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Designing HMIs for Advanced Driver-Assistance Systems

Master's thesis in Industrial Design Engineering

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Cover: Visualization of the HMI concept.

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Abstract

Driving safety improves as automakers implement advanced driver assistance systems (ADAS) into vehicles. However, these systems can potentially diminish drivers' situation awareness and negatively affect their mental model of the system. Therefore, this thesis aims to understand how human-machine interfaces can be designed to enhance drivers' situation awareness and facilitate a more accurate mental model. Firstly, a literature study was conducted where design guidelines were identified to improve drivers' situation awareness and facilitate an accurate mental model of the system. These guidelines informed the design of an HMI concept. Afterward, an interview study was conducted to find criteria for the evaluation of situation awareness in the traffic environment. Subsequently, a 2x2 mixed design experiment was conducted using pre-recorded video clips to evaluate the HMI concept in terms of its impact on drivers' situation awareness, mental model, perceived awareness, and perceived understanding of the system. Lastly, the final iteration of the HMI concept is presented that aims to alleviate the issues identified in the first iteration during the evaluation.

The findings of the evaluation show that the HMI concept has improved participants' understanding of the system's intentions and requests. However, no improvements were observed in terms of situation awareness of the external driving environment. This lack of improvement was attributed to the highly distracting nature of the HMI concept. Furthermore, the interview study identified that the information requirements are mostly unique among different driving situations, making it necessary for the HMI to adapt to each situation to support the driver in maintaining their situation awareness of the external driving environment. The results emphasize the importance of display position, display technology, and potential information overload for causing distraction and negatively affecting drivers' situation awareness of the external traffic environment.

Keywords: advanced driver assistance system, automated driving, situation awareness, mental model, human-machine interaction

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Amirreza Aghaei, Gothenburg, June 2022

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis, listed in alphabetical order:

ACC	Adaptive Cruise Control
ADAS	Advanced Driver Assistance Systems
ECOM	Extended control model
EID	Ecological Interface Design
GDTA	goal-directed task analysis
HMI	human-machine interfaces
LKA	Lane Keeping Assist
ODD	Operational design domain
SA	Situation Awareness
SAGAT	Situation Awareness Global Assessment Technique
TOR	Take-over request

Contents

1
Introduction

1.1 Background

Advanced Driver Assistance Systems (ADAS) are technical support systems that provide drivers with information and help relieve drivers by automating driving-related tasks [27]. It is believed that they can bring positive societal and economic outcomes like increasing safety, improving quality of life, decreasing emissions, and reinvigorating the automotive industry [32]. However, many non-technical challenges face drivers of these systems, which must be addressed before achieving the aforementioned positive outcomes. One of the challenges that drivers face is their diminished situation awareness as a result of high levels of automation. Situation awareness (SA) is defined as "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. "[16]. Moreover, another challenge with ADAS technologies is that drivers often have an inadequate mental model of the automated system. A mental model is defined as "a cognitive structure that enables a person to describe, explain, and predict a system's purpose, form, function, and state. "[35].

The American Automobile Association discovered that a "lack of understanding or confusion about the proper function of ADAS technologies could lead to misuse and over-reliance on the systems, resulting in a deadly crash. "[23]. Automation can reduce drivers' situation awareness and diminish their ability to detect errors in the system, which can lead to failures when tasks are to be completed manually in the event of automation malfunction [19].

Importantly, studies suggest that poor design of human-machine interfaces (HMI) may counteract the potential benefits of ADAS and negatively affect safety [6]. HMIs play an important role in ensuring that the driver and automated system can collaborate together safely [10]. Therefore, this thesis concerns how the HMI of automated vehicles can be improved to counteract the challenges mentioned above.

1.1.1 Industrial Partner

This thesis project is conducted at RISE Research Institutes of Sweden within the project Enhanced ADAS[1]. The Enhanced ADAS project aims to integrate existing ADAS systems for environmental sensing with driver monitoring systems, map data,

[1] https://www.vinnova.se/en/p/enhanced-adas-improving-drivers-experience-acceptance-and-trust-in-assistance-systems/

and dynamic driver-vehicle interaction strategies (HMI and/or vehicle behavior) to create an enhanced ADAS technology that provides novel threat assessment. The project is formed on the hypothesis that this enhanced ADAS technology will improve safety, performance, driver experience, and acceptance compared to an ADAS without these functions.

During the Enhanced ADAS project, a baseline HMI concept was developed by RISE (See Figure 1.1). It included a sensor view window, which showcased the ego vehicle in a 3D scene and an indicator of what the sensors captured in the traffic environment. It also included a notification banner called the "handover icon" to indicate to the driver when they should take over the control of the vehicle from the automated system. While the handover icon was displayed, an auditory signal consisting of three consecutive beeps was played. RISE has tested this HMI concept on public roads; however, the results were not promising. The test participants had difficulties understanding what the baseline concept was trying to communicate.

Therefore, this thesis project focused on redesigning the HMI to improve understanding by facilitating a more accurate mental model of the system. Another important aspect of the Enhanced ADAS is the novel threat assessment it provides. However, if drivers do not become aware of these threats, they will miss the threats that the system has identified. Therefore, this project also focused on designing HMIs that support drivers' in constructing an adequate situational awareness of the traffic environment.

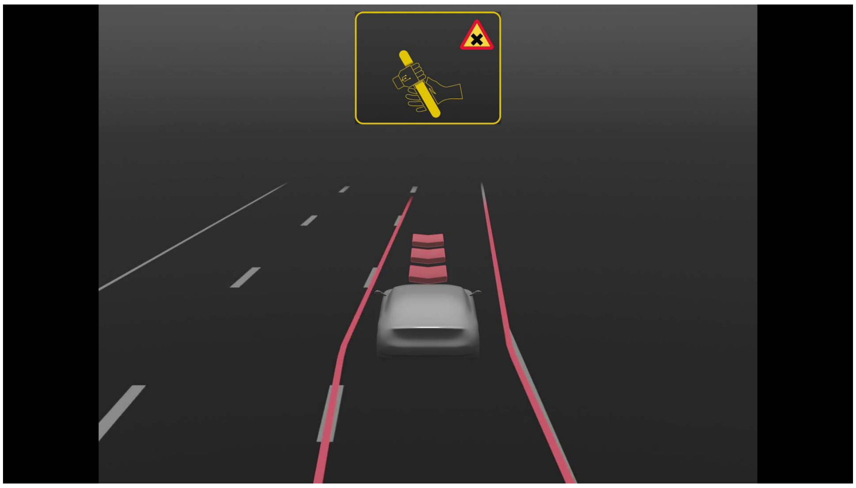

Figure 1.1: The recreation of the baseline concept with sensor view and handover icon

1.2 Aim

This thesis aims to understand how human-machine interfaces can be designed for future ADAS to enhance drivers' situation awareness and facilitate a more accurate mental model. Additionally, the objective of the thesis is to answer the following research questions:

- RQ1: How does ADAS influence the drivers' situation awareness and mental model?

- RQ2: How can relevant human factors considerations regarding situation awareness and mental models inform the design of HMIs?

1.3 Process

The four-stage design process of Nigel Cross [12] was used to bring order to the different activities and methods used during the thesis (See Figure 1.2). Each of these phases is briefly described in the paragraphs below.

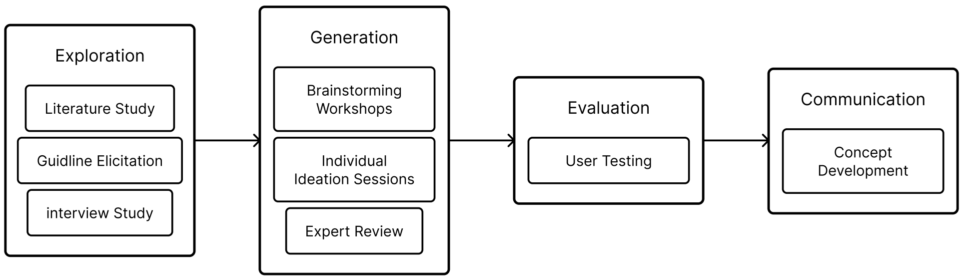

Figure 1.2: The four-stage model of the design process; adapted from [12]

First, during the exploration phase of the design process, a literature study was carried out that gathered findings regarding the research questions mentioned above and elicited requirements and guidelines that provided input to the design of HMIs. Additionally, an interview study was conducted to identify drivers' information requirements and perquisites for adequate situation awareness of the external driving environment for possible driving situations where a take-over might be necessary. The findings from this study provided objective measures for evaluating the impact of different HMI concepts on drivers' situation awareness of the external driving environment.

Second, in the generation phase of the design process, workshops were held by RISE where different stakeholders ideated on the functionalities and HMI of the ADAS. Subsequently, concepts for the HMI were created based on the gathered requirements and guidelines. Lastly, a human factor expert at the Chalmers University of Technology reviewed the concepts. The concept was presented as an animation that was used in the evaluation phase.

Third, multiple methods were used in a study to assess the participants' situation awareness and the accuracy of their mental model using questionnaires and a semi-structured interview.

Lastly, in the communication phase, the final iteration of the HMI concept was created, and changes were made to the HMI based on the evaluation findings.

1.4 Thesis Structure

The Introduction (Chapter 1) is followed by the Literature Study (Chapter 2), which provided findings regarding the research questions, discovered guidelines for HMI design, and explored different methods for evaluating situation awareness and mental models. An HMI concept is generated in Chapter 3 based on the guidelines gathered in chapter 2. Chapter 4 presents an interview study that identified drivers' information requirements and perquisites for adequate situation awareness of the external driving environment in order to take over the driving task from the automated system. The HMI concept is evaluated in Chapter 5 to assess its impact on participants' situation awareness and mental model. In Chapter 6, the HMI concept is redesigned and improved based on the findings of the evaluation in Chapter 5. Chapter 7 provides a discussion of the finding, followed by a conclusion (Chapter 8).

2

Literature Study

To address the issues of drivers' reduced situation awareness and an inadequate mental model, an understanding of these constructs and driving automation's influence on them is necessary. Additionally, it is important to understand what these considerations imply for the design of HMIs. This chapter seeks to address these concerns through a literature study. The literature study aimed to gather findings regarding the research questions posed in the previous chapter, identify guidelines for the HMI design, and explore different methods for evaluating drivers' situation awareness and mental model. The findings of this chapter provided the basis for the design of an HMI concept in the following chapters.

2.1 Method

Literature searches were conducted in the Scopus database using relevant search terms including "advanced driver assistance system," "automated driving," "situation awareness," "mental model," and "HMI." This step resulted in 36 articles that were screened by reviewing their title and abstract. After the screening process, 21 articles were excluded that were irrelevant to the aims of the thesis. The same search terms were used in the Google Scholar search engine in a more exploratory way to discover 21 additional articles. Not to mention, the literature study also included 16 articles introduced by Chalmers supervisors. The literature was analyzed by going through the articles' findings, recommendations, principles, and requirements to identify guidelines for HMI design that address the issues of drivers' reduced situation awareness and inadequate mental model.

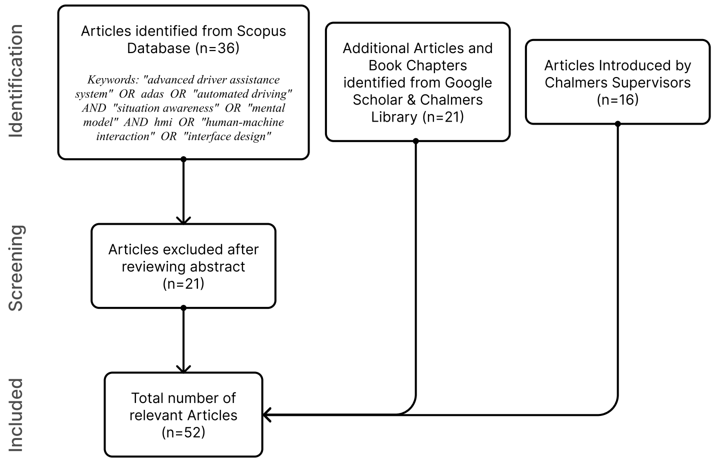

Figure 2.1: Process of the Literature Study

2.2 Findings

To introduce the findings, first, an overview of ADAS is presented, followed by a summary of their influence on drivers' situation awareness and mental model. Different methods for evaluating these constructs are also described. Lastly, the HMI design guidelines are presented.

2.2.1 Advanced Driver-Assistance Systems

Throughout the history of automobile development, the automotive industry has taken steps to increase the safety of vehicles by implementing a diverse set of safety systems. These systems can be categorized into passive safety systems and active safety systems. Passive safety systems help mitigate the consequences of accidents and include widely used and mandated technologies like seat belts, airbags, etc. Over the last decade, however, we have witnessed the rise of active safety systems that help prevent accidents from happening in the first place. These technologies are classified as Advanced Driver-Assistance Systems.

Advanced Driver Assistance Systems are technical support systems that provide drivers with information and help relieve drivers by automating driving-related tasks [27]. ADAS leverages advanced sensors such as cameras, radars, and lidar equipment to sense the surrounding environment. It also has a software component to use this information for post-processing and decision-making [21].

A common way to organize and understand the different ADAS technologies is to categorize them based on the SAE international's taxonomy of driving automation [36]. According to this taxonomy, there are six discrete and mutually exclusive levels of automation. The basis for the classification of these levels is the changes in the role between the human agent and the driving automation system. They start with "no driving automation (Level 0)", in which the driver retains full responsibility for driving the car, to "full driving automation (Level 5)", where the automation system takes complete control of the vehicle [36]. The section below will provide a description of the level 2 automation system. Since the ADAS system concerned in this thesis is considered a level 2 automation system.

2.2.1.1 Level 2, Partial Driving Automation

In level 2, partial driving automation, the system performs part of the dynamic driving task by executing lateral and longitudinal vehicle motions within a specific operational design domain [36]. The driver's responsibility is to perform the remainder of the dynamic driving task that the system cannot cope with. The driver should also supervise the driving automation system and intervene as necessary to keep the vehicle running [36].
Two different ADAS technologies perform the lateral and longitudinal vehicle motions, namely the lane-keeping assistance (LKA) and the adaptive cruise control (ACC). According to ADAS Alliance [1], the lane-keeping assistance feature "makes steering adjustments or displays a warning when the driver unintentionally starts to change lanes." According to SAE International [36], "the adaptive cruise control (ACC) feature performs longitudinal vehicle motion control functions to support the driver in maintaining consistent headway to a lead vehicle in its lane when traveling at higher speeds."

2.2.1.2 Take-Over Requests

As previously mentioned, partial driving automation cannot cope with every driving task. This includes situations such as a system failure or circumstances exceeding the system's operational design domain (ODD) [29]. Therefore, drivers should be prepared to take back control of the vehicle in a timely manner. Take Over Request (TOR) is a request triggered by the automated driving system in which the system initiates a transition process from the ADAS engaged mode to manual driving [29]. Before taking over the control of the vehicle, the driver should gather information about the internal driving state and the external driving situation to ensure a safe outcome [29]. One of the most important aspects of a TOR is providing a safety buffer for the transition time after presenting the TOR to give the driver enough time to take over the driving task [28]. Take-over requests are usually triggered and communicated through a TOR prompt that employs a combination of auditory, visual, and tactile modalities.

2.2.2 Ironies of Automation

There is the assumption that we can increase safety in systems by keeping humans away from them as much as possible by automating the system [14]. However, this assumption has proved futile as it results in a phenomenon that Bainbridge calls the "ironies of automation". It occurs where "automation can make the difficult parts . . . more difficult, by taking away the easy parts of human tasks" [3].

Like all other automated systems, automated driving systems are no different. High levels of automation can significantly reduce a driver's situation awareness. Reduced levels of SA can lead to late or inappropriate reactions from the driver when the automation system reaches its boundaries or when automation failure occurs [3, 19]. Moreover, another challenge is that drivers often have an inadequate mental model of the automated system. Deficiencies in mental models can lead to failures in reclaiming control of the vehicle because the driver does not clearly understand the system's limitations [40]. Therefore, it is necessary for the driver to have a high level of situation awareness and an adequate mental model of the system to appropriately supervise an automated system and react to external hazards and take-over requests. Both situation awareness and mental models are further described in the following sections. In each section, evaluation methods for situation awareness and mental model are described. These evaluation methods were used in the evaluation phase of the design process (Chapter 5) to assess the concept developed during the concept generation phase (Chapter 3).

2.2.2.1 Situation Awareness

There are different schools of thought that each defines situation awareness differently. The prevalent views on SA are the cognitive and interactionist perspectives. According to Sandom [38], the cognitive perspective views situation awareness as a cognitive phenomenon that occurs 'in the head' of an individual, while the interactionist perspective views it as an observed construct located 'in the interaction' between the actor and the environment. In the cognitive tradition, Endsley's definition of situation awareness has been widely cited and highly influential within human factors and automated driving research. Thus, this definition is referred to when this thesis discusses situation awareness.
According to Endsley, situation awareness 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 [19]." This definition of situation awareness encompasses three different levels. Level 1 SA encompasses the perception of the elements in the environment, level 2 includes the comprehension of the current situation, and level 3 is the projection of future status [16].

Challenges Induced by Automation Automation has a significant impact on reducing the operator's situational awareness, which can lead to the out-of-the-loop syndrome [19]. This issue also extends to driving automation as well. The out-of-the-loop syndrome is defined as the automatic system operators' diminished ability to detect system errors and subsequently perform tasks manually in the face of automation failures [19]. It results from reduced feedback due to high levels of automation and the higher demands on vigilance due to the necessity for passive supervision of the system [16]. A reduced situational awareness could lead to drivers' safety being compromised during take-over requests. Having an adequate level of situation awareness is critical in safely taking control of the vehicle, as the driver might only have a few seconds to react. If the system is not designed properly to tackle the reduced situation awareness of drivers, then the higher levels of automation can negatively affect safety.

Measuring Situation Awareness The main means of communication between the vehicle and humans is the human-machine interface. Besides, studies have shown that the design of HMIs can directly affect the driver's situation awareness [46]. Thus, understanding how the HMI influences drivers' situation awareness can be critical for evaluating its impact on driving safety and provide guidance for choosing the right path for further development. This requires an accurate measurement of the drivers' situation awareness.

There are two main approaches for measuring situation awareness. They include direct measures and indirect measures. Indirect measures attempt to deduce the amount of SA of a person by measuring the cognitive processes involved in the development of SA or by measuring the performance of the operator in relation to their interaction with the system [16]. An example of an indirect measure includes the behavioral and performance-based measures, which try to derive the SA of the subjects from their observable actions or the effects of these actions on system performance [16]. However, there are limitations to indirect measures in that they don't provide diagnosticity, and it's difficult to know whether the performance achieved by the operator is due to their situation awareness or other causes.

On the other hand, direct measures of SA, as the name implies, attempt to assess a person's situational awareness directly and include both objective and subjective methods. One of the mainly used objective measures of SA is the situation awareness global assessment technique (SAGAT) [15]. SAGAT is used during simulation exercises where the simulation is stopped, and a set of queries is made available to participants. The data collected are then evaluated as correct or incorrect, based on what was actually happening in the scenario at the time [16]. The SAGAT method has proven to have predictive validity, but its greatest limitation is the time and effort it takes to discover the SA requirements for developing appropriate queries for the domain under investigation [16]. These queries are derived from a goal-directed task analysis (GDTA) [9]. A GDTA focuses on the goals the driver must accomplish, the decisions they have to make to achieve those goals, and the information requirements needed to make the correct decisions [16].

Moreover, the subjective measures of SA work by asking the operator or an expert observer to rate the quality of the operator's SA during a specified period [16]. One of the greatest limitations of these techniques is that operators will report what they think their SA is but may not be aware of the lack of precision in their SA or of the existence of information they do not know about, and as a result, the subjective measures should always be interpreted in conjunction with performance data or direct SA measures in order to obtain a correct understanding of SA versus the actual SA [16].

2.2.2.2 Mental Model

A wide range of terminology is used to describe and define mental models. Simply put, they are incomplete cognitive representations of external reality [25]. According to Rouse and Morris [35], mental models are "mechanisms whereby humans are able to generate descriptions of system purpose and form, explanations of system functioning and observed system states, and predictions of future states."

Challenges Induced by Automation With the advances in driving automation, it is becoming increasingly difficult to create an accurate mental model of the system. The use of machine learning and AI in developing autonomous systems has made these systems' inner workings, operations, and decisions oblique to drivers. As a result, maintaining an accurate mental model of the system has become extremely challenging. Due to an inadequate mental model of the automated system, drivers may fail to reclaim control of the vehicle because they do not clearly understand the functional limitations of the system [40].
It is believed that the emergence of many accidents in high-reliability systems seems to be the result of deficiencies in mental representations [33]. Thus, having an accurate mental model of the system is crucial for safely using the automated system. A mental model that corresponds to the capabilities of the system would avoid misuse and disuse of automated vehicle systems and provide the basis for developing trust and acceptance [7, 26].

Evaluating Mental Models There are two main approaches for eliciting mental models. They consist of direct and indirect elicitation techniques. The direct method requires that the interviewees present their understanding of an issue by asking them to identify the concepts they consider important to a domain [25]. On the other hand, the indirect approach relies on open-ended and semi-structured interview questions to extract the interviewee's understanding of concepts and relations within a given domain [25].

2.2.3 Guidelines for HMI Design

Guidelines for HMI design have been identified from the literature to help enhance drivers' situation awareness, facilitate an accurate mental model of the system, and improve take-over requests.

2.2.3.1 Enhancing Situation Awareness

Guidelines have been developed to address the reduced situation awareness and out-of-the-loop syndrome caused by driving automation. For a full description of these guidelines, see Table 2.1.

Table 2.1: The guidelines for addressing reduced situation awareness

#	Description	References
1	The driver should have a high-level overview (the big picture) of the situation.	[16]
1.1	Provide information based on driver's current goals.	[16]
2	Multiple modalities should be used to support parallel processing of information.	[16]

to be continued on the next page

Table 2.1: (continued from previous page)

#	Description	References
2.1	Use visual, auditory, and tactile modalities for warnings.	[5]
2.2	Use different levels of salience for warnings depending on driver's attention level.	[10]
2.3	Take measures when the driver is inattentive to prevent unsafe situations.	[10]
3	Level 2 SA (comprehension) information should be visualized to support comprehension.	[16]
3.1	Provide explicit feedback on the current automation level, automation state, status, required actions, available functionalities, potential risky driving conditions, and recommendations.	[37], [20], [49]
3.1.1	Provide an automation monitor to visually display vehicle's current state.	[20], [5]
3.1.2	Provide an Information Portal to show messages and warnings.	[37], [20]
3.1.3	Provide a one-dimensional automation scale to show active automation levels & functions	[20]
3.2	Show objects on the sides, rear, and the blind spot of the vehicle, obstacles below the bumper, exceedance of speed limits, and stationary vs. moving objects on sides.	[17]
4	It should be possible for the driver to ascertain which modes are on with one glance.	[10]
4.1	Adaptively filter information based on an assessment of the current traffic situation.	[37]
4.2	Display what the vehicle is seeing, its capabilities and limitations.	[10]
5	The driver should be able to predict the future state of the vehicle.	[16], [10], [43]
5.1	Show the ego vehicle's future trajectory and actions.	[10]
5.2	Show the other vehicles, and pedestrians trajectory on the road.	[17]
5.3	Show future road hazards, traffic condition, actions of the automation, and side collision warnings.	[18], [17]
5.3.1	Use a Head-up display to show level 3 SA (projection) Information.	[10]
5.3.2	Provide a look-ahead feature similar to navigation systems to show what is about to happen.	[10]
5.4	Provide system confidence information (SCI) to indicate how well the automation is performing.	[17], [41]

2.2.3.2 Facilitating an Accurate Mental Model

Guidelines have been discovered that aim to address the inaccuracy of mental models resulting from driving automation. For a full description of these guidelines, see Table 2.2.

Table 2.2: The guidelines for facilitating an accurate mental model

#	Description	References
1	Automation behavior should be consistent with driver's goals and mental model.	[17]
1.1	Provide different HMI's to communicate internal (internal decisions of the automation) and external information (external hazards imposed on the vehicle).	[49]
1.2	Provide the ability to set the time gap for ACC by changing the number of longitudinal markings using arrow buttons on the steering wheel.	[20]
1.3	Show lane markings for indicating lateral support and horizontal markings for indicating longitudinal support.	[20]
1.4	Provide the ability to use lever or buttons for selecting higher or lower levels of automation.	[20]
1.5	Use standardized symbols and icons.	[16], [10]
2	The logic of ADAS modes should be transparent and not oblique.	[17]
2.1	Minimize the number of automation modes and logic branches possible.	[18], [10], [17]
2.2	Provide the driver with definite information of the boundary conditions.	[11]
2.3	Provide the driver with visual information on vehicle detection, its orientation, and moving/static attributes.	[11], [48]

2.2.3.3 Improving Take-Over Requests

Guidelines have been discovered that aim to improve take-over requests. For a full description of these guidelines, see Table 2.3.

Table 2.3: The guidelines for improving take-over requests

#	Description	References
1	The vehicle should identify which road conditions ahead it cannot operate and inform the driver that it cannot cope.	[10], [17]
1.1	Use a multi-modal warning that escalates in a step-wise manner if the driver does not take over control.	[20]
1.2	Bring the vehicle to a safe stop if the driver does not take over control.	[20]
1.3	Inform the driver about why the automation cannot cope in a situation.	[10], [17], [48], [11]
1.4	Provide a countdown to the required takeover.	[10]
1.5	Show a preview of the upcoming road to indicate future take-over requests.	[10]
1.6	Provide a look-ahead feature similar to navigation systems to show what is about to happen.	[10]
1.7	Provide an explicit feedback to the driver about successful or refused transitions.	[20]

to be continued on the next page

Table 2.3: (continued from previous page)

#	Description	References
1.8	Accept driver inputs like braking, accelerating, or strong steering for taking back control of the vehicle.	[20]
1.9	Provide a visual representation if required inputs for an ADAS function are available.	[10]
1.10	Provide auditory warnings when the required input by an active functionality is no longer available to avoid automation surprises.	[10]
2	The activation of functions that are not available should be prevented.	[10]
2.1	Provide auditory warnings when the required input by an active functionality is currently not available to avoid automation surprises.	[10]

2.3 Conclusion

The literature study identified that ADAS technologies could diminish drivers' situation awareness and negatively affect the driver's mental model of the system. These negative influences of ADAS have implications for driving safety. As a result, a poorly designed ADAS system intended to increase road safety can potentially undermine it.

Accordingly, guidelines were identified to alleviate these negative influences of ADAS and inform the design of the HMI concept. The guidelines were classified into three distinct categories. The first category was aimed at improving SA on all levels of situation awareness. The second category aimed at facilitating an accurate mental model of the system. The last category is aimed at improving take-over requests. As described in Chapter 3, these guidelines were used to design a new concept for the HMI.

3
Concept Generation

This chapter presents the process behind the generation of a new HMI concept. The concept generation phase aimed to ideate design solutions to develop an HMI based on the guidelines gathered in chapter 2. The new concept is evaluated against the baseline concept (See Figure 1.1) in the evaluation chapter (Chapter 5).

3.1 Method

Three different methods were used in the concept generation phase. They included two brainstorming workshops, individual ideation sessions, and an expert review.
First, two brainstorming workshops were held by RISE to brainstorm ideas with different stakeholders from the industry. Eight stakeholders participated in the workshops, including representatives from RISE, APTIV, and Smart-Eye, alongside the author of this thesis. The workshops were held to generate ideas for the ADAS functions and the HMI. The workshops were organized online using online collaboration tools, and they were held for the duration of 90 minutes. After the brainstorming sessions, the participants voted on all the ideas, and the highest voted ideas were selected for further design and development.
Second, individual ideation sessions were held to explore different ideas based on insights from the guidelines gathered in chapter 2. Different rapid prototyping software was used to create and develop the interface ideas. The individual ideation sessions lasted a week.
Third, after developing the concepts, they were reviewed by a human factors expert at Chalmers University using Nielsen's heuristic evaluation method. Nielsen's heuristic evaluation was used in order to identify any usability issues with the concept before it was evaluated in Chapter 5.

3.2 Results

The results of the brainstorming workshops, the individual ideation sessions, and the expert review will be demonstrated in the sections below.

3.2.1 Brainstorming Workshop

During the brainstorming workshops, 14 different ideas were generated by the participants. Out of the fourteen ideas, seven were ruled out due to technical limitations and impracticality, such as sensor and technological limitations. The remaining ideas were voted on, and the three most promising ones were chosen for further development. These three ideas will be described in the sections below.

Idea I: A non-urgent take-over request based on known, challenging scenarios This idea is formed on the basis that the HMI should provide the driver with information regarding a possible take-over in the road ahead. It becomes possible by employing map data to identify upcoming roads that the system cannot operate. The information provided to the driver should communicate what ADAS functionality will be unavailable, why it will become unavailable, and when it will become unavailable.

Idea II: A combined map view and sensor view pane Within this idea, the aim is to increase system transparency by visually displaying the objects that the vehicle sensors have detected in the traffic environment. In addition, it seeks to increase trust, situation awareness, and knowledge of upcoming road infrastructure by integrating it with map data.

When designing a combined sensor and map view, the most important thing to keep in mind is to ensure that the right information is provided to the driver to avoid information overload. It is clear that automation will completely change the division of labor between the driver and the automated system and the associated communication needs [42]. However, it is important to understand how the combination of map and navigational data will further influence this change. To that end, an Extended control model (ECOM) [24] of the driving task within a level 2 automation system was created to understand the changes in the driver's responsibilities during driving (See Figure 3.1).

In the ECOM illustrated below, we can see that while the automation system executes the tracking and regulating control layers, the driver is responsible for monitoring the system and setting goals for the destination. However, when we combine the system with map data to identify upcoming take-over situations and provide navigation, parts of the targeting layer will also be delegated to the automation system. Consequently, the information needs of the driver would differ in this case.

	Control Layer			
	Tracking	Regulating	Monitoring	Targeting
Level 2 Automation System	ADAS	ADAS	Driver	Driver
Level 2 Automation System with Navigation and Map Data	ADAS	ADAS	Driver	Driver ADAS

Figure 3.1: ECOM of the influence of level 2 automation system and map/navigation data on the driving task

On that account, a map/sensor view pane was created that builds upon the sensor view of the baseline concept and provides additional content to meet the new information needs. This additional information includes roads, buildings, and street names alongside the sensor view data (See Figure 3.2). Since turn-by-turn navigation is based on procedural knowledge [2], it is hypothesized that information like roads and buildings in a 3D scene would help the driver in identifying the correct procedures and paths to take.
Additionally, the map/sensor view also takes inspiration from the guidelines discovered in chapter 2. The lane markings on the baseline concept will be changed to make it easier to see the availability of longitudinal and lateral control and the detection of vehicles, their orientation, and other attributes.

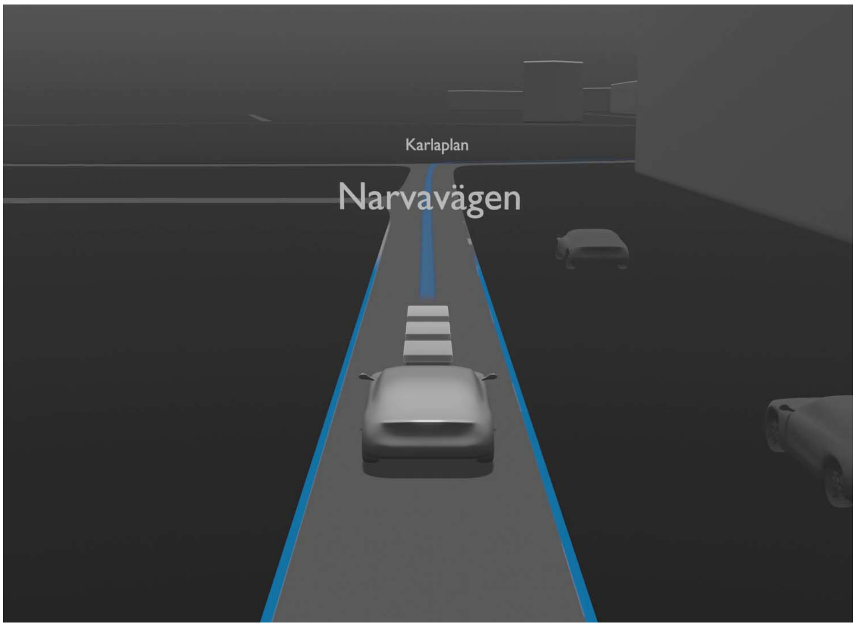

Figure 3.2: The new map/sensor view pane

Idea III: A multi-level warning design based on the driver's attentiveness
This idea aims to decrease information overload by providing more salient warnings only when the driver is inattentive.

Accordingly, different levels of warnings were defined from a low salience warning to a high salience warning. The warning levels were adapted from the MIL-STD-1472G standard of the US army [13]. They are represented to the driver depending on the urgency for action, the criticality of the situation, and the driver's attention levels (See Figure 3.4). According to the MIL-STD-1472G standard, criticality refers to the severity of the damage, and urgency refers to the imminence of the danger [2].

Warning Level	Attributes			
	Description	Color	Expected Driver Response	Modality
Level 1: Advisory Signal	Indicate safe or normal Condition		No Immediate action Required	*Visual*
Level 2: Caution	Indicate an impending dangerous situation		Attention	*Visual + Auditory*
Level 3: Warning	Indicate a dangerous condition		Immediate action Required	*Visual + Auditory*

Figure 3.3: The multi-level warning design adapted from [13].

The lowest warning level is devised to indicate safe or the normal condition of use, with no immediate action expected from the driver. On the other hand, the highest warning level indicates a dangerous condition that requires immediate action.

Distracted	Urgency & Criticality	Warning Level
✗	✗	Level 1
✓	✗	Level 2
✗	✓	Level 3
✓	✓	Level 3

Figure 3.4: Representation of different warning levels depending on the attention level of the driver

3.2.2 Individual Ideation Sessions

The individual ideation sessions aimed to create HMI concepts based on the guidelines gathered in chapter 2 and integrate them with the ideas discussed in the previous section to create a unified HMI concept.
The guidelines were examined to find the ones that were interconnected and could be addressed via a single solution. The dot-voting technique was used to pinpoint the guidelines that had the potential to be addressed together (See Appendix B). The result was three different interface elements that together addressed 21 different guidelines. A description of these interface elements is provided below.

3.2.2.1 System Status Icons

The system status icons were created by combining multiple guidelines that aim to improve SA, mental models, and take-over requests. These guidelines include recommendations like allowing the driver to easily ascertain which modes are enabled, using standardized icons, and preventing activation of unavailable functions (For the full list of utilized guidelines, see Table3.1.)

Table 3.1: The utilized guidelines for the development of the system status concept

Guideline	Table
3.1.3. Provide a one-dimensional automation scale to show active automation levels & functions.	2.1
4. It should be possible for the driver to ascertain which modes are on with one glance.	2.1
5. The driver should be able to predict the future state of the vehicle.	2.1
1.5. Use standardized symbols and icons.	2.2
1.10. Provide auditory warnings when the required input by an active functionality is no longer available to avoid automation surprises.	2.3
2. The activation of functions that are not available should be prevented.	2.3
2.1. Provide auditory warnings when the required input by an active functionality is currently not available to avoid automation surprises.	2.3

The system status icons use a close adaption of the ISO 7000-2580 and ISO 7000-3180 for the ACC and LKA icons (See Figure 3.5). They employ different colors to showcase the currently active mode of the aforementioned ADAS functions.

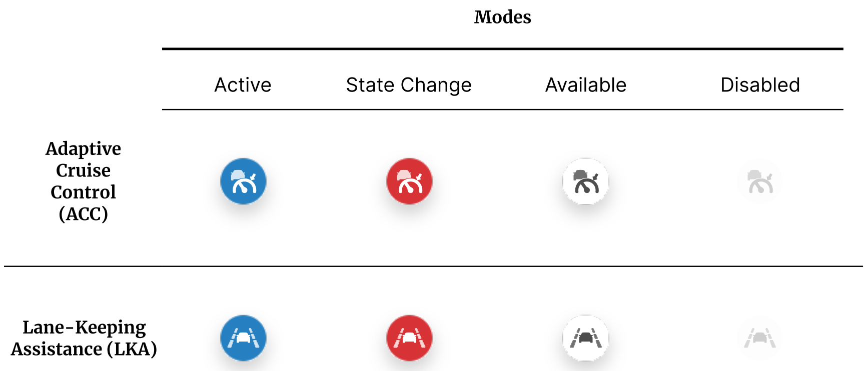

Figure 3.5: The system status icons during different modes

3.2.2.2 Information Portal

The information portal was created by combining multiple guidelines to improve SA, mental models, and take-over requests. These guidelines include recommendations like providing information based on the driver's current goals, incorporating a look-ahead feature similar to navigation systems, and providing the driver with information on reaching ADAS's boundary conditions (For the full list of utilized guidelines, see Table3.2.)

Table 3.2: The utilized guidelines for the development of the information portal concept

Guideline	Table
1.1. Provide information based on driver's current goals.	2.1
3.1.2. Provide an Information Portal to show messages and warnings.	2.1
5. The driver should be able to predict the future state of the vehicle.	2.1
5.3.2. Provide a look-ahead feature similar to navigation systems to show what is about to happen.	2.1
2.2. Provide the driver with definite information of the boundary conditions.	2.2
1. The vehicle should identify which road conditions ahead it cannot operate and inform the driver that it cannot cope.	2.3
1.1. Use a multi-modal warning that escalates in a step-wise manner if the driver does not take over control.	2.3
1.3. Inform the driver about why the automation cannot cope in a situation.	2.3
1.6. Provide a look-ahead feature similar to navigation systems to show what is about to happen.	2.3

The information portal concept combines navigation information with take-over prompts and ADAS information. Thus, it acts as a single place for the driver to learn what they need to do next. The information portal uses familiar design features of turn-by-turn software in order to capitalize on drivers' existing experience and understanding of these systems. It has two sections that show the current action and the upcoming action the driver needs to be aware of. It employs the multilevel-warning design discussed in the previous section (See Figure 3.6).

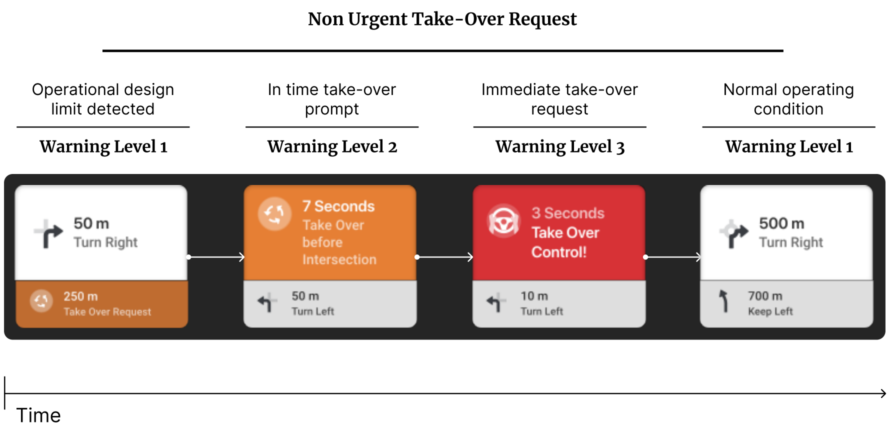

Figure 3.6: The flow of the information portal during a non-urgent take-over request

3.2.2.3 Journey Progress Bar

The journey progress bar was created by combining multiple guidelines that aim to improve SA, mental models, and take-over requests. These guidelines include recommendations like enabling the driver to predict the future state of the vehicle and showing a preview of the upcoming road for indicating future take-over requests. (For the full list of utilized guidelines, see Table3.3.)

Table 3.3: The utilized guidelines for the development of the journey progress bar concept

Guideline	Table
5. The driver should be able to predict the future state of the vehicle.	2.1
5.3. Show future road hazards, traffic condition, actions of the automation, and side collision warnings.	2.1
2.2. Provide the driver with definite information of the boundary conditions.	2.2
1. The vehicle should identify which road conditions ahead it cannot operate and inform the driver that it cannot cope.	2.3

to be continued on the next page

Table 3.3: (continued from previous page)

Guideline	Table
1.5. Show a preview of the upcoming road to indicate future take-over requests.	2.3

The journey progress bar visualizes the trip by showing the distance the vehicle has traveled, the distance remaining to a potential take-over, and the distance remaining to the end of the trip.

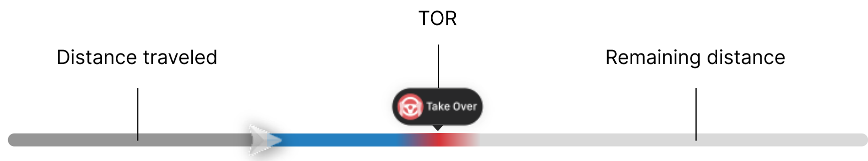

Figure 3.7: The journey progress bar showcasing a potential take-over request

3.2.2.4 Auditory Warnings

Morales-Alvarez et al. classify auditory signals into two categories [29]. The acoustic auditory signal and the informative auditory signal. They mention that the advantage of the informative signals is that they are explicit and easy to understand voice messages; however, they take longer to transmit urgent information and require more attentional resources [29]. On the other hand, the acoustic signals do not require eyes off the road, but their intended message might be unclear to the driver [29].

As a result, both types of auditory signals are provided in the HMI concept by utilizing them in situations that would maximize their advantages while minimizing their disadvantages. The informative signal would be used in non-critical and non-urgent situations. In comparison, the acoustics signal would be used in urgent and critical situations (See Figure 3.8).

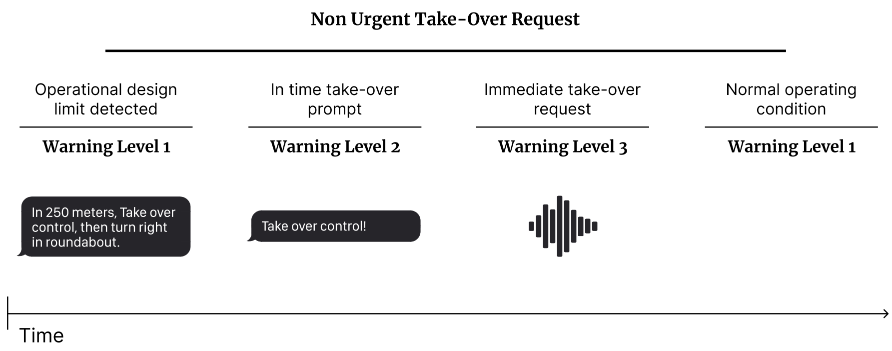

Figure 3.8: Application of auditory signals during a non-urgent take-over request

3.2.2.5 Layout

The layout, typography, and sizing of all the different interface elements aligned with Google's design guidelines for Android Auto [22]. The finalized design of the new HMI concept is shown in Figure 3.9. An animated version of this HMI concept was created for the purposes of evaluation.

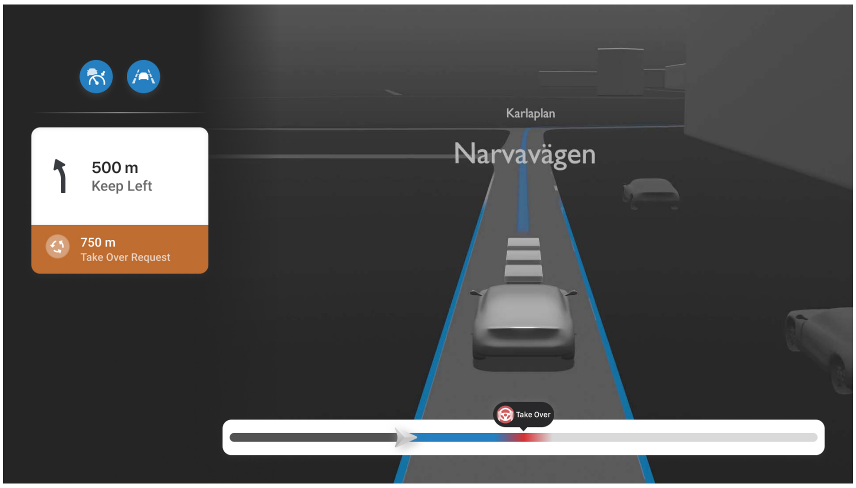

Figure 3.9: The new HMI concept

3.2.3 Heuristic Evaluation

A human factors expert from Chalmers University of technology evaluated the HMI concept using Nielsen's heuristics method [31]. The results are presented in the Table below.

Table 3.4: Expert Review

#	Element	Heuristics	Issue
1	Information Portal	1. Visibility of system status	Not clear if driver or vehicle is in charge (only shown with the two icons on top left)
2	Information Portal	2. Consistency and standards	What does the light grey colour and the brown / dark orange mean?
3	Information Portal	5. Error prevention	Only colour is carrier of information. (Harder for persons with colour vision deficiency)
4	System Status Icons	5. Error prevention	Only colour is carrier of information. (Harder for persons with colour vision deficiency)
5	Journey Progress Bar	2. Match between system and the real world	Point of reference is missing.
6	Journey Progress Bar	2. Match between system and the real world	Point of reference is missing.

3.3 Conclusion

A new HMI concept was created (See Figure 3.9) based on the ideas from two brainstorming workshops and the guidelines gathered in Chapter 2. The HMI concept was evaluated using Nielsen's heuristics method to identify probable usability issues. The final version of the HMI concept was animated for use during the evaluation in Chapter 5.

4

Interview Study

It is necessary for drivers to be both aware of the system's status and have situational awareness of the external driving environment to safely take over the control of the vehicle from the automated system. During a take-over request, the driver should be aware of their surroundings and all the other vehicles, pedestrians, and obstacles in the driving environment that might cause an imminent accident and negatively impact safety. Since the design of human-machine interfaces can directly affect the driver's situation awareness [46], being able to measure their situation awareness will enable comparisons of different HMI concepts in terms of SA. In Chapter 2, the SAGAT method was discussed as one of the most widely used methods for measuring SA. The SAGAT method requires queries that are informed by a goal-directed task analysis of the domain under investigation [9]. As previously mentioned in Chapter 2, a GDTA consists of the goals the driver must accomplish, the decisions they have to make to achieve those goals, and the information requirements needed to make the correct decisions [16]. Thus, this chapter presents an interview study that aimed to discover decisions and information requirements for possible driving situations where a take-over might be necessary. These information requirements informed queries of the SAGAT method employed during the SA evaluation in Chapter 5.

Zhang et al. have created an exhaustive GDTA of driving for partially automated vehicles [50]. Since this study aimed at finding decisions and information requirements for a specific portion of the driving task, an exhaustive GDTA of the entire driving task was not recreated. Rather, the study focused on expanding the GDTA created by Zhang et al. (See Figure 4.1) by including possible take-over situations under the sub-goal of preparing for emergency situations. Within that sub-goal, another five sub-goals were identified based on known, challenging scenarios that the client's ADAS technology cannot cope with, and a take-over is necessary (See Figure 4.2).

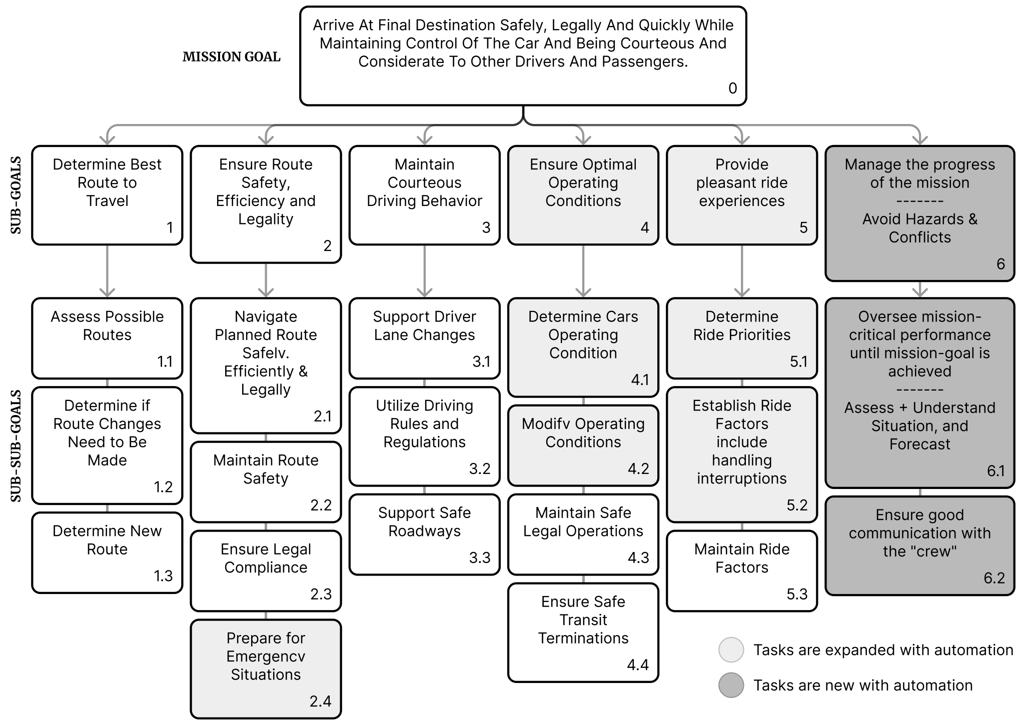

Figure 4.1: Goal-Directed Task Analysis (GDTA) of driving for partially automated vehicles; adapted from [8], [50].

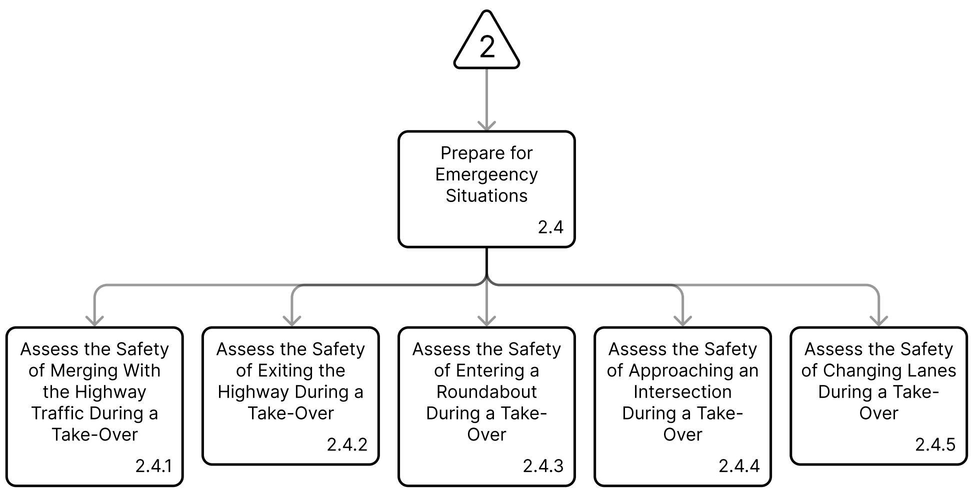

Figure 4.2: Sub-goals of preparing for emergency situations.

4.1 Aim

This Interview study aimed to identify drivers' decisions and information requirements for the five sub-goals (See Figure 4.2):

- Assess the safety of merging with the highway traffic during a take-over.
- Assess the safety of exiting the highway during a take-over.
- Assess the safety of entering a roundabout during a take-over.
- Assess the safety of approaching an intersection during a take-over.
- Assess the safety of changing lanes during a take-over.

4.2 Method

An interview study was conducted that included quantitative and qualitative methods to understand drivers' information requirements. Six people participated in the study. The participants were aged between 25 and 33 years (Mean = 28.5, SD = 3.3) and held a driving license for an average of 10.1 years. Of the six participants, only one participant did not have any experience with ADAS technologies. Five participants had experience with lane-keeping assist. Two participants had experience with adaptive cruise control, and one participant had experience with parking assistance. All participants read and agreed to a consent form before the start of the study and completed a brief demographic questionnaire asking questions regarding age, driving experience, and their experience using ADAS technologies.
The participants had to watch short videos of five different driving scenarios. After the end of each video, they were shown the last frame of the video, where they could select and highlight any object in the frame (See Figure 4.3). Next, they were instructed to select all objects or elements in the traffic situation that they should look for/be aware of to be able to proceed safely. These selections resulted in quantitative data that corresponded with information requirements for the level 1 SA, i.e., perception of the driving scenario.

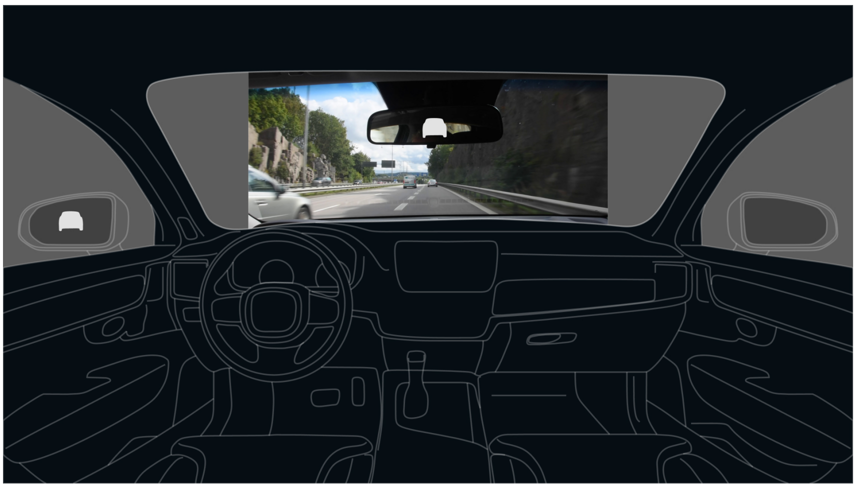

Figure 4.3: The frame for the merging with the highway traffic sub-goal

Subsequently, the participants were presented with fourteen different stickers, which they could select from and drag and drop into the frame. The stickers were taken from Bostad's structured requirements questionnaire for driving and included a list of important driving elements, such as location, distance, direction, and comparative speed [8] (See Figure 4.4). By selecting each sticker and dropping it on the highlighted elements in the frame, the participants specified what each element meant for them and what aspect of it was relevant in terms of safety. Since level 2 SA is equivalent to the comprehension of the meaning of each element [16], the selection of stickers resulted in quantitative data that corresponded with information requirements for level 2 SA.

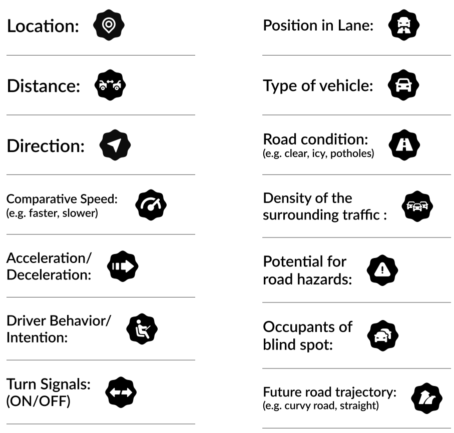

Figure 4.4: The list of stickers

The participants were asked to think aloud and elaborate on their decisions and selections during the entire study. The think-aloud protocol was meant to provide insights into why each object or sticker was selected and the decisions they had to make during that specific driving scenario. The elaborations resulted in qualitative data that provided insight into drivers' decisions in each driving scenario.

Lastly, two more questions were asked to identify what was the participant's opinion on the main cause of failure in each scenario and how it could be improved in future automated vehicles. These questions were aimed at eliciting further insights on the topic. The questions of the interview study are presented in Appendix A.

4.2.1 Video Clips

The videos of the driving scenario were selected from a library of driving footage that was recorded within a project at the design and human factors department at Chalmers University, and they lasted between 15 to 20 seconds each. They included five different driving scenarios: entering a highway, exiting a highway, approaching a roundabout, approaching an intersection, and performing a lane change.

4.2.2 Analysis

All the quantitative data were gathered and analyzed inside an excel sheet. All the selected objects and stickers in the frame were counted. The stickers which were selected less than two times for a certain element were discarded from further analysis. The NVivo software was used for the thematic analysis of the qualitative data from the interviews.

4.3 Findings

A summary of the findings for each driving scenario is provided in the sections below. The findings are formatted according to the sub-goal, decisions, and information requirements.

4.3.1 Merging with the Highway Traffic

To merge with the highway safely, the participants mentioned the necessity to make critical decisions regarding the traffic situation in the left lane. These decisions included deciding whether to let the vehicles pass or speed up, whether there is enough room to merge, and making judgments on other drivers' intentions to change lanes.

All participants stated that it was necessary to be aware of the existence of potential vehicles in the left lane and the left-side view mirror to be able to make these decisions safely. They specified that they need to be aware of these vehicles' distance, their speed compared to the ego vehicle, their use of turn signals, and their position within their lane (See Figure 4.6).

Some of the participants also discussed issues like making judgments on the possibility of a rear-end collision. They believed it was crucial to be aware of their distance from the vehicles in the front and the cars behind.

Moreover, most participants saw the failure to look for blind spots as the leading cause of accidents in this scenario. See Figure 4.6 for a more comprehensive list of decisions and information requirements for this driving scenario.

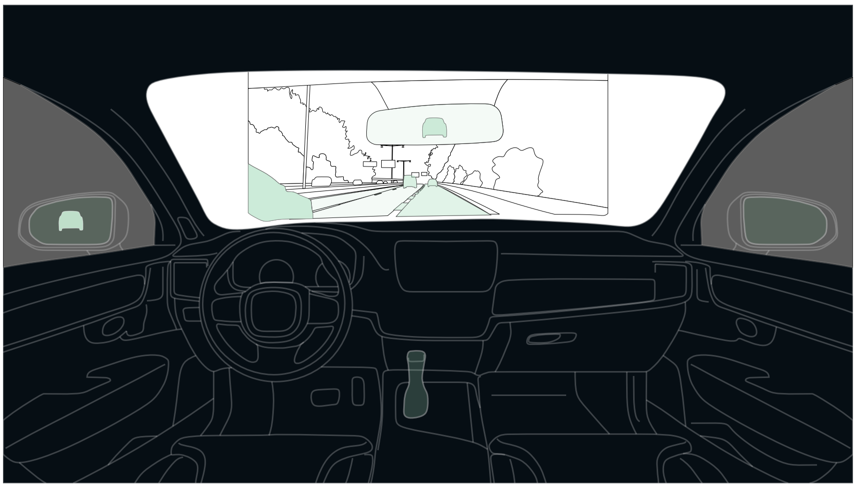

Figure 4.5: Selections for merging with the highway traffic sub-goal. The green color corresponds to a selected object, and the opacity of the green color corresponds to the number of selections.

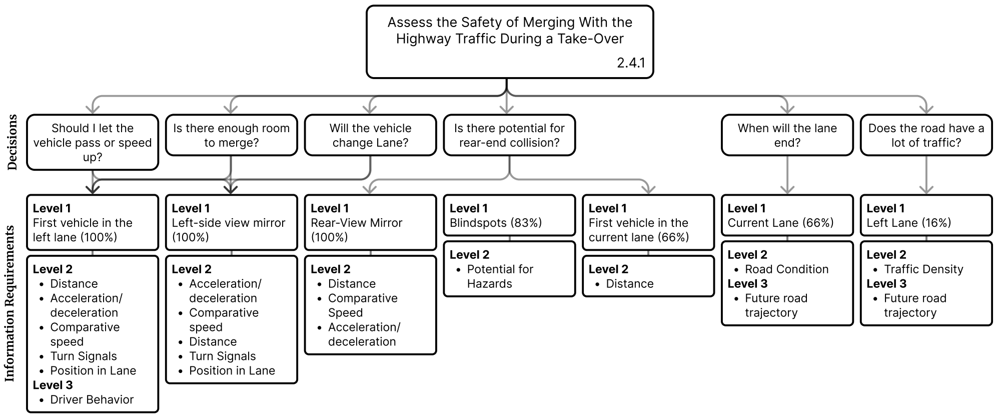

Figure 4.6: Decisions and information requirements for merging with the highway traffic sub-goal (Percentage indicates the percentage of participants who have selected a given element).

4.3.2 Exiting the Highway

To safely exit the highway, the participants discussed having to make decisions bearing in mind the traffic situation surrounding the vehicle. They were mainly concerned with deciding when to brake and its influence on causing a rear-end collision with other cars.

All participants stated that it was necessary to be aware of the existence of potential vehicles in front and the rear-view mirror to be able to make this decision safely. They specified that they need to be aware of these vehicles' distance, their speed compared to the ego vehicle, their acceleration or deceleration, and also the overall traffic density of the current lane (See Figure 4.8).

Moreover, all participants were highly concerned with the intentions of the drivers in the left lane. They believed that a sudden merging of the vehicles in the left lane would immediately impact their safety. Thus, making judgments on these drivers' intentions was seen as necessary. To make this judgment, they looked into aspects like the direction, use of turn signals, and position of these vehicles. Similarly, most participants viewed last-second merging into the exit lane as the main cause of accidents in this scenario. For a more comprehensive list of decisions and information requirements for this driving scenario, see Figure4.8.

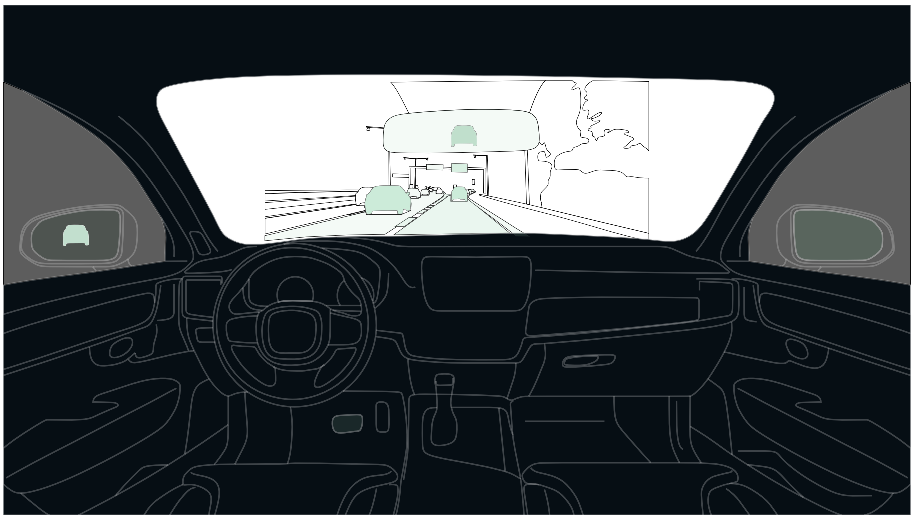

Figure 4.7: Selections for exiting the highway sub-goal. The green color corresponds to a selected object, and the opacity of the green color corresponds to the number of selections.

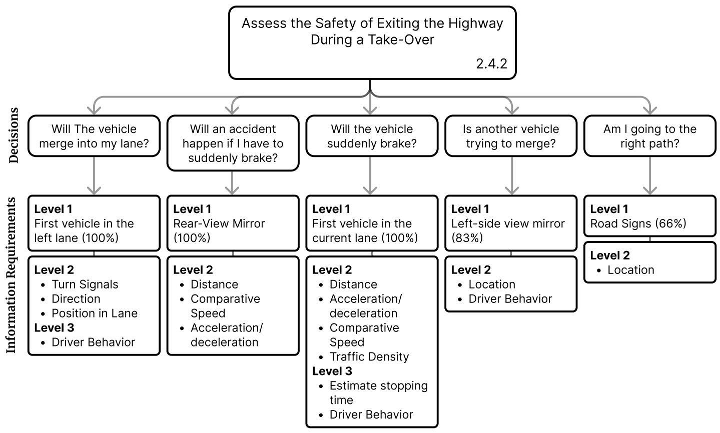

Figure 4.8: Decisions and information requirements for exiting the highway sub-goal (Percentage indicates the percentage of participants who have selected a given element).

4.3.3 Entering a Roundabout

The participants mentioned the importance of making critical decisions regarding the surrounding traffic and the incoming traffic to the roundabout from the left side. These decisions included deciding on the right time for entering the roundabout, whether to let the vehicles pass or enter, whether they could squeeze between the vehicles, and making judgments on other drivers' intentions to allow them to enter.

Most of the participants stated that it was necessary to be aware of vehicles in the left lane and other vehicles entering the roundabout to be able to make this decision safely. They specified that they need to be aware of these vehicles' use of turn signals, their speed compared to the ego vehicle, their vehicle type, and their distance (See Figure4.10).

Moreover, most participants were concerned with the unanticipated actions of the vehicle in the front that would lead to a rear-end collision. To make a correct judgment on this issue, they looked into the vehicle's distance, its speed compared to the ego vehicle, and whether it uses turn signals. Most participants believed that not using turn signals was the leading cause of failure in this scenario. See Figure 4.10 for a more comprehensive list of decisions and information requirements for this driving scenario.

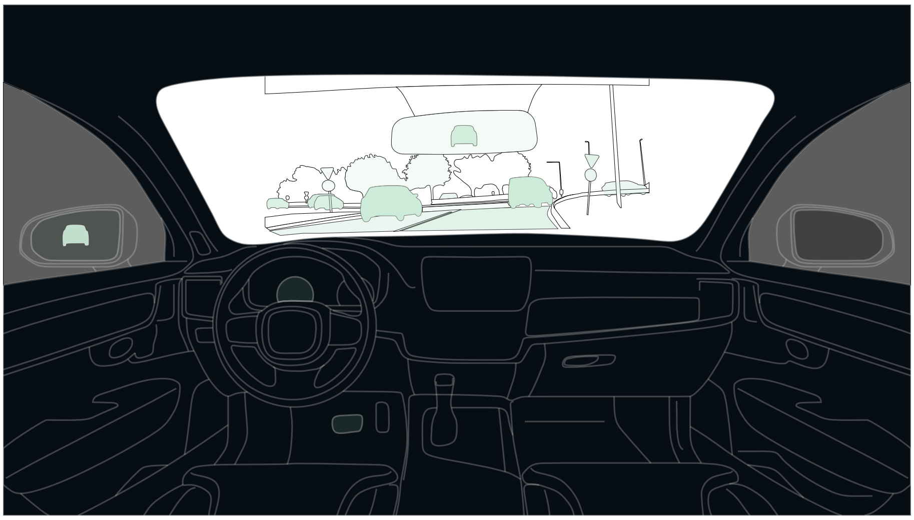

Figure 4.9: Selections for entering a roundabout sub-goal. The green color corresponds to a selected object, and the opacity of the green color corresponds to the number of selections.

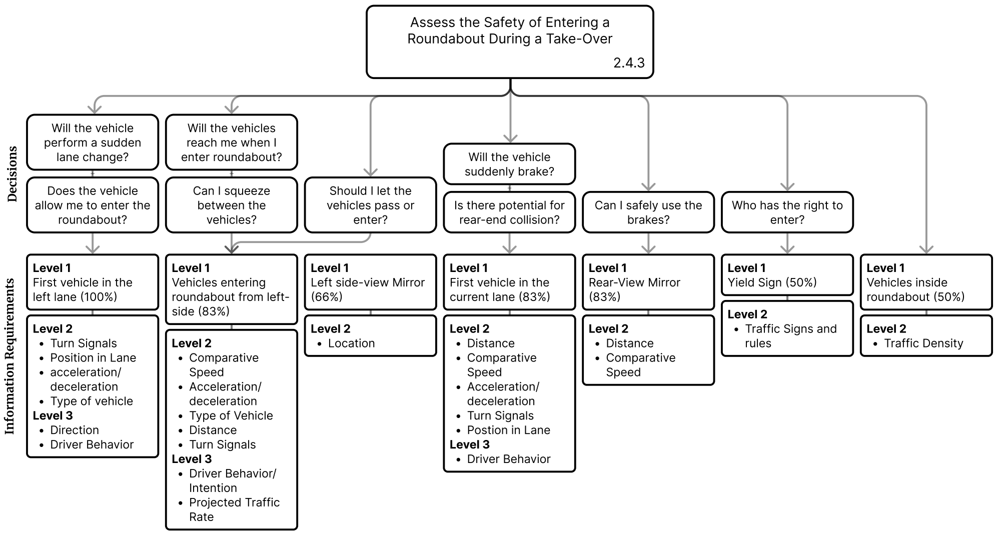

Figure 4.10: Decisions and information requirements for entering a roundabout sub-goal (Percentage indicates the percentage of participants who have selected a given element).

4.3.4 Approaching an Intersection

The participants discussed making decisions on whether it was the right time to proceed, whether there was potential for vehicles/pedestrians to enter, whether another vehicle was overtaking them from behind, and making judgments on the intentions of other drivers inside the intersection.

Most of the participants stated that it was necessary to be aware of the vehicles inside the intersection and the oncoming traffic to be able to make these decisions safely. They specified that they need to be aware of these vehicles' use of turn signals, their direction, and the traffic density of the intersection (see Figure 4.12).

Moreover, there was no consensus among participants regarding the main cause of failure in this scenario; however, they mentioned signaling too late, failure to look both ways, and not attending the traffic signs. See Figure 4.12 for a more comprehensive list of decisions and information requirements for this driving scenario.

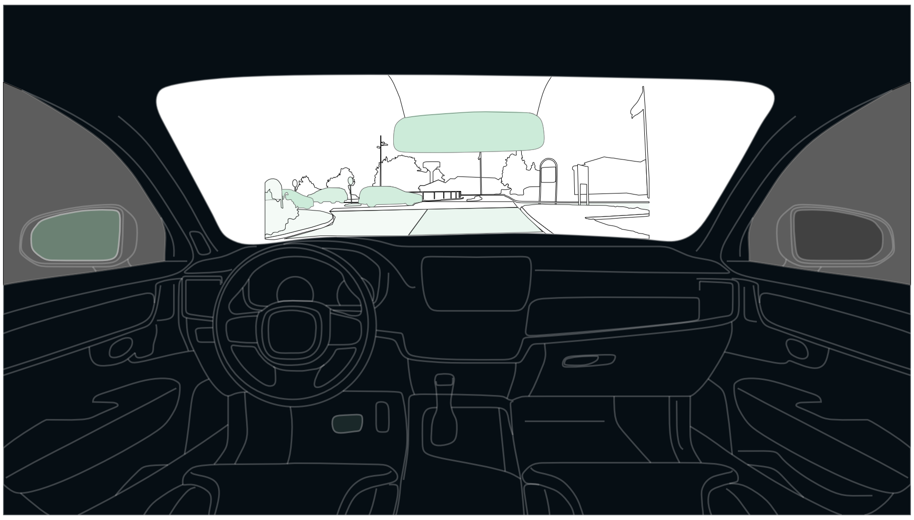

Figure 4.11: Selections for approaching an intersection sub-goal. The green color corresponds to a selected object, and the opacity of the green color corresponds to the number of selections.

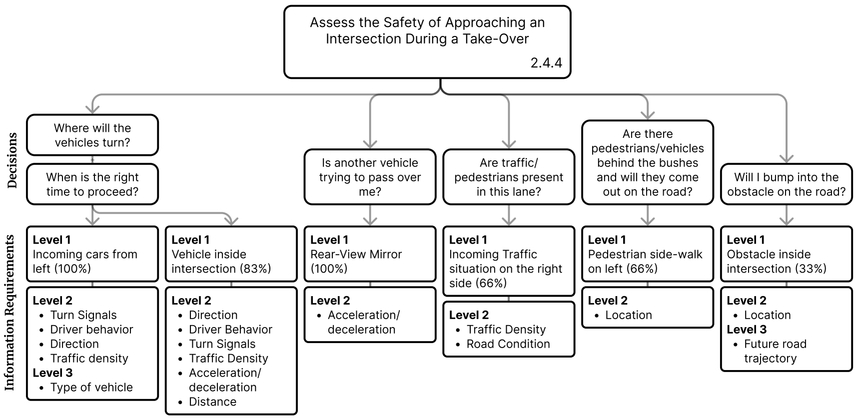

Figure 4.12: Decisions and information requirements for approaching an intersection sub-goal (Percentage indicates the percentage of participants who have selected a given element).

4.3.5 Changing Lanes

The participants discussed making decisions on whether to let the vehicles in the left lane pass, whether there was enough room to merge, and whether the traffic situation in the left lane allowed a lane change to happen.

All participants stated that it was necessary to be aware of the vehicles in the left lane, vehicles in the left-side and rear-view mirrors, and vehicles in the current lane to be able to make these decisions safely. They specified that they need to be aware

of these vehicles' distance, relative speed, acceleration or deceleration, and the traffic density of the left lane (See Figure 4.14).
Moreover, the participants were concerned with the possibility of a rear-end collision due to high traffic density and a sudden lowering of the speed of the preceding vehicles. Therefore, they believed that increasing their speed and performing a lane change depended on situational information regarding those issues. All participants believed that missing the blind spots was the leading cause of accidents in this scenario. See Figure 4.14 for a more comprehensive list of decisions and information requirements for this driving scenario.

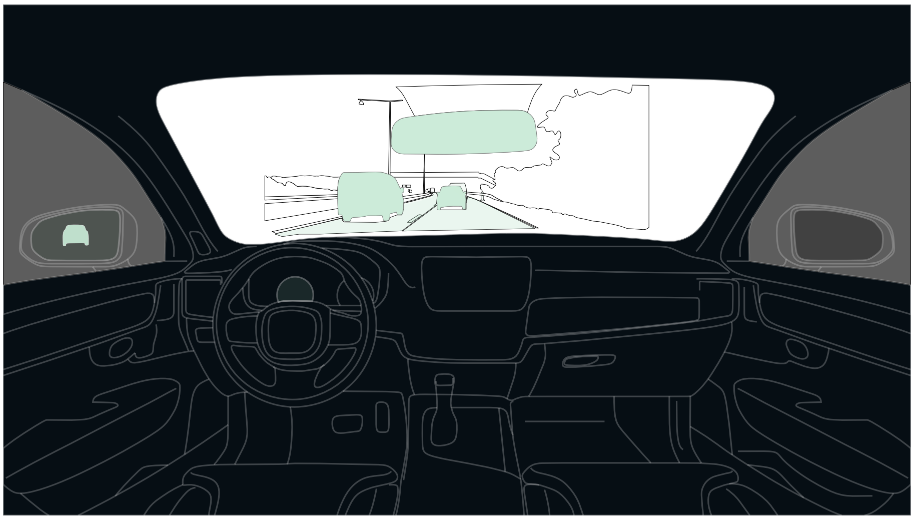

Figure 4.13: Selections for changing lanes sub-goal. The green color corresponds to a selected object, and the opacity of the green color corresponds to the number of selections.

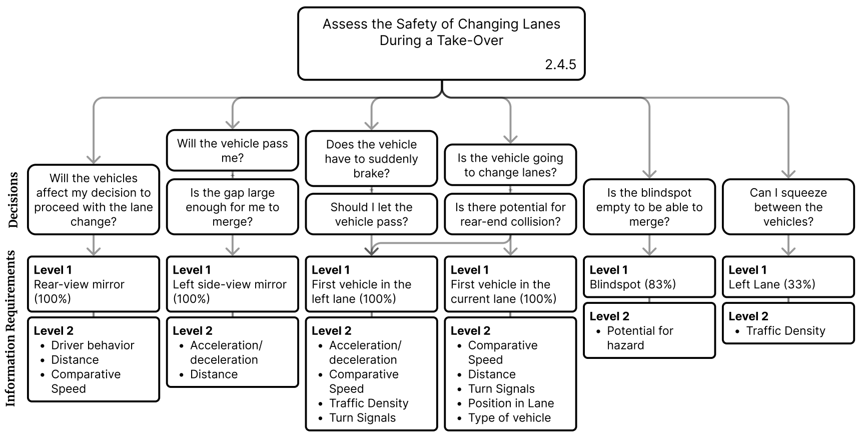

Figure 4.14: Decisions and information requirements for changing lanes sub-goal (Percentage indicates the percentage of participants who have selected a given element).

4.4 Summary

This study identified the decisions and information requirements for five possible driving situations where a take-over might be necessary. Even though the gathered insights might not be applicable to all driving scenarios, they still provide a clue on what drivers scan in the driving environment to gain situational awareness in similar situations. The study found that drivers must make a range of decisions in order to control the vehicle safely.

The study's most important finding is that information requirements are unique for each driving situation. Thus, the HMI should be adapted to each driving situation to support the driver in maintaining situational awareness of the traffic environment. Moreover, the findings revealed that some information requirements were common among all driving scenarios. During all scenarios, the intentions of drivers of adjacent vehicles were the biggest concern for participants in terms of safety. To make a correct decision on this issue, awareness of aspects like these vehicles' relative speed, distance, and position within their lanes was necessary for safety.

Lastly, the information requirements discovered during this study informed queries of the SAGAT method employed during the SA evaluation in Chapter 5. The queries inquired about participants' awareness of the identified information requirements for each driving situation. If the participants answered the queries correctly, it could be concluded that they had an awareness of that particular information requirement in the traffic environment.

5

Evaluation

This chapter evaluates the HMI concept developed in the previous chapter in terms of situation awareness and facilitating an accurate mental model.

5.1 Aim

The evaluation aimed to understand how the HMI concept affects participants' situation awareness and whether it successfully facilitated an accurate mental model of the system. Consequently, a user study was conducted that tried to answer the following questions:

- Does the new HMI concept improve situational awareness of the external driving environment compared to the baseline concept?
- Does the new HMI concept lead to an improved mental model of the system compared to the baseline concept?
- Do the different interface elements contribute positively to participants' understanding of the system?

5.2 Method

A 2x2 mixed design experiment was conducted using pre-recorded video clips. A comprehensive description of the experiment is provided in the paragraphs below.

5.2.1 Participants

Twenty people participated in the study, and they were all students of either the Chalmers University of Technology or the Gothenburg University. The participants were aged between 22 and 33 years (Mean = 25.9, SD = 3.02) and held a driving license for an average of 7.25 years. Of the 20 participants, ten participants did not have any experience with ADAS technologies. Six participants had experience with adaptive cruise control. Three participants had experience with lane-keeping assist. One participant had experience with the blind-spot assist, and one participant had experience with parking assist. All participants provided written consent and were provided a movie ticket as compensation for participating in the study.

5.2.2 Apparatus

Two different videos were simultaneously presented to participants on two separate displays. A video of a driving scenario was displayed on a 15-inch display with a resolution of 1920 x 1080 pixels. The HMI concept was displayed on a separate 11-inch tablet positioned on the right side of the first display (See Figure 5.1).

Figure 5.1: The study apparatus and setup

5.2.3 Animated Video Clips

The two driving scenarios of entering an intersection and performing a lane change were selected from the five driving scenarios discussed in chapter four because they aligned better with the research objectives of the project's industrial partner. A video clip for each driving scenario was selected from YouTube [34], and they lasted around 45 seconds each.
The video for the intersection scenario involved a medium-density traffic situation, showcasing an urban environment with a two-lane road and a four-way intersection. The footage contained incoming vehicles from both sides of the intersection with no pedestrians passing the intersection.
The video for the lane change scenario involved a medium-density traffic situation. It showed a three-way highway, with the ego-vehicle driving in the right lane. All surrounding vehicles had a higher speed than the ego vehicle. Animated HMI concepts accompanied all driving videos on a secondary display.

5.2.4 HMI Concepts

Two different HMI concepts were compared to each other during the study. The first HMI concept was the concept developed in chapter three (HMI A). It included five visual interface elements: the map/sensor view, status icons, information portal, and

journey progress bar. It also included two auditory interface elements: informative signal and acoustic signal.
The second HMI concept was the baseline concept introduced in chapter one (HMI B). It included two visual interface elements: the sensor view and the handover icon. It also included the same auditory acoustic signal from the previous HMI concept.

Figure 5.2: The HMI A concept (left) and the HMI B concept (right).

5.2.5 Procedure

The study had a 2x2 mixed design in which all participants experienced both the HMI A and HMI B (See Figure 5.2) alongside either the intersection video or the lane change video. The scenarios were randomized for each participant using the Latin square matrix (See Table 5.1).

Table 5.1: The experimental design

#	Scenario 1	Scenario 2
1	Intersection + HMI A	Lane Change + HMI B
2	Intersection + HMI B	Lane Change + HMI A
3	Lane Change + HMI A	Intersection + HMI B
4	Lane Change + HMI B	Intersection + HMI A
...		

Initially, the participants were briefed on the definition of adaptive cruise control and lane-keeping assist. Then, they were shown a sample video of a similar driving scenario that they would be watching during the study. They were told that they should imagine they were driving in an automated vehicle and that their main task was supervising the driving scenario.
During both scenarios, a TOR prompt was presented after 42 seconds. The participants were told that the automated system was not perfect, and they might need to take back control of the vehicle. To take back control of the vehicle, they were instructed to click on a button that logged when the button was pressed. This logged time can provide insights into whether the participants understood the TOR prompt and how long it took them to react to the prompt. It acts as a behavioral measure of the accuracy of their mental model and can partly answer the second

research question of this study.
After the end of each scenario, the participants were presented with a questionnaire that included questions to assess participants' situation awareness and mental model. The questionnaires used a 5-point Likert scale that ranged from -2 to 2. After watching both scenarios and answering the corresponding questionnaires, the participants were asked eight open-ended questions in a semi-structured interview format. A brief description of the questionnaires is provided in the paragraphs below.

5.2.5.1 Questionnaires

First, the participants were presented with SAGAT queries [16] to measure their awareness of the external driving environment during and after the take-over request. These queries were based on the information requirements gathered in chapter 4 for the sub-goals related to approaching an intersection (See Figure 4.12) and performing a lane change (See Figure 4.14). The queries are presented in Appendix,C and they answer the first research question of the study.
Next, the participants were presented with questions that aimed to evaluate the accuracy of their mental model. These questions were adapted from the mental model questionnaire of Beggiato [4]. They included aspects like recognition of operational design limits, its cause, and the general capabilities of the system. This questionnaire answers the second research question of the study.
Lastly, the participants were presented with questionnaires that assessed different HMI elements' contribution to their situation awareness and questions regarding each element's clarity and effectiveness in communicating the intended meaning and its contribution to the overall understanding of the automated system. This questionnaire answers the third research question of the study. All questionnaires are presented in Appendix C.

5.2.5.2 Semi-structured Interview

After watching both scenarios and answering the questionnaires, the participants were interviewed. The interview used a semi-structured format and included open-ended questions regarding the participants' general thoughts on both concepts, the reasons behind the effectiveness or ineffectiveness of different interface solutions, and the challenges induced by the HMI.

5.2.5.3 Analysis

The quantitative data from the questionnaires were analyzed using the Kruskal-Wallis test in the SPSS software. The NVivo software was used for the thematic analysis of the qualitative data from the semi-structured interviews.

5.3 Findings

This section summarizes the findings gathered from the questionnaires and interviews. It also includes an overview of the suggestions mentioned by the participants for improving the HMI.

5.3.1 Reaction to the TOR Prompt

The reaction to the TOR prompt was measured by subtracting the moment the participants clicked the allocated button from the moment when the HMI displayed the take-over request.
For the HMI B concept, 13 participants missed the take-over request and did not click the allocated button, while for the HMI A concept, only one participant missed the take-over request. As the HMI A showed the upcoming actions of the system in the information portal and the journey progress bar, the participants had a tendency to take back control of the vehicle before the system initiated the take-over request. For that reason, 11 participants took over control before the system initiated the take-over request resulting in a mean of -3 seconds for the HMI A concept. The HMI B concept had a mean score of 1 second, which means a four-second difference in the mean score of both concepts.

5.3.2 Situation Awareness

Both HMI concepts scored similarly for the SAGAT queries that measured the participants' awareness of the external driving environment. By looking at the percentage of correct answers, we can see that the HMI A scored better on four queries while the HMI B concept scored better on six queries (See Figure 5.3 & Figure 5.4). There was no statistically significant difference between the two HMI concepts for twelve SAGAT queries.
However, the HMI A performed significantly worse in the query that was related to the number of vehicles passing the intersection ($\alpha = 0.05$, $\sigma = 0.042$). The significantly worse performance of the HMI A concept in this query can be attributed to the complexity of the intersection scenario and, most importantly, the higher information overload induced by this concept. Eight participants expressed that too much information was presented in the HMI A concept during the interviews. They mentioned that they had a hard time understanding where to look. On top of that, five participants mentioned that combining all the different elements made the interface too cluttered and distracting. They said that The HMI A concept drew away their attention from the road as they could not comprehend everything that was happening in the interface with a quick glance. Similarly, four participants thought that the map/sensor view was distracting as it had quite a lot of information inside it. Three participants suggested that the wording for the information portal can be reduced to lower attentional demands.
Moreover, one of the queries inquired about the next action that the driver should perform after taking control of the vehicle. This query was exclusive to the HMI A concept as this information was not provided in the HMI B concept. For this query, seven out of ten participants answered correctly in the intersection scenario, while five out of ten participants answered correctly in the lane change scenario. The lower scores for the lane change scenario can be attributed to the fact that the graphical icon used for indicating a lane change was not a standard traffic sign used

on Swedish roads. Thus, many participants struggled to understand what it meant, as they had never experienced it before.

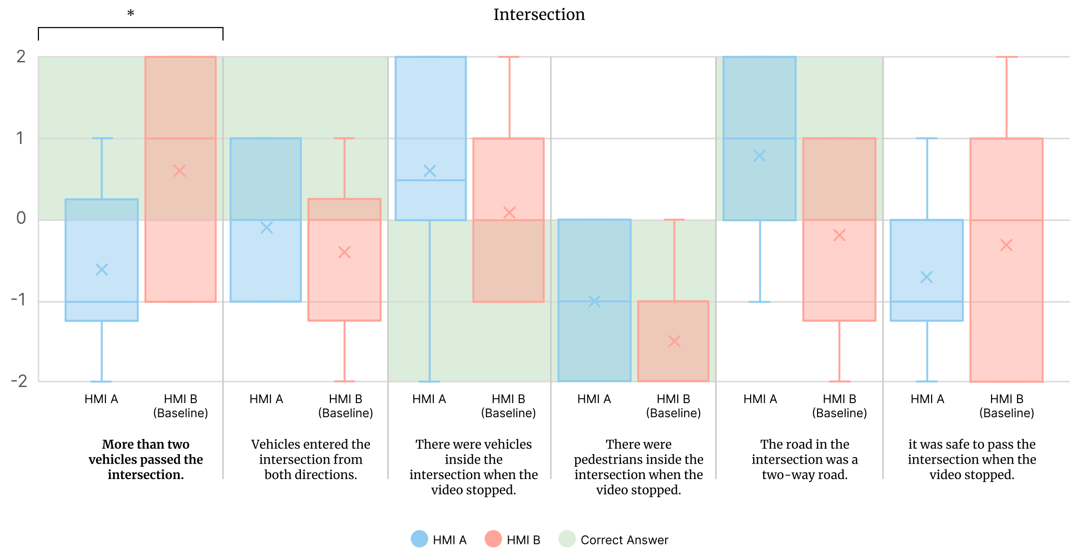

Figure 5.3: The box and whisker plot of SAGAT queries for the intersection scenario (Asterisks indicate the level of statistical significance: * $\sigma \leq 0.05$, ** $\sigma \leq 0.01$, *** $\sigma \leq 0.001$).

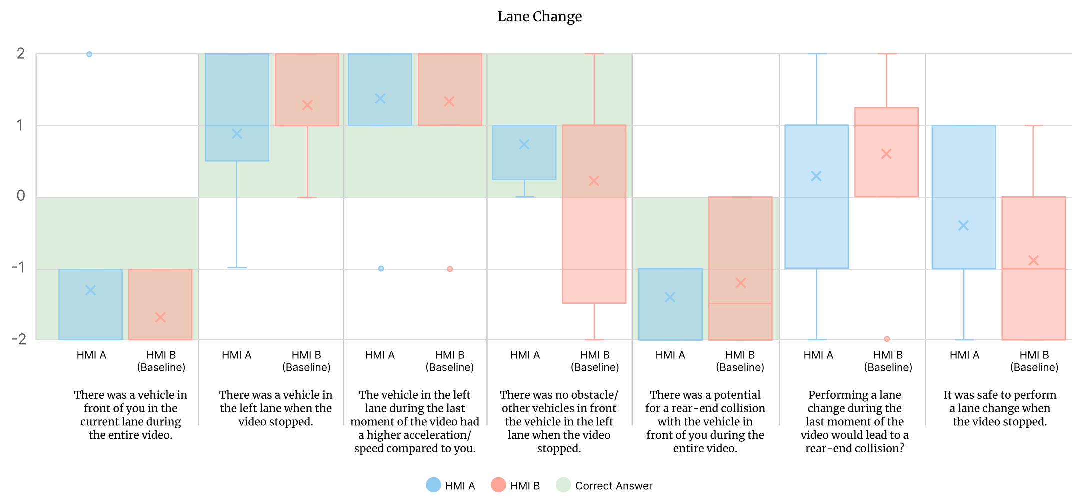

Figure 5.4: The box and whisker plot of SAGAT queries for the lane change scenario.

5.3.3 Perceived Situation Awareness

There was a statistically significant difference between different HMI elements ($\alpha = 0.05$, $\sigma < 0.001$) regarding their impact on participants' perceived awareness of what the system was doing or sensing in the environment. The informative auditory signal and the map/sensor view from the HMI A concept received the highest mean scores of 1.15 and 0.85, respectively. In comparison, the handover icon and the acoustic auditory signal (B) from the HMI B concept received the lowest scores of -0.95 and -0.15 (See Figure 5.5). The results of the previous section support the higher ratings given to the HMI A interface elements; since a significantly higher number of participants correctly reacted to the TOR prompt while experiencing the HMI A.

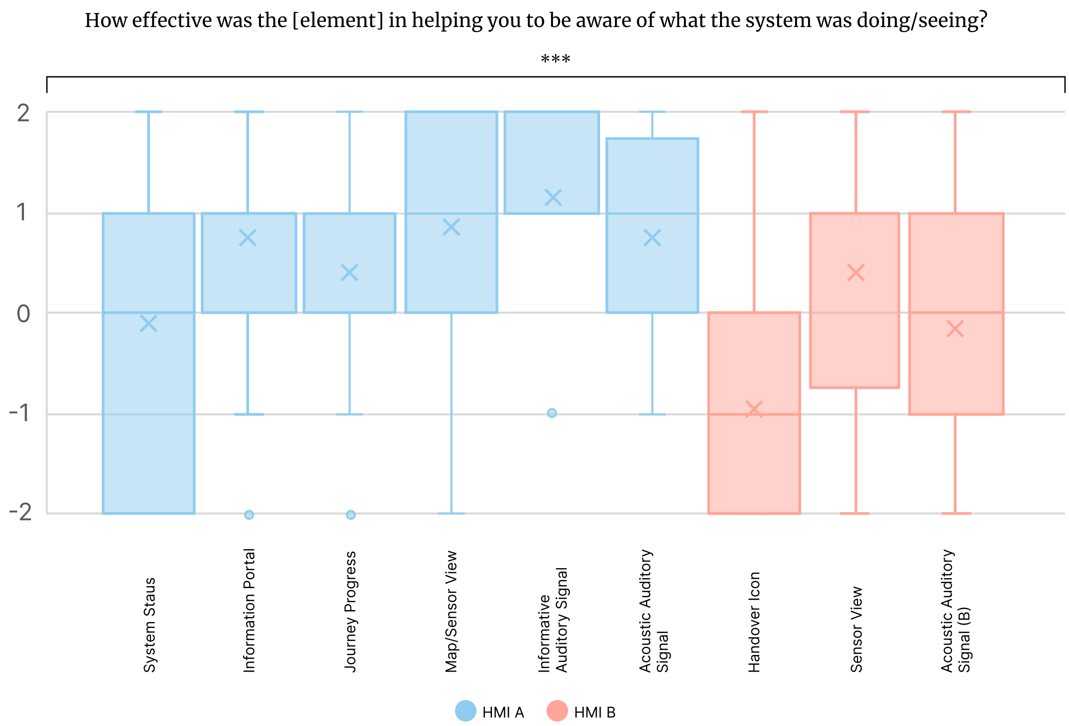

Figure 5.5: The box and whisker plot for the HMI's contribution to perceived situation awareness of the system's performance (Asterisks indicate the level of statistical significance: * $\sigma \leq 0.05$, ** $\sigma \leq 0.01$, *** $\sigma \leq 0.001$).

Similarly, there was a statistically significant difference between different HMI elements ($\alpha = 0.05$, $\sigma = 0.001$) regarding their impact on participants' perceived awareness of the traffic environment. The map/sensor view had the highest mean score of 0.65, while the sensor view from the HMI B concept came second with a mean score of 0.40. In comparison, the system status icons and the handover icon received the lowest scores of -0.90 and -0.85, respectively (See Figure 5.6). In this question, both map/sensor view and sensor view performed comparatively well, which supports the results of the SAGAT queries where both HMI concept performed similarly in most cases.

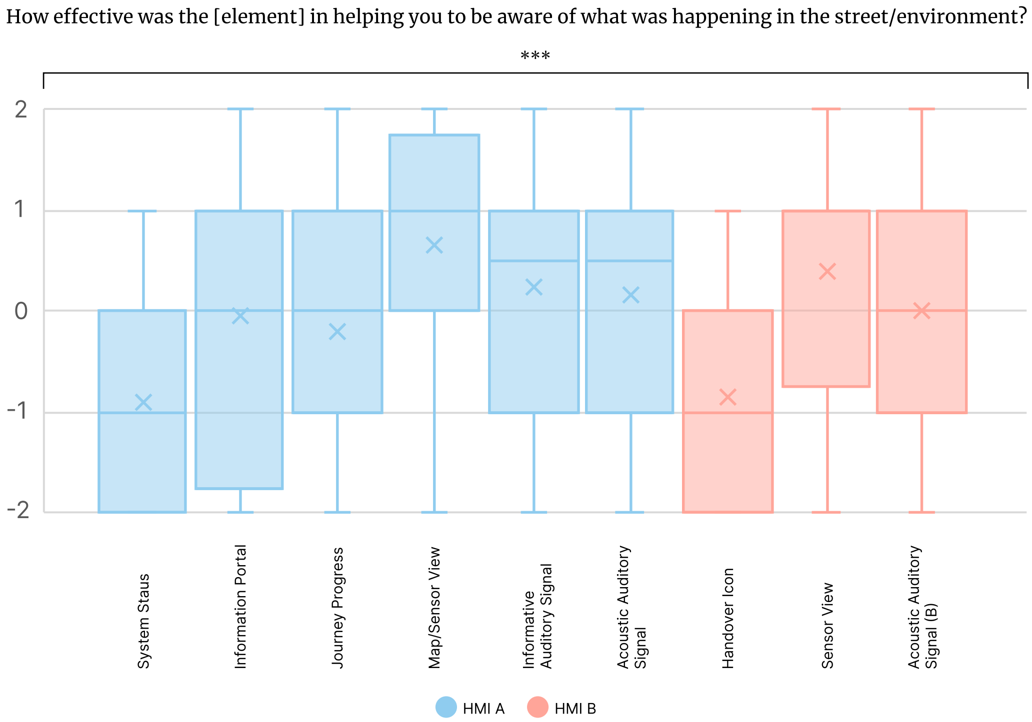

Figure 5.6: The box and whisker plot for the HMI's contribution to perceived situation awareness of the traffic environment (Asterisks indicate the level of statistical significance: * $\sigma \leq 0.05$, ** $\sigma \leq 0.01$, *** $\sigma \leq 0.001$).

5.3.4 Mental Model

The HMI A performed significantly better for the understanding of whether a take-over was requested ($\alpha = 0.05$, $\sigma < 0.001$). This significant difference in understanding the TOR prompt was also manifested in the previous section, where more than half of the participants failed to click on the take-over button when they were experiencing the HMI B concept.
Moreover, both HMI concepts performed similarly when the participants were asked about the system's ability to recognize the surrounding vehicles ($\alpha = 0.05$, $\sigma = 0.655$). One participant elaborated on the reason for not observing the surrounding vehicles in the HMI by stating that the use of gray colors on both concepts made the vehicles difficult to discern.
Furthermore, both HMI concepts performed similarly when the participants were asked about the system's ability to recognize the lane markings on the road ($\alpha = 0.05$, $\sigma = 0.453$).
Lastly, one of the questions inquired about understanding the reason why the system initiated a take-over request. In both scenarios, the TOR was initiated because the system could not handle intersections and it could not perform a lane change. For the intersection scenario, more participants correctly understood the reason behind the Take-over request when they were experiencing the HMI B concept (HMI A = 40%, HMI B = 60%). However, for the lane change scenario, no participant was

able to correctly understand the reason behind the take-over request when they were experiencing the HMI B concept, while the majority of participants correctly understood the reason when they were experiencing the HMI A concept (HMI A = 88.9%, HMI B = 0%).

The reason why HMI B performed poorly in the lane change scenario can again be attributed to the fact that the participants did not understand the graphical icon for indicating a lane change. Unlike the HMI A concept, which hinted at the reason for the TOR via the informative auditory signal, there was no other way of obtaining this information for the HMI B concept.

On the other hand, the worse performance of the HMI A during the intersection can be ascribed to the complexity of both the intersection scenario and the HMI A concept itself which many participants stated during the interviews. The inherent complexity of this scenario would have meant that the participants had to focus more on the road, which resulted in overlooking the information transmitted via the HMI. Interestingly, six participants mentioned that they overlooked the journey progress bar and the system status icons and believed that their information was insignificant or repetitive. In two cases, the information portal was not noticed by the participants while they mentioned that they were mainly looking at the journey progress bar throughout the test.

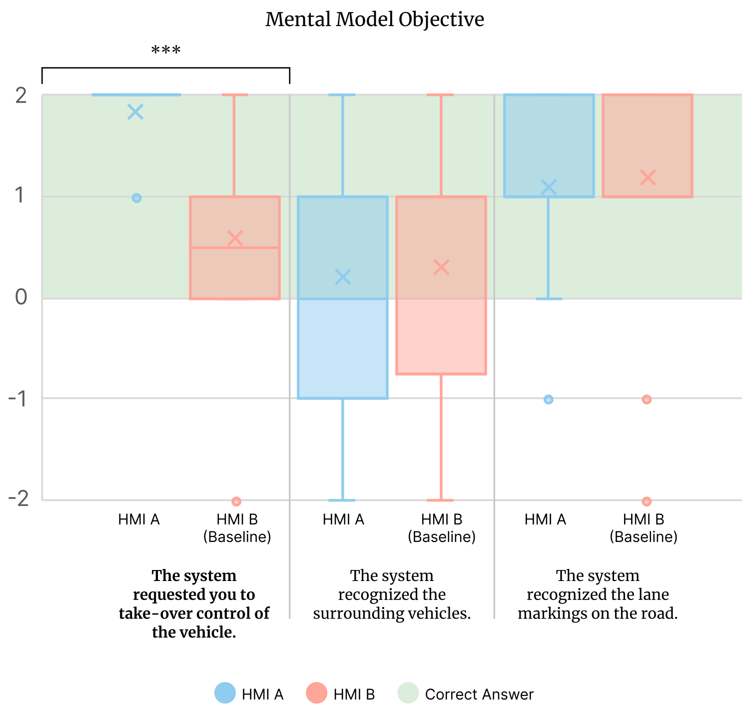

Figure 5.7: The box and whisker plot for the HMI's contribution to facilitating an accurate mental model of the system (Asterisks indicate level of statistical significance: * $\sigma \leq 0.05$, ** $\sigma \leq 0.01$, *** $\sigma \leq 0.001$).

5.3.5 Perceived Understanding of the System

The participants rated the HMI A as being significantly better in terms of clearly communicating the take-over request ($\alpha = 0.05$, $\sigma < 0.001$). The participants further elaborated upon these results during the interviews. Fourteen participants mentioned that the handover icon in the HMI B concept was difficult to understand. They stated that they did not understand the symbol, and a few misunderstood it as a seat-belt icon. Likewise, six participants stated that they were distracted by the handover icon as they had to look at it intently to comprehend what it meant. Seven participants were confused by the color-coding of the sensor view, as they did not understand what it referred to or what it meant. Lastly, each participant had a different interpretation of the meaning the colors entailed. These issues led to the overall confusion caused by the HMI B concept. It also further explains the results of the previous sections where participants did not realize that a take-over was requested.

However, it should be noted that the HMI A also had caused some confusion for the participants. During the interviews, six participants mentioned the journey progress bar was difficult to comprehend as one cannot get a correct sense of the remaining distance or time. Similarly, three participants were discontent with the journey progress bar's color-coding. They mentioned that the color-coding of the journey progress was difficult to understand and did not match the information portal. Other participants mentioned that the visualization of the journey progress bar stressed them as it implied an impending collision and danger.

Furthermore, three participants mentioned that it was difficult to comprehend and keep track of how many meters were left until the take-over request in the information portal. Two participants believed that using seconds instead was much more intuitive, while one participant thought that using only meters would be the better option.

Lastly, two participants mentioned that when hearing the informative auditory signal, they did not understand whether the vehicle was reporting its own actions or requesting an action from the driver.

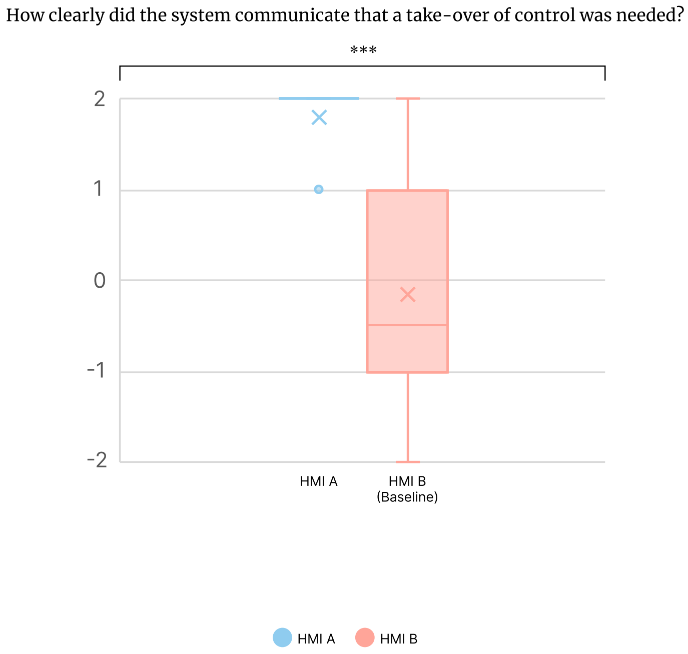

Figure 5.8: The box and whisker plot of HMI concepts' perceived clarity of communication (Asterisks indicate level of statistical significance: * $\sigma \leq 0.05$, ** $\sigma \leq 0.01$, *** $\sigma \leq 0.001$).

The participants' ratings on the effectiveness of the HMIs in communicating a take-over request varied significantly among the different HMI elements ($\alpha = 0.05$, $\sigma < 0.001$). The informative auditory signal received the highest mean score of 1.60, accompanied by the information portal and acoustic auditory signal, both with a mean score of 1.30. In contrast, the sensor view, the handover icon, and the system status received the lowest scores of -0.80, -0.65, and 0.25, respectively (See Figure 5.9).

Interestingly, both concepts used the same sound file for the acoustic auditory signal; however, the results show a huge disparity between the acoustic signal in the HMI A concept and the HMI B concept. Four participants elaborated on this issue by stating that the acoustic signals in both concepts were difficult to interpret on their own. They mentioned that they did not associate the acoustic signal with a take-over request. They believed that the co-occurrence of the acoustic signal with other visual signals yielded a better understanding for them. By looking at the Figure 5.9, we can understand that the combination of acoustic signals with the information portal was substantially more effective than its combination with the handover icon.

Not to mention, the map/sensor view scored relatively poorly in this question compared to the other questions. Two participants elaborated on this notable difference by stating that the information provided by the map/sensor view was not helpful for them. One participant also mentioned that they were surprised that the map/sensor view did not provide street directions and other relevant map data.

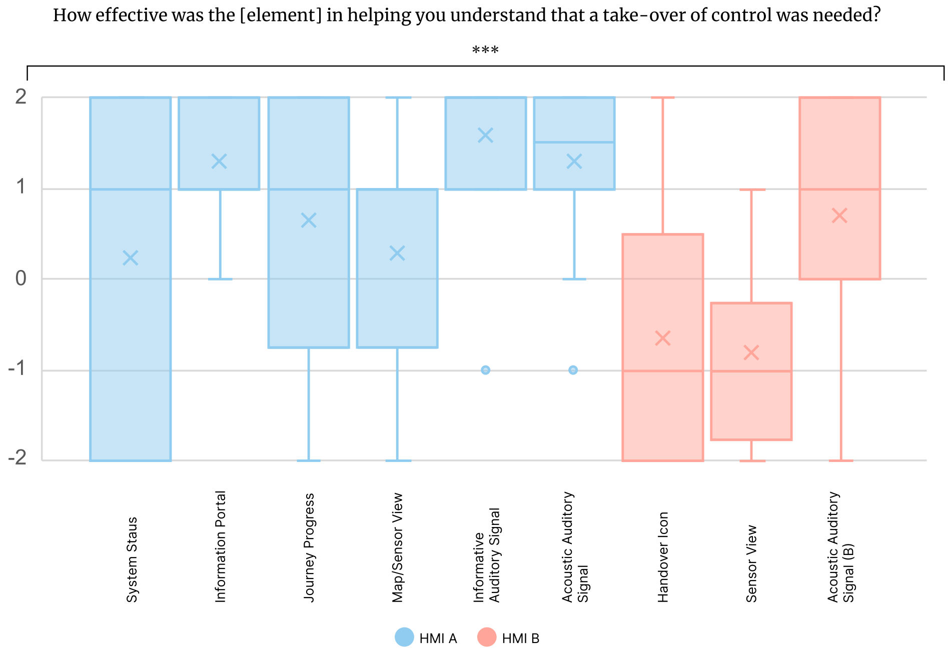

Figure 5.9: The box and whisker plot for the perceived effectiveness of HMI concepts' during a take-over request (Asterisks indicate level of statistical significance: * $\sigma \leq 0.05$, ** $\sigma \leq 0.01$, *** $\sigma \leq 0.001$).

Lastly, the quality of the concepts' communication with the participants was evaluated. The participants rated the HMI A as being significantly more distracting ($\alpha = 0.05$, $\sigma = 0.021$). These results are supported by the statements participants made during the interviews and the results of the SAGAT method. In contrast, the HMI A was rated better in terms of being more straightforward and easier to read compared to the HMI B concept; however, no statistically significant difference was identified between them ($\alpha = 0.05$, $\sigma_{straightforwardness} = 0.22$, $\sigma_{readability} = 0.18$). Similarly, the participants rated the HMI A as being significantly easier to interpret and finely timed ($\alpha = 0.05$, $\sigma_{interpret-ability} = 0.023$, $\sigma_{timeliness}$ <0.001).

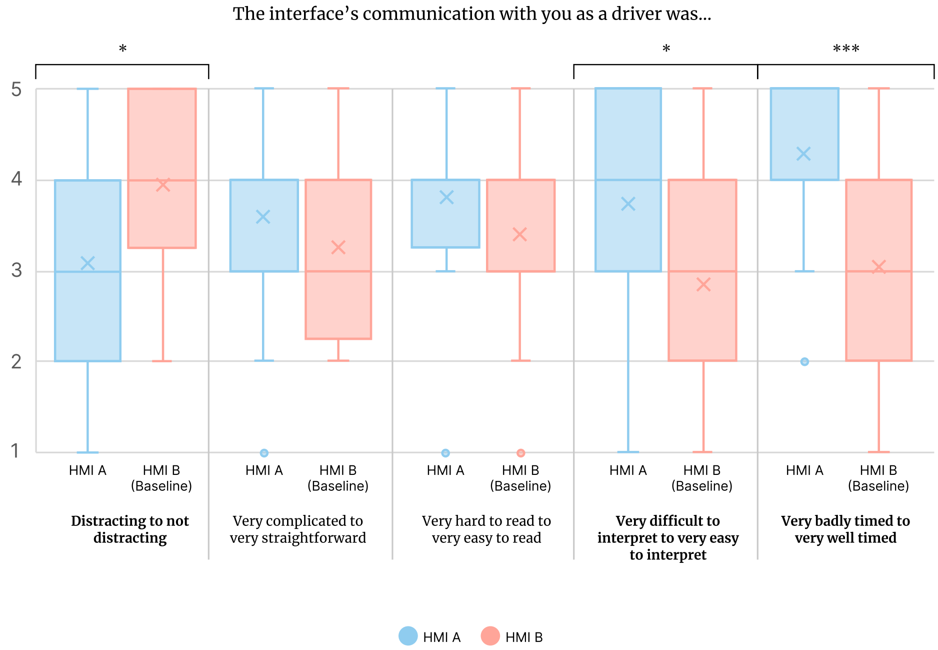

Figure 5.10: The box and whisker plot of HMI concepts' perceived communication quality (Asterisks indicate level of statistical significance: * $\sigma \leq 0.05$, ** $\sigma \leq 0.01$, *** $\sigma \leq 0.001$).

5.3.6 Suggestions for Improvement

5.3.6.1 Changing Display Position or Display Technology

Ten participants believed that the position of the display was sub-optimal and highly distracting. Literature shows that people are more reluctant to make scans when neck rotation and body movement are involved [47]. In the current position, the participants had to perform a slight neck rotation to be able to absorb the information on the screen. They preferred other positions closer to the windscreen and their line of sight. They believed that the addition of side-view and rear-view mirrors in a real driving situation would make the current position of the display an even bigger disturbance for driving. There were Suggestions for moving the display closer to the instrument cluster. Two participants mentioned that the system status and the information portal could be transferred to the instrument cluster entirely; Since they provide more critical information and should be closer to the driver's line of sight. Participants also suggested using display technologies like heads-up displays, AR windshields, and instrument clusters instead of the current implementation.

5.3.6.2 Changes to the Map/Sensor View

The participants suggested many changes to the map/sensor view. One participant mentioned that they wanted the sensor view to more notably specify when a vehicle was behind them or on their side. Four participants mentioned that they would like

the map/sensor view to identify pedestrians, bike lanes, obstacles, and small objects. Three participants also said they would like feedback regarding what the car intends to do inside the sensor view. Two participants mentioned that they would like to see the distance to other vehicles provided in numbers on the sensor view. These requests are in line with the information requirements identified in chapter 4 as well (see Figure 4.12).
Moreover, three of the participants thought that the addition of the buildings and roads made the sensor view cluttered. Four participants mentioned that they preferred that the sensor view would only show what the sensors are actually seeing. They believed that it is difficult to discern what the car is aware of and what it is not aware of in the current implementation. They believed that this implementation would confuse them as they would not take action on what is shown in the map/sensor view since, as far as they are concerned, whatever is shown in the map/sensor view has been detected by the sensors, and the vehicle will not crash into it. In contrast, two participants believed that adding roads and buildings was beneficial as they helped better grasp the vehicle's situation relative to its environment. It seems that the graphics of the map/sensor view can lead to an inaccurate understanding of the vehicle sensors' abilities.

5.3.6.3 Changes to the Auditory Signals

A few participants suggested that the acoustic signals could be improved by making changes to their rhythm and variation. Two participants mentioned that the acoustic beeps from the auditory signal were a bit stressful and startled them. They suggested that the acoustic signal could become more smooth and indicate the imminence of a take-over through a change in rhythm. On a similar note, two participants mentioned that the auditory signals should differ depending on the driving situation. Moreover, four participants mentioned that they would like to have the option of customizing or turning off the informative auditory signal. They believed that the informative auditory signal might become disturbing after getting hold of the automated system.

5.3.6.4 Other Suggestions

The participants also made other suggestions, including a video tutorial for first-time users, having the ability to change font sizes, combining the information portal and the journey progress bar, and using tactile vibrations for people with hearing disabilities.

5.4 Summary

The two HMI concepts were evaluated using a video-clip study to assess their impact on participants' situation awareness, mental model, and understanding of the system.
There was a significant improvement in the new HMI concept (HMI A) in terms of recognizing the need for a take-over request. 95% of participants correctly inter-

preted the take-over prompt for the HMI A, while only 35% correctly interpreted the take-over prompt for the HMI B concept. Similarly, there was a four-second improvement in reacting to the TOR prompt for the HMI A compared to the HMI B concept.

On the other hand, the SAGAT queries showed no significant difference between the HMI concepts in terms of situation awareness of the external environment. The new HMI A concept may have received lower ratings than expected due to the information overload and distraction it causes. Many participants expressed this issue during the interviews by stating that the combination of all the different HMI elements made the interface too cluttered and distracting. Thus, the HMI A concept drew more of their attention away from the road and resulted in a slightly worse situation awareness of the external driving environment. The participants perceived awareness was significantly higher when they were exposed to interface elements from the HMI A, namely the map/sensor view.

Moreover, the questionnaires for measuring the accuracy of the participants' mental model showed results that are comparable to the behavioral measure of recognizing the take-over prompt. The participants had a significantly better understanding of the TOR prompts in the HMI A concept. The questionnaires indicate that the HMI A TOR prompts were significantly easier to interpret, more well-timed, and exceedingly clear compared to their HMI B counterpart. On the other hand, the HMI A concept was significantly more distracting than the HMI B concept. A considerable number of participants have mentioned that some of the information provided by the HMI A concept was repetitive or excessive.

It can be concluded that the new HMI concept has proven to be significantly more clear and easier to interpret for the participants and would lead to a more accurate understanding of the system's intentions. However, moving forward, the amount of information provided by it should be significantly reduced or simplified. It could be hypothesized that a more simplified version of the HMI A would also lead to a better situation awareness of the external driving environment. This is because the distracting nature of this HMI concept seems to be the biggest bottleneck for achieving higher ratings of situation awareness. Additionally, it seems that the current graphics of the map/sensor view can lead to an inaccurate understanding of the vehicle sensors' abilities. Thus, in the following iteration of the HMI concept, the map/sensor view should be redesigned to better discriminate between the sensor information and the map data.

6
Communication

The final iteration of the HMI concept is presented in the following sections.

6.1 Aim

The communication phase aimed to redesign the HMI concept created in chapter 3 (See Figure 3.9) in an attempt to improve the design based on the findings from the evaluation.

6.2 Method

The final iteration of the HMI concept was developed using rapid prototyping software. The changes were made in light of the findings from both questionnaires and interviews. The suggestions pointed out by the test participants during the evaluation were also implemented.

6.3 Results

The results of the final iteration of the HMI concept will be demonstrated in the sections below.

6.3.1 Simplified Interface

One of the main drawbacks of the HMI A was that it created a lot of distraction due to providing an excessive amount of information. It is believed that the combination of all the different elements contributed to this issue. During the interviews, it became apparent that the information portal and journey progress bar competed for attention. The information portal rated higher than the journey progress in all the mean scores. Thus, the logical step forward is to combine a simplified version of the journey progress bar into the information portal.
The new information portal includes a progress bar between the current navigation prompt and the upcoming navigation prompt (See Figure 6.1). The progress bar shows when the current navigation prompt ends since some participants said it was difficult to comprehend when they should take over using indicators like seconds or meters.

The color-coding of the information portal has been simplified as well. It now uses the same color-coding of the multi-level warning design discussed in chapter 3 (See Figure 3.4) and blue color to indicate active Automation (See Figure 6.1).

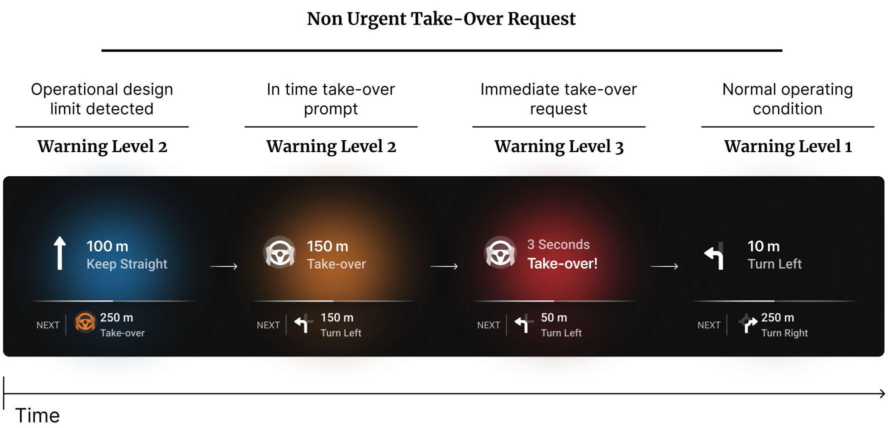

Figure 6.1: The new information portal

Moreover, the system status icons were redesigned. In the previous implementation, a change in the status of ADAS features was shown only through color. Thus, it made information processing impossible for persons with color vision deficiency. The new design uses a change in opacity and blinking to indicate a state change (See Figure 6.2). The blinking frequency is between 2 to 10 Hz and is based on the MIL-STD-1472G standard of the US army [13].

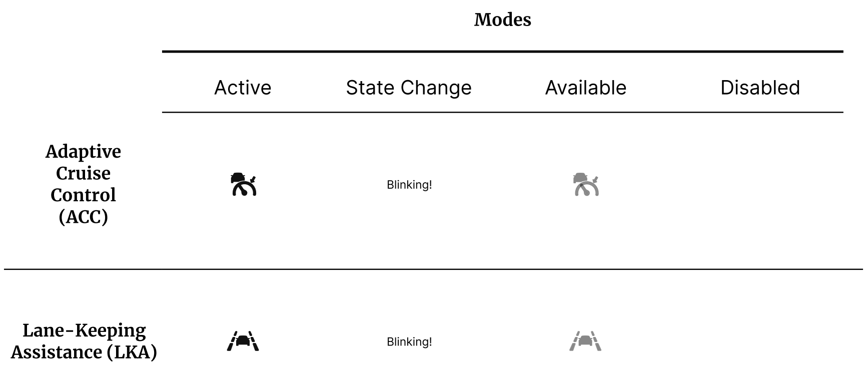

Figure 6.2: The new system status icons during different modes

6.3.2 Map/Sensor View

The test participants said they would trust that the ADAS would take appropriate action when sensors detect something in the environment. However, in the current implementation, the sensor and map data are not distinguished from one another. Thus, the test participants did not know which parts of the map/sensor view were the inputs from the sensors. This issue can lead to confusion and unsafe behavior because participants might mistakenly think that the sensors have detected something and refrain from taking appropriate action.
As a result, in the new map/sensor view, sensor data are distinguished from map data using a distinct blue color and differences in opacity (See Figure 6.3). It is now clear what the sensors have detected in the environment and what they have not.

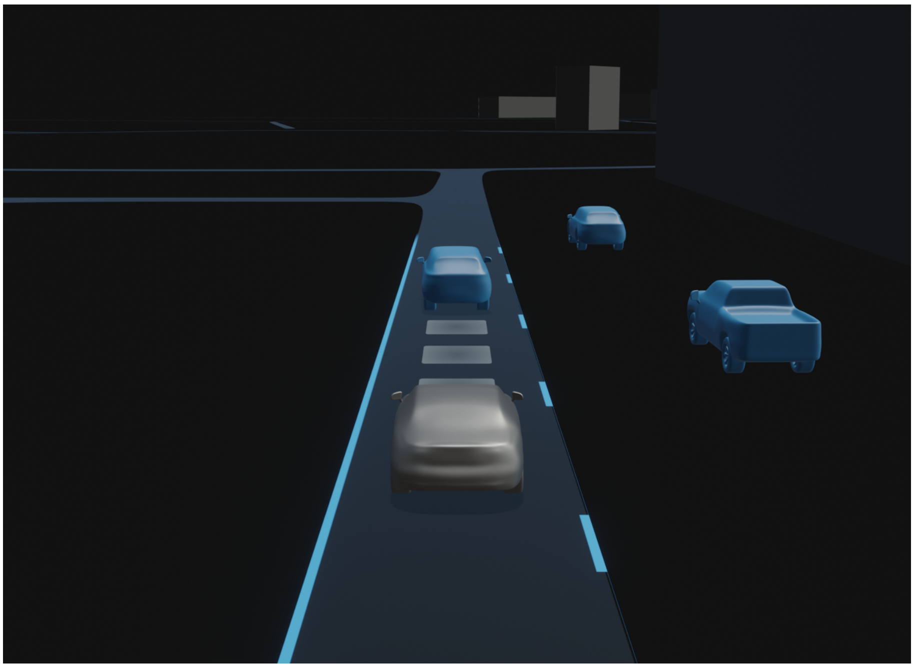

Figure 6.3: The new map/sensor view

Moreover, the detected lane markings are now more clearly represented, as many participants did not notice them during the evaluation. The color of buildings and roads are toned down to put more focus on sensor information. Not to mention, the map/sensor view now uses the same multi-level warning design discussed in chapter 3 (See Figure 3.4) when other road users get dangerously close to the ego vehicle (See Figure X).
subsectionAttention Reminders It was discovered during the interview study in Chapter 4 that the information requirements for driving were unique for different driving situations. This uniqueness of information requirements for each situation would entail that it is necessary for the HMI to adapt to each situation to support the driver in maintaining their situation awareness of the external driving environment. To this end, reminders were designed for the map/sensor view that would invite the driver to attend to different parts of the traffic environment depending on the situation (see Figure 6.4). These reminders are adapted to and are unique for

different driving scenarios and are based on the information requirements gathered in Chapter 4. These reminders are intended to increase drivers' situation awareness of the external driving environment, and they disappear from the screen after the driver monitoring system detects that the driver has attended to them.

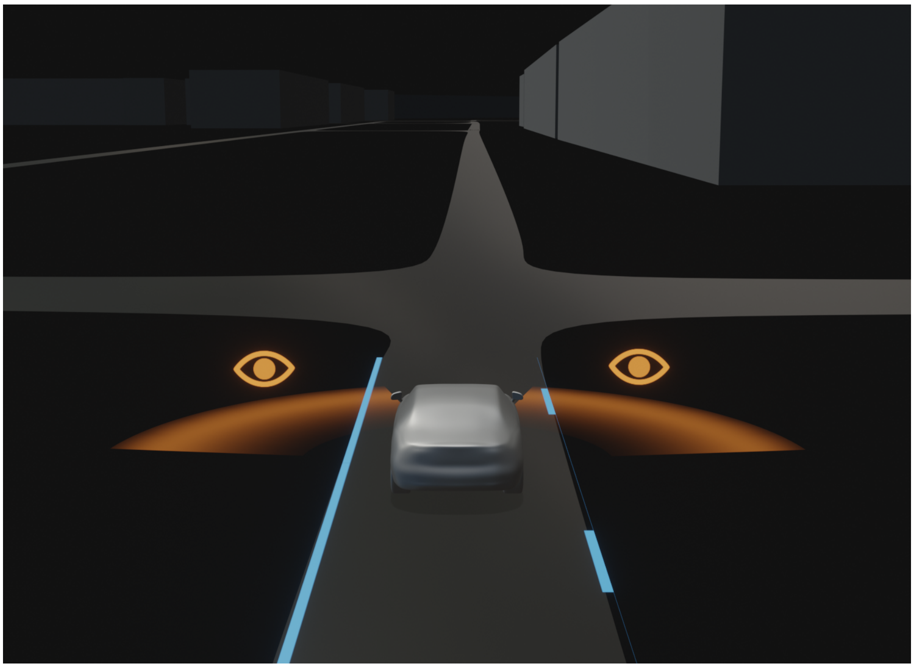

Figure 6.4: The attention reminder for inviting the driver to look both ways before approaching an intersection

6.3.3 Layout

The final iteration of the HMI concept uses the same layout format as the previous iteration. The finalized design of the HMI concept can be seen in Figure 6.5.

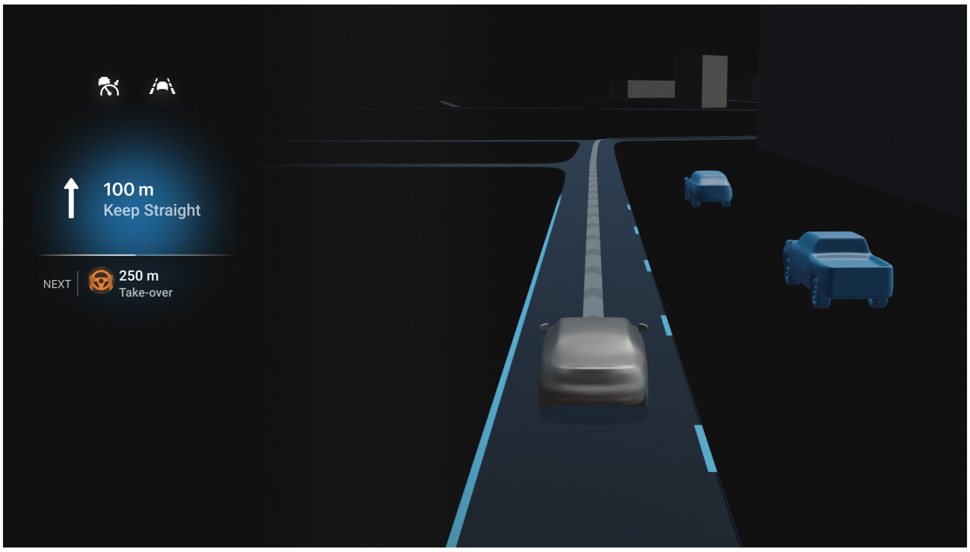

Figure 6.5: Final HMI concept

6.4 Conclusion

A new iteration of the HMI concept was designed based on the findings from the evaluation phase in Chapter 5. This new iteration significantly simplifies the interface to avoid major problems discovered during evaluation, including distraction and clutter.

7 Discussion

This chapter discusses the key findings and provides reflections on the methodological approach. Firstly, the findings of the influence of ADAS on drivers' SA and mental model (RQ1) are summarized and discussed. Secondly, investigations on how human factors considerations inform HMI design (RQ2) are discussed. Lastly, there are some reflections on the methods used.

7.1 Negative Influences of ADAS

To answer the first research question of how ADAS influences drivers' situation awareness and mental model, the literature study pointed out some of the negative influences of ADAS technologies. ADAS technologies can potentially diminish drivers' situation awareness, making it difficult for drivers to detect system errors and adequately perform when facing automation failures. ADAS can also negatively affect the driver's mental model of the system. Automation can conceal the operations and inner workings of the system from drivers. Thus, the driver might not accurately understand the system's capabilities and limitations.

These issues were also exemplified during the evaluation phase. The findings for the evaluation of situation awareness (See Chapter 5) show that many participants could not correctly answer the SAGAT queries while experiencing both HMI concepts. These results are in line with the literature where a loss of situation awareness is observed while driving in a level 2 partial driving automation [17]. These findings mean that the changes made to the interface did not have the intended effect of increasing participants' situation awareness of the external driving environment.

One explanation for this lack of improvement could be that the position of the display negatively influenced drivers' situation awareness. Many participants mentioned that the necessity to look at and be aware of both the traffic environment and the HMI display adds to the challenges of driving and makes it difficult to relax as the driver needs to always be on their toes. They believed that the position of the display was sub-optimal and distracting and preferred other positions closer to the windscreen and their line of sight. Therefore, future research should also look into the impact and influence of HMI display positions on drivers' situation awareness and visual behavior.

7.2 Enhancing SA & Mental Model Through HMIs

The second research question was answered by discovering HMI design guidelines in the literature and through findings of the evaluation in Chapter 5. The guidelines aim to alleviate the negative influences of ADAS, namely drivers' reduced SA and inaccurate mental model of the system. The guidelines were classified into three distinct categories: enhancing situation awareness, facilitating an accurate mental model, and improving take-over requests. These guidelines informed the design of different interface concepts. The effectiveness of these interface concepts in improving drivers' situation awareness and mental model is discussed below.

First, an interface element called the information portal was created during concept generation based on multiple guidelines with the aim of improving situation awareness and mental model. It provides the driver with information regarding the automated system, navigation system, and potential take-over requests and acts as a single place for them to learn what they need to do next. The evaluation findings show that the information portal positively affected participants' perceived awareness of what the system was doing or sensing in the environment and was highly effective in helping them understand that a TOR was needed. However, the information portal was somewhat ineffective in improving participants' awareness of the traffic environment. These findings are in line with findings of the literature, which suggest that drivers' drivers understanding of ADAS can be improved by providing them with the right information at the right time [39, 40]. Thus, an information portal that showcases information regarding the system's limitations, warnings, and boundary conditions can be recommended to improve drivers' understanding of the system's intentions.

Second, the system status icons were created based on multiple guidelines to improve drivers' SA and mental model. However, the evaluation findings indicate that they were not very effective in improving participants' perceived awareness and understanding of system intentions. These findings are in contrast to the insights from the literature. It is believed that providing drivers with feedback on the system's status can improve drivers' mental model and avoid confusion and automation surprises [10]. The ineffectiveness of the system status icons can be attributed to the experimental design of the evaluation. The participants were only exposed to this interface element for 45 seconds, and many mentioned that they did not notice them during the experiment at all. Similarly, the journey progress bar was overlooked by many participants as well. Therefore, no significant improvements were observed when drivers experienced this interface element. It remains to be seen if the system status icons and the journey progress bar prove to be more effective in future experiments where the participants have a better chance of experiencing their utility.

Third, both auditory signals in the new HMI concept (See Chapter 3) were highly effective in improving participants' understanding of system intentions and helping participants understand that a TOR was needed. The participants also believed that the warnings were very well-timed. These results align with insights from the literature. Morales-Alvarez et al. mention that the informative signals are easy to understand, but their disadvantage is that they take longer to transmit urgent information and require more attentional resources [29]. The new HMI concept seems

to have alleviated these disadvantages by using informative signals in non-urgent and non-critical situations. It can be said that the informative auditory signals can be highly effective during non-urgent take-over requests; however, participants mentioned that they should be provided with the ability to turn them off based on their preferences.
Furthermore, one of the novel aspects of the new HMI concept was combining map data with sensor data in a single window. The combination of map and sensor data aimed to reduce the attentional demands of the HMI. The findings show that the map/sensor view was highly effective in improving participants' perceived awareness of system intentions, and it performed significantly better than the sensor view. Therefore, the map/sensor view can be recommended for improving drivers' understanding of the system and their perceived awareness.
However, the interviews uncovered an insight that the current implementation of the map/sensor view might result in an inaccurate mental model of the system that might negatively affect safety. During the evaluation, the sensor and map data were not distinguished from one another. Thus, the test participants did not know which parts of the map/sensor view were the inputs from the sensors and which parts were from the map data. They believed that this implementation would confuse them as they would not take action on what has been shown and represented in the map/sensor view. They might think that the system has detected an object in the environment, while in reality, the ADAS is not aware of such a thing since it comes from the map data. Not knowing this distinction, the driver will let the vehicle proceed, leading to an accident and a potential safety hazard. Thus, any implementation of a map/sensor view should make this distinction to improve safety.
Lastly, the evaluation findings show that the new HMI concept was easier to interpret for participants, they perceived to have a higher awareness of what the system was doing, and it was significantly better in communicating to participants that a take-over was needed. However, the biggest bottleneck of this concept was its highly distracting nature. The new HMI concept had three more interface elements compared to the baseline. The combination of all these different interface elements made the HMI more cluttered and distracting. As a result, the new HMI did not improve the situation awareness of the driving environment compared to the baseline. In one case, the new HMI concept has proved to be significantly worse than the baseline concept. It can be assumed that the simplification of the new HMI concept would build upon its strengths and mitigate these problems. However, further research would be needed to identify if it would have a significantly positive effect on situation awareness compared to the baseline.

7.3 Drivers' Varied Information Requirements

The interview study performed during this thesis provided insights on drivers' information requirements for five different driving situations where a take-over might be necessary. It was identified that information requirements are unique for each driving situation, making it necessary for the HMI to adapt to each situation to support the driver in maintaining situation awareness.
Moreover, it was revealed that some information requirements were common in

all driving scenarios. During all scenarios, the intentions of drivers of adjacent vehicles were the biggest concern for participants in terms of safety. The necessary information requirements for these vehicles included aspects like the vehicles' relative speed, distance, and position within their lanes.

7.4 Methodological Approach

This section discusses the methodological approaches chosen to answer the research questions posed in this thesis.

7.4.1 Development of Design Guidelines

Another explanation for the lack of improvement in terms of situation awareness could be attributed to the ineffectiveness of the design guidelines. These guidelines were informed by the findings from the literature study in Chapter 2. The literature study relied on search terms like "human-machine interfaces" and "automated driving" to find guidelines for HMI design. However, the literature on HMI design for a level 2 automated driving system is rather limited. There are many papers available that provide findings and guidelines for HMI design that are suited for higher levels of automation; however, these findings were not considered in this thesis since the capabilities and limitations of the level 3, and level 4 driving automation is inherently different from level 2.
Moreover, it is recommended to use ecological interface design (EID) principles when designing an HMI [44]. These principles were not explored during the elicitation of the guidelines. Perhaps ecological interface design principles could have provided insights that might have positively affected the outcome of the HMI concept. Not to mention, the elicited guidelines were not validated by a human factors expert or an expert in driving automation.

7.4.2 Goal-directed Task Analysis (GDTA)

Goal-directed task analysis is usually constructed by obtaining insights from unstructured interviews with operators within the domain under study [16]. The interview study conducted in chapter 4 employed prerecorded video clips of specific driving scenarios to provoke discussions and gather insights for the GDTA. As a result, the gathered insights might not be generalizable to all take-over scenarios. It would be more accurate to construct a GDTA using multiple scenarios for each take-over situation.
Another limitation of using videos is a limited field of vision. Thus, the participants might not have given input on what's outside the bounds of the video. Nevertheless, they were asked to imagine similar situations, and all participants were able to provide input regarding the outside environment.
Furthermore, the participants were asked to select all objects in the environment that were relevant for safety and use stickers to elaborate on their selections. All participants comfortably selected the objects, used the stickers, and were able to speculate how the traffic situation would evolve based on what they saw during the

video. However, elaborating on their decisions seemed to be extremely taxing since driving touches upon the tacit knowledge of the driver, and it isn't easy to verbalize. Lastly, Endsley recommends between 3 to 10 iterative interview sessions with the participants to help ensure an accurate GDTA [16]. However, the GDTA constructed in chapter 4 was based on one interview session with each participant from a small sample size of university students. Research shows that drivers' visual behavior and scanning patterns differ depending on their driving experience [30]. Perhaps a more representative sample of the population could have resulted in information requirements that better showcase the differences in drivers' information needs and scanning patterns.

7.4.3 Evaluation Study

Video clips were also used during the evaluation of the HMI concepts. Similarly, participants' field of vision was limited due to the use of videos in this study as well. A lack of side-view and rear-view mirrors negatively affected the validity of the SAGAT method. During the interview study in Chapter 4, it was identified that being aware of the side-view and rear-view mirrors was critical in having a high situation awareness of the traffic environment. Thus, all indicators of having an adequate situation awareness could not be measured. Due to these limitations, this study does not have the same ecological validity as similar simulator studies. Nonetheless, the performance of both HMI concepts can be evaluated relative to each other as they both have been tested in the same experimental setting.
Moreover, the use of animated videos only allowed to measure how well participants understood the need for a take-over. This measurement was done by clicking on a button to take over the control of the vehicle. However, an interactive simulator study with steering wheels and brakes would have allowed the measurement of participants' take-over performance. It could have also contributed to an assessment of participants' situation awareness and mental workload using established performance measures [45].
Furthermore, the existence of many changed variables between the new HMI concept and the baseline concept made a diagnostic evaluation of the concepts more challenging. For future research, it is important to test two similar variations of the final HMI concept with and without map data in the sensor view to understand its impact on the driver's SA and mental model.
Lastly, it should be noted that the sample size for the study was relatively small. Not to mention, all the participants were university students between the ages of 22 to 33. For future research, the HMI concept should be evaluated against a more representative sample of the population. The changes mentioned above

7.5 Future Work

Based on the evaluation findings in Chapter 5, it is hypothesized that a more simplified version of the HMI (See Figure 6.5) would lead to a better understanding of the external driving environment. The simplified HMI should be examined in future work to see whether it has improved drivers' situation awareness.

Moreover, it is believed that the display position has negatively affected participants' situation awareness and has led to distraction. Future work should also investigate the influence of display position and technology on driver distraction and its impact on drivers' situational awareness and vigilance.
Lastly, the final iteration of the HMI should be evaluated in a simulator with both rear-view and side-view mirrors to get more valid results in terms of situation awareness. The simulator study should also include steering wheels and brakes to measure the participants' performance during and after take-over requests to evaluate the HMI's impact on drivers' situation awareness and mental workload.

8
Conclusion

This thesis aimed to understand how human-machine interfaces can be designed for future ADAS to enhance drivers' situation awareness and facilitate a more accurate mental model. This was achieved by gathering guidelines from the literature, designing a new HMI concept based on those guidelines, and evaluating the concept's impact on drivers' situation awareness of the external driving environment and the accuracy of their mental model.

The findings of the evaluation show that the HMI concept has improved participants' understanding of the system's intentions and requests. To that end, the interface elements, including the information portal, the auditory signals, and the map/sensor view, were highly effective. However, no improvements were observed in terms of situation awareness of the external driving environment. This lack of improvement was attributed to the highly distracting nature of the HMI concept. Thus, a new iteration HMI concept was redesigned to simplify the interface and reduce information overload.

Additionally, the interview study identified the decisions and information requirements for five possible driving situations where a take-over might be necessary. It was discovered that the information requirements were mostly unique among different driving situations, while some information requirements were common in all the studied scenarios. The uniqueness of information requirements for each situation makes it necessary for the HMI to adapt to each situation to support the driver in maintaining their situation awareness of the external driving environment.

In summary, it can be concluded that the new HMI concept is significantly more understandable and easier to interpret for participants. However, given the current display position and display technology, the addition of more information in the HMI should be treated with caution since it might result in information overload and be entirely overlooked by the driver.

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Appendices

A
Interview Study Questions

The questions used during the interview study in Chapter 4 are presented below.

Table A.1: The questions for the interview study.

#	Question
1	Please select all objects or elements in this traffic situation that you should look for/be aware of to be able to safely proceed?
2	What aspect of the each element makes it important? Why?
3	What do you think people typically fail to consider when accidents happen in this scenario?
4	How do you think future cars should assist you in this situation?
5	Which traffic situation do you think would be the hardest to conduct in a safe way? Why?

B

Dot-Voting of Guidelines

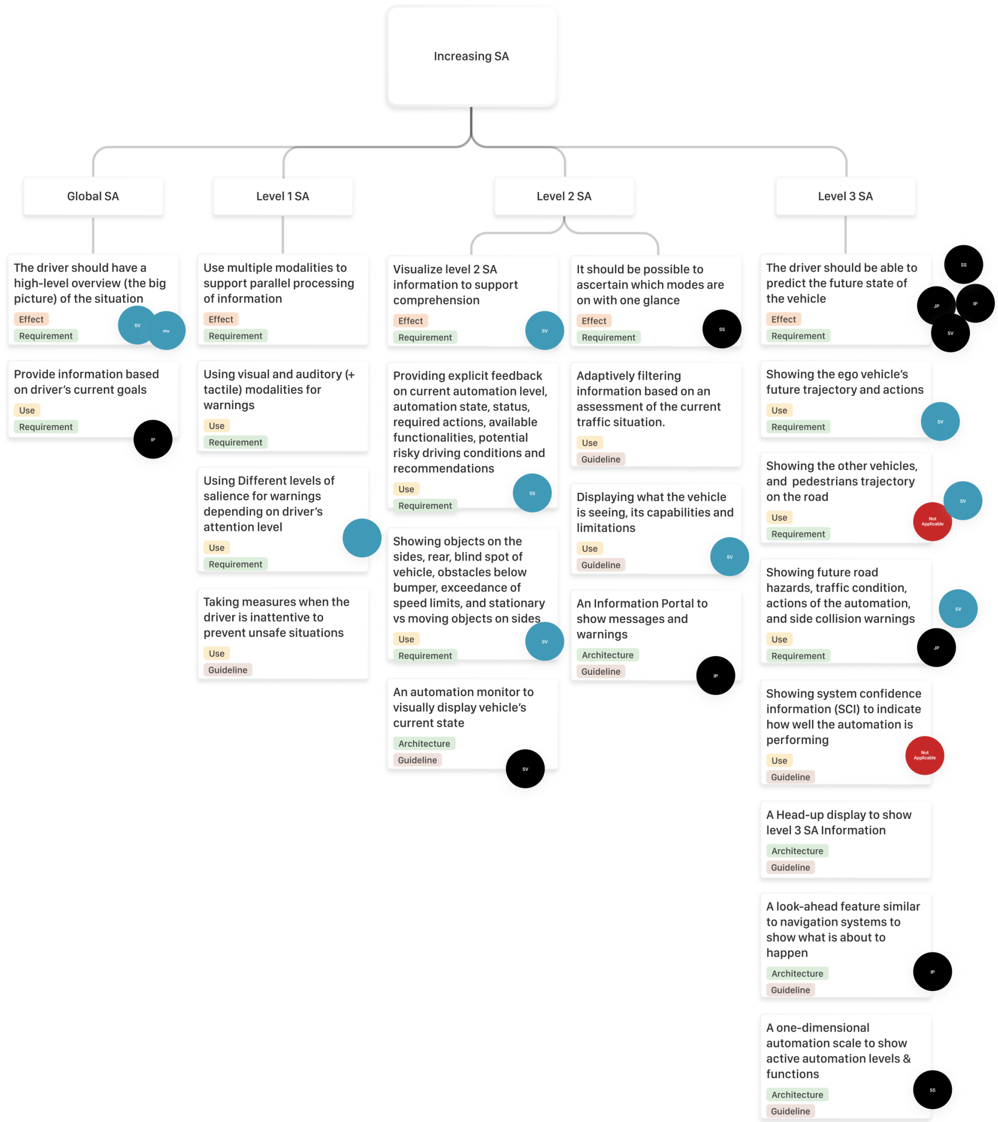

Figure B.1: Dot-voting of enhancing situation awareness guidelines to find potential solutions

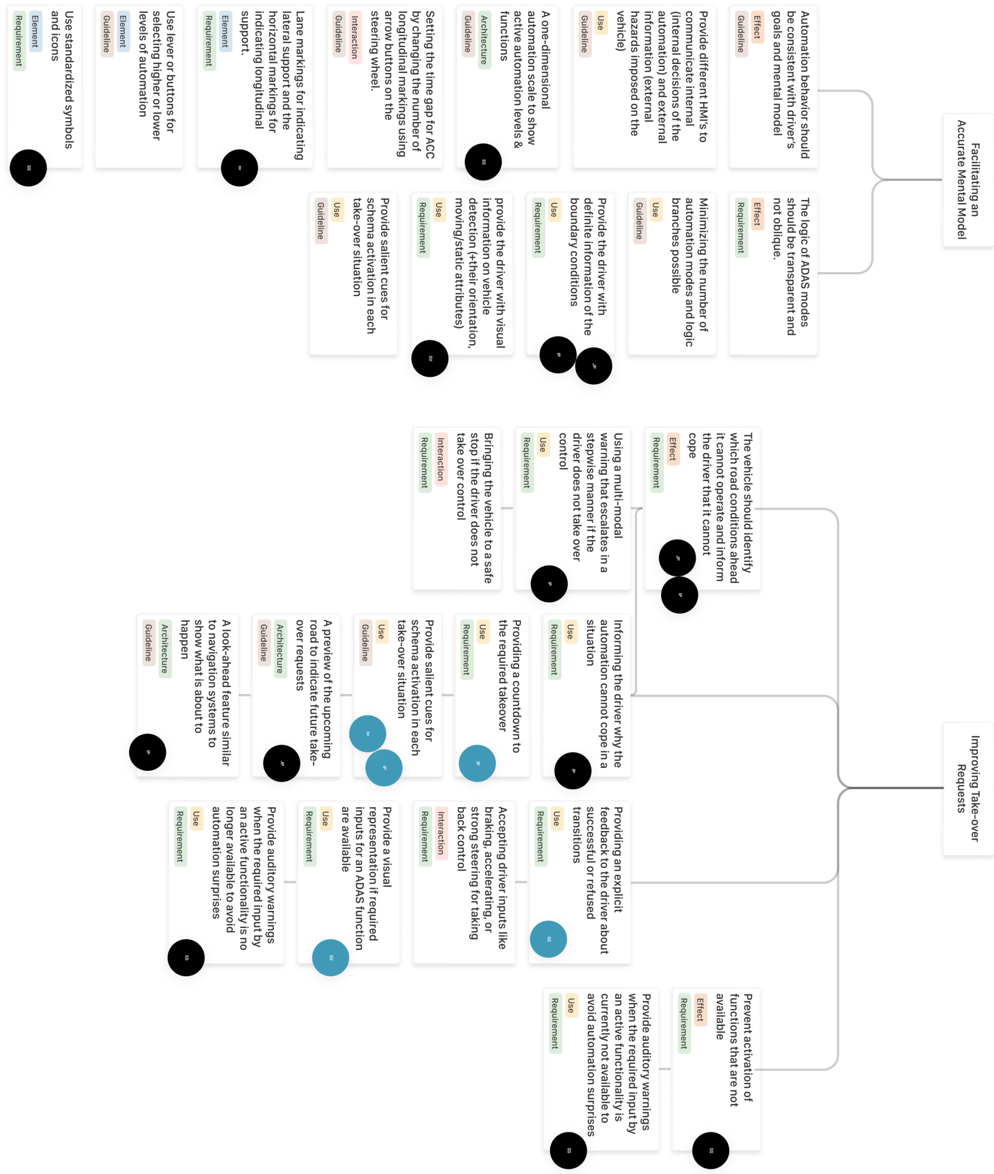

Figure B.2: Dot-voting of improving mental model and take-over guidelines to find potential solutions

C

Questionnaires

The questionnaires used during the evaluation in Chapter 5 are presented below.

C.1 SAGAT Queries

The SAGAT queries for both the intersection and lane change scenario are presented below.

Table C.1: The SAGAT queries for the intersection scenario.

#	‘Rate your level of agreement with each statement’	Strongly Disagree				Strongly Agree
1	More than two vehicles passed the intersection.	-2	-1	0	1	2
2	There were vehicles inside the intersection when the video stopped.	-2	-1	0	1	2
3	There were vehicles inside the intersection when the video stopped.	-2	-1	0	1	2
4	There were pedestrians inside the intersection when the video stopped.	-2	-1	0	1	2
5	The road in the intersection was a two-way road.	-2	-1	0	1	2
6	It was safe to pass the intersection when the video stopped.	-2	-1	0	1	2

Table C.2: The SAGAT queries for the lane change scenario.

#	‘Rate your level of agreement with each statement’	Strongly Disagree				Strongly Agree
1	There was a vehicle in front of you in the current lane during the entire video.	-2	-1	0	1	2
2	There was a vehicle in the left lane when the video stopped.	-2	-1	0	1	2
3	The vehicle in the left lane during the last moment of the video had a higher acceleration/speed compared to you.	-2	-1	0	1	2

to be continued on the next page

Table C.2: (continued from previous page)

#	'Rate your level of agreement with each statement'	Strongly Disagree				Strongly Agree
4	There was no obstacle/other vehicles in front the vehicle in the left lane when the video stopped.	-2	-1	0	1	2
5	There was a potential for a rear-end collision with the vehicle in front of you during the entire video.	-2	-1	0	1	2
6	Performing a lane change during the last moment of the video would lead to a rear-end collision.	-2	-1	0	1	2
7	It was safe to perform a lane change when the video stopped.	-2	-1	0	1	2

C.2 Perceived Situation Awareness

The questionnaire for perceived situation awareness is presented below.

Table C.3: The questionnaire for perceived situation awareness.

#	'Rate your level of agreement with each statement'	Very Ineffective				Very Effective
1	How effective was [interface element] in helping you to be aware of what the system was doing/seeing?	-2	-1	0	1	2
2	How effective was [interface element] in helping you to be aware of what was happening in the street/environment?	-2	-1	0	1	2

C.3 Mental Model Questionnaire

The mental model questionnaire is presented below.

Table C.4: The mental model questionnaire.

#	'Rate your level of agreement with each statement'	Strongly Disagree				Strongly Agree
1	The system requested you to take-over control of the vehicle.	-2	-1	0	1	2
2	The system recognized the surrounding vehicles.	-2	-1	0	1	2
3	The system recognized the lane markings on the road.	-2	-1	0	1	2

C.4 Perceived Understanding of the System

The questionnaires for perceived understanding of the system are presented below.

Table C.5: The question regarding HMI's clarity in communication.

#	'Rate your level of agreement with each statement'	Very Unclear				Very Clear
1	How clearly did the system communicate that a take-over of control was needed?	-2	-1	0	1	2

Table C.6: The question regarding each interface element's effectiveness during take-over request.

#	'Rate your level of agreement with each statement'	Very Ineffective				Very Effective
1	How effective was [interface element] in helping you understand that a take-over of control was needed?	-2	-1	0	1	2

Table C.7: The questionnaire regarding each interface element's percieved communication quality.

#	'The interface's communication with you as a driver was…'	1	2	3	4	5
1		Distracting				Not Distracting
2		Very complicated				Very straightforward
3		Very hard to read				Very easy to read
4		Very difficult to interpret				Very easy to interpret
5		Very badly timed				Very well timed

C.5 Semi-Structured Interview Questions

The questions for the semi-structured interview are presented below.

Table C.8: The questions for the semi-structured interview.

#	Question
1	Now that you have experienced both concepts, what are your first thoughts?
2	Which elements were the most effective in helping you understand that a take-over of control was needed? Why?
3	Which elements in the interface would you keep? Why?
4	Which elements in the interface would you remove? Why?
5	Do you see any challenges with this way of communicating to drivers?
6	If this interface was implemented in your car, would it make driving better or worse?
7	Did you find any of the concepts/elements distracting?
7	Did you find any of the concepts/elements distracting?
8	Do you have any suggestions on what needs to be changed?

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