account real-time conditions and the driver's current focus, is essential to prevent overloading them with simultaneous warnings, ultimately enhancing safety and usability.

4. Training Initiatives:

To maximize the effectiveness of ADAS warning systems, comprehensive training programs and educational resources should be implemented. These resources should extend beyond the technical aspects of the warning system and delve into the psychology of driver responses across various scenarios. Special emphasis should be placed on less experienced drivers, who can benefit from tailored training modules aimed at familiarizing them with the system's features and fostering an understanding of how to interpret warnings effectively. Leveraging technology to facilitate training, such as through interactive simulations and virtual environments, provides drivers with the opportunity to practice responding to warnings in a safe and controlled setting, further enhancing their preparedness and competence.

By adopting these integrated recommendations, future multi-warning designs can navigate the complexities of ADAS interactions, ultimately contributing to safer and more efficient driving experiences while accommodating the diverse needs of drivers.

8 Conclusion and Future Work

This research primarily aims to observe the impact of driving experience on drivers' responses to multi-warning scenarios and explore the design of multi-warning modes for future applications. The established ontology provides a comprehensive overview of ADAS driving environments and serves as a foundation for domain knowledge related to ADAS. It enables researchers to construct scenario analyses and conduct reasoning related to ADAS-driving distraction. Two examples of how ADAS can cause distraction are presented in sections 4.2.1 and 4.2.2, addressing Research Question 1.

The ADAS-based ontology also allows for the classification of ADAS warnings, encompassing both ADAS systems and driving task ontology. This classification aids in better understanding and prioritization of ADAS warnings. ADAS-detectable objects are further classified into dynamic traffic flow detection and status detection, with subdivisions such as longitudinal detection, lateral detection, real-time traffic sign detection, driver status monitoring, vehicle status monitoring, and message notification based on driving tasks (Section 4.2.3). The research identifies three typical types of multi-warning scenarios: non-conflict and non-cooperation, conflict, and cooperation scenarios. The establishment of these scenarios addresses Research Question 2.

Experiment 1 (Chapter 5) examines the impact of driving experience on a cooperative multi-warning scenario using a driving simulator. Participants with no relevant ADAS experience undergo a within subject experimental design involving four warning modes: no warning mode (control group), FCW-only mode, BSM-only mode, and multi-warning mode. The multi-warning mode, aimed at improving drivers' perception of the surrounding environment, does not effectively enhance driving behaviour compared to single-warning modes. Inexperienced drivers, in particular, exhibit more inappropriate driving behaviours in the multi-warning mode. The mode's effect on initial behavioural choice is insignificant. While inexperienced drivers express a preference for the multi-warning mode based on questionnaires, they struggle to respond effectively to it. However, less experienced drivers show notably faster reactions in the multi-warning mode, suggesting potential benefits for inexperienced drivers. These findings address Research Question 3.

Based on the results of Experiment 1, the multi-warning mode shows potential for improving driving behaviour and is preferred by participants. Considering potential advances in sensor technologies that may enhance ADAS detection accuracy, optimized warning designs for multi-warning scenarios are crucial. Experiment 2 is designed to explore such optimization. Three warning modes are implemented: colour-cue mode, flashing-cue mode, and main warning mode. Warnings are placed in the HUD to minimize position-related impact, and their priority is established in advance. The experiment adopts a between-group design with four groups: control, colour-cue, flashing-cue, and main warning groups. Eye trackers monitor participants' fixation frequency. The results reveal that in low-complexity driving environments, the three multi-warning modes show no significant differences. However, in high-complexity and urgent multi-warning scenarios, the main warning mode exhibits the longest reaction time and fewer fixation changes compared to the other groups, indicating increased cognitive load. Similar effects are observed with the flashing-cue mode, but it does not show a disadvantage in the cooperative scenario. Therefore, the conclusion of Experiment 2 suggests that using flash prompts to display warnings with the highest priority in the multi-warning mode may be a better approach to multi-warning mode design, addressing Research Question 3.

The future directions of this research encompass several aspects, including considering a wider range of participant groups, exploring new warning designs, incorporating richer scenario designs, and integrating scenarios that combine autonomous driving.

- Considering a wider range of participant groups

Firstly, the drivers recruited for the experimental phase of this study were from China, which has different driving cultural backgrounds compared to countries like the UK where right-hand drive cars are prevalent. While efforts were made to eliminate these differences by stipulating relevant driving standards before the experiment, future research could explore warning designs tailored to specific regions based on participant culture. Furthermore, in Experiment 1, participants were categorized as inexperienced or experienced drivers using the median split method. Future research could consider more range of driving experience group. Furthermore, in Experiment 1, participants were categorized as inexperienced or experienced drivers using the median split method. Due to the challenges posed by the COVID-19 pandemic, a small sample size was used in Experiment 2. It is important to acknowledge the limitations associated with small samples and their impact on generalizability. The participants in this study were carefully selected to represent inexperienced drivers, and although the small sample size restricts the generalization of the findings to a larger population, it allowed for an exploration of the influence of driving experience on responses to different warning designs. In future studies, it would be beneficial to include additional driving experience groups and compare inexperienced drivers with ADAS-related experience or training to experienced drivers without such experience or training.

- Exploring new warning designs

This research primarily focuses on visual early warning as the main modality for warnings, but future research can consider incorporating audio and haptic modes to enhance the warning system. As display technology, such as augmented reality-HUD (AR-HUD), continues to improve, there are opportunities for new displays in automotive research. Previous studies (Schömig et al. 2018; Schneider et al. 2019; Jing et al. 2022) have utilized AR-HUD, indicating its potential for creating new warnings that are visually similar. However, since some warnings may be triggered frequently, the acceptability of warnings by drivers should be carefully considered.

In Experiment 2, the BSM display is incorporated into the HUD instead of the window mirrors. Typically, BSM is designed to alert the driver about vehicles in the blind spot, and the recommended driving behaviour before changing lanes is to check the blind spot using the window mirrors. The intention behind this design change is to compensate for the inexperienced drivers' limited visual retrieval ability. However, it is important to consider that altering the design in this way may potentially impact driving behaviour, as drivers may rely solely on the HUD display and neglect checking their mirrors before changing lanes. Consequently, further testing is necessary in future studies to fully understand the effects and implications of this design alteration.

- Incorporating richer scenario designs

This research focuses on simulating relatively simple road conditions in its scenario design, with a clear differentiation between critical and non-critical situations. However, for future research, it is suggested to incorporate more variables related to road conditions into the scenario design. These variables may include road curvature, traffic density, weather conditions, advertisements, and pedestrians. Previous studies have explored the impact of these variables individually, but their influence on drivers' responses in multiple warning scenarios has not been thoroughly examined. To address this gap, higher fidelity simulators or real-world road studies could be utilized, representing potential avenues for future research in this direction.

Furthermore, this study explores three typical multi-warning scenarios where all warnings hold meaning for the drivers, even though some may not be directly related to the driving task. In future investigations, it would be interesting to explore whether drivers can still discern the urgency of the situation and perform the appropriate driving behaviour when faced with a false warning.

- Integrating scenarios that combine autonomous driving

Integrating scenarios that involve autonomous driving is an important aspect to consider in future research. The introduction of autonomous driving systems significantly reduces the workload for drivers, potentially leading to situations where drivers divert their attention from the road. This can result in drivers being unaware of the current road conditions. Understanding how drivers can react swiftly and effectively when the autonomous driving system fails or needs to be switched to manual mode within a multi-warning scenario presents an intriguing research direction. Exploring strategies to improve drivers' response time and accuracy in such situations would be valuable for enhancing overall driving safety.

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Appendix A Experiment Questionnaire

Experiment Questionnaire

1. The original questionnaire was written in Chinese.

Personal information

年龄：
性别：
驾龄：

Translate in English.

Age:
Gender：
Year of Driving：

2. Subjective measurement

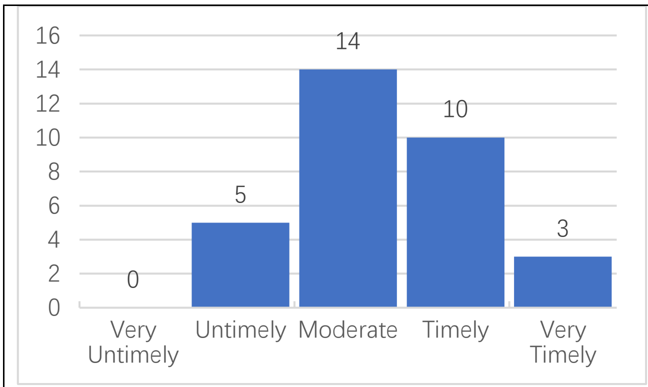
This table uses the Likert scale with 5-point rating.

问题	1	2	3	4	5
前车防碰撞警告是容易被注意到的。(从非常不及时到非常及时)					
盲区检测警告是容易被注意到的。(从非常不及时到非常及时)					
您觉得前车防碰撞警告对您有用吗？(从不太有用到非常有用)					
您觉得盲区检测警告对您有用吗？(从不太有用到非常有用)					
相比较单警告，您更喜欢接收两个警告? (从完全不同意到完全同意)					
两个警告同时触发的时候会让您感到困惑? (从完全不同意到完全同意)					
盲区检测警告让我驾驶分心了。(从完全不同意到完全同意)					
前车防碰撞警告让我驾驶分心了。(从完全不同意到完全同意)					

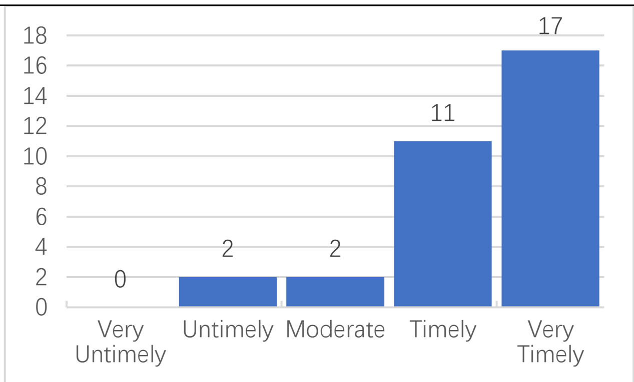
Translate in English

Question	**1**	**2**	**3**	**4**	**5**
Timeliness of blind spot warning (from very untimely to very timely)					
Timeliness of forward collision warning (from very untimely to very timely)					
The usefulness of blind spot warning (from not useful to very useful).					
The usefulness of forward collision warning (from not useful to very useful).					
I would prefer having two warnings if they both can be presented (from totally disagree to totally agree).					
I found it difficult to respond in a two-warning scenario (from totally disagree to totally agree).					
Blind spot monitoring was distracting to me under multi-warning mode (from totally disagree to totally agree).					
Forward collision warning was distracting to me under multi-warning mode (from totally disagree to totally agree).					

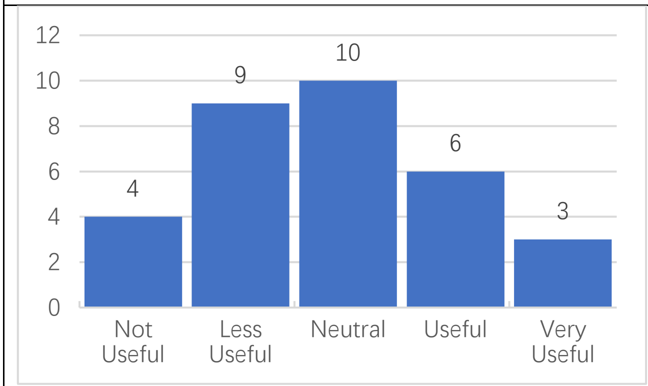
Appendix B The result of the overall questionnaire



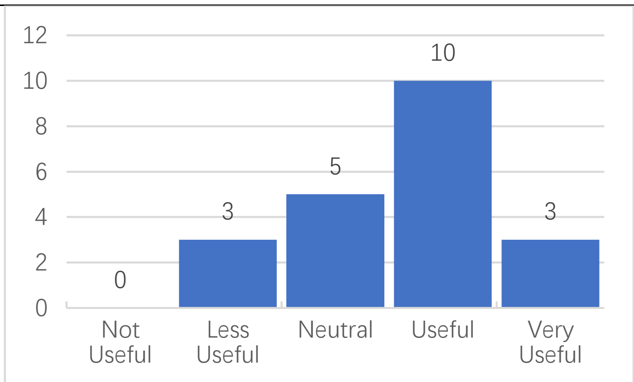
Timeless of BSM



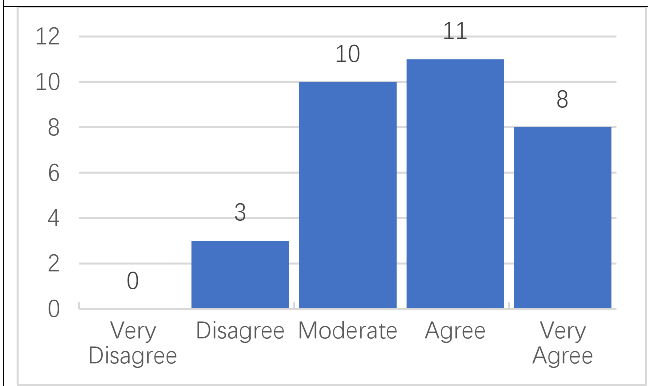
Timeless of FCW



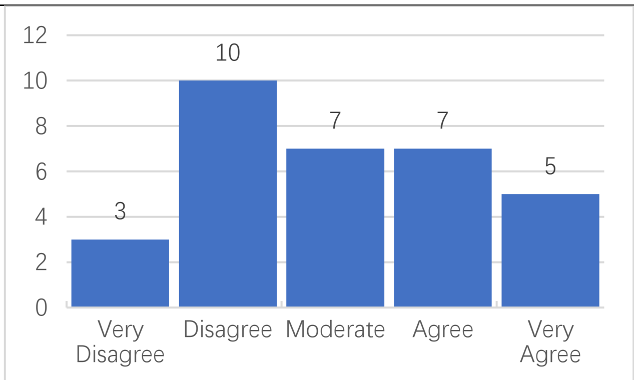
Usefulness of BSM



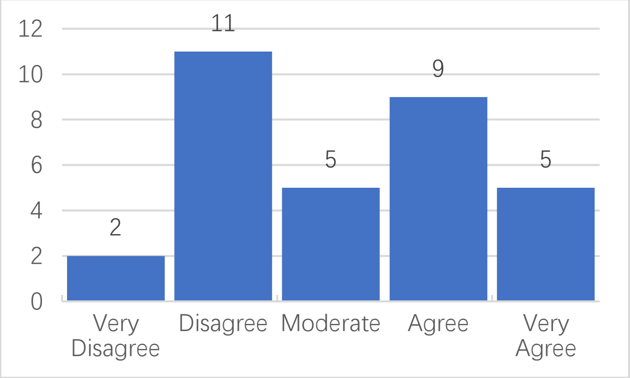
Usefulness of FCW



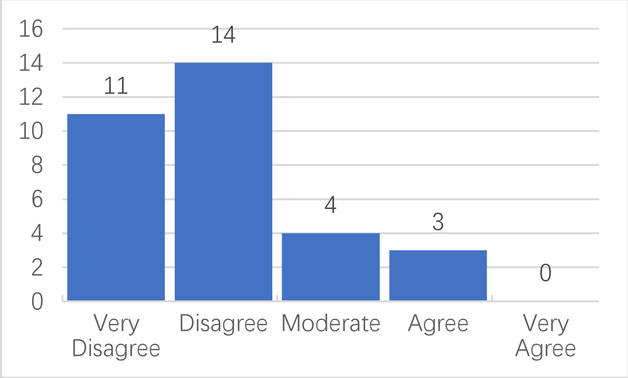
Preference of having multi-warning



Difficulty of responding multi-warning

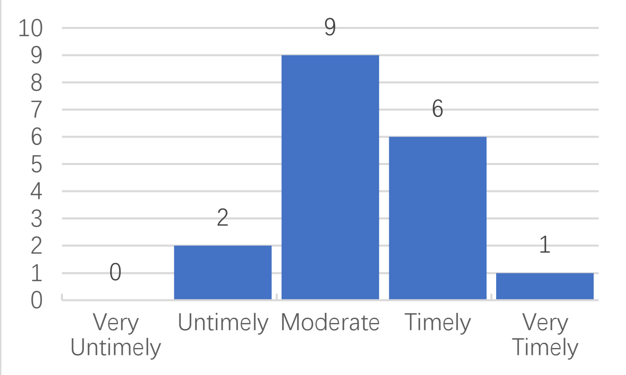


Distracting from BSM

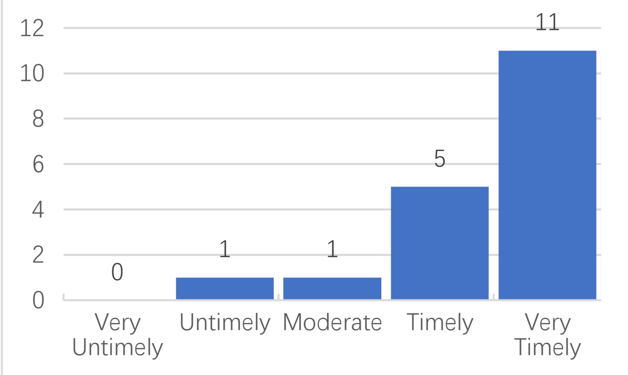


Distracting from FCW

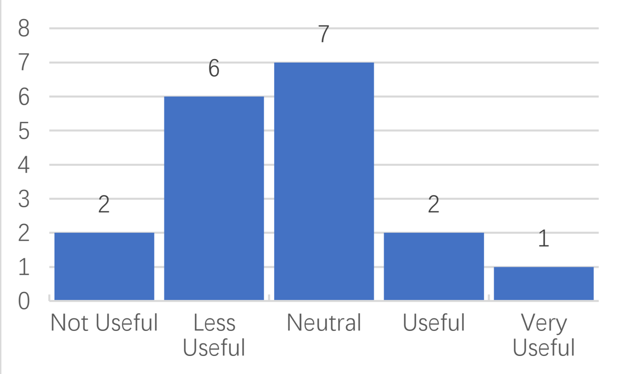
Appendix C The result of inexperienced driver questionnaire



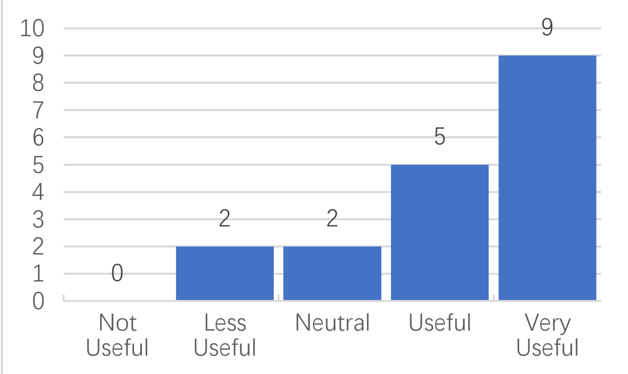
Timeless of BSM



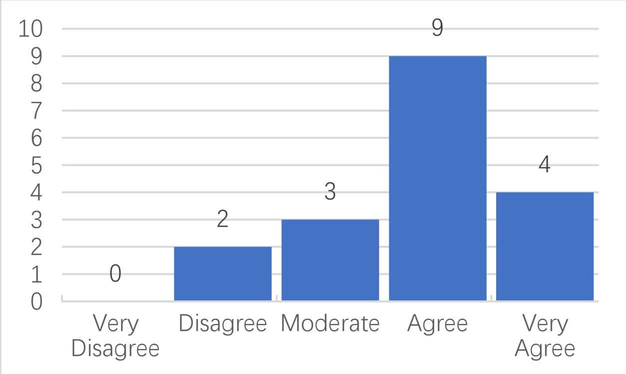
Timeless of FCW



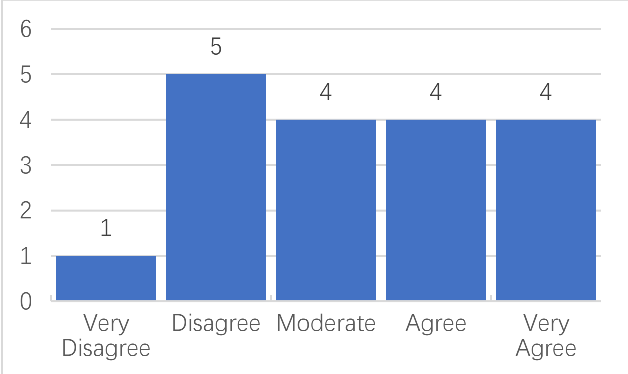
Usefulness of BSM



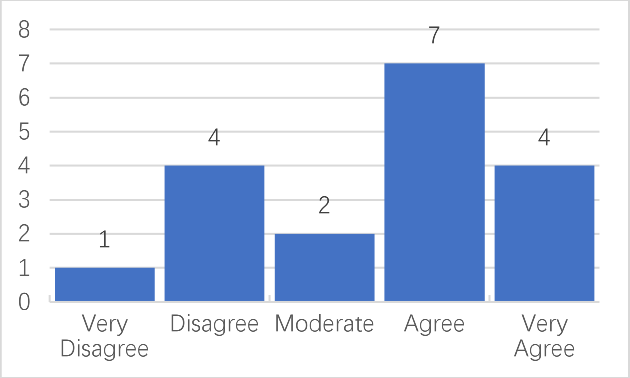
Usefulness of FCW



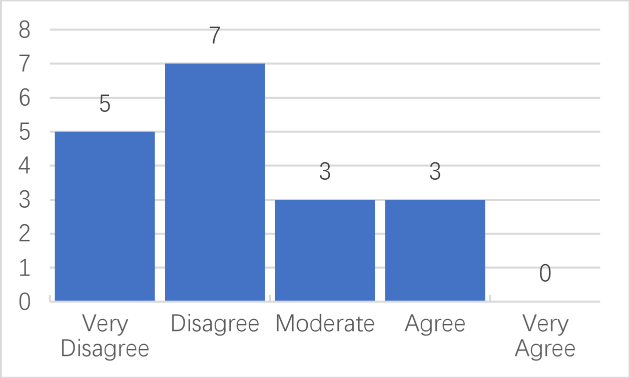
Preference of having multi-warning



Difficulty of responding multi-warning

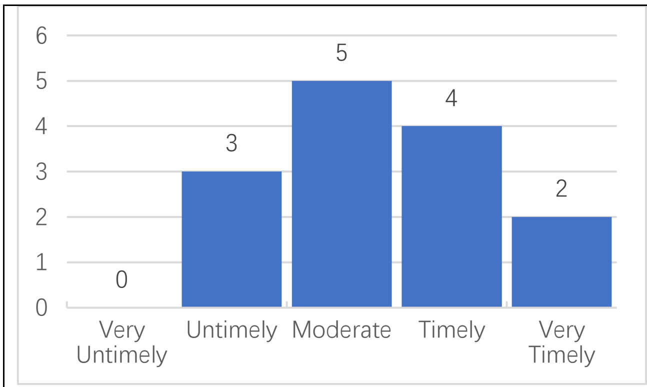


Distracting from BSM

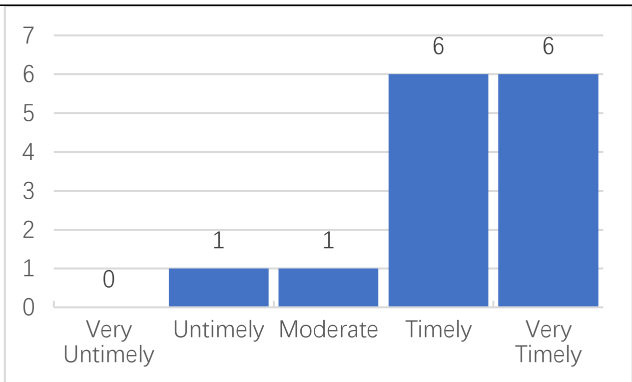


Distracting from FCW

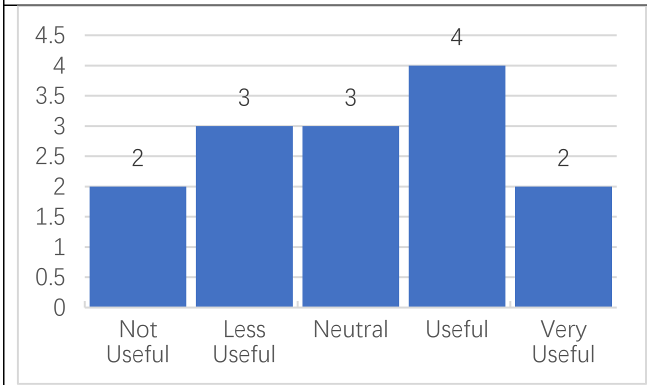
Appendix D The result of experienced driver questionnaire



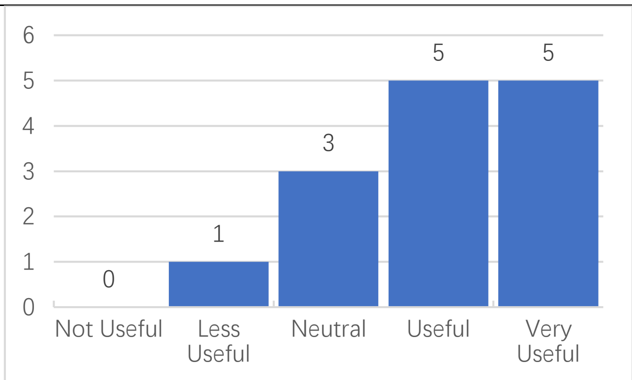
Timeless of BSM



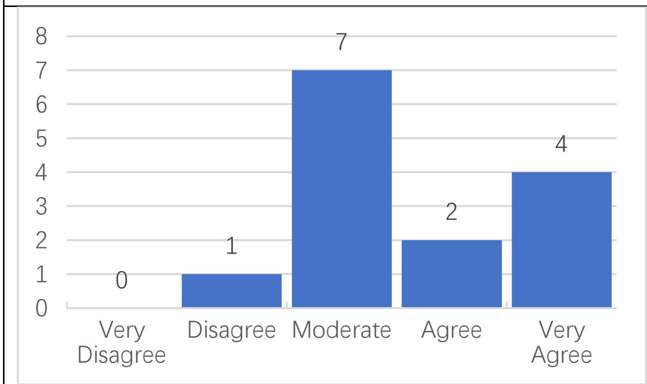
Timeless of FCW



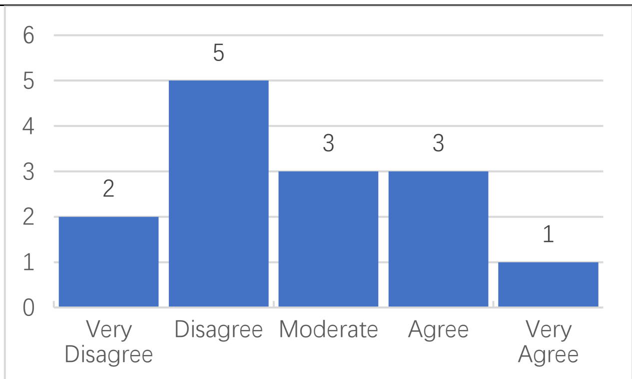
Usefulness of BSM



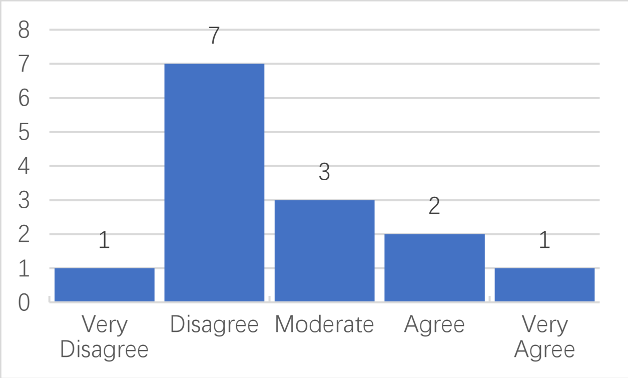
Usefulness of FCW



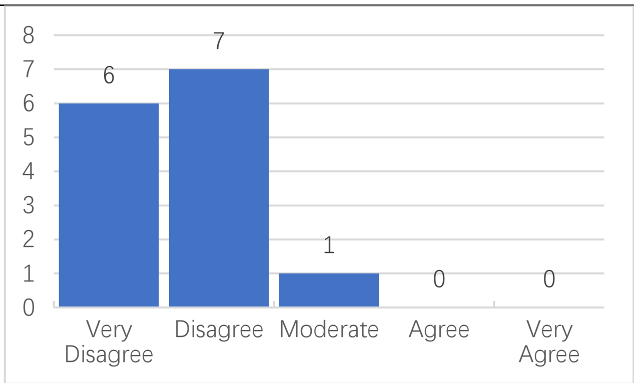
Preference of having multi-warning



Difficulty of responding multi-warning



Distracting from BSM



Distracting from FCW