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Is conditionally automated driving a bad idea? Observations from an on-road study in automated vehicles with multiple levels of driving automation

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ABSTRACT

With the increasing adoption of driving automation technologies, vehicles equipped with SAE Level 3 driving automation are becoming available on the market. This study explores drivers' behaviour when driving conditionally automated vehicles on-road, providing multiple levels of driving automation. Sixteen participants drove a Wizard-of-Oz vehicle offering several levels of automation (Manual, SAE Level 2 and Level 3) on a public highway. Data was collected during driving sessions (observations and think-aloud) and post-driving sessions (in-depth interviews). The results indicate that drivers show errors in mode transitions and mode awareness. These errors include unintended deactivation of Level 2 driving automation, confusion about driving modes after disengaging Level 3 driving automation, and confusion about the current driving mode. These findings highlight a fundamental limitation in the design of automation systems when humans are required to operate multiple modes within a single system, making it challenging to distinguish between them clearly. This ambiguity and lack of understanding affected how drivers interacted with, interpreted, and responded to the automated vehicle. The study provides insights for designing automated vehicles with multiple levels of driving automation, aiming to improve mode awareness and overall safety.

1. Introduction

Automated vehicles have the potential to improve road safety by supporting the driver in various situations, ranging from everyday driving to safety-critical events (Cicchino, 2017). SAE Level 1 driving automation, such as systems that provide steering or acceleration and braking support to the driver, such as adaptive cruise control (ACC), has become standard. SAE Level 2 driving automation systems, which assist the driver with lateral and longitudinal control within predefined circumstances, are also widely available. With the rapid advancement of automation technologies, the market is witnessing the emergence of vehicles equipped with SAE Level 3 driving automation (Greimel, 2022; Tarantola, 2023). Compared to SAE Level 2 driving automation, drivers with access to Level 3 driving automation are no longer obliged to monitor the system constantly (SAE International, 2021). They can, therefore, engage in non-driving-related activities. However, drivers must still be able to take control of the vehicle when requested by the system or in the case of an emergency due to system failure.

Although it is argued that driving automation systems can potentially increase road safety (Cicchino, 2017), several human factors-related challenges must be addressed. These challenges include such things as the driver misunderstanding or misusing the system (Trimble et al., 2014), automation surprise (Sarter et al., 1997) when the current automation state is unknown, yielding conflicts between human operators and automated systems, or the driver being unable to provide suitable fallback performance or not being aware of the status or mode of automation, effectively being 'out-of-the-loop' (Seppelt and Victor, 2016). Nowadays, a vehicle includes multiple levels of driving automation, and the driving mode may change during a drive cycle because of driving automation limitations or driver interventions. The advent of higher-level vehicle automation adds a further layer of complexity to human-factors design challenges due to different responsibility allocations between automation levels (Kurpiers et al., 2020). Therefore, this paper explores drivers' behaviour and interaction challenges drivers may experience in automated vehicles with multi-levels of driving automation.

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1.1. Mode awareness in automated vehicles

Mode awareness comprises knowledge about the currently active automation system, its performance level and the driver's tasks and responsibilities (Sarter and Woods, 1995). One of the most common reasons for deficient mode awareness is mode confusion, which occurs when there is a mismatch between system behaviour and the user's mental model (Halasz and Moran, 1983). Thus, mode confusion contributes to mode errors, resulting in users misinterpreting the information being provided and performing actions which are appropriate to the analysis of the situation but inappropriate to the actual situation (Norman, 1981). Mode confusion in automated vehicles generally refers to situations where the driver assumes that the system is operating in a different mode than it actually is, resulting in inappropriate responses (Bredereke and Lankenau, 2005). Beyond this, drivers may correctly recognise the current automation mode but experience functional misunderstandings regarding the expected behaviour. Additionally, drivers may be aware of the automation mode and its functional demands but fail to align their behaviour accordingly. For example, a driver may understand that SAE Level 3 allows hands-off driving but continue to keep their hands on the steering wheel out of habit or a perceived need for control, or they may recognise that the vehicle is operating in SAE Level 2 but fail to realise that continuous hands-on supervision is still required (Nordhoff et al., 2023). In this study, we expand the scope of investigation of mode confusion beyond misperceptions of the driving mode itself to include a broader range of interaction issues, such as driver role confusion, where drivers are uncertain about their responsibilities regarding the system's capabilities. We collectively refer to these diverse interaction challenges under the broader framework of mode confusion.

Different research streams have investigated the phenomenon of mode confusion. Early studies on mode confusion in vehicle automation focused on ACC systems, that is, SAE Level 1 driving automation (Eom and Lee, 2015; Lee et al., 2014). Based on a driving simulator experiment, Furukawa et al. (2003) found, for example, that participants failed to infer system behaviour correctly in that, even though the ACC function was active, some participants predicted that the system would not accelerate. Later, the results of studies of drivers' interaction with Level 2 automated vehicles reported similar confusion (Banks et al., 2018; Endsley, 2017; Wilson et al., 2020). For instance, Wilson et al. (2020) identified situations in which the drivers incorrectly thought the vehicle was in the automated mode when it was not, and they were, in fact, responsible for primary driving tasks. Similarly, Banks et al. (2018) found that drivers failed to engage an autopilot feature properly and did not understand that the autopilot feature was engaged, even though the user interface indicated otherwise. Other examples of drivers' failure to understand system levels, system modes and drivers' responsibilities have been described by Novakazi et al. (2021a). Based on an analysis of interviews with participants in a Wizard-of-Oz field trial, the former found that in Level 2 automated vehicles, the high level of control and the good performance that the system was perceived to have led participants to conclude they were not responsible for the driving task, even though they were. Furthermore, drivers' awareness of the currently active mode is at particular risk when two or more automation levels are available. In a study of higher-level automated vehicles. Complementary to this, Feldhutter et al. (2018) compared the result of a study which involved one stage with alternating partially and conditionally automated driving and another stage with only partially automated driving. The result showed that shifting modes between partially and conditionally automated driving led to a loss of mode awareness and resulted in more mode errors than when there was only access to one automation mode.

1.2. Mitigation of mode confusion

The aforementioned evidence suggests that addressing mode confusion is critical for ensuring both driver safety and the effective operation of automated vehicles. Several approaches have been proposed to mitigate this issue, focusing on human-machine interaction design, user training, and cognitive models. Several researchers have debated the importance of user interfaces (UI) to support drivers in developing an appropriate understanding of automation and mitigating mode confusion. For instance, Carsten and Martens (2019) have argued that when the driver is decoupled from active control, the user interface design becomes even more critical. Seppelt and Victor (2016) disputed the need to design UIs to support driver situation awareness and appropriate mental model development to support the transfer of control from a higher to a lower level of automation. Lee et al. (2014) provided more detailed design guidelines by suggesting that mitigating mode confusion means providing the driver with a transparent display of the automation state and correct and concise information via different in-vehicle UIs. Heymann and Degani (2002) proposed that consistent and predictable behaviour in UI elements across different modes can help users form accurate mental models, reducing the likelihood of mode errors. While UIs can enhance mode awareness (Carsten and Martens, 2019; Lee et al., 2022), mode confusion still can occur if drivers fail to perceive or comprehend the automation mode indicated (Monsaingeon et al., 2021) or if UIs do not provide sufficient feedback about the system's state. In addition, user training is often suggested to enhance drivers' understanding of different modes and to help them become familiar with the various modes and their associated behaviours. For instance, several studies (Krampell et al., 2020; Ogitsu and Mizoguchi, 2015; Viktorová and Sucha, 2019) demonstrated that drivers who received training made fewer mode-related errors than those who did not. Furthermore, understanding the cognitive processes behind mode confusion has led to developing models that predict when and why mode confusion might occur. Norman (1983) emphasised the importance of designing systems that align with natural human cognitive processes, thereby addressing mode confusion by designing systems that match the users' cognitive models. Similarly, an online survey conducted by Kim et al. (2024) showed that drivers do not have a clear mental representation of the different driving modes in automated vehicles and suggested designing the mode transition logic to align with the driver's mental model to prevent mode confusion.

1.3. The current study

As automated vehicle technology advances, effective interaction design becomes increasingly important in ensuring safe, efficient and user-friendly interactions with automated systems. While mode confusion has been a critical issue in automated vehicles, it is increasingly recognised as part of a broader set of interaction challenges that arise when drivers are required to interpret, manage, and transition across different levels of automation. Therefore, this paper explores drivers' behaviour and interaction challenges in automated vehicles with multiple levels of driving automation in a real-world setting. To investigate, we conducted an on-road study with sixteen participants who drove a Wizard of Oz vehicle offering several levels of automation (Manual, SAE Level 2, SAE Level 3) on a public highway. Data was collected during driving sessions (observations and think-aloud data) and post-driving sessions (personal interviews). This research focuses on real-world behavioural responses, capturing how drivers' understanding and behaviour emerge under naturalistic conditions.

This study contributes empirical evidence from a real-world driving environment using a multi-level automated vehicle, which enhances ecological validity. It extends the understanding of mode confusion by revealing a broader spectrum of interaction challenges during transitions between automation levels, including gaps between mode awareness and appropriate behavioural responses.

2. Method

We used an on-road Wizard-of-OZ car (Dahlback et al., 1993) to explore the interaction between drivers and automated vehicles. The study was conducted in September 2022 in Gothenburg, Sweden and was designed to simulate real-world driving scenarios. The research vehicle used in the study was approved for road usage by relevant authorities, and the study design adhered to the ethical principles outlined in the WMA Declaration of Helsinki. All participants provided informed consent, including their agreement to collect various data points and participate in the research project. The collected data's retrieval, storage and processing strictly followed the European General Data Protection Regulation (GDPR) guidelines.

2.1. Participants

Sixteen participants were recruited through a professional recruiting agency, which was provided with a screener. The average age of the participants was 44 years (SD = 13.48). Seven participants were female, and nine were male. All participants possessed valid driving licenses, regularly drove vehicles equipped with automatic gears and adaptive cruise control and commuted daily by car. None of the participants indicated any occupational involvement in vehicle manufacturing or companies associated with vehicle development.

2.2. Vehicle

A modified Volvo XC90 served as the test vehicle, and Level 2 and Level 3 driving automation were simulated using the Wizard-of-Oz approach. The experimental setup is shown in Fig. 1, with the participant in the driver's seat behind the steering wheel, the test leader in the passenger seat and a driving wizard and UI wizard in the back seat concealed from the participant. The backseat driving wizard controlled the simulated Level 3 driving automation, while the UI wizard controlled the prompts and feedback presented to participants via a visual UI. Furthermore, two cameras were installed: one facing the driver and another facing the steering wheel and controls to capture observation data related to the driver's interaction with the vehicle and the systems.

User Interfaces (UIs), located in the cluster panel, are provided to support drivers in receiving the mode change indication and remaining aware of the current driving mode. Two audio-visual UIs - UI A (Novakazi et al., 2021b) and UI B (Novakazi et al., 2025) - were implemented. Participants experienced both UIs in a different order. Table 1 describes the visual and auditory UI sequences and states. Note that we utilised these two user interfaces not to compare their effectiveness directly but to explore how drivers interact with the system on multiple levels of driving automation. Therefore, our analysis focuses on mode transitions and mode awareness issues, but we note specific driver behaviours linked to the user interface.

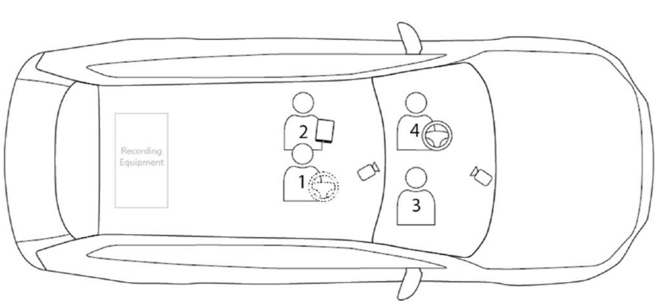


Fig. 1. The Wizard-of-Oz vehicle, with video cameras facing the UI and (1) driving wizard, (2) UI wizard, (3) test leader and (4) participant.

2.3. Driving automation operation

During the driving session, participants could engage in three driving modes: manual, Level 2, and Level 3. Participants operated the manual and Level 2, while the Wizard-of-Oz vehicle operated Level 3.

The Level 2 driving automation was a supervised system that provided: a) longitudinal control by maintaining a set speed and adjusting the distance to the vehicle ahead, and b) lateral control using lane keeping assist (LKA), automatically adjusting the steering to ensure that travel was within the lane. As it was an assistive system, the driver had to monitor the automation and the road and remain responsible for the driving task. The Level 2 could be engaged at any time except during Level 3, and participants were encouraged to use it as much as they desired. Participants could activate Level 2 by pressing a button on the left side of the steering wheel. The speed of the driving automation could be adjusted using the (+) and (−) buttons on the steering wheel, but there was no option to change the distance setting. The system could be deactivated by pressing the same button used to activate it, stepping on the brake, or overriding the function by prolonged pressure on the accelerator. Upon deactivation, the vehicle returned to manual driving mode. In certain driving conditions where the LKA function was unavailable (such as when the car could not detect lane markings), the driving automation continued to offer longitudinal control of the vehicle.

The Level 3 was designed to operate without supervision within a specified operational design domain (ODD). It was described to the participants as a system that prompted the driver when it was available and requested the driver to take over when the conditional requirements were no longer met. Upon activation, the system assumed complete control of the vehicle until the specified conditions were no longer met. The participants could remove their hands from the steering wheel and engage in non-driving-related tasks. The availability conditions varied based on the external transportation environment and were defined as follows: (1) partially controlled access roads with a speed limit of up to 80 kph; (2) free-flowing traffic with a level of service triggering the system to prompt takeover when approaching merging traffic; and (3) clear visibility of lane markings. If these conditions were met, the driver could activate the system, and the driving wizard would assume control of the vehicle. It was not possible to manipulate the speed or distance settings. Participants could engage or disengage the Level 3 unsupervised driving function by simultaneously prolonged pressure on two buttons, one on the left and one on the right side of the steering wheel. For safety reasons, the participants were instructed not to intervene in the unsupervised driving mode by any means other than pressing the buttons (not using the brake or steering wheel). A description of the respective systems' capabilities and limitations and the information the participants received before the driving session is available in Table 2.

2.4. Procedure

The study was divided into two parts: (i) the on-road driving session and (ii) a post-driving session. In (i), data on drivers' behaviour was collected by two video cameras mounted in the vehicle, directed at the driver and the steering wheel and dashboard (see Fig. 1), with any comments made by the participants recorded by that same equipment. In (ii), data on participants' experiences was collected in audio-recorded semi-structured interviews.

2.4.1. Part I – on-road driving session

Before the driving session, participants received a brief explanation of the study's structure. They were then guided to the test vehicle and introduced to the driving automation systems and how to interact with them. Table 2 provides an overview of the two driving modes and the information given to the drivers before the driving session. The introduction was designed to replicate the experience one would have when picking up a new car at a dealership, thus ensuring a high level of

Table 1
A description of the visual user interface (UI) states each driving automation system. Accompanying sounds are exemplified by the dotted lines below the UI states, indicating length and intensity of the auditory notifications for each state.

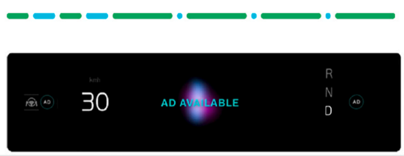
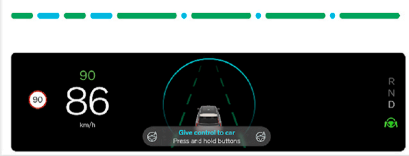
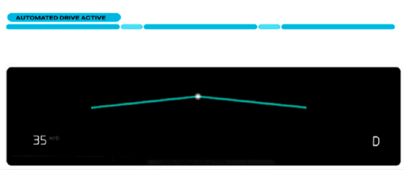
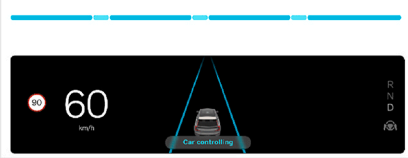
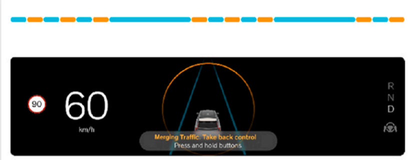
	UI A	UI B
State 1 Manual driving		
State 2 Level 2 driving automation active		
State 3 Hands-off warning in Level 2 driving automation		
State 4 Level 3 driving automation available		
State 5 Level 3 driving automation active		
State 6 Level 3 driving automation take-over from car		

Table 2
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	- 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/deactivation via steering wheel button
Level 3 Unsupervised driving	- 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/deactivation via a long press on steering wheel buttons

realism.

After the introduction, participants were given a moment to familiarise themselves with the car and settle in. The driving session lasted approximately 45 min on a partially-controlled-access city highway with speeds of up to 80 kph. The route started from the Volvo Cars Torslanda office and led to the southern part of Gothenburg (Slingan South), taking about 20 min. At that point, a short stop was made to switch UI (from UI A to UI B or vice versa). After the switch, the drivers returned to the car and drove the same route back to the starting point of the session (Slingan North) in approximately 20 min. Fig. 2 shows the route taken, indicating the starting and ending points and the location where the UI was changed. It also highlights the predetermined stretches where Level 3 driving automation was available and the duration of availability, resulting in approximately 8 min of automated driving and four take-

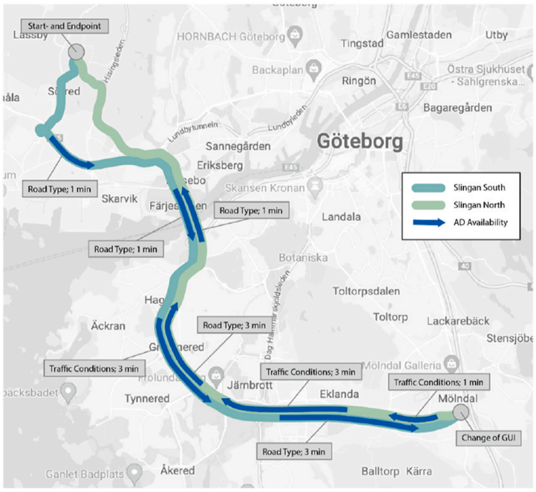


Fig. 2. Route of a driving session, highlighting stretches of Level 3 availability and exposure time.

over and hand-over requests in each direction.

2.4.2. Part II –post driving interviews

Following the driving session, the test leader and participant returned to the Volvo Cars office and entered a designated interview room. The semi-structured interview lasted approximately 30 min and primarily aimed to gather insights into the drivers' understanding of the two distinct driving automation systems, including their functionalities and limitations. Additionally, the two UIs were compared and supported by presenting screenshots of their sequences and states (Fig. 2). During this comparison, drivers were encouraged to provide feedback on any elements that aided their understanding of the systems, plus any confusing aspects.

2.5. Data analysis

The data analysis aimed to examine the driver's understanding of the automated driving system and information received via the UIs by analysing the data from the driving session. This entailed the video recordings of driver behaviour and think-aloud data, plus the interviews from the post-driving session. The combined results of the data analysis are described in Section 3. *Results*, where are grouped into the identified themes and enriched with think-aloud and interview data exemplifying drivers' comments at the moment of observation.

2.5.1. Driving session observations

As a first step, the think-aloud information collected during the driving sessions and the post-driving interviews was transcribed verbatim. Following that, Authors 1 and 2 conducted a pair-coding session using a deductive a priori template of the codes (Azungah, 2018) to analyse the video data of driver actions collected during the driving sessions. Drivers' comments from the think-aloud protocol were noted and connected to the coded observation data. Subsequently, Author 1 performed a second coding round. The initial clustering of codes relating to driving observations led to identifying two main themes that categorise the use errors observed during the participants' interaction with the automated driving system: (i) Transition Challenges and (ii) Mode Confusion.

These categories were discussed and chosen by the authors as the categories contain sub-themes that include the identified mode confusion regarding the multi-levels of driving automation and interaction-related issues.

Each main theme contains a cluster of sub-themes describing the nature of the different errors observed. The 'Transition Challenges' theme comprised two sub-themes: (1) Unintended deactivation of Level 2, and (2) attempt to activate Level 3 driving automation outside of ODD. The theme 'Mode Confusion' comprised three sub-themes: (1) Driver's engagement during different driving modes and (2) Mode confusion after take-over requests from the vehicle.

2.5.2. Post-driving interviews

In the next step, the authors familiarised themselves with the interview transcriptions. After the familiarisation phase, it was decided to use a deductive coding scheme (Azungah, 2018), applying a terminology proposed by Novakazi (2023), which identifies factors shaping the drivers' perception of driving automation systems and serves as a coding framework. Subsequently, the interview data were analysed, and comments and reflections from the participants regarding their interaction with the driving automation systems and the two UIs were investigated. Throughout the process, Authors 1 and 2 discussed the resulting sets of codes to address any inconsistencies. Krippendorff's Alpha was used to assess the inter-coder reliability (Krippendorff, 2004) and yielded a high level of agreement between the two authors ($\alpha = 0.917$).

In the last coding round, Author 1 coded the interview data from the post-driving session by addressing the following question: *What interaction challenges do drivers have in vehicles with several levels of automation?* This led to the identification of insights where the participants described their experience with the different driving automation, which were then used to enrich the identified main themes and find further explanations for the use errors observed during the driving sessions. The authors then discussed and related the participants' descriptions to transition challenges and mode confusion in a vehicle offering multiple levels of automation.

Although we reported the number of observations of user error during driving in this study, we did not focus on the frequency of terms mentioned by drivers regarding their understanding and experience of driving a vehicle with multiple levels of automation. Instead, we emphasise how participants described these topics and how such narratives contribute to explaining driver behaviour.

3. Results

During the driving sessions, several recurring use errors were observed. Considering the observed use errors, it became evident that both UIs posed challenges during the interaction with the driving automation. Thus, the following analysis does not compare the two UIs in detail but concentrates on identifying common themes observed during the engagement with both and will discuss the implications of these findings for the role of the UI during the interaction with a vehicle offering several levels of automation. The different identified themes were categorised as *Transition Challenges* and *Mode Confusion*, under which further sub-themes are discussed in the following sections. Table 3 overviews the number of Transition Challenges and Mode Confusion during the driving sessions.

3.1. Transition challenges

During the driving sessions, several incidents concerning hand-over and take-over requests (TOR) were observed. The observed errors could be categorised as transition challenges, as they all pertained to understanding how to interact with the driving automation system in the transition situation.

3.1.1. Unintended deactivation of level 2 driving automation

Level 2 driving automation could be disengaged by either pressing the button on the steering wheel, pressing the brake pedal, or prolonged overriding of the speed setting. Three participants were in Level 2 driving automation when they unintentionally disengaged the automation by pressing the brake pedal or overrode the speed control by pressing the accelerator. While the participants noticed after some time

Table 3
The number of observations of transition challenges and mode confusion divided per main theme and sub-theme, participants and UI.

Transition Challenges (N = 16)	Number of Observations			Number of Participants
	Total	UI A	UI B	
Unintended deactivation of Level 2 driving automation	6	4	2	3
Attempt to activate Level 3 driving automation outside ODD	19	16	3	15
Mode Confusion (N = 16)	Number of Observations			Number of Participants
	Total	UI A	UI B	
Hands-off during Level 2 driving automation	11	4	7	5
Hands-on during Level 3 driving automation	12	7	5	3
Mode confusion after take-over request from the vehicle	3	0	3	3

that Level 2 driving automation was deactivated through information provided in the visual UI (such as the lane not being detected), they did not understand why it happened, as indicated by the think-aloud data: *"I do not know why (it disengaged) … Maybe I am pressing something that it does not want me to."* (TP13). For these participants, deactivation of Level 2 driving automation occurred repetitively: *"Disengaged. Something again."* (TP06).

3.1.2. Attempt to activate level 3 driving automation outside of ODD

Level 3 driving automation was only available when specific requirements of the ODD were fulfilled (see 2.3 for detailed description) and would then prompt the driver with a hand-over request when it was available. The test leader explained this procedure and the ODD to the participants before the driving sessions. Nevertheless, four drivers attempted to activate the Level 3 driving automation outside its ODD. These attempts were observed several times during the drives, as shown in Fig. 3. For example, one participant stated: *"Maybe this system is not possible when it is going to smaller roads, or … I am not sure how it is working."* (TP05). Drivers did not understand that they could not activate Level 3 driving automation without a prompt from the vehicle. In addition, there was no information about the reason for the error, so they repeatedly attempted it. In addition, as shown in Table 3, there was a noticeable numerical difference between UI A and UI B, which we will discuss in Discussion 4.1.3. Learning Experience.

3.2. Mode confusion

Several mode awareness errors were observed during the driving sessions. The errors could be categorised as mode confusion, as they related to understanding the driving automation.

Fig. 3. The driver attempts to activate Level 3 using the steering wheel buttons in a situation where this mode is not available.

3.2.1. Driver's engagement during the different driving modes

A widespread misunderstanding amongst the participants was the extent of engagement expected from the driver in each of the different driving modes, i.e., Level 2 and Level 3 driving automation. While during engagement with the Level 3 driving automation, the driver remained in control of the driving task, they could disengage from the driving activities fully until the system requested a take-over.

Nevertheless, despite the instructions provided by the test leader before the driving session, about one-third of the participants (5 out of 16 participants) failed to place their hands on the steering wheel when using the active Level 2 driving automation. In two out of 11 observed cases, the participants seemed to be checking whether they could release their hands but with their hands still hovering by the steering wheel (Fig. 4 left), which indicates ambiguity about the capability of the driving automation, e.g., drivers testing the limits of the system. In the remaining nine cases, participants took their hands off after activating the Level 2 driving automation (Fig. 4, right), which leaves room to discuss whether the drivers were aware of the requirement or whether they mistook Level 2 for Level 3 driving automation: in other words, an instance of mode confusion.

On the other hand, during the activation period of the Level 3 driving, although not obliged to keep their hands on the steering wheel, three participants did so. Two out of the three participants did this during the entire Level 3 driving (Fig. 5), and one of them commented: *"I am trying to figure out the difference between the two different systems."* (TP14), indicating that the driver is not aware of the current mode sufficiently through the user interface.

3.2.2. Mode confusion after take-over request from the vehicle

While the participants understood the TOR, there was ambiguity about their driving mode after the transition from Level 3 driving automation. This was evident by statements collected during the driving sessions, such as: *"I was not exactly clear on what kind of mode I was in."* (TP03). However, all observed cases of this type of mode confusion only occurred at the first TOR. Further, two out of three participants expressed confusion when the system did not revert to the previous level of assistance (Level 2) when they deactivated the Level 3 supervised driving automation: *"If I was in cruise control, I still wanted to be in that one when I go out and exit the Level 3."* (TP05). In all cases, this was the Level 2 supervised driving mode. This shows that the mode confusion was created by the expectation that the driving mode would revert to the previously active mode and not to the manual driving mode. Evidently, the interface's indications were insufficient to remove all ambiguity.

4. Discussion

The results of this study highlight, similar to other studies (Banks et al., 2018; Feldhutter et al., 2018), the challenges associated with

Fig. 4. Left: Driver testing the steering capability of the Level 2 driving automation; Right: Driver removing hands fully from the steering wheel during Level 2 driving automation.

Fig. 5. Two drivers kept their hands on the steering wheel during all Level 3 unsupervised driving.

communicating levels of driving automation and mode transitions in vehicles to drivers. This section discusses interaction issues caused by mode confusion in automated vehicles and the implications of system design.

4.1. *Difficulties in mode transitions*

For safe and efficient use of driving automation, it is imperative that drivers possess an unambiguous understanding of when and how to transition between driving modes. In the study, participants faced problems transitioning from Level 2 to manual driving, as well as from Level 3 to manual driving, although the types of issues differed.

4.1.1. *The transition from level 2 driving automation to manual driving*

Transitioning from Level 2 driving automation to manual driving was not always intentional (i.e., by pressing the steering wheel button). Instead, it was observed that a few participants unintentionally deactivated the Level 2 driving automation by pressing the brake pedal. It can be argued that the unintentional deactivation of Level 2 driving automation could be attributed to a mere mistake, but it is not unreasonable to attribute the behaviour to a lack of understanding. Despite receiving visual feedback from the user interface, some participants failed to notice mode transitions, or, after noticing, were unable to understand the reason for the change, both of which reflect mode confusion. In a similar on-road study by Wilson et al. (2020), drivers often detected changes in driving automation (cruise control activation or deactivation) not through UI feedback, but by observing changes in vehicle speed. For example, when drivers believed the vehicle was in Level 2 automation, they expected the system to control the speed. They realised the system was no longer engaged when the vehicle failed to slow down, indicating that manual driving was active. This type of mode confusion may lead to safety-critical situations.

Unintentional disengagements and consequent mode confusions have also been observed in other studies due to, for example, physical control errors (Banks et al., 2018; Feldhutter et al., 2018) and, as in the present study, this led to a state of mode confusion. In the study by Wilson et al. (2020), these unintentional disengagements occurred early in their trials. Therefore, even though some participants in the present study repeated the observed error, further experience using such systems would probably lead to reduced unintended deactivations. As a solution to this, it is easy to suggest that the UI should provide clear indications. However, whereas the UI can provide information to support anticipation of upcoming changes in the automation mode (Tinga et al., 2023), it is less evident to what degree UIs can hinder unintentional disengagements or how reliably drivers can perceive the mode transition through the UI. UI is considered to provide clear feedback on a driver's actions, intentional or unintentional, to ensure that they become aware of any mode transitions and of the currently active mode. The UI design implications include modifications to notify and differentiate between mode statuses to enable drivers to notice any changes more easily. It is necessary to consider ways beyond simply increasing modalities. For example, it is easy to argue that adding auditory feedback to visual feedback will help drivers notice mode changes. However, in the study by Wilson et al. (2020), where this was attempted, the drivers did not notice an unintended deactivation despite the accompanying auditory feedback to the visual cues. Therefore, it may be inferred that this study would have seen comparable outcomes. This highlights the need for a more comprehensive approach to the design of driving automation systems, considering not only the addition of sensory modalities to the UI but also the complexity of the driver's understanding of the system dynamics to ensure effective communication and interaction in automated driving scenarios.

4.1.2. *The transition from level 3 driving automation to manual driving*

Mode confusion in the transition from Level 3 driving automation to manual driving is related to the fundamental automated system design. A few participants (3/16) were confused about the driving mode following the change from Level 3 driving automation to manual driving. Based on the interview results, these individuals had expected the system to revert to the previous level of assistance (Level 2, as this was engaged before entering the Level 3 driving automation) instead of transitioning to manual driving. However, it is essential to note that participants' ability to remember the previous automation mode may be influenced by the duration of Level 3 driving automation, as extended periods of Level 3 automated driving may lead drivers not to recall the prior automation mode. Additionally, a survey study investigating the drivers' expectations during mode transitions has shown that drivers would rather go from Level 3 driving automation to manual driving after the transition by the TOR (Kim et al., 2024). It was found that the participants' understanding of the automated system and their expectations for its behaviour lie at the root cause of this observed error. Nevertheless, from a user-centred design perspective, implementing a consistent mode transition logic would ensure a comprehensible transition of control, irrespective of the preceding intervention and the level of automation engaged and help drivers learn and comprehend their responsibilities regarding the driving task at any given time.

4.1.3. Learning Experience

Some participants in the study experienced an error only once, and some participants were observed to repeat the same errors. For example, it was observed that the system was unintentionally deactivated when drivers pressed the accelerator pedal while in Level 2. Still, some drivers failed to grasp the rationale behind this deactivation and repeated the error. Moreover, some drivers attempted to engage in Level 3 driving automation despite the conditions not being met (outside of ODD) and did so repeatedly. As shown in Table 3, there was a noticeable numerical difference between UI A and UI B in the occurrence of the '3.1.2. Attempt to activate Level 3 driving automation outside ODD.' While this initially appeared to suggest that the UI might have influenced the error, we did not interpret it as caused by the interface itself. To elaborate, both UIs during Level 2 driving automation do not include information related to activation of Level 3 driving automation (State 3 in Table 1) and provide information about activation availability in text format (State 4 in Table 1). Neither the UI analysis nor participant interviews offered sufficient evidence to suggest that one UI communicated more effectively than the other. Therefore, we believe this error was more likely due to trial-and-error behaviour stemming from a lack of understanding of the system's operational principles, rather than differences in the information presented by the two UIs.

Catino and Patriotta (2013) concluded that a system's functions are often learned through error experiences, and earlier studies on automated vehicles have shown trial-and-error as drivers' main approach to learning driving automation (Nandavar et al., 2023; Viktorová and Šucha, 2019). It is possible that further exposure to the systems could have mitigated the observed errors, but it is also possible that, without understanding the underlying causes, users may be trapped in a cycle of repeated errors. This aligns with Johansson and Novakazi (2023), who analysed drivers' usage of driving automation patterns and found that, although most drivers generally perform tasks correctly after following repetitive procedures and their use of the system changes over time, there are instances where they are unable to complete the task on their own, requiring intervention from the test leader.

In the current study, the UIs no doubt played an important role in drivers' interaction with automated vehicles, but it is possible that the UIs could have played a more active role in participants' learning of the systems by providing more informative feedback when repeated errors occurred. For example, visual and auditory information could explain the reasons behind deactivations or interaction errors by displaying relevant messages. However, the UI must be considered one of several information channels, in part because studies have shown that drivers use different information channels in learning about automation: information from salespersons or user manuals (Nandavar et al., 2023).

4.2. Mode confusion

During this study, the driving automation was set in a way that in Level 3, the driver may hand over and let go of the driving task completely if the conditions allow so, and in Level 2, the vehicle has longitudinal and lateral control, but the driver is still required to supervise the system and to keep their hands on the steering wheel. However, participants who did not keep their hands on the steering wheel were observed in Level 2 driving automation. One explanation is that these participants did not fully understand the instructions provided before the trial. Another explanation is that they wanted to test whether the system operated appropriately. This claim supports observations of participants hovering over the steering wheel (Fig. 4 left). A third explanation is mode confusion, and that they thought they were driving with the Level 3 system, as the differences between the levels were not obvious to them, either based on the vehicle's behaviour, or the explanations of the differences had not been understood (Rodak and Pełka, 2023). A related explanation is that even though the exposure to Level 3 driving automation was fairly short, it is possible that participants' trust in the overall driving function was elevated after the Level 3 experience and that they unconsciously adopted their habit of relinquishing control of the steering wheel at Level 2 due to their experience with Level 3 driving automation – even if they were aware of the mode change. Earlier research has shown that when an automated system operates consistently and reliably, this will build trust (Gold et al., 2015; Koustanai et al., 2012), and with increasing trust, drivers may become more complacent and more prone to distractions or engaging in secondary tasks (Parasuraman and Riley, 1997). As a result, when transitioning from Level 3 back to Level 2 driving automation, drivers might have become familiar with a higher level of vehicle control, leading them to believe that active supervision is not required. However, this unintended carryover of behaviour poses a safety risk, as Level 2 driving automation relies on the driver being attentive and in control of the driving tasks at all times.

This mode awareness may have been influenced by the UI. In State 2 of Table 1, UI A prominently displays an image of a hand on the steering wheel in the centre, while UI B uses a small icon instead. As shown in Table 1, hands-off behaviour during Level 2 driving automation was observed more frequently with UI B than with UI A. This difference can be interpreted as a result of the way each UI presents information on the hands-on steering wheel. In other words, the UI can mitigate this mode confusion. Previous studies have shown that, in the UI of the current commercial Level 2 automated vehicles, which does not provide information about the requirement for a hands-on steering wheel UI, drivers were confused about whether they should keep a hands-on steering wheel in Level 2 (Kim et al., 2025; Perrier et al., 2021). It appears that there are complex reasons why drivers do not have their hands on the steering wheel in Level 2, as discussed above. In terms of enhancing mode awareness via UI, it seems that the vehicle needs to provide information about hands-on the steering wheel through the user interface. For example, Kim et al. (2025) found that fixed information (icon or text-based hands-on steering wheel information) in the cluster display enhances the understanding of the hands-on steering wheel requirement in Level 2 driving automation. At the same time, participants in the current study raised concerns regarding the potential distraction risks associated with detailed in-vehicle displays, especially considering that drivers of Level 3 driving automation do not necessarily need to monitor the external roadway continuously. Hence, it is essential to find a balance by presenting clear and concise information that assists drivers in understanding driving automation without causing unnecessary distraction.

In contrast to behaviour observed in Level 2 driving automation, some drivers kept their hands on the steering wheel during Level 3 automation. This behaviour may indicate a lack of understanding regarding the differences between Level 2 and Level 3 functionalities, and more broadly, the shifting role of the driver. Alternatively, it may also reflect a lack of trust. Even when drivers were aware that hands-on steering was not required in Level 3 driving automation, they may have chosen to keep physical control due to insufficient trust in the system's capabilities or the driving situation.

5. Limitations

To the authors' knowledge, there are few on-road studies of drivers' interaction with and experience of different UI designs in automated vehicles offering several levels of automation. The study reported here took place in real traffic, providing a dynamic driving environment (Bengler et al., 2019; Pai et al., 2020), and this is believed to have increased the ecological validity of the findings. Nevertheless, there are several limitations to the current study. First, the study was conducted under controlled conditions, driving the highway for less than 60 min in total. While the results indicate a learning curve, it is impossible to assess how prolonged usage over longer distances or various road types might affect drivers' interaction and observed use errors (Carney et al., 2022; Pradhan et al., 2023). At the same time, several studies (Forster et al., 2019; Novakazi et al., 2020; Pereira et al., 2015) demonstrated that there is no big change in learning and how drivers use the system after a short exposure to it. Therefore, the data obtained in our study is acceptable for showing the driver's interaction in automated vehicles. Second, the presence of researchers was maintained for the entirety of the driving session to guarantee safety, act as wizards, and observe participant behaviour (Novakazi et al., 2021b). The potential impact of researchers on participants' behaviour throughout the study may have led to deviations from their natural driving behaviour in real-world situations, for example, in terms of less trial-and-error in learning the system's limitations. Despite the limitations, the authors argue that the study provides valuable insights into the challenges associated with drivers' interaction with and use of driving automation systems.

6. Conclusions

For safe and efficient use of driving automation, it is important that drivers develop an appropriate understanding of driving automation and its modes of operation. This study aimed to observe the interaction between drivers and automated vehicles, offering multiple levels of driving automation to investigate interaction errors that are potentially caused by accidents. These included errors related to mode confusion and issues associated with mode transitions. The findings emphasise issues previously noted in the interaction design of vehicles offering multiple levels of driving automation. While some issues in vehicles equipped with multiple levels of driving automation can be mitigated through the user interface (UI), the complexity inherent in the system architecture fundamentally affects interaction (Lewis and Norman, 1995). This means that UI changes alone have limitations in resolving interaction issues for effective human-machine interaction. For example, simply enhancing visual or auditory cues within the UI does not address the root causes arising from system design, such as understanding the logic behind transitions between automation levels. It is necessary to acknowledge the limitations of relying solely on UI modifications and consider system design that differs from driver expectations or mental models in how drivers interact with automated vehicles.

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.

CRediT authorship contribution statement

Soyeon Kim: Writing – review & editing, Writing – original draft, Validation, Methodology, Formal analysis, Conceptualization. **Fjollë Novakazi:** Writing – review & editing, Writing – original draft, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **I.C. MariAnne Karlsson:** Writing – review & editing, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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