# Mind Over Matter - Investigating the Influence of Driver's Perception in the Misuse of Automated Vehicles



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# Mind Over Matter - Investigating the Influence of Driver's Perception in the Misuse of Automated Vehicles

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## Abstract

As vehicles with several levels of automation become increasingly common, there is an increase in incidents involving the misuse of Driving Automation Systems (DAS). The manner in which drivers interact with DAS indicates that the problem extends beyond UI design. We investigate how drivers' perceptions and expectations affect the understanding and consequent usage of DAS. The study employed a Wizard-of-Oz approach to simulate a vehicle with a Level 2 and Level 3 DAS on a public highway. Sixteen participants were exposed to the two driving modes and two distinct UIs. Observations, think-aloud protocols, and in-depth interviews documented their interaction with the different DAS. Irrespective of the UI, various errors were detected, including omission, commission, and mode confusion. Deeper investigation into the sources led to the conclusion that drivers' preconceptions of the DAS were a major contributor, resulting in misuse. This highlights the need to look beyond UI design as a sole solution to address driver-vehicle interaction.

## CCS Concepts

• **Human-centered computing → Empirical studies in HCI**; **User studies**; **Field studies**.

## Keywords

Driving Automation, Automated Vehicle, Perception, Mental Model, Use Error, Misuse

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## 1 Introduction

In recent years, the car industry has seen a substantial transformation as a result of the integration of automation technology in vehicles, bringing about a new era of interaction between drivers and their vehicles, where the control over the driving task is increasingly shared between the driver and the driving automation system (DAS). According to SAE International [41], DAS are a cluster of several functions enabling drivers to hand over different parts of the driving task, e.g., maintaining a set speed or keeping the vehicle in the lane, offering the potential for enhanced driver comfort, efficiency, and, most importantly, traffic safety [47]. Thus, DAS can perform some or all of the driving tasks, contingent upon the environmental conditions and the level of automation. The environment and conditions in which the automated system is meant to operate without human intervention are referred to as operational design domains (ODD). The levels of driving automation, as defined by SAE International [41], are as follows: Level 0 (no driving automation) to Level 5 (full driving automation). Automation levels ranging from Level 0 to Level 2 are equipped with driver assistance systems that have different features and functionalities. According to Marcano et al. [32], Level 1 vehicles are outfitted with adaptive cruise control (ACC), whereas Level 2 vehicles combine lane-keeping and ACC features. In certain ODDs, vehicles fitted with Level 3 and Level 4 DAS can function without requiring any input or action from the driver. No driver input is needed while using Level 5 DAS since it can fully automate the car in all ODDs.

However, for drivers, navigating the realm of vehicle automation is not without its challenges. Various studies have emphasised the crucial significance of automation in transforming the dynamics of the interaction between driver and vehicle and its effects on safe usage [43]. Particularly in vehicles offering several levels of automation, drivers' understanding, overreliance, and subsequent misuse of the systems have been of critical concern [14, 40]. For example, Wilson and colleagues [49] observed situations in automated vehicles equipped with a Level 2 DAS where participants incorrectly believed the vehicle to be in automation mode and therefore assumed responsibility for key driving tasks when, in fact, it was not. Similarly, Banks and colleagues [4] found instances where drivers failed to activate automated functions and misunderstood the operation of DAS despite receiving information in the user interface. In other cases, drivers mistakenly believed that the automation level was deactivated when it was indeed active. This phenomenon, also known as mode confusion [42], has been widely observed in different studies, where it was found that when there are multiple levels of automation in a vehicle, drivers face significant ambiguity about the active driving mode [4, 19, 49].

Furthermore, several studies conducted over the years have consistently found that there is cause for concern regarding the driver's understanding of the capabilities and limitations of driving automation systems, their knowledge of the active and available driving modes, and their capacity to sustain the required level of involvement and intervention in critical situations [8, 20]. A Wizard-of-Oz study conducted on-road investigating the drivers' understanding of a vehicle offering a Level 2 and Level 3 DAS revealed interaction difficulties beyond UI-specific issues, including misunderstandings of system capabilities and limitations, use outside the operational design domain (ODD), and challenges in comprehending vehicle feedback [26]. These unresolved errors could not be solely attributed to the user interface and underscore the need for a deeper exploration into their underlying causes. Building directly on those findings, this paper provides the necessary in-depth analysis. Therefore, it is important to conduct an in-depth analysis of interaction issues, such as lack of understanding and consequent usage errors, that arise when drivers use driving automation to identify the root causes of these problems in order to address the issues at their core and not only treat the symptoms.

## 1.1 The Influence of Expectations in the Use of DAS

Previous research investigating drivers' misconceptions has primarily focused on analysing the User Interface (UI) within vehicles, which is deemed a crucial element that greatly influences drivers' understanding and interaction with a vehicle. Results of such studies often propose interface modifications as solutions to usage errors, e.g., [11], by providing information about the system through the user interface, such as vehicle detection [3], planned actions [27], upcoming mode changes [16], and clear take-over requests (TOR) [35]. These approaches undoubtedly aid drivers in using the system. However, some research has shown that drivers' understanding of the system is not only shaped by their interaction with the interface but also by their perception and consequent expectations of such systems inherent in users prior to the actual use (e.g., [22, 31]). Results from a 7-month Naturalistic Driving Study (NDS) with newly purchased vehicles, equipped with Level 1 and Level 2 DAS, showed that the drivers' perception of a DAS determined their understanding and consequent usage of the systems [39]. The study revealed that the drivers' mental model of the new functions was largely influenced by previous experiences and their a priori perception of the systems. Other research has examined the influence of exposure to and usage of a system on the driver's mental model of a DAS [10, 25], as well as that a more comprehensive mental model can affect the interaction with a DAS positively [21]. In search of explanations for the observed challenges, some works have highlighted that the existing design of DAS does not sufficiently consider the driver's mental model of interacting with a DAS (e.g., [5, 33, 38]. Lee and See [30] demonstrated that a divergence between expected and actual system behaviour can lead to a loss of trust. Furthermore, Kraus et al. [28] found that pre-interaction information significantly influences trust, with this effect being moderated by the driver's existing knowledge. Research also indicates that incomplete or mismatched mental models negatively impact situation awareness and the ability to comprehend system limitations, anticipate system behaviour, and understand the driver's own responsibility in such situations [7]. Finally, Beggiato and Krems [5] suggest that a driver's mental model also plays a crucial role in their acceptance of and attitude towards driving automation. These findings suggest that a driver's mental model of a system is influenced by biases or prejudices that individuals may have, influencing their attitudes or interactions even before encountering certain situations. Among these influences, misconceptions are a critical factor that needs to be prevented to ensure traffic safety as well as user acceptance. It has been found that misconceptions stem from various sources, such as media, terminology [46], or inadequate knowledge about automated vehicles [17]. As a result of that misinformation, users have misguided preconceptions, resulting in overtrust and/or misuse of such systems. A cross-study analysis of four studies investigating the aspects shaping drivers mental model, and identifying factors that influence the drivers' perception and consequent understanding of DAS [36]. The results were consolidated into a conceptual model that described perceptual sets as a key in shaping the driver's mental model and consequent use of DAS. Among these were preconceptions such as the extent to which a system is supposed to support the driver with executing the driving task and anticipations about the capabilities of the vehicle and in which situations to trust the DAS. The work argues that drivers' interactions with a DAS are not only shaped by their interaction with it and the information received from a UI during driving but also by abstract ideas, such as previous experiences and social discourse, which shape the driver's expectations and subsequent use of such systems.

It can be inferred that regardless of whether drivers have prior experience with a DAS or are encountering it for the first time, their pre-existing knowledge of DAS will influence their interaction with these systems. This mental predisposition, or readiness to perceive sensory stimuli in a particular way based on previous experiences, expectations, beliefs, and context, is influenced by 'perceptual sets' [1]. Perceptual sets guide choices between competing activities and, consequently, affect the outcomes of the perception process. Fundamentally, perceptual sets determine what sensory data we notice and what we disregard, thereby shaping our existing knowledge of the world. Hence, a mismatch between expectations and the actual capabilities of a DAS may lead to drivers misusing the systems and potentially experiencing hazardous situations. However, there is still a lack of research elucidating which preconceptions lead to what understandings and, consequently, how they influence the driver's interaction with the vehicle.

Therefore, the primary objective of this paper is to investigate how drivers' pre-existing beliefs and expectations lead to misconceptions and the misuse of driving automation systems. Building on previous findings by [26], who reported that UI design only offered limited support in addressing interaction problems, we aim to show that the root of many critical misuse issues lies in these underlying perceptions and thus the driver's mental model, making them a primary cause of error independent of specific interface designs. Our approach involved analysing interactions from an on-road

Wizard-of-Oz study where drivers used a vehicle with Level 2 and Level 3 DAS, presented with two distinct user interfaces (a baseline and an improved version). By examining whether fundamental use errors persisted across both interfaces, we aim to demonstrate that the root of many critical misuse issues lies in the driver's underlying perceptions, not merely in UI-specific usability problems. To achieve this, observation material and think-aloud protocols from an on-road Wizard-of-Oz driving study simulating an automated vehicle offering a Level 2 and Level 3 DAS [41], with 16 drivers, were analysed in order to identify different errors in the use of the systems. Specifically, this paper aims to delve into how drivers' pre-existing beliefs and expectations about automated vehicles lead to misconceptions and ultimately result in the misuse of driving automation systems.

## 2 Method

This semi-controlled Wizard-of-Oz (WOz) on-road driving study simulated Level 2 and Level 3 Driving Automation Systems [41]. The study was conducted in the Gothenburg area, Sweden, in September 2022. The road-approved research vehicle operation adhered to the Declaration of Helsinki, and all participants provided informed consent in compliance with the General Data Protection Regulation (GDPR) for data collection, storage, and processing.

### 2.1 Equipment

*Vehicle.* The test vehicle was a modified Volvo XC90 and equipped to simulate the two tested driving modes, as well as to control the GUI through controls in the backseat, through the utilisation of a Wizard-of-Oz approach. In this setup, a driving wizard was in control and responsible for the driving of the simulated Level 3 DAS, and a GUI wizard was in charge of controlling the prompts and feedback the driver received from the GUI. In-vehicle cameras facing the GUI and interaction were placed behind the driver in order to collect observation material of the interaction with the vehicle and systems. For an illustrated overview of the setup, see Figure 1.

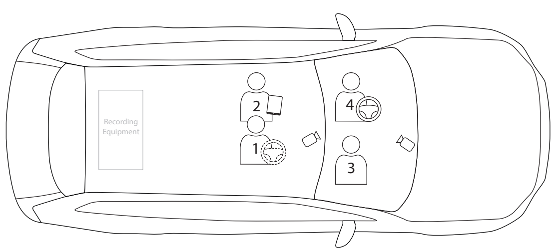


**Figure 1: The setup of the Wizard-of-Oz vehicle, with video cameras facing the UI, and (1) driving wizard, (2) GUI wizard, (3) test leader and (4) participant. Noteworthy, the drivers were not able to see the setup for the driving or GUI wizard in the back, as all equipment was concealed from view.**

*Systems.* Participants experienced a Level 2 Partial Driving Automation (Volvo Cars Pilot Assist), described as maintaining speed and distance and providing steering assistance, with the driver remaining responsible. This system was available at all times. A Level 3 Conditional Driving Automation was simulated, designed to operate within a specific operational design domain (ODD): (i) partially controlled-access roads (≤80 kph), (ii) free-flowing traffic (LOS A-B, with take-over prompts for merging traffic), and (iii) clear lane markings.

Participants experienced two main control transitions. First, when the Level 3 ODD conditions were met, the vehicle issued a hand-over request (HOR), signaling that the driver could hand over control to the system. At this point, the driving wizard took control. Conversely, when conditions were no longer met, the system issued a take-over request (TOR), prompting the driver to resume manual control of the vehicle.

*User Interface.* Two distinct audio-visual user interfaces, GUI A and GUI B, were presented to the participants in a randomised order (Figure 2). The two UIs were not included for a direct effectiveness comparison but rather to investigate whether improvements in interface design could mitigate the persistent issue of driver misuse or if errors stemming from perception would remain regardless of the interface. GUI A was adapted from a previous study that found it could lead to misunderstandings regarding system state and driver responsibility in a vehicle with multiple automation levels [38]. Its design philosophy was to provide only the most pertinent information for each driving mode to avoid overwhelming the driver. In contrast, GUI B was developed specifically for this study based on the learnings from GUI A's deployment. Its design was informed by a conceptual model of driver perception [36] and aimed to be more explicit, incorporating clearer visual cues and prompts to help drivers understand the system's capabilities and their current responsibilities. The goal was to see if such a targeted UI redesign could resolve common use errors. The specific visual and auditory elements for each state in both GUIs are detailed in Figure 2.

The Level 2 DAS was activated via a steering wheel button, triggering a GUI change (state 2). Deactivation (button or brake) returned the GUI to manual mode (state 1). A hands-off warning (state 3) was prompted by the GUI wizard if the driver removed their hands from the wheel during Level 2 operation. Speed could be adjusted using steering wheel buttons. When Level 3 became available, the GUI wizard initiated a TOR (state 4) with an auditory cue. Participants activated Level 3 by a long press of two steering wheel buttons, indicated by a loading bar. Speed and distance settings were not adjustable in Level 3. Upon Level 3 unavailability, a TOR (state 6) was issued, and after driver take-over, the system reverted to manual driving mode (state 1).

### 2.2 Participants

In total, 16 participants (7 female and 9 male), ranging from 23 to 70 years old (M = 44, SD = 13.48), were recruited and reimbursed through a recruitment agency. The recruiter received a screener and exclusion criteria, and all participants fulfilled the following criteria: (i) hold a valid driver's licence, (ii) drive a car with an automatic gearbox and (iii) be equipped with Adaptive Cruise Control (Level 1 Driver Assistance according to SAE [41]). All participants were frequent drivers and commuted to work by car on a daily basis. None of the participants had jobs related to vehicle manufacturing

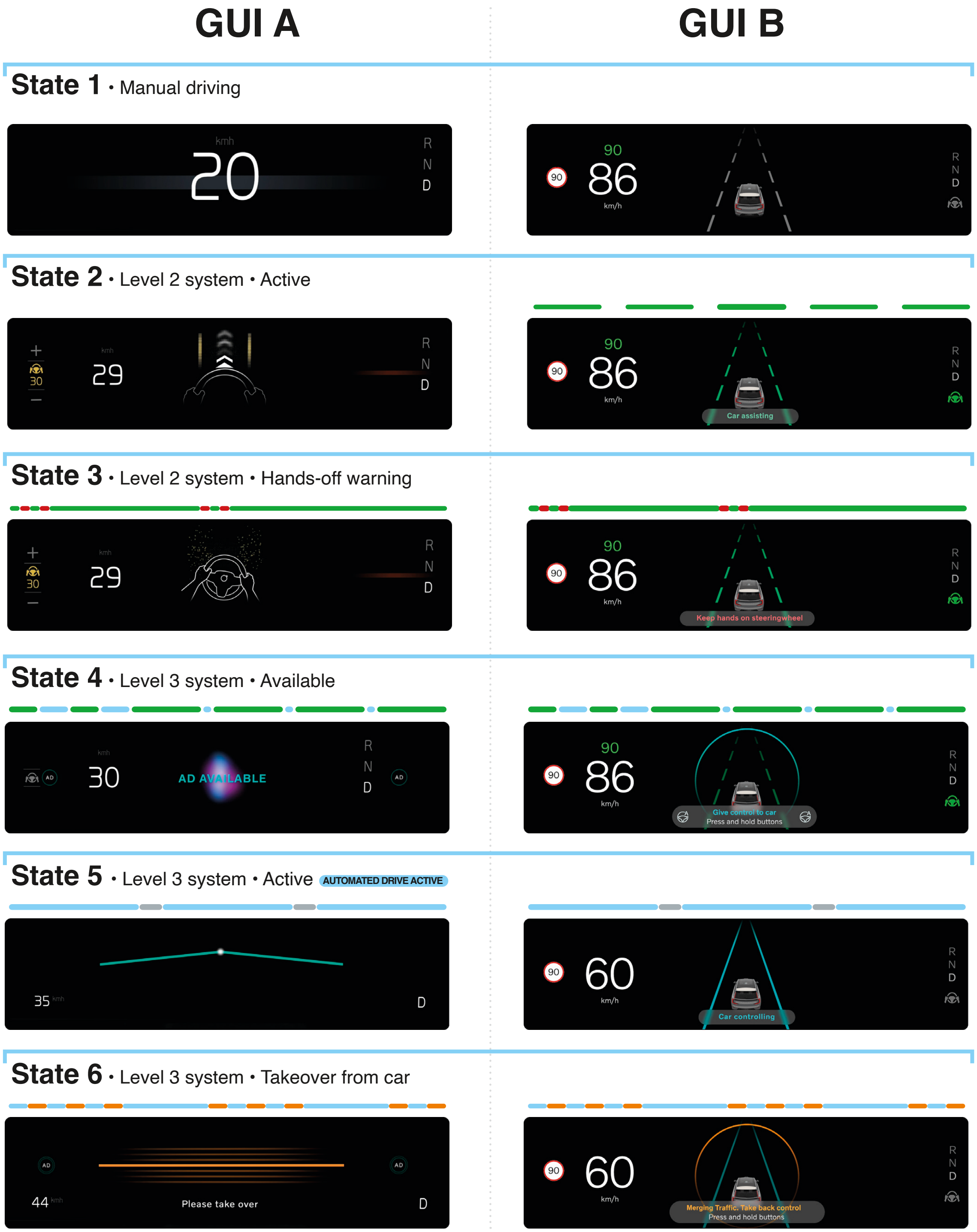


**Figure 2: Depiction of GUI sequence and states for each of the driving modes and comparison of concept GUI A and GUI B.**

or companies related to vehicle development or drove a Volvo as a personal vehicle.

## 2.3 Procedure

Prior to the session, participants received written information about the study via email; this included information about the driving automation systems. The data collection involved two main phases: an on-road driving session simulating Level 2 and Level 3 DAS, followed by a semi-structured in-depth interview.

*Phase I – Driving Session.* Participants were first briefed on the study structure and then introduced to the test vehicle. Inside the vehicle, they received detailed instructions on the two DAS to ensure a clear understanding before the drive began. See Table 1 for an overview of the information, including system capabilities and limitations, given to the participants. The Level 2 DAS was described as a supervised system providing speed, distance, and lane-keeping assistance. It was emphasised that the driver remained fully responsible for the driving task at all times. The Level 3 DAS was presented as an unsupervised system capable of fully managing the driving task, allowing the driver to disengage. Its use was explicitly limited to its Operational Design Domain (ODD): partially controlled-access roads with speeds up to 80 kph, in free-flowing traffic, and with clear lane markings. It was also stressed that drivers needed to be prepared to resume control when prompted by the system. The driving session thereby involved a dynamic mix of automated and manual control. The vehicle returned to manual driving mode, requiring full driver engagement, under two conditions: (1) following a system-initiated take-over request (TOR) when the Level 3 system reached the end of its ODD or (2) following a participant-initiated deactivation of either the Level 2 or 3 system. Participants were encouraged to think aloud throughout the drive to provide insights into their interaction with the DAS. The approximately 45-minute

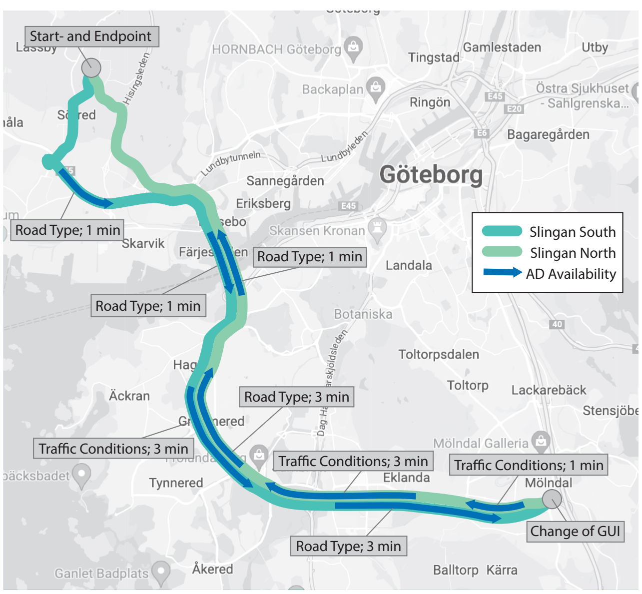


**Figure 3: Route for driving session highlighting stretches for Level 3 DAS availability and exposure time with arrows.**

driving session took place on a partially controlled-access city highway with a speed limit of 80 kph. Participants were encouraged to think aloud throughout the drive to provide insights into their interaction with the DAS. The route, illustrated in Figure 3, started in northern Gothenburg, proceeded to a southern point where the GUI was switched, and then returned. Predefined sections totalling approximately 8 minutes in each direction were designated for Level 3 automation availability.

*Phase II – Post-Driving Interviews.* Following the driving session, participants engaged in an approximately 30-minute semi-structured in-depth interview in a designated room. The interviews aimed to explore the drivers' understanding of the experienced Level 2 and Level 3 DAS. Topics included awareness of system prerequisites, capabilities, limitations, and perceived responsibility during automation engagement. Screenshots of the two GUIs were provided to facilitate the discussion, and participants were encouraged to offer feedback on elements that influenced their understanding and interaction with the systems.

## 2.4 Data Analysis

The data analysis aimed to move beyond a simple categorisation of use errors to understand their underlying causes. To avoid the common pitfall of conflating an error's manifestation with its cause—a principle articulated by Hollnagel [24] —our analysis moves beyond simple categorisation to link behaviours to their cognitive origin. To avoid this common conflation, our analytical framework was designed to explicitly link the observed error manifestations to their cognitive origins—the drivers' misconceptions, based on the terminology proposed by [36]. The analysis observed participant errors during driving sessions and determined their underlying causes by examining observation videos, think-aloud transcripts, and post-driving interviews. A hybrid qualitative thematic analysis approach was employed, using a deductive a priori code template [13] for observational video data and an inductive, data-driven approach [9] for think-aloud transcripts. Data from all sources were then triangulated to gain deeper insights. ATLAS.ti (v.24) [2] was used for all the analysis steps.

### 2.4.1 *Driving Observation and Think-Aloud Protocols.*

Think-aloud protocols were transcribed verbatim and synchronised with driving session video and audio recordings. Video analysis focused on participants' steering wheel interaction, hand positions, active GUI, and driving mode (manual, Level 2, Level 3). See Figure 4 for an example. An a priori codebook was developed to categorise observed participant errors during driving sessions. The defined error codes were (i) error of omission, operationally defined as a failure to perform a required action prompted by the system (e.g., failing to respond to a TOR); (ii) error of commission, operationally defined as performing an action that was incorrect, inappropriate for the context, or not required (e.g., attempting Level 3 activation outside the ODD); and (iii) mode confusion, a specific error that is characterised by actions or verbalisations indicating a mismatch between the driver's perceived and the actual automation state (e.g., uncertainty about available or active driving modes). Data coding was conducted through co-coding sessions, applying and refining the a priori template by consensus. It is important to note that driver actions identified through the think-aloud protocol as deliberate exploratory behaviours — for instance, accelerating to test the system's override functionality — were not classified as

**Table 1: Description of system capabilities, limitations, and information participants received before the driving session.**

| Driving Mode | Description | Operational Design Domain (ODD) | Limitations | Interaction |
|---|---|---|---|---|
| Level 2 | Supervised driving automation; maintains speed; adjusts speed and distance to the vehicle in front; lane-keeping assistance | Always available | Clear view of lane markings; driver responsible at all times | Activation or deactivation via steering wheel button |
| Level 3 | Unsupervised driving automation; maintains speed; adjusts speed and distance to the vehicle in front; steers the vehicle | Partially controlled-access roads; speeds up to 80kph; free-flowing traffic | Clear view of lane markings | Activation or deactivation via a long press on steering wheel buttons |

use errors. These actions were considered part of the driver's process of building a mental model rather than misuse stemming from misconception.


**Figure 4: Example screenshot from the video data used to extract the observation data. Shows a participant holding the steering wheel while driving with the Level 3 DAS active.**

*2.4.2 Post-Driving Interviews.* Interviews were transcribed verbatim. The authors then familiarised themselves with the transcripts before applying an inductive coding strategy [9]. Interview data was reviewed to explore participant understanding of the experienced automation systems. Emerging codes were discussed throughout the process to resolve discrepancies and find consensus. Inter-coder reliability was assessed using Krippendorff's Alpha ($\alpha$ = 0.917) [29] indicating substantial agreement. This involved using a terminology proposed by [36]. This work identified four key factors influencing a driver's perception and understanding of DAS. Accordingly, the interview analysis used these factors to categorize the sources for the observed errors as: (i) *Purpose of the System*: The extent to which the driver assumes that the system is supposed to support with executing the driving task; (ii) *Anticipation*: Aspirations about an event or interaction with a DAS, e.g., capabilities and future development of automated vehicles, often based on information from social circles and media outlets; (iii) *Experience of Usage*: Driver's comparison to a DAS they have used before and key events that influence their understanding of the interaction with the system; and (iv) *Situational Trust*: The driving contexts that the driver assumes the system is capable of handling, e.g., traffic conditions or road types. It is important to note that while these four sources are conceptually intertwined in a driver's mind and therefore not strictly mutually exclusive, for the purpose of classification in this analysis, each error was attributed to the single, most dominant source of misconception as evidenced by the triangulated data. This simplification was necessary to quantify and visualise the primary drivers behind the different error types observed.

*2.4.3 Linking Errors to Sources.* To establish the analytical link between an observed error and its underlying source of misconception, a systematic triangulation process was used for each case. First, an error was identified and coded from the video data. Second, the corresponding timestamped think-aloud protocol was analysed to understand the driver's in-the-moment reasoning. Finally, the post-drive interview data was reviewed for the participant's broader explanations of their mental model and beliefs. An error was attributed to a source (e.g., 'Anticipation') only when evidence from the qualitative data converged. For example, the error of attempting L3 activation in the city was linked to the source 'Anticipation' when a driver stated they had read about such capabilities in the media. This matching process was conducted through co-coding sessions by the authors to ensure consensus, and the a priori template was refined throughout.

## 3 Findings

The analysis of driver interactions revealed that observed errors could be categorised based on underlying misconceptions stemming from their perception of DAS. Table 2 summarises the frequency of these errors across participants. Further analysis of think-aloud protocols and observational data, triangulated with interview responses, identified four key sources contributing to these misconceptions. The first source, *Purpose of the System*, refers to the driver's understanding of the intended functionality and operational boundaries of the Driving Automation System. This includes their perception of whether the system is designed for assistance with specific tasks like maintaining speed or lane position or if they believe it is capable of more comprehensive driving automation

**Table 2: Summary of the frequency of observed errors among participants.**

| Error Type | # Cases | # Participants |
|---|---|---|
| Error of Omission | 2 | 2 |
| Error of Commission | 37 | 5 |
| Mode Confusion | 25 | 8 |

under certain conditions. Misunderstandings about the system's intended purpose can lead to using it in inappropriate situations or expecting it to perform beyond its capabilities (cf., [20, 38]. The second source, *Anticipation*, encompasses the drivers' preconceived notions and aspirations regarding the present and future capabilities of automated driving technology. These anticipations are often shaped by media portrayals, technological advancements, and general societal trends, leading drivers to sometimes overestimate the abilities of currently available systems or expect features that are not yet implemented (cf. [17, 36, 46]. *Experience of Usage*, the third source, highlights the influence of prior interactions with both current and previous generations of driver assistance and automated systems. Positive or negative experiences with similar technologies can create strong mental models and biases that affect how drivers perceive and interact with new systems. For example, a driver with extensive positive experience with a highly reliable adaptive cruise control might develop an unwarranted level of trust in a more limited Level 2 system. Lastly, *Situational Trust* describes the driver's assessment of the system's reliability and competence in various driving contexts and conditions. This trust is not solely based on prior experiences but also on the perceived demands of the current driving situation, such as traffic density and weather conditions, and the driver's assumed responsibility for the driving task (cf. [7, 28, 39]. Drivers might trust the system in some situations but be hesitant to engage it in others, sometimes based on accurate assessments and sometimes on inaccurate preconceptions. It is important to note that these four sources are not mutually exclusive but rather interconnected and can interact in complex ways to shape a driver's overall perception and lead to various forms of misuse.

Figure 5 illustrates the relationship between the observed error types and the identified sources of misconception in the participants' perception. As shown, Errors of Omission were infrequent (2 cases) and linked to confusion regarding the *Purpose of the System.* Errors of Commission were more prevalent (37 cases) and primarily associated with Anticipation (12 cases), *Situational Trust* (11 cases), and Experience of Usage (12 cases), with only a few instances related to the *Purpose of the System* (2 cases). Mode Confusion (25 cases) predominantly arose from a lack of clarity regarding the *Purpose of the System* (24 cases), specifically distinguishing between Level 2 and Level 3 functionalities, with a single instance linked to *Experience of Usage.*

## 3.1 Errors of Omission

Errors of omission occurred when a driver failed to take a required action. For example, a driver is using a Level 3 DAS on a highway. The system is designed to handle most driving tasks under specific conditions. However, the system encounters a situation it cannot manage and issues a clear and timely request for the driver to take over control, but the driver fails to notice or respond to the system's TOR. The analysis indicated that the two observed cases of this error type were rooted in a misunderstanding of the *Purpose of the System.*

Figure 6 compares the frequency of errors for GUI A and GUI B, showing that the few instances of omission were associated with this error type. Specifically, these errors arose in situations requiring a proper transition of control while in Level 3 DAS. Whereas the Level 2 DAS needed to be supervised at all times, the Level 3 DAS allowed the drivers to disengage from the driving task. However, drivers seemed to perceive little difference between the two systems, stating, "*[...] pretty much the same conditions. You know, both hands on the steering wheel. You should have the visual, you know, control of the vehicle moving.*" (TP04). This ambiguity regarding the purpose of the two DAS levels and the driver's responsibility is further highlighted in the following quote from TP14: "*But with the [Level 3 DAS], I wouldn't say you could relax because I don't really... I'm not sure if you're supposed to not hold the steering wheel.*". This resulted in the participants continuing to supervise the vehicle even during the unsupervised driving mode. These misconceptions about how and to what extent the different DAS support the driving task led to errors of omission, where participants repositioned their hands on the wheel instead of pressing the steering wheel buttons to take over control, assuming that they simply had not placed their hands right on the steering wheel during Level 3 automated driving. The interview results indicated that drivers failed to understand the differences between the two experienced DAS and what their responsibility was during the use of the different driving modes.

## 3.2 Errors of Commission

Errors of commission were defined as any action performed by the driver that was not required by the system. For example, a driver is using a Level 2 DAS on a highway. The system is actively assisting with steering and maintaining speed, but the driver is still expected to remain attentive and supervise the vehicle. The driver, becoming impatient with the following distance maintained by the ACC, repeatedly taps the accelerator pedal to temporarily override the system and close the gap to the vehicle in front. Analysis of the data revealed that the most frequent sources of errors of commission were *Anticipation* and *Experience of Usage*, followed by *Situational Trust* and a few instances related to the *Purpose of the System.*

Figure 7 provides a comparative overview of the identified sources of errors of commission for the two tested user interfaces, showing that the observed errors were prevalent with both GUI A and B.

The inaccuracies linked to *Experience of Usage* (12 cases) appeared to originate from participants' assumptions based on their prior experience with driving automation in their personal vehicles. Notably, all participants reported owning a vehicle equipped with a Level 1 DAS, specifically Adaptive Cruise Control (ACC), which maintains speed and distance to other vehicles. This prior experience seemed to lead some participants to not fully differentiate the Level 2 DAS encountered in the study from their own systems. For example, TP06 described it as *"[. . . ] the adaptive cruise control works*

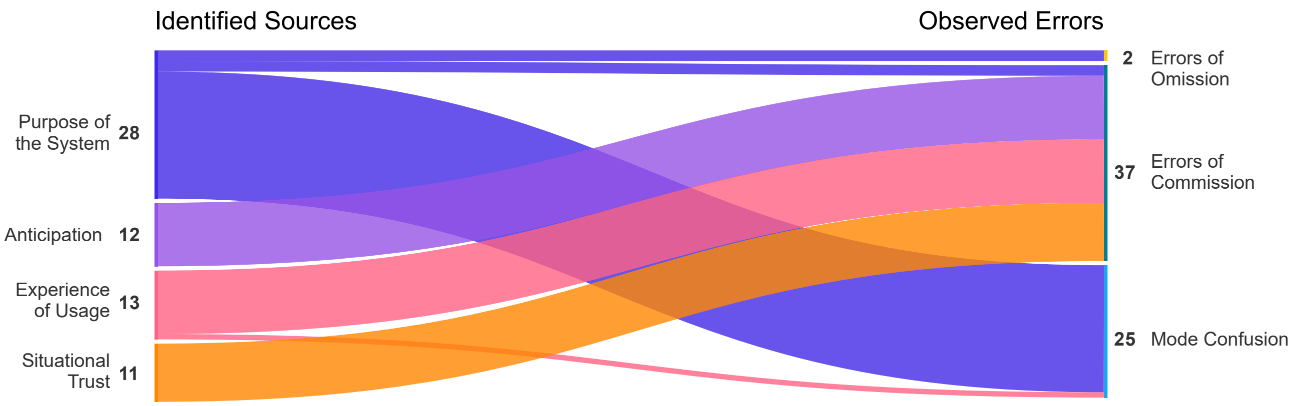


**Figure 5: Sankey diagram illustrating the attribution of the 64 observed errors (right column) to the four primary sources of misconception identified in the analysis (left column). The width of each flow is proportional to the number of error cases.**

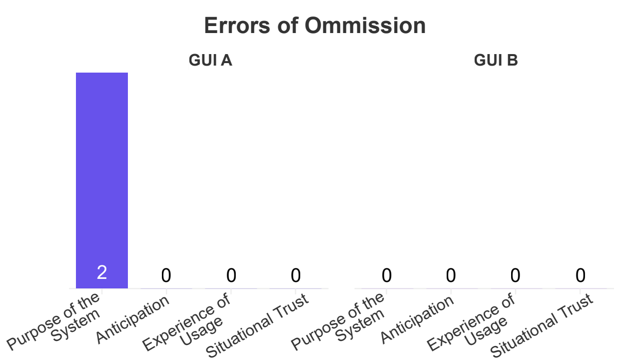


**Figure 6: Observed Errors of Omission and identified sources in the participants' perception reported by case count and GUI comparison.**

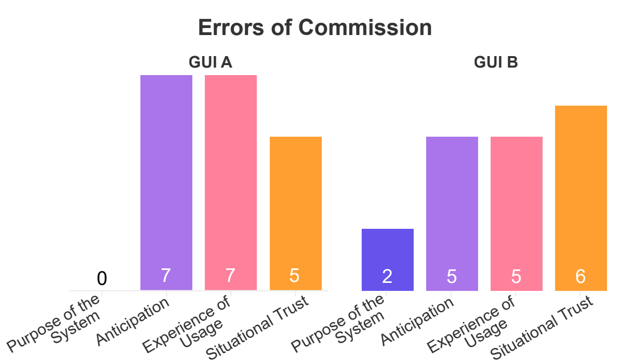


**Figure 7: Observed Errors of Comission and identified sources in the participants' perception reported by case count and GUI comparison.**

*like any other car.",* and TP15 stated, "*That's where I think the [Level 2 DAS] would be great. And also, I use it a lot in my car.*".

Errors associated with *Anticipation* (12 cases) stemmed from preconceived notions about DAS capabilities that were not based on direct experience with the study vehicle. Participants seemed to have formed these expectations from media reports and magazines about other, unrelated automated vehicle systems. Some even presumed a direct equivalence between these media-portrayed systems and the prototype experienced in the study. For instance, TP02 stated, "*Yeah, but I'm really interested about the [Level 3 DAS] just in the city because I read about it, and I think it works good even in the city.",* and TP12 explained, "*I've read about the systems before and how it works just because of the general interest I have. So, I did have, how to say, expectations on what it was supposed to do and how.*". This anticipation, based on external information rather than the study's introduction to the system's specific capabilities and limitations, often led drivers to believe they could engage the Level 3 DAS at will, resulting in actions classified as errors of commission.

The source *Situational Trust* (11 cases) emerged as participants exhibited a high degree of confidence in the automation systems, leading them to attempt usage even outside the defined ODDs. This tendency to overtrust is exemplified by TP09's exclamation: "*But I think it's...as long as you trust the car, I think you can use it almost anywhere.*", and TP05's confidence in that: "*You can use it anywhere, everywhere.*" This is particularly noteworthy as the pre-drive instructions explicitly stated that Level 3 automation was available only on highways and would be offered to the driver when conditions were met.

Finally, there were a few instances associated with the *Purpose of the System* (2 cases). In these situations, participants appeared to not fully grasp the extent to which the DAS would take over the driving task, leading them to repeatedly attempt to override the steering. Post-interview investigations revealed that these participants were often uncertain about the division of responsibility between the driver and the system across the different driving modes. A common sentiment was expressed by TP03: "*I consider myself responsible 100% of the time.*", even when Level 3 was engaged and the driver could theoretically disengage from the driving task until prompted. The reasons provided for this belief often intertwined with their anticipations about the system and were further supported by their understanding of current legal frameworks. For example, TP03 elaborated, *"[...] because it's the driver that can activate it [DAS] and also deactivate what makes me responsible for what to choose and what to activate."*, while TP06 stated, "*Legally speaking, I'm fully responsible for everything I do in my car.*". TP08 similarly noted, "*Because I have hard time seeing that a car could take responsibility for an accident happening. [...] it's the law. I don't think we get away from it.*". This suggests that existing knowledge about legal and ethical considerations can influence a driver's perception of the system's purpose and their role during engagement.

## 3.3 Mode Confusion

Mode confusion occurred in instances where participants were uncertain about the currently active driving mode or confused the vehicle's two distinct driving modes. For example, the driver is using a vehicle equipped with both a Level 3 DAS, allowing for unsupervised highway driving, and a Level 2 system requiring constant supervision. The driver has just exited the highway and entered a busy city street. The Level 3 DAS has automatically disengaged, and the vehicle is now operating with the Level 2 system active. However, the driver mistakenly believes that the vehicle is still in the fully automated Level 3 mode. Across both user interfaces, GUI A and B, the primary source of mode confusion was a misunderstanding of the *Purpose of the System*.

Figure 8 illustrates the frequency of mode confusion occurrences for GUI A and GUI B. The analysis revealed a total of 25 cases of mode confusion (see Table 2). Of these, 24 instances were linked to a lack of understanding regarding the *Purpose of the System*, with 10 cases observed during participants' interaction with GUI A and 14 cases with GUI B. An additional single instance of mode confusion during interaction with GUI B was associated with *Experience of Usage*. In numerous situations where the underlying cause of

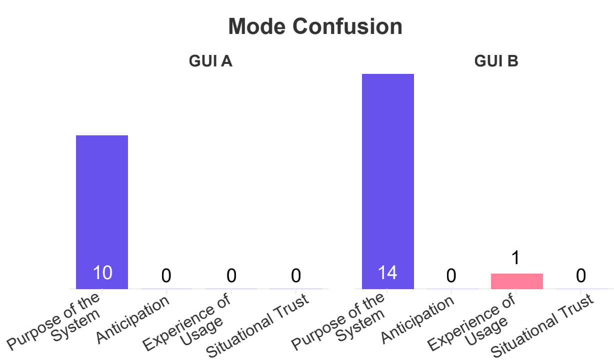


**Figure 8: Observed Mode Confusion errors and identified sources in the participants' perception reported by case count and GUI comparison.**

confusion was attributed to the *Purpose of the System*, participants, regardless of the user interface, did not fully comprehend that the Level 3 DAS allowed them to relinquish both the physical act of driving and the cognitive task of supervision. Consequently, some individuals continued to operate the vehicle while the Level 3 DAS was engaged, treating it as a mere assistive system by keeping their hands on the steering wheel and their attention fixed on the road. One participant, while toggling between the two systems, commented, "*I'm trying to figure out the difference between the two different systems.*" (TP14), indicating an understanding of the existence of two modes but a lack of clarity regarding their distinct functionalities.

Conversely, some participants mistakenly perceived the Level 2 system as a hands-free system, leading them to release their grip on the steering wheel. For example, TP06 let go of the steering wheel while driving and stated: "*it's not clear when it wants to help me and when I should be in control. [...] if I just I just let it go now it doesn't tell...*". Similar observations across participants suggested a confusion between which system was providing assistance and which was taking over control, despite the pre-drive explanations.

Notably, one participant's interaction pattern with the Level 3 DAS appeared to be influenced by their *Experience of Use* with a Level 1 DAS in their personal vehicle. This participant presumed that they had the authority to intervene in the Level 3 DAS at any time, based on their prior experiences with similar but less automated systems.

# 4 Discussion

This study aims to investigate how drivers' perception of DAS contributes to misconceptions and consequent use errors and misuse of DAS. To achieve this, we conducted a WOz driving study with 16 participants using two user interfaces (UIs) on public highways. Our findings indicate that participants exhibited various types of misuse during the interaction with the DAS, including errors of omission, errors of commission, and mode confusion. The observed errors appear to stem from misconceptions related to *Purpose of the System, Experience of Usage, Anticipation,* and *Situational Trust.* Existing research on take-over interactions suggests that providing contextual information beyond simple take-over requests [18], or binary indications (on vs. off) [34] is beneficial for the driver's understanding. However, while many studies emphasise the importance of clear and timely feedback through user interfaces, our findings suggest that feedback alone may not be sufficient. Instead, drivers' pre-existing beliefs and expectations influence their interpretation and interaction with the DAS, highlighting a need to consider factors beyond immediate UI design.

## 4.1 The Role of Perception in the Misuse of DAS

Upon closer examination of the observed Errors of Commission, which constituted a large part of the observed misuses, findings suggest that prior experience with similar systems and expectations for the current system influenced participants' interaction with the DAS. Despite receiving detailed explanations about the capabilities and limitations of Level 2 and Level 3 DAS prior to the driving sessions, participants nevertheless demonstrated several misuses. For instance, participants generally believed that they could activate the Level 3 DAS whenever they wanted and also had raised expectations regarding the capabilities of the system. Several explanations can account for these behaviors. First, participants may have assumed that their past interactions with Level 1 DAS would apply to higher-level automation as well. For example, drivers who were accustomed to activating Level 1 systems in any driving condition might have expected the same flexibility with higher-level systems, leading to repeated activation attempts under unsuitable conditions. **This suggests that as automation levels increase, inconsistencies in activation conditions may lead to system design flaws that inadvertently shape driver expectations**.

Another possible explanation is the overconfidence and misplaced trust in advanced Level 2 and Level 3 systems. Even though we provided clear protocols for system use, participants frequently relied on their own interpretations or assumptions, believing they could engage the system at will. **This highlights that the observed errors were not solely attributable to a lack of knowledge but were also significantly influenced by inaccurate mental models regarding the system's intended function and an overestimation of its capabilities.** Upon closer inquiry during the interviews, we found that participants' expectations were shaped by preconceived notions derived from external sources, such as media coverage and marketing materials. This aligns with recent discussions that critique the communication about DAS to consumers. For example, Dixon [15] argued that vehicle manufacturers, marketing campaigns, and media sources tend to exaggerate the abilities of partial automation, leading consumers to misinterpret their functionalities, which is noted to have led to system misuse. Similarly, Singer [44] found that branding, instructional materials, and training resources influenced drivers' mental model of a driving automation system, ultimately impacting drivers' expectations and utilisation of the encountered DAS.

Regarding Errors of Omission, our findings revealed instances where participants missed take-over requests. While such errors may root in a misunderstanding of the system's purpose, i.e., in Level 3, drivers are not required to keep their hands on the wheel, but they have to take over the driving task when the vehicle requests it. If the goal is solely to correct the erroneous behaviour itself, one solution could be to provide clear feedback instructing the driver to press a button along with placing their hands on the wheel. In this case, although perceptions may not be directly corrected through interface design, the erroneous behaviour itself could be mitigated. In contrast to commission errors, which were largely influenced by preconceptions, many omission errors appeared to result from ambiguity of the system's purpose and the extent to which it supports the driving task. **This infers that interface-based interventions alone may not be particularly effective in addressing omission errors**.

Regarding the observed instances of Mode Confusion, we observed considerable uncertainty among half of the participants in distinguishing between different driving modes or correctly identifying the functionalities for two separate DAS. This led to instances of hands-off driving when the Level 2 DAS was activated or hands-on driving when the Level 3 DAS was activated. Occasionally, participants mistakenly equated manual driving with the Level 3 DAS. These results indicate a high ambiguity regarding the system's purpose. Despite receiving prior instruction on the different driving modes and the capabilities and limitations of the systems, participants failed to differentiate the different driving modes. This is in line with previous studies that have also demonstrated that drivers frequently encounter difficulties in understanding the intricate levels of driving automation [4, 20, 49] leading to misconceptions of the system's capabilities and limitations [6] as well as the driver's responsibility in the different driving modes [38][37].

An argument might be made that the limitation of the here-presented study is that the participants were only exposed to the DAS for a short period of time, and a prolonged exposure could potentially impact their mental model. Regarding the errors of commission related to *Experience of Usage*, while longer exposure to the specific Level 2 and Level 3 systems in our study might lead to some adaptation and a more accurate understanding, the findings from Novakazi and colleagues [39], based on a Naturalistic Driving Study with Level 1 and 2 systems, showed that even longer-term exposure alone does not guarantee better understanding and that the driver's perception of the systems had a significant influence on usage strategies. **This conclusion suggests that while familiarity might play a role, addressing the underlying preconceptions is crucial.**

## 4.2 Addressing the Misuse of DAS

Before discussing potential mitigation strategies, it is crucial to address the role of the user interface itself. A foundational aspect of this study's design was the inclusion of two distinct GUIs: a baseline with known ambiguity (GUI A) and an improved version designed to be clearer (GUI B). Our findings revealed that while GUI B may have addressed some minor usability issues, the most significant error types—particularly errors of commission and mode confusion—persisted across both interfaces. Participants continued to demonstrate misuse rooted in their pre-existing *Anticipation*, *Experience of Usage*, and fundamental misunderstanding of the *Purpose of the System*, irrespective of the GUI they were interacting with. This outcome provides strong support for our central argument: **while UI design is undoubtedly important, it cannot be the sole solution**. The persistence of these errors, even with an improved interface, indicates that the more powerful influence on driver behaviour is their pre-existing mental model. Therefore, addressing the misuse of DAS requires a broader approach that targets the formation of these underlying perceptions.

A potential mitigation strategy might involve enhancing clarity through the UI to provide the system's current status accurately. However, this issue appears rooted in a fundamental gap between system design (several modes in a vehicle) and the driver's understanding, where a UI alone may assist but cannot fully resolve mode ambiguity or prevent mode confusion. To address these issues, the topic of driver training is frequently debated due to findings indicating its positive impact on the driver's mental model [12], and its greater efficiency compared to mere exposure [10].

Nevertheless, critics contend that driver training may be appropriate for inexperienced drivers, but it fails to address the needs of drivers who are already operating vehicles equipped with rapidly evolving technology and over-the-air software updates [23]. Hence, certain enquiries advocate for the standardisation of driving automation technologies and stricter guidelines regarding over-the-air deployment of innovative technologies, with the intention of moderating existing safety concerns pertaining to human-automation interaction [45][48].

These suggestions conclude that **a more comprehensive approach to driver training and communication and regulation**

**of DAS development and deployment through standardised lines is necessary to ensure the safe integration of automation technologies in vehicles**, ultimately enhancing overall road safety. However, these approaches do not address the root of the here-discussed misconceptions but rather seek a way to mitigate misuse of DAS. While updates to regulations and guidelines are a crucial tool to address advancements in DAS, ensuring safe and positive experiences is dependent on addressing misconceptions by establishing education schemes for DAS and/or raising the public's awareness of these technologies.

Therefore, moving forward, the emphasis should shift towards proactive educational strategies and public awareness campaigns that aim to cultivate realistic expectations and a thorough understanding of DAS, thereby mitigating the errors stemming from the persistent misconceptions highlighted in this study.

## 5 Conclusion

This study underscores significant human factors challenges in the interaction with automated vehicles offering multiple levels of automation, concerns that our findings suggest have not been adequately addressed by the research community. While previous efforts have focused on establishing design principles for user interfaces, our results indicate that these endeavours alone are insufficient to resolve the multitude of usage issues observed. Given that a substantial portion of the use errors and misuse identified in this study appears to originate from preconceived notions transferred to the experienced system, we conclude that the design of a DAS and its UI, while important, cannot guarantee error-free interaction.

Critically, our research highlights the significant influence of external factors beyond the control of development teams, such as public communication about DAS and the broader social discourse shaped by media and individual narratives. Furthermore, our findings emphasise the necessity of investigating factors influencing driver interaction and mental models of driving automation that extend beyond the immediate in-vehicle experience. This reveals a currently understudied gap: the need for a driver-centric approach to DAS design that incorporates cognitive perspectives to better understand and address these pre-existing beliefs.

In conclusion, to effectively mitigate misuse and enhance human-automation interaction, future research must prioritise clearer communication strategies, more targeted education initiatives, and the standardisation of DAS development, moving beyond a singular focus on user interface design.

## Disclaimer

Please note that the visuals included in this document are merely intended to illustrate development efforts by Volvo Cars and are not indicative of the exact capabilities or applications of the technology onboard current or future Volvo cars. Any future offering from Volvo Cars may deviate materially from what is illustrated in this document.

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