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Assessing driver reactions to emergency navigation prompts in head-up displays

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ABSTRACT

This study examines the effectiveness of warning messages via Head-up displays (HUDs) that provided navigation-based evasion instructions in enhancing driver performance and safety during critical traffic events. A dual-method approach was employed, combining an online survey with a driving simulator study. The online survey evaluated drivers' initial reactions to different visual HUD designs, such as directional arrows, lane markings, and textual cues, within a simulated emergency scenario. The insights gained from the survey were used to identify the most effective warning design, which was subsequently implemented in a driving simulator experiment. There, the real-time responses of drivers to the preferred HUD design were examined under controlled conditions. The results show that the instructions improve drivers' understanding of the required actions and significantly reduce reaction time to approaching emergency vehicles, as reflected by behavioural and perceptual indicators associated with improved situational awareness. Participants who received visual instructions in the HUD reported reduced cognitive workload, greater confidence in their actions and a more accurate understanding of lane navigation requirements. Data from eye movement analyses and lane deviation analyses confirmed faster and more precise reactions in critical situations, such as forming an emergency lane, while physiological measurements, including heart rate, showed no significant increase in stress levels. These results highlight the potential of head-up displays as effective tools for improving traffic safety and optimising rescue chain operations during critical incidents.

1. Introduction

Cardiovascular arrest outside of hospitals is the third most common cause of death in Germany. Every year, the emergency services are called to around 120,000 such emergencies. Despite resuscitation attempts in half of these cases, only 11 per cent survive, even when help is nearby. (Fischer et al., 2023) In such a case, survival is largely dependent on the smooth interaction of the rescue chain (Bürger et al., 2018; Gässler et al., 2020; Gräsner et al., 2020). A key factor is the rapid arrival of emergency personnel. Key issue papers recommend reaching the patient within 8 min of the emergency call (Fischer et al., 2016), but this target is met in only about 70 % of cases (Fischer et al., 2023). Such delays can be critical to patient outcomes. Therefore, improving these conditions is essential for faster and more effective emergency care. Alongside immediate chest compressions, the timely arrival of emergency services plays a decisive role in increasing survival rates (O'Keeffe et al., 2011).

Traffic related delays, particularly those caused by the inadequate formation of rescue lanes, remain a significant obstacle to timely emergency response (Griffin and McGwin, 2013). The successful creation of rescue lanes depends on the timely and coordinated actions of other drivers, who must provide sufficient space for emergency vehicles to pass. To enable this, drivers must be informed early enough about the approaching emergency vehicle and its intended path. Robinson and Khattak (2011) have shown that a better and more effective use of advanced traveller information systems in emergency situations, particularly under traffic disruption conditions, can lead to improved and more reliable travel times as well as enhanced safety and emergency response capabilities. Furthermore, drivers may benefit from clear, context-specific action recommendations that facilitate the efficient formation of rescue lanes.

Increased digitalisation in transportation can support the development of systems that assist drivers in such a critical situation and facilitate timely arrival of emergency services. Emerging technologies like AI

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(Artificial Intelligence) and IoT (Internet of Things) can contribute to this by enabling enhanced data collection and analysis (Eskandari Torbaghan et al., 2022). Head-up displays (HUDs) in vehicles have evolved significantly since their initial research and development (Evans et al., 1989), and their acceptance in the automotive industry has grown substantially. As a result, an increasing number of manufacturers now offer HUDs as optional features in their vehicles (Korentsides et al., 2022).

In this regard Head-up displays (HUDs) have been identified as effective tools for delivering real-time information to drivers, helping to reduce distraction and cognitive workload, enhance reaction times and improve overall driving performance (Niu et al., 2024; J. Park and Im, 2021). Yang et al. (2020) also showed that warning graphics in the HUD significantly improve driving performance and additional information can positively influence driving behaviour. Wang et al. (2020) underlines that visual information helps drivers navigate more accurately and efficiently. User evaluations of HUDs in real driving contexts have shown positive feedback and a high sensation of safety (Sánchez et al., 2016).

Supporting these findings, Y.-C. Liu and Wen (2004) demonstrated that HUDs result in faster reaction times and lower mental stress compared to head-down displays (HDDs). Similarly, Niu et al. (2024) found that using HUDs for warning displays significantly reduced drivers' reaction times and minimised speed fluctuations, ultimately enhancing overall driving performance. Milicic (2010) emphasises that the use of intuitive, clear symbols in a HUD can improve communication by replacing text with symbols, making it easier for users to focus on the road. Besides, targeted animations can effectively direct attention by emphasising key information through movement or magnification, thus enhancing comprehensibility and perception. Finally, results of Werneke and Vollrath (2013) underscore the importance of timely warnings, which allow drivers to adjust their expectations and reduce stress.

To ensure a robust comparison between stated preferences and observed behaviour in response to dynamic prompts, this study adopts a combined approach involving both a questionnaire and a driving simulator study. The questionnaire component provides a well-established framework for assessing driver behaviour and performance, with the effectiveness of HUDs shown to depend strongly on factors such as timing and display modality (Maroto et al., 2018). Complementing this, the use of a driving simulator allows for the examination of driver behaviour in a safe, controlled environment, where independent variables can be systematically manipulated to create critical scenarios and identify causal relationships (Boyle and Lee, 2010; Wynne et al., 2019). Driving simulators offer credible and transferable results and are particularly valuable in evaluating intelligent transportation systems such as HUDs in high-risk traffic situations, including encounters with emergency vehicles (Blana, 1996). The study by Ardeshiri et al. (2015) further emphasises that decisions captured through questionnaires may diverge from behaviour observed in simulator settings, highlighting the necessity of employing multiple methods to ensure the validity of the findings.

This study investigates the potential of HUD-based warning messages, first identifying effective content and design features before testing the favoured configuration in a driving simulator. Building on previous research findings, this study employs a mixed-method approach. It combines an online survey with a driving simulator study, each conducted with independent groups of participants. Both approaches complement each other and enable a comprehensive evaluation of the effectiveness of head-up display warnings in road traffic. The aim is to investigate the acceptance of this technology and evaluate its influence on the behaviour of road users in critical situations.

2. Methods

2.1. Online survey

As the first step of this study, an online survey was conducted to examine how personalised HUD navigation prompts influence driver reactions during emergencies. A between-subjects design was employed to assess drivers' responses to various HUD designs in simulated traffic scenarios, specifically examining behaviour, usability, and comprehension. The survey pursued two complementary objectives. On the one hand, identifying the most effective HUD design, and on the other, assessing how different types of adjacent areas influence acceptance and the perceived appropriateness of the evasion prompt.

In the initial phase of the survey (see chapter 2.1.2), the HUD prompt depends on the type of right-hand area available for evasive action, which varied between a bus lane, a bicycle lane, and a hatched area. The aim was to examine the influence of contextual conditions on the acceptance and implementation of the HUD recommendation, depending on the specific nature of the adjacent area. It was assumed that each of these areas is associated with distinct normative and social meanings, which significantly affect drivers' subjective perceptions of their appropriateness for evasive manoeuvres.

In the second part of the survey (see chapter 2.1.3), the type of adjacent area remained constant, while the visual presentation of HUD elements (arrow, depiction evasion area, text hint) was systematically varied. This allowed for an evaluation of different design approaches in conveying navigation instructions.

Based on the survey results, the most effective HUD variant will be developed to support drivers in emergency situations. The insights from both phases of the survey serve as the foundation for the driving simulator study, informing the choice of scenario and HUD configuration.

2.1.1. Participants

Participants were primarily recruited from RWTH Aachen University (Germany) through a combination of poster advertising and digital outreach. Additionally, invitations to participate were distributed via several email lists, broadening the potential respondent pool. The recruitment period spanned from 30 November 2023 to 10 January 2024.

The inclusion criteria required participants to possess a valid driving license, ensuring that all respondents had prior driving experience. A total of 198 individuals initially participated in the survey. However, 21 respondents were excluded from the analysis due to the absence of a valid driving license. Additionally, an exploratory data analysis was conducted to identify potential outliers. Based on reported annual mileage, 14 responses were classified as outliers ($\leq$100 km/year or $\geq$ 45,000 km/year) and removed to preserve the integrity of the data analysis. Consequently, the final dataset comprised 163 participants, whose responses were fully included in the subsequent analysis.

The final sample consisted of 103 male and 60 female participants. The age distribution of participants ranged from 17 to over 65 years, with the majority (79.2 %) falling within the 17–34 age group (40.5 % aged 17–24 and 38.7 % aged 25–34). Regarding driving experience, most participants had held their licence for six or more years, with the largest group (41.7 %) having between six and fifteen years of experience. Additionally, nearly a quarter of the participants (23.9 %) had been licensed for over fifteen years, representing the more experienced drivers in the study. The average (M) annual mileage is 9,218 km/year (median (Md): 8,000 km/year, standard deviation (SD): 8,211 km/year). Familiarity with head-up display (HUD) technology was also assessed. A significant proportion (61.3 %) reported having no prior experience with HUDs, while 51 participants (31.3 %) had used them before, and 12 participants (7.4 %) had experience using HUDs in their own vehicles.

2.1.2. Video stimuli design

This section details the creation and structure of video stimuli used in the online survey to accurately simulate driving scenarios and assess drivers' reactions to HUD-based navigation prompts during emergency situations. Three videos were developed within a virtual environment using Unity software, which facilitated the implementation of vehicle displays and behaviours. Each video depicted a 13 s journey from the perspective of a driver traveling at 50 km/h through an urban area. Notably, the HUD prominently displayed the vehicle's speed and introduced a visual warning as an ambulance (AV) approached from behind partway through the journey. Sound was not included in the videos.

The videos showcased additional elements such as the instrument cluster and the rear-view mirror. Participants could see a small image on the windscreen that simulated a head-up display. The speed was constantly visible, see Fig. 1 (a). During the drive, an ambulance appeared from behind shortly after the start, visible in the rear-view mirror. Nine seconds into the video, a warning, see Fig. 1 (b) flashed temporarily on the HUD along with the speed, visible for approximately three seconds before the video concluded.

The scenarios varied based on the type of lane adjacent to the right of the vehicle: a bus lane, see Fig. 1 (a) and Fig. 1 (b), a cycle lane (Fig. 1 (c)), or a hatched blocking area (Fig. 1 (d)), each designated as a potential evade area. Each of these lane types represented a different degree of perceived rule violation or social undesirability, intentionally creating a decision-making conflict for the driver. This type of conflict scenario was essential to prevent a potential ceiling effect, in which participants might follow the HUD recommendation unconditionally if the adjacent space was perceived as clearly permissible (Ho and Yu, 2015). The HUD directed drivers with a green arrow to evade right, with the swerving area varying depending on the scenario. Additionally, the right-hand section of the HUD displayed the text 'Evade!' in combination with a triangular warning sign with a red border and an exclamation mark, commonly used in Germany to indicate a general danger zone, and the words 'Emergency doctor'. According to the experimental design, each participant was exposed to and evaluated only one of the three possible videos variants.

2.1.3. Picture stimuli design

To gain a more detailed evaluation of the displayed prompts, six still images were generated, highlighting specific HUD elements from the videos. These images allowed for a closer examination of the clarity and effectiveness of the directional arrow, lane depiction, and emergency text warnings. Each element was presented in two contrasting formats, facilitating an analysis of their influence on driver comprehension and decision-making during simulated emergencies. The images primarily differed in the presentation of the three HUD display components:

- Arrow: Two variants were used to depict this element. In variant 1 (Fig. 2 (a)), a static curved arrow is displayed, while variant 2 (Fig. 2 (b)) features a moving arrow that is dynamically reconstructed from below.
- Depiction evasion area: This element analysed the depiction of the evasion lane in the bus lane scenario. Variant 1 (Fig. 2 (c)) does not explicitly label the bus lane in the HUD, merely showing the road marked by carriageway edges. Variant 2 (Fig. 2 (d)) includes explicit labelling of the bus lane with the word 'BUS'.
- Text hint 'Evade' (see Fig. 2 (e) and Fig. 2 (f)): For this element, variant 1 (Fig. 2 (e)) does not display any text, whereas variant 2 (Fig. 2 (f)) shows the text 'Evade!' indicating the required action in a restricted area scenario.

As in the video sequences, all six images featured the German traffic sign for 'danger spot', accompanied by the phrase 'Emergency doctor'. This sign is a triangular warning symbol with a red border and a white background, displaying an exclamation mark at its centre. It serves to alert drivers to potential hazards ahead, indicating the need for heightened caution. In the HUD, the sign was positioned at the bottom right corner. Although the study did not follow a fully factorial design, the specific structure of the image variants enabled targeted pairwise comparisons. In several cases, image pairs differed in only one display element, allowing the effects of individual HUD components to be assessed in isolation. During the study, each participant was exposed to only one variation of each image component, ensuring that no participant saw both variations of the same component.

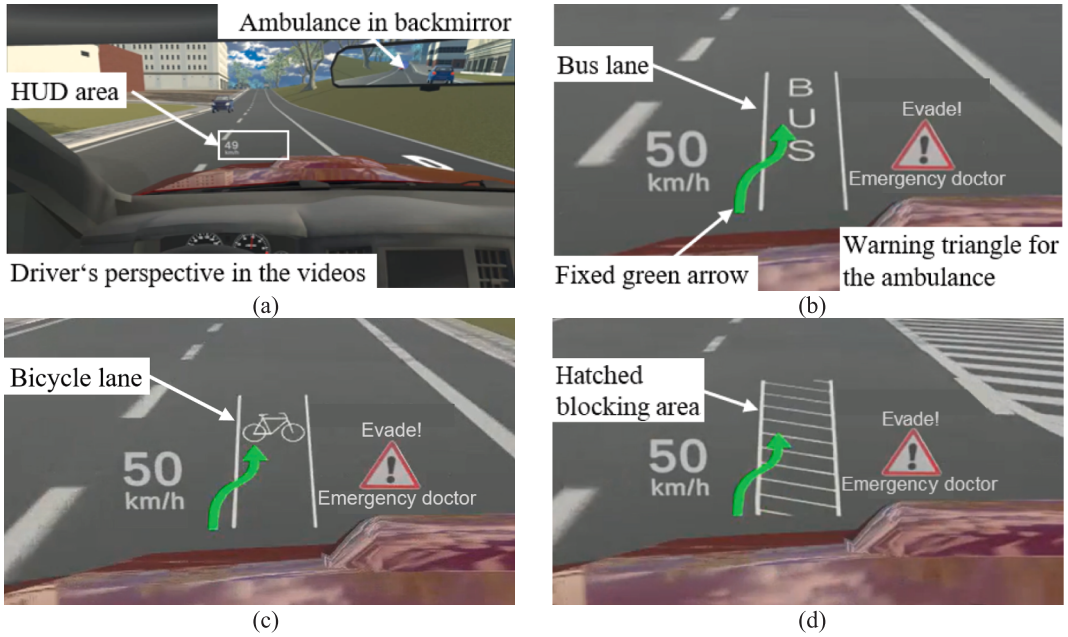


Fig. 1. Screenshot from the driver's perspective in the videos with full view of driver's front (a). Zoom on HUD area in panels (b) – (d): bus lane (b), bicycle lane (c) and hatched blocking area (d).

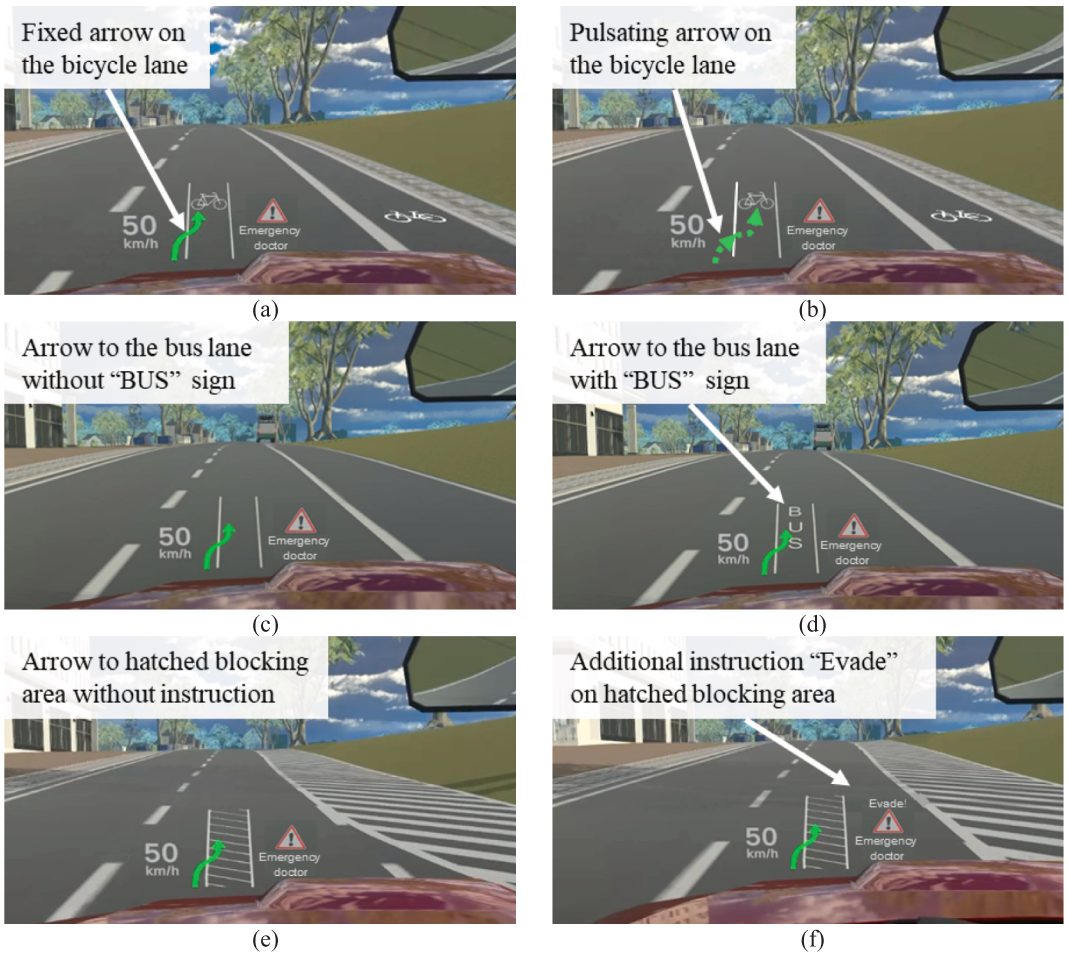


Fig. 2. Screenshot from the driver's perspective in the photos. (a) Arrow, static version, (b) arrow, dynamic version, (c) evasion area, unlabelled bus lane, (d) evasion area, labelled bus lane 'BUS', (e) text hint 'Evade', no text displayed and (f) text hint 'Evade' with text 'Evade!' displayed.

2.1.4. Questionnaire design

To effectively measure the impact of HUD-based navigation prompts on driver behaviour during emergency situations, this section describes the structured questionnaire used in the online survey. The online survey was hosted on the SoSci Survey platform (V. 3.6.12) and could be completed from any location. Participants were informed that the survey would require a device with a sufficiently large screen, such as a computer or tablet, to adequately view the video and image content integral to the study. This requirement was emphasised to ensure that all participants could fully engage with the interactive elements of the survey without technical limitations affecting their responses.

The questionnaire was designed to gain well-founded insights into participants' perceptions and reactions, thereby enabling an evaluation of the usability and effectiveness of the navigation prompts. Demographic data were collected through single-choice questions with predefined response options. The evaluation items were answered using a 5-point Likert scale (1 = strongly agree, 2 = agree, 3 = neutral, 4 = disagree, and 5 = strongly disagree), which is recognised in the social sciences as a reliable tool for measuring attitudes and perceptions (Boone and Boone, 2012; Kokolakis, 2017). The use of an odd-numbered scale allows for differentiated responses through a central neutral option and balanced answer categories (Kyriazos and Stalikas, 2018), thereby promising greater accuracy in the data collected (Guerra et al., 2016; Warmbrod, 2014). The questions were based on established usability criteria and were adapted to align with the content presented in the video stimulus (Castro and Horberry, 2004; Klee, 2023). An overview of the questionnaire items is provided in Table 1.

Participants began the questionnaire with an introductory section

Table 1
Questionnaire description.

Part	Classification	Sample Items
Introductory information	Subject area and procedure	–
Personal details	Demographic information	Sex, Age
	Characteristics of driver	Duration driving licence, mileage, experience HUD
Rating questions for the video presentation (5-point-Likert-Scale)	Comprehensibility	I stop and wait in my lane until the emergency vehicle has passed me.
	Intuition	I immediately realise how I have to react.
	Acceptance/ discomfort	I feel uncomfortable following the navigation instructions.
		I am aware that cars are allowed to use the bus lane/bicycle lane/ restricted area in case of an emergency event.
Rating questions for the picture presentation (5-point-Likert-Scale)	Comprehensibility	The bus lane/arrow/text hint is clearly understandable in the display.
	Informativeness	The display includes all necessary information.
	Intuition	I am immediately aware of how to react.
	Distraction	The information makes me feel distracted in an emergency situation.

that provided written information about the general topic, the procedure, and the technical requirements for completing the survey via the online platform. The specific objectives of the study were not disclosed in this introduction in order to maintain the neutrality of participants' responses. This approach ensured that the participants' reactions were genuine and unaffected by any preconceived notions about the study's goals.

The questionnaire first collected essential demographic information from participants, such as age (17–24, 25–34, 35–49, 50–65, >65), gender, and driving experience. This section included questions about participants' possession of a driving license, a requirement for the study, and queries about their annual mileage and experiences with HUD technologies. This data helped correlate driving behaviours and familiarity with technology to the responses given in later sections. (see Table 1).

After this, each participant watched one of three videos chosen at random to prevent bias. Their perceptions of the video scenario were then rated against five statements on a 5-point Likert scale detailed in Table 1. To control for potential order effects, the statements were presented in a randomised order for each participant. These evaluations shed light on the participants' ability to interpret and act upon HUD prompts during emergency situations.

In the final section of the survey, participants evaluated key components of the HUD design using the picture stimuli described in Section 2.1.3, assessing comprehension, perceived informativeness, intuition and the level of distraction. Each participant evaluated three images depicting different driving scenarios, varying in arrow representations, evasion areas, and text cues (see 2.1.3). Using the same five-point Likert scale, they rated their impressions based on four descriptive statements (see Table 1), which were also randomly ordered for each individual.

2.2. Driving simulator study

Based on these findings, the subsequent driving simulator study was conducted to examine real-time decision-making in the emergency vehicle scenario and how this is influenced by a supporting HUD. The most promising HUD design identified in the preliminary survey (Fig. 1 (d)) was compared to a baseline condition (Fig. 1 (a)) without supporting HUD information using a between-subjects design. The study aimed to evaluate the effectiveness and functionality of the developed HUD design in the simulation, analyse participants' responses, and assess its potential to improve driving behaviour in emergency situations.

2.2.1. Participants

For the driving simulator study, 68 participants (27 female, 40 male, and 1 diverse) were recruited using a similar approach as in the online study. The inclusion criteria required participants to possess a valid driving license, be at least 18 years old, have no history of epilepsy, and not wear glasses (contact lenses OK). Glasses cannot be worn during the study, as participants are required to wear sensor glasses for eye tracking.

The majority of participants (55.9 %) were aged between 18 and 24 years, followed by 35.3 % in the 25–34 age group. Six participants were aged 35 years and older. Regarding driving experience, 19 participants had held their driving licence for less than three years, 17 for three to five years, and 32 had been licensed for six years or more. The reported annual driving mileage varied among participants, with an average of 7,855 km/year (Md = 5,000 km/year, SD = 7,941 km/year). This diverse range of driving experience and exposure ensured a broad spectrum of insights into navigation and driving-related factors. Regarding to the familiarity with head-up display (HUD) technology more than half (55.9 %) had no prior experience with HUDs, while 35.3 % had some experience, and 8.8 % reported using a HUD in their own vehicle. Regarding the assessment of their driving behaviour, 62 % of participants stated that they adapt their driving style to traffic conditions and consider themselves to have a dynamic driving approach. An additional 30 % described themselves as calm drivers, characterised by anticipatory and considerate driving.

2.2.2. Simulator setup and equipment

The driving simulator used in this study is located at RWTH Aachen and provides a realistic driving environment. Equipped with a curved 360° video screen, it offers participants a highly immersive driving experience that replicates the physical conditions of real-world road scenarios. The simulator uses the chassis of the Life electric vehicle from E-Go, which includes a full car interior to simulate a realistic driving experience (Fig. 3). It is equipped with specialised simulation hardware, such as a steering wheel and pedals, and records data on the vehicle's position, speed, and driver interactions with the controls (e.g., steering wheel angle, pedal use) at high fidelity every 50 ms. The engine and surrounding noises are simulated through a loudspeaker installed in the vehicle.

To capture detailed biometric data, this study utilised the Tobii Pro Glasses 3, a research-grade eye-tracking system with a sampling rate of 50–100 Hz. The integrated cameras recorded the driver's field of vision at a resolution of 1920 × 1080 pixels, allowing researchers to correlate eye movements with visual stimuli. The system provided a gaze trajectory accuracy of 0.6°, ensuring precise tracking of visual attention and fixation patterns. Additionally, heart rate data were collected using the Polar Verity Sense optical heart rate monitor (OHRM). OHRM technology employs photoplethysmography to measure blood volume changes in microvascular tissue (Singh et al., 2018; Valenti and Westerterp, 2013). The device, worn on the forearm, continuously recorded heart rate, providing real-time data that could be analysed alongside other biometric and behavioural data. This setup enabled the comprehensive analysis of physiological responses and driving behaviours during the simulation.

2.2.3. Experimental design and simulation scenario

Before commencing the driving simulation, participants underwent a preliminary briefing to familiarise themselves with the simulation environment and the controls of the driving simulator. This initial engagement included an online questionnaire identical in structure to the one used in the online survey, gathering personal information such as age, gender, driving license status, annual mileage, and previous experience with HUD technologies. Additionally, participants were asked to assess their driving behaviour based on five predefined driver type descriptions.

The following driving simulation involved a drive through an urban

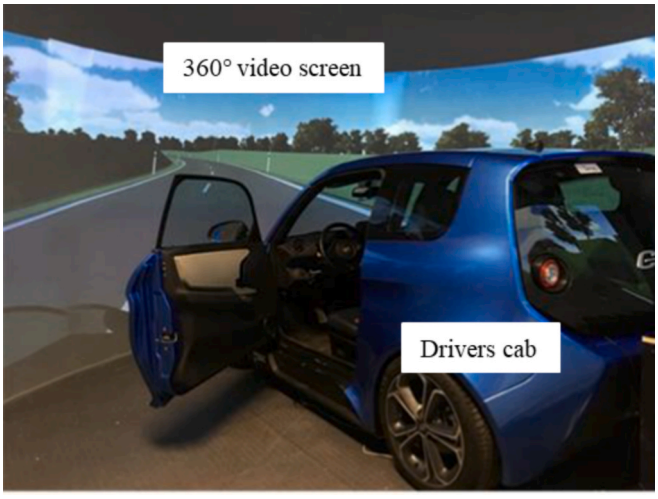


Fig. 3. Driving simulator setup. E-Go Life Driver's Cab and partially visible projection screen.

environment before culminating in an emergency scenario requiring participants to evade an approaching emergency vehicle, necessitating a rapid and precise response. Two distinct variations of the emergency situation were implemented, with each participant randomly assigned to one of the two conditions. This approach ensured controlled exposure to specific HUD prompts, enabling focused data collection on participants' reactions to the different scenarios of the emergency situation described below:

- Scenario 1 (with warning): In this scenario, the participant drives through an urban environment for approximately 2 min, approaching an intersection from the south where three cars are waiting at a red light. An overview of the scenario is shown in Fig. 5. After a short time, a siren is heard, and the participant sees an ambulance approaching from behind in the rear-view mirror. The appearance of the ambulance was triggered contextually by the participant reaching a predefined point in the scenario (start of the bus lane) ensuring consistency across all trials. At the time of the ambulance's arrival, participants were typically stationary, having assumed a waiting position behind the last vehicle at the traffic light. With the lane ahead blocked by three stopped vehicles, the participant is required to respond appropriately to the approaching emergency vehicle. When the siren sounds, in addition a navigation message appears in the HUD, instructing the participant to move into the bus lane on the right. The display with the highest rating from the preliminary online survey (Fig. 1 (d)) was used in the situation. This scenario tests the participant's ability to follow the HUD instructions while managing the additional stress caused by the emergency vehicle.
- Scenario 2 (without warning): After travelling the same route, the participant approaches the same red light intersection. The siren sounds again and the ambulance becomes visible in the rear-view mirror after a short time. In this scenario, the participant does not receive a separate instruction to drive into the bus lane. Only the navigation instruction to turn right at the next junction is displayed in the HUD. In this scenario, it was investigated how well the drivers react to sudden changes in the driving environment without receiving additional assistance via the HUD.

The scenario setup is illustrated in Fig. 4, showing the simulation location where the two conditions occurred, including the visual HUD prompt in the warning condition.

After the simulator ride, participants continued the questionnaire they had begun earlier, assessing their subjective impressions, initial reactions to the emergency, and perception of the HUD. Important performance indicators such as responsiveness, comfort, distraction and usefulness were considered. In addition, the perceived workload was to be indicated using the NASA Task Load Index (NASA-TLX), one of the most widely used method of measuring mental workload (Bustamante and Spain, 2008; Hart, 2006).

2.2.4. Measurements

To investigate the effectiveness of navigation aids and overall driving efficiency, the driving simulator study primarily utilised the following data sources: simulator data (lateral vehicle position, speed), heart rate sensor data, eye movement data, and a questionnaire.

The dependent variables (DV) examined in this study to quantitatively assess the effects of HUD-based navigation prompts on driving behaviour and the driver's physiological reactions to an approaching emergency vehicle are listed in Table 2:

As part of the driving simulator study, reaction time was used as a key evaluation metric. This metric was recorded using both eye-tracking data and simulation data and was analysed using the Kaplan-Meier curve. This technique was applied to measure the time to event data, specifically the time it took for drivers to respond to navigation changes prompted by the HUD. This analysis helped in understanding how quickly drivers reacted to critical navigation instructions in emergency scenarios, which was crucial for evaluating the effectiveness of these

Table 2
Dependent variables monitored in the driving simulator study during the ride.

Indicator	Description
Reaction time	Refers to the duration (in seconds) between the moment an ambulance becomes visible in the rear-view mirror and the point at which the participant fully cleared the lane.
Lateral deviation	Measures the vehicle's lateral position relative to the lane center, recorded continuously during the emergency scenario. This was used to determine when the participant initiated and completed the lane change.
Fixation Points	Denote stable gaze positions ($\geq$ 60 ms) recorded by the eye-tracking system from ambulance appearance to evasion completion, indicating areas of visual attention during the critical response phase.
Heart Rate	Continuously measured via an optical sensor (1 Hz), it provides data on the driver's physiological stress response during the assigned driving scenario

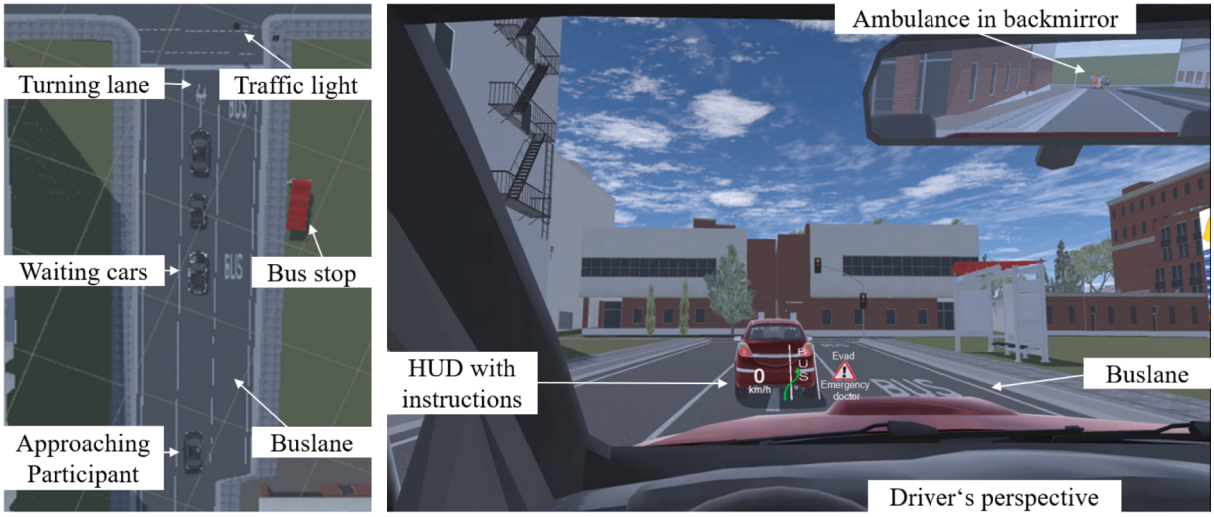


Fig. 4. Driving scenario location and HUD emergency prompt. (a) View from above. (b) Driver's point of view.

systems in enhancing driving safety.

For a rescue lane to be considered successfully formed, the vehicle had to deviate by a specified distance from its original path, creating adequate space for an emergency vehicle, such as an ambulance, to pass. This measure was critical for evaluating compliance with rescue lane formation regulations and assessing its practical execution under simulated conditions.

During the simulated drives, participants' fixation points and gaze durations were tracked using eye-tracking glasses, particularly during avoidance manoeuvres. The analysis tool Tobii Pro Lab 1.241 was used to determine fixation times (≥60 ms) and to generate heat maps to visualise areas of focus, providing insights into participants' visual attention during high-stress scenarios. These maps offered a deeper understanding of where drivers directed their attention during split-second decisions, highlighting cognitive load and situational awareness in critical traffic situations.

At last, heart rate data were continuously recorded throughout the simulation at a sampling rate of 1 Hz to examine participants' physiological and emotional responses. Statistical analysis of heart rate variability was conducted to assess stress levels during the task of forming a rescue lane. The integration of physiological data provided a comprehensive perspective on the cognitive and emotional demands drivers faced in emergency situations.

In addition to the recorded measurements, the questionnaire assessed participants' subjective impressions during the emergency situation, focusing on their overall perception, the application-related assessment of the display, and their mental workload (based on the NASA-TLX framework). The following dependent variables were examined (see Table 3).

The initial section of the questionnaire assessed participants' fundamental understanding of the task. They were prompted to describe their driving reactions using free-text fields, providing a preliminary indication of the comprehensibility of the scenario and accompanying video. Additionally, participants rated statements related to their general understanding on a 5-point Likert scale. Dependent variables such as reactivity, comfort, and awareness of traffic rules under stress were documented to gain deeper insights into their responses.

To further evaluate cognitive and physical demands, the standardised NASA Task Load Index (NASA-TLX) was employed. Participants assessed their subjective workload in response to HUD prompts across six dimensions: mental, physical, and temporal demands, effort, performance, and frustration. The analysis of NASA-TLX results provided a detailed understanding of the perceived workload associated with the HUD design, offering critical insights into driver behaviour and the challenges encountered during the formation of a rescue lane. (Hart, 2006).

In the final section of the questionnaire, variables such as distraction, acceptance and perceived utility, understood in terms of improved reaction time and situational awareness, were assessed. Participants rated specific statements using a 5-point Likert scale to express their level of agreement or disagreement with the displayed warning. At this stage, all participants, regardless of whether they had previously seen the warning during the study, were shown an image of the warning and asked to evaluate it. These data points contribute to a comprehensive evaluation of HUD features, providing actionable insights for improving their design and functionality in emergency scenarios.

2.3. Statistics

Statistical analyses were conducted using IBM SPSS Statistics 29.0.2.0 to evaluate the effects of various HUD designs on driver behaviour during simulated emergency situations, as well as to analyse participants' reactions in the two driving simulator scenarios (with warning vs. without warning).

In the online survey, descriptive statistics were calculated to compare group differences in the evaluation of navigation elements.

Table 3
Dependent variables monitored in the survey after the simulation run.

Section	Item	Description
General questions	Reaction	How did you react when the ambulance approached from behind?
	HUD prompt (only for variant with warning)	Which prompts did you receive through the HUD when the ambulance approached from behind?
Assessment of the situation	Reaction	I was immediately aware of how to react.
	Discomfort	I felt uncomfortable following the navigation instructions.
	Knowledge of the driving rules	I was aware that cars are allowed to use the bus lane in case of an emergency.
NASA-TLX (Perceived workload)	Mental demand	How much mental effort was required to absorb and process information?
	Physical demand	How much physical activity was required? Was the task physically relaxing or taxing?
	Temporal demand	How did you perceive the time pressure during the task accomplishment? Was the task hurried or leisurely?
	Performance	How successfully did you reach the set goals? How satisfied were you with pursuing the goals?
	Effort	How hard did you have to work to achieve your task completion?
	Frustration	How insecure, irritated, stressed, and annoyed vs. secure, satisfied, relaxed did you feel during the task?
Assessment of the displayed warning	Distraction	By displaying the notice, I feel distracted in the emergency situation.
	Utility (safety)	The embedding of the hint made me feel more secure to navigate.
	Utility (time)	By displaying the notice, I was able to react more quickly.
	Acceptance	I would welcome the embedding of such warnings in my vehicle.

Independent samples t-tests ($\alpha \leq 0.05$) were used to assess differences between groups based on independent variables (e.g., arrow type, evasion area, text hint) (Jankowski et al., 2018). Additionally, a three-way ANOVA and a Welch-ANOVA were conducted to analyse differences in intuition, acceptance, and distraction across the three driving conditions (bus lane, bike lane, restricted area). To account for multiple comparisons, post hoc analyses using Bonferroni and Games-Howell corrections were applied depending on variance homogeneity (Sawyer, 2009). As each participant rated multiple stimuli, the assumption of complete independence of observations is only partially met. This constitutes a methodological limitation. To reduce the risk of Type I error inflation associated with this dependency, appropriate correction procedures were applied, and all statistical results were interpreted with corresponding caution.

In the driving simulator study, descriptive statistics summarised performance metrics such as reaction time, heart rate trends, and workload scores. Independent samples t-tests were again applied to analyse differences in reaction times and subjective workload under various conditions (e.g., with or without HUD prompt) (Jankowski et al., 2018). Spearman's rank correlation tests were applied to examine the relationships between perceived distraction, utility (time and safety), and acceptance, as it provides robust estimates for ordinal data and non-normally distributed variables (Kornbrot, 2014). To assess the effect of the warning on response timing, a Kaplan-Meier survival analysis was conducted to determine the time until lane clearance, followed by a Log-Rank test to compare survival distributions between the two groups and test for significance, evaluating the impact of the warning on behaviour

and lane clearance efficiency. To investigate participants' physiological stress responses A Linear Mixed Effects Model (LME) was used to account for repeated heart rate measurements over time within subjects. This allowed testing for group differences (warning vs. no warning), temporal effects, and their interaction while controlling for variability.

3. Results

3.1. Evasive area perception and effects of HUD configuration

Regarding the video stimuli (see Fig. 1), participants in the online survey reported significantly lower comfort levels when instructed to use the cycle lane compared to the bus lane and restricted-area scenarios. An ANOVA showed a significant difference in acceptance ($p < 0.001$), and a Welch-ANOVA revealed a significant difference in intuition ($p < 0.004$). Therefore, the differences in driving conditions were further examined for the two usability criteria. For the criterion 'intuition', the Games-Howell post hoc analysis identified significant differences between the cycle lane and the restricted area ($p = 0.003$) as well as the cycle lane and the bus lane ($p = 0.013$). Regarding acceptance, Bonferroni correction was applied. This analysis revealed significant differences between the cycle lane and the bus lane ($p = 0.028$) and between the cycle lane and the restricted area ($p < 0.001$). Since the bus lane represents a realistic and commonly encountered option for evasive manoeuvres in urban traffic, and was rated as moderately accepted, this scenario was selected for the subsequent driving simulator study.

Concerning the HUD configuration (picture stimuli), the static arrow received slightly higher mean (M) ratings than the pulsating arrow for both (3) intuition ($M = 1.47$, $SD = 0.83$ vs. $M = 1.70$, $SD = 0.97$) and (1) understanding ($M = 1.47$, $SD = 0.77$ vs. $M = 1.58$, $SD = 0.94$). However, these differences were not statistically significant, with $t(161) = –1.625$, $p = 0.106$ for intuition and $t(161) = –0.783$, $p = 0.435$ for understanding. The *t*-test results likewise showed no significant differences for (4) distraction ($t(161) = 0.838$, $p = 0.403$) or (2) informativeness ($t(161) = –0.119$, $p = 0.905$) between the two arrow types. Comparing the means, slightly less distraction was reported for the static arrow ($M = 3.59$, $SD = 1.27$) compared to the pulsating arrow ($M = 3.43$, $SD = 1.25$), while informativeness was rated similarly ($M = 1.89$, $SD = 1.10$ vs. $M = 1.91$, $SD = 1.14$) Based on these results, the static arrow was selected as the preferred option for further driving simulator investigation. (See Fig. 5).

In regard to the depiction of the bus lane, the version featuring additional markings received higher mean ratings for both (1) understanding (2.95 vs. 1.45) and (2) informativeness (2.27 vs. 1.61). These differences were statistically significant, as indicated by the *t*-test results for understanding, $t(161) = 8.123$, $p < 0.001$, and for informativeness, $t(161) = 3.667$, $p = 0.001$. In contrast, no significant differences were found regarding (3) intuition ($t(161) = 1.568$, $p = 0.097$) or (4) distraction ($t(161) = 0.664$, $p = 0.949$) between the two versions (see Fig. 6). The results suggest that the version with additional marking was consistently rated as more informative and easier to understand, while it did not significantly influence participants' perception of intuition or distraction.

As shown in Fig. 7, the addition of the textual hint 'Evade!' alongside the visual symbol influenced several usability ratings. Statistically significant improvements were observed for (1) understanding ($t(126.5) = 2.102$, $p = 0.038$) and (3) intuition ($t(130.7) = 2.167$, $p = 0.032$), with lower mean scores indicating better perceived clarity in the condition with text. No significant difference was found for (2) informativeness ($t(161) = 1.081$, $p = 0.281$). For the criterion of (4) distraction, the condition with the text hint resulted in a significantly higher mean score ($M = 4.04 \pm 0.12$) compared to the condition without text ($M = 3.34 \pm 0.15$), $t(154.1) = -3.632$, $p < 0.001$, indicating that the additional hint was not perceived as more distracting by participants.

The HUD configuration identified as most effective in the online study (Fig. 2 (f)), featuring a static arrow, the hint 'Evade!', and a marked target lane, was subsequently implemented in the driving simulator to evaluate its impact on driver behaviour.

3.2. Evaluation of HUD design

Following the implementation, the two groups differed in their responses to three statements regarding driver behaviour observed during the driving simulation. Among those who received a warning ($N = 33$), 72.8 % agreed that they knew immediately how to react, compared to 42.8 % in the group without a warning ($N = 35$). An independent samples *t*-test ($\alpha \leq 0.05$) confirmed this result, showing a significant difference between the group with and without warning ($p = 0.005$). Regarding general well-being during the evasive manoeuvre, test subjects without prior warning reported feeling less comfortable (54.3 %) than those who received information (15.2 %), with a significant difference between the two groups ($p = 0.005$). For the statement, 'I was aware that cars are allowed to use the bus lane in an emergency', more than half of the participants in both groups fully agreed, with no significant difference observed ($p = 0.475$).

The results from the embedded prompt evaluation indicate that perceived distraction was minimal. A majority (57.4 %) disagreed with the statement that the HUD prompt interfered with their attention ($M =$

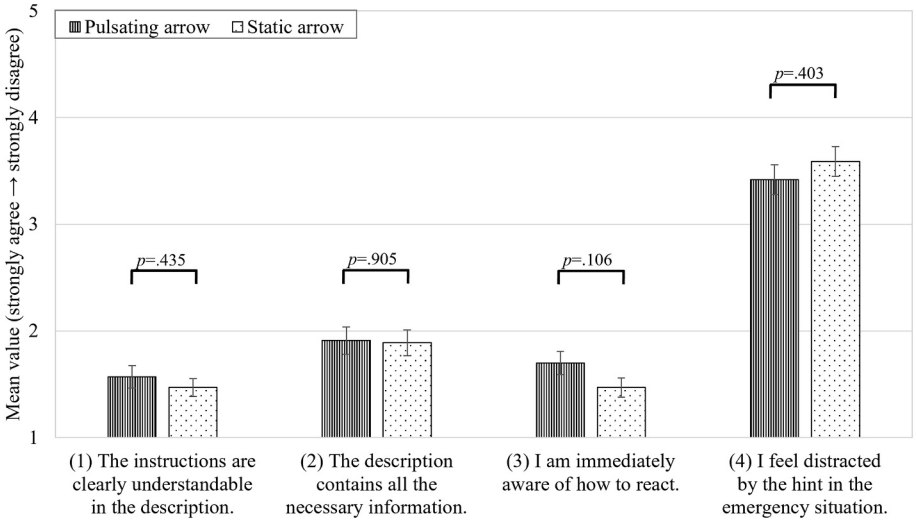


Fig. 5. Comparison of mean values (± SE) for responses to the different arrows.

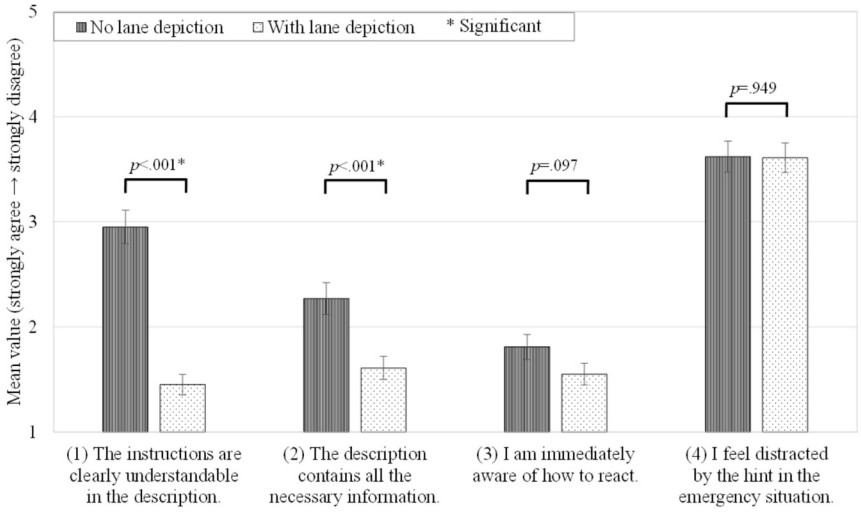


Fig. 6. Comparison of mean values (± SE) for responses to the lane depiction 'BUS'.

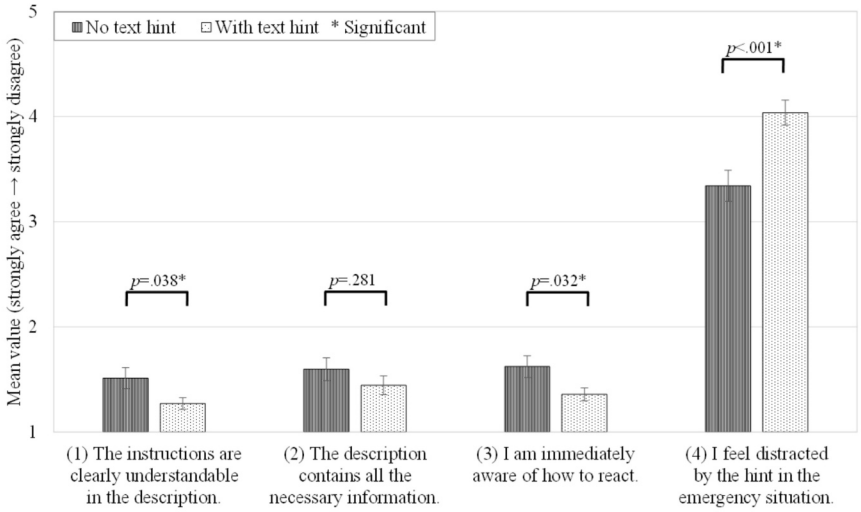


Fig. 7. Comparison of mean values (± SE) for responses to the text hint 'Evade'.

4.19, SD = 1.162). In contrast, the HUD significantly improved perceived reaction time (M = 2.35, SD = 1.207), with over 50 % agreeing that it facilitated a quicker response. Similarly, situational awareness was enhanced (M = 2.46, SD = 1.309), as 58.8 % found the warning beneficial for assessing emergency situations. Notably, acceptance of HUD-based warnings was high, with 70.6 % of participants supporting their integration into real-world driving (M = 2.06, SD = 1.232). Spearman-Correlation analysis revealed that perceived distraction negatively influenced acceptance ($r = -0.40$, $p = 0.001$), suggesting that higher distraction levels were associated with lower support for HUD integration. Conversely, perceived utility in terms of reaction time ($r = 0.56$, $p < 0.001$) and safety ($r = 0.69$, $p < 0.001$) strongly predicted acceptance, indicating that participants who found the HUD beneficial for improving response time and safety were more likely to support its use.

3.3. Reaction times and visual attention

To examine the extent to which reaction times can be influenced by a HUD, the analysis focused on a combination of driving simulator recordings and eye-tracking data. These data are particularly relevant for assessing the impact of additional information displayed in the HUD. Based on the simulator recordings, lane clearance times were determined, which reflect the number of seconds it takes for a car to leave the lane after the ambulance becomes visible in the rear-view mirror. Validation was conducted using the eye-tracking data. The Kaplan-Meier analysis results reveal that with the HUD warning (N = 25), lane clearance occurred 60–70 % faster (15 to 20 s) compared to the scenario without this information (N = 26) (see Fig. 8). The Log-Rank test confirms the statistical significance of the observed differences between the groups ($p < 0.001$), ensuring that these differences are not due to chance. The calculated Chi^2 value of 30.18 underscores the substantial disparity between the survival curves.

The heat maps (see Fig. 9) depict participants' visual attention distribution during the driving simulation, comparing scenarios with and without a warning. In the HUD warning condition (top image), gaze intensity is primarily concentrated on the navigation prompt to evade and also on the evasion area, with high-intensity (red) regions indicating frequent fixation. Additional, though lower-intensity, fixations can be observed on the rear view mirror and side mirrors, suggesting secondary

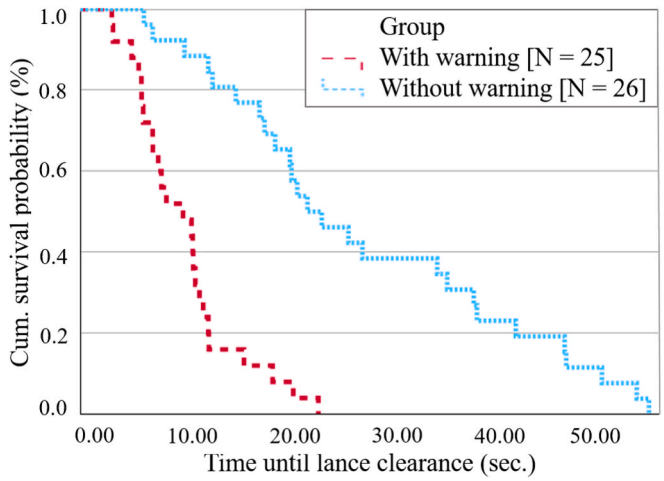


Fig. 8. Survival analysis of emergency car visibility in back mirror until lane clearance.

visual checks. In contrast, in the no-warning condition, participants' gaze was more dispersed across different elements of the driving scene. Areas of high intensity can also be seen in the area of the HUD or the vehicle in front, the traffic light as well as the rear-view mirror and the side mirror, suggesting that participants in the no warning condition were checking their surroundings rather than focussing on the HUD. The lower gaze intensity on the evasion area suggests that their attention was more distributed between monitoring other vehicles and assessing their environment, rather than pre-emptively looking at a designated escape path. The heat maps indicate different gaze allocation strategies between the two conditions, reflecting the participants' varying attention distributions in response to emergency vehicle approaches.

3.4. Perceived workload and psychological stress responses

The cognitive load of the participants was evaluated by using the NASA-TLX, providing valuable insights into their subjective experience during the evasion. Six distinct areas of workload were assessed through targeted questions, see Table 3. The distinction was made between mental, physical, time, performance, effort and frustration. The results are shown in Fig. 10.

The results indicate that perceived workload was significantly lower in all categories for participants who received a warning, while their performance was rated higher. A *t*-test revealed a significant difference in mental demand between the two groups ($t(66) = -2.745$, $p = 0.008$), with participants in the warning group reporting a lower mean score ($M = 7.3$, $SD = 5.084$) compared to those without a prompt ($M = 10.6$, $SD = 4.822$). Similarly, physical demand was significantly lower for participants with a prompt ($M = 4.27$, $SD = 3.685$) than for those without ($M = 7.83$, $SD = 5.843$), $t(66) = -3.019$, $p = 0.004$. For temporal demand, participants who received the warning reported significantly lower perceived time pressure ($M = 7.64$, $SD = 6.466$) compared to the no-prompt group ($M = 11.69$, $SD = 5.831$), with a *t*-test confirming a significant difference ($t(66) = -2.803$, $p = 0.007$). Similarly, effort was rated lower in the warning group ($M = 5.85$, $SD = 3.985$) than in the no-waning group ($M = 8.91$, $SD = 4.931$), with a significant difference ($t(66) = -2.809$, $p = 0.007$). Frustration levels were also significantly reduced for participants who received the prompt ($M = 7.09$, $SD = 5.468$) compared to those without ($M = 11.54$, $SD = 6.185$), as confirmed by the *t*-test ($t(66) = -3.137$, $p = 0.003$). A similarly positive result can be observed in terms of goal achievement. Although overall performance was assessed as moderate, a noticeable difference between the two groups was identified. Approximately 65 % of the test subjects who received the warning achieved significantly higher scores ($M = 12.55$, $SD = 5.831$) than those without ($M = 9.51$, $SD = 6.284$), with a *t*-test showing a significant effect ($t(66) = 2.058$, $p = 0.044$).

To gain a more detailed understanding of the participants' physiological responses, Fig. 11 illustrates mean heart rate deviations (HRD) over time for the two groups: with warning (red line) and without

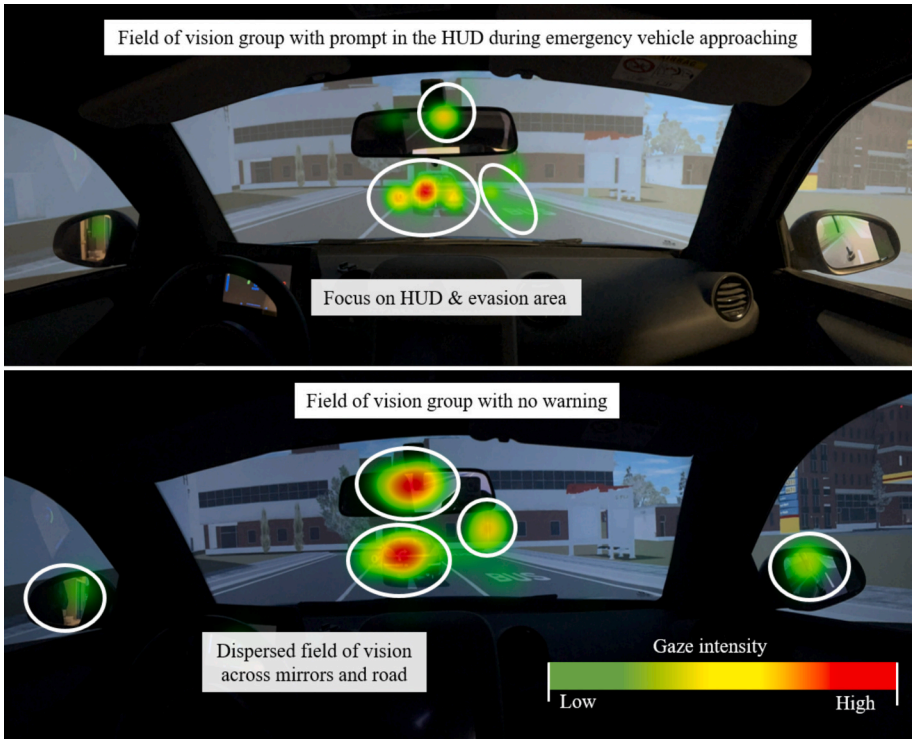


Fig. 9. Heatmap of visual attention during emergency vehicle approach. Comparison between the group with warning (top) and without warning (bottom).

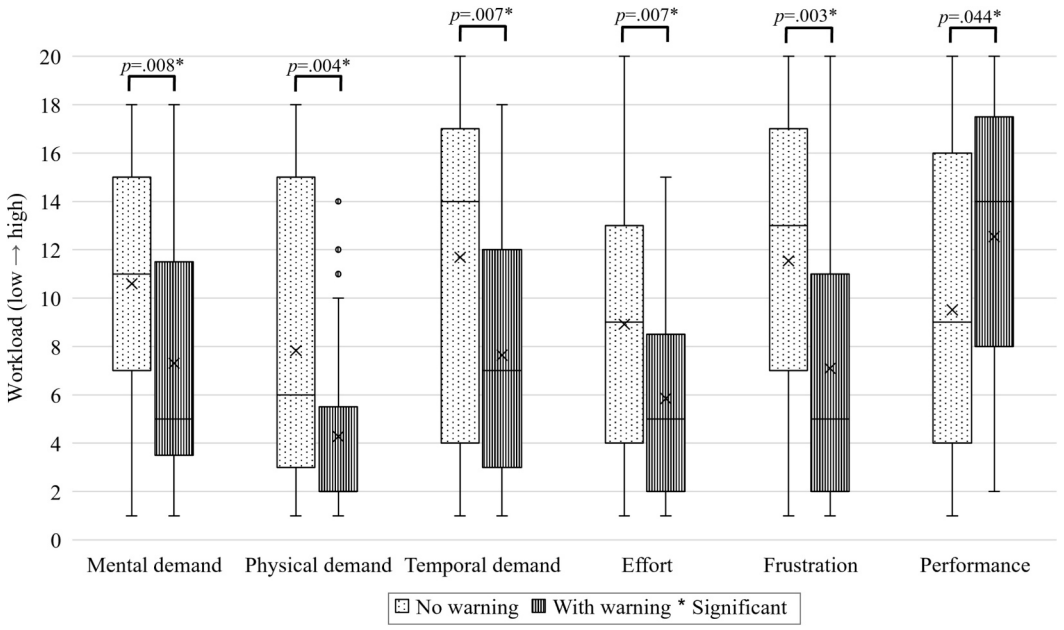


Fig. 10. NASA-TLX to record the workloads during the evasion task.

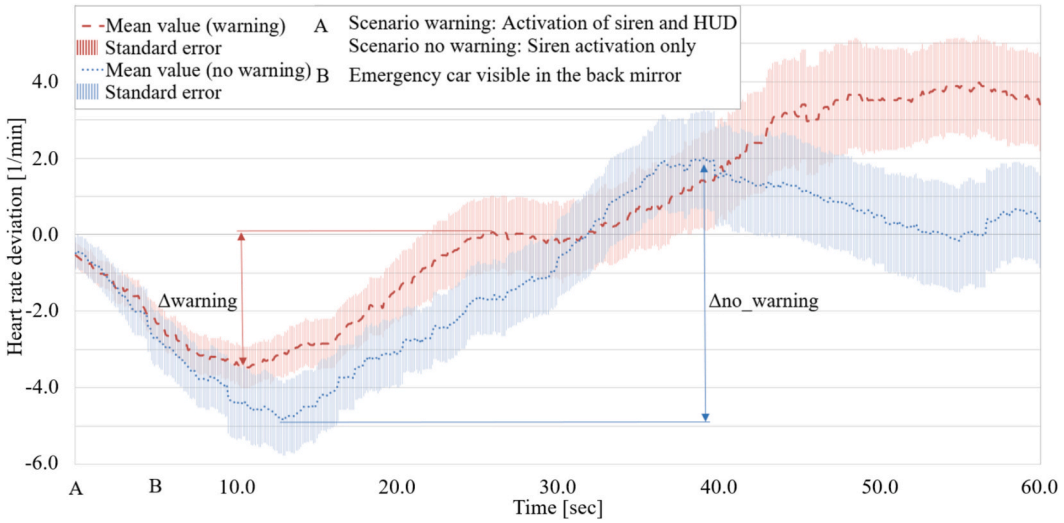


Fig. 11. Heart rate deviation over time for participants separated by scenario (M ± SE).

warning (blue line). Time zero marks the onset of the siren (Point A), and the emergency vehicle becomes visible in the rear-view mirror at five seconds (Point B). The baseline was defined as the average heart rate during the 10 s preceding the siren, and HRDs from this baseline were calculated for each second thereafter. Shaded areas indicate the standard error of the mean.

The heart rate trajectories show three distinct temporal patterns. In the initial phase (0–15 s), both groups exhibit a slight decrease in HRD, likely reflecting physiological response delays and sensor latency (Cavalcanti and Belardinelli, 1996; Y. Liu et al., 2025). No immediate cardiovascular response to the stimulus is measurable at this point.

In the transition phase (15–35 s), where the critical event unfolds, HRDs begin to rise. The warning group shows a more gradual and earlier increase, suggesting a faster physiological response triggered by the visual and auditory cues. In contrast, the no-warning group shows a sharper and more delayed rise, indicating a reactive pattern in the absence of anticipatory guidance.

During the final phase (35–60 s), the trajectories diverge. Heart rate deviation in the no-warning group begins to decline as the situation resolves, whereas the warning group maintains an elevated level. This sustained elevation may reflect cognitive processing of the novel visual instruction. However, the overall deviation remained lower in the warning group, suggesting that participants were able to respond earlier and with less physiological strain.

Quantitatively, the peak deviation was lower in the warning group ($\Delta = 3.46$ bpm) than in the no-warning group ($\Delta = 6.41$ bpm), indicating a more controlled physiological response when HUD support was available.

To quantify these patterns and test their significance, a Linear Mixed Effects Model (LME) was applied. Heart rate deviations were calculated relative to an individually defined baseline (t_0) and analysed across a 60-second window following the onset of the critical event.

In a first model, time was treated as a continuous variable within three behaviourally defined segments (0–15 s, 15–35 s, 35–60 s). Across all intervals, main effects of time were significant (all $p < 0.001$), indicating systematic changes in heart rate deviation over time.

Additionally, interaction effects between condition and time were significant in all three intervals ($p < 0.001$), suggesting different temporal patterns of physiological responses between groups.

To deepen the analysis, a second model with categorically coded time intervals was fitted. This model revealed significant main effects for the intervals 15–35 s ($\beta = 1.423$, $p < 0.001$) and 35–60 s ($\beta = 4.048$, $p < 0.001$), relative to the reference interval (0–15 s). Importantly, interaction effects between group and time interval were also significant: HRDs were significantly higher in the warning group during both 15–35 s ($\beta = 0.314$, $p = 0.005$) and 35–60 s ($\beta = 1.099$, $p < 0.001$), indicating heightened reactivity in the warning group. These findings are summarised in Table 4 and correspond closely with the patterns observed in Fig. 11.

4. Discussion

With the aim of identifying the most comprehensible and accepted configuration for a HUD to indicate evasive manoeuvres, and examining how different types of evasive areas are perceived by drivers, the online study formed the foundation of this investigation. Building on these findings, a driving simulator study was conducted to assess whether the preferred HUD design could improve driving performance and reduce stress in critical traffic situations. Combining both methods enabled a multi-layered analysis of subjective assessments and observable behaviour under controlled but dynamic conditions. The combined results indicate that HUD-based navigation prompts, when appropriately designed, can significantly enhance driving behaviour and decision-making in safety–critical scenarios.

The online study showed that both the visual design and the type of suggested evasive area significantly influence perceived comfort and intuitive decision-making. In particular, prompts directing drivers to evade onto a bicycle lane were perceived as less acceptable and less intuitive than those suggesting a bus lane or a restricted area. The heightened uncertainty observed in the bicycle lane scenario can be interpreted in light of previous research, which has demonstrated that drivers often have limited awareness of cyclists, particularly those approaching from the right (Jansen and Varotto, 2022; Sieker et al., 2015; Summala et al., 1996). This reduced visibility may lead to an increased risk of potential conflicts and likely contributes to the lower willingness of drivers to comply with HUD instructions directing them into bicycle lanes. The associated anticipated risk of collision not only diminishes drivers' subjective sense of safety but also negatively impacts their readiness to act intuitively. Thus, the type of suggested evasive zone significantly influences both acceptance and the perception of safety. These findings underscore that the effectiveness of HUD instructions depends not only on visual clarity but also on semantic plausibility and contextual appropriateness. HUD systems should therefore propose evasive zones that appear realistic and low-risk to drivers, especially in situations requiring rapid, intuitive decisions.

Table 4
LME Fixed Effects Summary.

Effect	Interpretation	β	p-value	95 % CI lower	95 % CI upper
Intercept	Baseline HR deviation (0–15 s, no-warning)	−3.167	< 0.001	−4.61	−1.723
Group	Group difference (0–15 s)	0.691	0.507	−1.35	2.733
Time interval [15–35 s]	HR change (15–35 s vs. 0–15 s, no-warning)	1.423	< 0.001	1.268	1.578
Time interval [35–60 s]	HR change (35–60 s vs. 0–15 s, no-warning)	4.048	< 0.001	3.898	4.198
Group × Time interval [15–35 s]	Additional effect (15–35 s, warning vs. no-warning)	0.314	0.005	0.094	0.535
Group × Time interval [35–60 s]	Additional effect (35–60 s, warning vs. no-warning)	1.099	< 0.001	0.88	1.318

Beyond subjective responses, a comparable pattern of hesitant behaviour was also observed in the driving simulator study, where significant differences in reaction times were recorded. Participants who received HUD warnings cleared the lane up to 70 % faster, potentially contributing to a noticeable shortening of the emergency response chain. As highlighted in the introduction, the rapid and coordinated implementation of measures plays a crucial role in the efficiency of emergency care, as survival rates decrease by 7–10 % for every minute without medical intervention (Dorian et al., 2020) and time savings could be relevant, especially over longer distances (Brown et al., 2000; O'Keeffe et al., 2011). A central explanation for these differences lies in the uncertainty faced by drivers without visual support. Especially in densely built urban environments, it is difficult to localise the source of a siren due to sound reflections and ambient traffic noise (Caelli and Porter, 1980; Marchegiani and Newman, 2022). Many drivers, particularly younger ones, are initially unsure whether and how they are affected by the approaching emergency vehicle. This uncertainty often results in passive behaviour, with reactions occurring only after visual confirmation in the rear-view mirror. Supporting the present findings, Lidestam et al. (2020) also demonstrated that in-car warnings significantly increase the likelihood of timely evasive manoeuvres. These results reinforce the potential of HUD warnings to promote anticipatory behaviour and reduce delays in emergency scenarios.

Regarding the visual design of the HUD prompt, the static arrow received consistently higher ratings in terms of intuitiveness and clarity compared to the pulsating variant. This observation aligns with previous studies indicating that simple, static representations facilitate cognitive processing, promote faster understanding, and support smoother task execution (K. Park and Im, 2020). The green colour alone was perceived as sufficiently salient to attract attention. In contrast, the added motion of the pulsating arrow was viewed as excessive and potentially distracting from other critical elements. These findings are consistent with Currano et al. (2021), who demonstrated that visual complexity can negatively affect the distribution of attention. Overall, the results emphasise the importance of simple and clearly structured HUD elements to support user perception and effective information processing. The addition of the text hint 'Evade!' led to significant improvements in both comprehension and intuitiveness. This suggests that combining symbolic and verbal information facilitates user understanding (Schwambach et al., 2023). Notably, the inclusion of textual cues did not increase perceived distraction, supporting their integration in HUDs. Concerning distraction, the HUD elements were generally not perceived as disruptive. This finding aligns with previous studies (Kim and Gabbard, 2019; Normark et al., 2009), which have shown that information presented within the driver's line of sight does not impair driving attention. On the contrary, such systems support hazard recognition, even among younger drivers (Hajiseyedjavadi et al., 2018).

The eye-tracking analysis showed that the HUD warning effectively guided drivers' attention toward critical areas, particularly the indicated evasive lane, the rear-view mirror, and the central HUD element itself. At the same time, drivers maintained sufficient peripheral awareness, avoiding tunnel vision. This balanced attention allocation represents a core objective of well-designed HUD systems and supports effective situational awareness (Winkler et al., 2015). Increased fixations on the target lane and reduced use of side mirrors further highlight the HUD's role as a central and relieving source of information that reduces cognitive load and facilitates fast decisions in stressful conditions (Horrey et al., 2003). As the HUD is positioned directly in the driver's field of view, no visual diversion from the road is required. Rather than acting as a distraction, the display supports focus on safety-relevant areas while enabling less critical elements, such as traffic lights, to be

deprioritised as needed in the situation.

The differences in perceived workload can largely be attributed to the clarity and anticipatory support provided by the HUD prompt. Participants who received the prompt were better able to anticipate the task and prepare their response, which reduced uncertainty and the cognitive effort required to process unexpected scenarios (Y.-C. Liu and Wen, 2004; Smith et al., 2015). These performance differences are primarily linked to the clear action recommendation and the time advantage provided by the warning, which fostered a calmer and more confident driver response. In contrast, participants without HUD support felt overwhelmed and dissatisfied, as they struggled to complete the task under stress. Concerns raised in the literature that HUDs may interfere with driving performance or cause excessive cognitive load (Gish et al., 1999; Smith et al., 2020) are not supported by the present findings.

Although the heart rate response curves of the two groups followed a similar general trend, a noticeably smaller deviation was observed in the HUD group immediately after the ambulance appeared. In contrast, the control group without HUD showed a delayed and more prolonged increase in heart rate, indicating greater deviation from baseline, likely due to uncertainty about the appropriate response and increased stress levels. Notably, the significant interaction effects suggest that the presence of a warning altered the temporal trajectory of heart rate deviations across intervals. The increased deviation in the HUD group during the 15–35 s phase may reflect an anticipatory or stress-related reaction that occurs after initial exposure but before physiological habituation. Despite this short-term spike, the early visual prompt enabled more efficient stress management overall, as reflected in the subjective stress ratings (Fig. 10). These findings align with Y.-C. Liu and Wen (2004), who found that HUD warnings can effectively mitigate perceived stress.

The present samples consisted predominantly of younger individuals. While this should be taken into account when interpreting the findings, it does not represent a substantial limitation for the evaluation of HUD systems, as this age group is likely to constitute a large proportion of future users. Nevertheless, to assess the generalisability of the results to real-world traffic environments, follow-up studies should include more age-diverse samples and be conducted under natural driving conditions.

In conclusion, HUD-based warning signals that are visually simple, contextually plausible, and reinforced with textual prompts can enhance situational awareness, reduce cognitive workload, and improve driver behaviour in critical traffic scenarios. However, environmental conditions continue to influence driver response. The integration of survey and simulator-based findings demonstrates the practical value of combining these methodological approaches and supports a more comprehensive assessment for the development of effective in-vehicle assistance systems.

5. Conclusions

In line with the findings from the online survey, the driving simulator study clearly confirmed the effectiveness of HUD-based warning prompts in improving driver behaviour during critical traffic situations. Participants responded more quickly, demonstrated greater situational awareness, and reported lower cognitive workload. The two-stage approach adopted in this study proved effective both for developing a suitable HUD design and for the application-oriented investigation of the potential of such warnings to support driving performance in critical scenarios. The results of the online survey showed that participants perceived evasive manoeuvres into bus lanes as significantly more acceptable and intuitive than into cycle lanes or restricted areas. These findings informed the choice of scenario in the simulator study. In addition, the combination of a static arrow, the text hint ‘Evade!’, and a clearly marked target lane received the highest usability ratings in terms of comprehension and intuitiveness. This configuration was therefore selected for implementation in the simulation, enabling a differentiated evaluation of HUD warning effectiveness under controlled conditions, during which real-time decision-making, reaction times, perceived workload, gaze behaviour, and heart rate data were systematically recorded. The integration of both study phases provides a comprehensive assessment of the potential of personalised HUD messages to enhance driving performance and traffic safety. The key findings include:

- A well-designed HUD combines clear symbols, textual prompts, and explicit lane markings to enhance comprehension, reduce cognitive load, and support fast, intuitive decisions in emergencies.
- HUD-based navigation warnings improved driving performance and safety by enhancing drivers’ situational awareness and significantly reducing reaction times in simulated emergency scenarios.
- Drivers who received additional HUD warnings experienced reduced cognitive load, which allowed for quicker, more accurate decision-making and subjectively less stressful responses under time pressure.
- Eye-tracking analysis demonstrated that HUD prompts effectively guided drivers’ visual attention towards critical areas such as the target lane and rear-view mirror, supporting efficient information processing without causing distraction.
- Physiological data, particularly heart rate monitoring, indicated no significant increase in stress levels, suggesting that HUD warnings do not contribute to additional mental overload, at least within the scope of the scenarios investigated.
- The two-stage methodological design, combining an online survey with a controlled driving simulation, proved effective for developing and validating context-sensitive HUD warning messages tailored to critical traffic scenarios.

The present findings highlight the potential of context-sensitive HUD warnings to make a meaningful contribution to improving road safety. In particular, such systems can enhance decision-making and facilitate coordination with emergency vehicles in urban environments characterised by high complexity and limited reaction time. Integrating these warnings into modern vehicle interfaces not only increases response speed in critical situations but also improves the usability of in-vehicle assistance systems. As such, HUD-based prompts represent a promising step towards safer, more intuitive, and more efficient human–machine interaction in road traffic.

Despite the promising results, several limitations of this study should be acknowledged. The simulated driving environment can only partially reflect the complexity and unpredictability of real-world traffic, where factors such as spontaneous driver behaviour, environmental variability, and real-time distractions are difficult to replicate. The limited sample size and demographic composition may also restrict the generalisability of the findings, as differences in driving experience and familiarity with digital systems could have influenced performance. Furthermore, heart rate measurements via optical sensors on the forearm provide only limited accuracy and do not meet clinical standards. Additional biometric indicators, such as pupil dilation, could offer a more differentiated understanding of cognitive load.

While the controlled simulator setting enabled focused and consistent observations, future studies should be conducted under real traffic conditions to validate the practical relevance and effectiveness of HUD-based navigation prompts in dynamic environments. Particularly promising is the in-depth investigation of augmented reality HUD implementations and user comprehension, as well as their targeted integration with other driver assistance systems to support a comprehensive and context-sensitive driving experience.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used chatgpt in order to improve the readability and language of the manuscript. After using this tool/service, the author(s) reviewed and edited the content as

needed and take(s) full responsibility for the content of the published article.

CRediT authorship contribution statement

Maximilian David: Writing – review & editing, Writing – original draft, Visualization, Validation, Formal analysis, Data curation, Conceptualization. **Dirk Kemper:** Resources, Project administration, Funding acquisition. **Martin Baumann:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Alvaro Garcia-Hernandez:** Writing – review & editing, Supervision, Resources, Methodology, Conceptualization.

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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Data availability

Data will be made available on request.

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