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"It's just another car driving" – Perceptions of U.S. residents interacting with driverless automated vehicles on public roads

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ABSTRACT

Driverless, SAE Level 4 automated vehicles (AVs)—vehicles operating without on-board human operators—have become operational in some cities in the U.S. The driving style and behaviors of AVs can induce changes in the behavior of road users interacting with AVs in traffic. Prior research has not collected data from road users residing in areas in which AVs are deployed and who have solid experience with AVs by regular interactions with them. As a result, a comprehensive and rich analysis of road users' responses to AVs in traffic based on solid experience and the underlying reasons is missing. The two main research questions of this study are: 1) How *do* road users respond to AVs in traffic? and 2) Which factors affect road users' responses to AVs in traffic? Semi-structured interviews were conducted with individuals residing in U.S. cities in which driverless AVs are deployed to explore *how* and *why* road users respond to driverless AVs in traffic. Content analysis was applied to manually identify themes in the data, complemented by using large language models. We also computed Spearman rank-order correlations to determine significant associations between the sub-themes. The most common road user behaviors were being more cautious around AVs, letting the AV pass and waving and gawking at them. Road users took advantage of the capabilities of AVs, cutting them off, slowing them down, or recklessly crossing the road in front. The AV safety operators typically monitored the operation of the AV, contributing to the perception that AVs are safe and predictable. Other participants reported incidences of inattentive drivers / human operators of Tesla's SAE Level 2 partially automated driving system, being observed sleeping in the AV and rear-ending one of our participants. The most common external communication cue between road users and human drivers was eye contact, in some cases also when there was no operator present. Media reports / personal stories involving fatal accidents with AVs, particularly those linked to Tesla's partially automated driving system, were linked to concerns about AV safety. Our study reveals significant associations between the behavior of AVs (e.g., AV being stuck) and road users' changes in behavior, cognition (e.g., trust, distrust) and affect (e.g., perceived safety, frustration or anger). More trials with AVs on public roads can promote the interest and curiosity of road users, and their acceptance and use of AVs. The need for eHMIs and their effectiveness in promoting safer, more efficient, and comfortable interactions needs to be further investigated.

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1. Introduction

The introduction of automated vehicles (AVs) is expected to accelerate the shift towards sustainable and smart mobility, contributing to safer, more efficient, comfortable, and equitable transport (Mirzahossein & Mashhadloo, 2024). Driverless SAE Level 4 AVs—vehicles operating without on-board human operators—have become operational in the U.S., perhaps more quickly than many experts in the AV domain anticipated.

Research indicates that AVs tend to adopt a more conservative driving style compared to human-controlled vehicles and demonstrate higher compliance with traffic rules (Paschalidis & Chen, 2022). Other studies have shown that AVs behave in unpredictable and erratic ways, which can lead to the confusion and frustration of other road users and possibly unsafe situations (Nordhoff, 2024). The driving style and behaviors of AVs can induce changes in road users interacting with AVs in traffic. This is referred to as behavioral adaptation, which represents the behaviors that may occur following the introduction of changes to the road-vehicle-user system that were not intended by the initiators of the change (OECD, 1990). Prior research that has examined the interactions between AVs and other road users, with a focus on pedestrians, have considerably enhanced our understanding of how road users interact and communicate with AVs in traffic. For instance, it has been shown that pedestrians accepted shorter gap distances when crossing the road in front of AVs, while others waited longer until they came to a stop (Eisele et al., 2024; Holländer et al., 2019; Hulse, 2023). Cyclists and human car drivers were also more likely to be aggressive in automated traffic (Alozi and Hussein, 2024; Jiang et al., 2024; Ma & Zhang, 2024; Rahmani et al., 2024). A specific form of aggressive behavior is taking advantage of, sabotaging or bullying AVs (Harkin et al., 2024; Nordhoff, 2024; Paschalidis & Chen, 2022). Other participants anticipated little change in their behavior except for being more cautious around AVs (Harkin et al., 2024), supporting research that has shown that the presence of AVs had no effect on the behavior of road users (Holländer et al., 2019). Interacting with AVs in traffic can also induce changes in road users' affect. Thus, the conservative driving style of AVs caused road users to be frustrated or annoyed (Nuñez Velasco et al., 2019). Other drivers felt more anxious, uncomfortable, and unsafe compared to their interaction with human drivers (Ma & Zhang, 2024).

Studies have also explored the reasons underlying changes in road users' behavior in automated traffic. Road user-related characteristics identified by prior studies are trust, the perception of the advantages and disadvantages of AVs and the information individuals receive about AVs from the media, marketing or advertising. A lack of trust in the AV contributed to pedestrians' and cyclists' hesitant and cautious behavior around AVs (Holländer et al., 2019; Nuñez Velasco et al., 2019). Having more trust in AVs than in human-driven vehicles motivated the decision to cross the road earlier (Zhao et al., 2024). Moreover, receiving information about AVs from social and traditional media reduced individual's trust in AVs (Zhou et al., 2023). In Harkin et al. (2024) different vulnerable road user groups considered the interaction with AVs advantageous given the rule compliance, information, and attention behavior of AVs. Maintaining a minimum distance was mentioned as advantage particularly by cyclists. Participants also mentioned disadvantages, such as the lack of communication, detection failures, and road users' limited experience with AVs.

Vehicle-related characteristics include the identification or detectability of vehicles as AVs and external Human Machine Interfaces (eHMIs). In Reddy et al. (2022), the AV recognizability did not affect drivers' gap distance to the AV irrespective of the AV's driving style. The clear identification or detectability of vehicles as AVs was considered critical, but insufficient for visually impaired people (Harkin et al., 2024). eHMIs are external communication devices located on the surface of AVs to communicate information about its status and behavior to surrounding road users (Bengler, Rettenmaier, Fritz, & Feierle, 2020). They are considered useful as they are expected to improve traffic safety and support other road users, particularly vulnerable ones, in their interactions with AVs, addressing the "social interaction void" created by the physical or mental absence of human operators in AVs (Aleva et al., 2024; De Winter & Dodou, 2022; Lau et al., 2024; Rasouli & Tsotsos, 2020). eHMIs were recently commercialized by some automakers who applied them to their latest models (Lou & Lou, 2024). Auditory eHMIs communicate via vehicle sound or noises. Visual eHMIs can communicate via light patterns or strips, icons / symbols and / or text, or via laser projections displaying messages on the road (Bengler et al., 2020). Visual eHMIs can display information about the vehicle's status, driving mode, perception of road users in the environment, next or intended vehicle actions, and cooperative capabilities (Bengler et al., 2020; Schieben et al., 2019; Wilbrink et al., 2023). Other forms of eHMIs are wearables or on-bike devices located on VRUs, which can establish connectivity with road users, supporting interactions in traffic (Berge, de Winter, & Hagenzieker, 2023; Harkin et al., 2024). It has been shown that auditory eHMIs have beneficial effects in traffic, such as helping vulnerable road users to identify the presence of the AV by sound (Parnell et al., 2024). Other participants preferred visual eHMIs (front brake lights) as they anticipated that this would help them identify the intention of the AV to slow down (Harkin et al., 2024). However, eHMIs can also lead to unintended behavioral effects. For example, pedestrians were observed crossing the road earlier when an eHMI was present on the AV, as it increased their trust and made them feel more comfortable and confident about crossing (Kaleefathullah et al., 2020; Zhao et al., 2024). In other studies, the eHMI had no effect on pedestrians' crossing decisions and behaviors (Carlowitz et al., 2023; Lau et al., 2024; Lee & Daimon, 2024; Wilbrink et al., 2021; Dey & Terken, 2017; Lee et al., 2021a.b).

While useful, prior research has focused on simple one-to-one interactions between pedestrians and AVs in controlled simulator, virtual or augmented reality environments (Aleva et al., 2024; Dey et al., 2020; Subramanian et al., 2024; Kaleefathullah et al., 2020; Lee et al., 2022; Wintersberger, Dey, & Löcken, 2023). There are also studies that examined the interactions between AVs and pedestrians or cyclists by conducting outdoor experiments, but in these cases the interaction was designed and the AV was not a real AV, but an experimental, Wizard-of-Oz vehicle (Peng et al., 2023). Other studies asked participants to imagine their interaction with AVs based on stimulus material (e.g., photo, video, power point presentation) (Hagenzieker et al., 2020; Harkin et al., 2024; Joisten, Niessen, & Abendroth, 2021; Parnell, Merriman, & Plant, 2024). Presenting participants with a hypothetical scenario rather than a real-life situation may lead to biased estimates because participants may make wrong assumptions about their beliefs and attitudes, a phenomenon known as hypothetical bias (Ajzen, Thomas & Franklin, 2004). To the best of the authors' knowledge, none of the prior studies collected data from road users residing in areas in which AVs are deployed and who have solid experience with AVs by regular interactions with them. As a result, a comprehensive and rich analysis of road users' responses to AVs in traffic based on solid experience and the underlying reasons is missing.

1.1. *The present study*

Unlike prior studies which asked participants hypothetical questions like 'How long *would* it take you to feel comfortable using/interacting with an AV?', 'How do you think private or shared AVs *could* improve or worsen your experience as a car driver/pedestrian in the transport system?' (Martínez-Buelvas et al., 2024), 'How *would* you behave in such a situation?' or '*Would* you cross the road?' (Harkin et al., 2024), our study provides novel and unique answers to the following two main research questions:

i) How *do* road users respond to AVs in traffic?
ii) Which factors affect road users' responses to AVs in traffic?

We expect that the knowledge generated by the present study helps policy makers and road authorities to better understand how AVs can influence traffic flow efficiency and safety, which can lead to the design of measures mitigating possible negative effects (Reddy, Hoogendoorn, & Farah, 2022). Moreover, understanding the concerns that road users associate with the introduction of AVs can prevent alienating the public (Nair & Bhat, 2021), promoting user acceptance and the acceleration of the safe development of AV technology (Rahman, Dey, Das, & Sherfinski, 2021). Finally, since only a limited number of eHMIs have been commercialized to date, our study offers valuable insights to guide the design of future eHMIs. By gathering perspectives from individuals with regular interactions with AVs, we provide critical information on the relevance and potential impact of eHMIs in traffic scenarios involving AVs.

2. Method

2.1. *Procedure*

We conducted 52 semi-structured interviews with vulnerable and motorized road users who interacted with driverless SAE Level 4 AVs on public roads in the U.S., where these vehicles were tested and deployed for commercial use. The number of interviews was guided by theoretical saturation—the point in qualitative research when data collection stops because no new insights are emerging (Vasileiou et al., 2018).

The study was approved by the Human Research Ethics Council of Delft University of Technology (ID: 2309). Seven out of 52 participants were recruited through the Reddit forum r/SelfDrivingCars, and two more were recruited through the social networks of those Reddit participants. The remaining participants were identified via the recruitment agency User Interviews Inc, which was asked to identify participants residing in the areas in which AVs were deployed.

To ensure data quality, User Interviews Inc. implemented these measures:

- Participants must verify their accounts, provide a LinkedIn URL for researchers to review, and list at least one social media account for extra verification;
- Each account is limited to one email address;
- Participants receive reminders about upcoming sessions and the cancellation policy. Missing a session flags their account, making future participation more difficult;
- Inconsistent responses to screener questions result in exclusion from future studies;
- Negative reviews by researchers can remove participants from the pool;
- An automated system detects and removes participants with fraudulent behavior (Lizzy, 2024).

Participants were informed the interview would take about 45 min. To ensure the sample included only those with regular interactions with driverless AVs, participants answered screener questions about their interaction frequency. Participants who indicated to never interact with AVs as a pedestrian, cyclist, motorcyclist or car driver were not invited to participate in the interview. Participants received financial compensation, redeemable as a gift card, ranging from $25 to $80 depending on their location.

2.2. *Instrument*

A questionnaire was developed comprising both open-ended and closed-ended questions.

At the beginning of the interview, participants provided informed consent to participate in the study. They were then asked to identify the type of road users they typically were (e.g., AV passenger, pedestrian, cyclist, car driver) and instructed to answer the subsequent questions based on these specific roles. The initial questions focused on participants' interactions with driverless AVs, including their appearance, features, and brand, as well as how they identified an AV as distinct from a conventional human-controlled car. Participants were asked whether the AVs had a steering wheel or a human driver and to describe a typical interaction with them. They also detailed how their communication and interaction with AVs compared to human-driven cars, the factors influencing these interactions, and how the AVs communicated with them. Further questions explored the role of eHMIs in communication, the importance of eye contact and hand gestures, scenarios where participants relied on or would rely on eHMIs, and their overall usefulness in traffic. Participants were also invited to describe any interactions where they felt unsafe.

Follow-up questions were asked on the spot to examine topics and dimensions that were brought up by participants and that were not covered by the interview protocol (e.g., "You mentioned previously or pointed out") or to ask participants to rephrase or clarify their responses (e.g., "Is it correct that…?") (see Roberts, 2020).

The interview questions were developed in such a way that they address the research questions and that were aligned with the research goal of the study. Moreover, they reflected the researchers' expertise and prior knowledge about the study topic (Roberts, 2020). They were developed in several iteration rounds between the authors of this study. The wording of the interview questions followed specific interview guidelines (see Roberts, 2020) to reduce the likelihood of unbiased responses and contribute to the generation of new knowledge. The questions were designed to be easy to understand, broad, and open-ended, enabling participants to freely share their perspectives. They were free of assumptions, allowed for nuanced responses, and focused on the topics of interest. Participants were encouraged to identify the topics they considered important and reflect on their personal experiences without interpreting the experiences of others. Additionally, we avoided questions that were lengthy, vague, or leading (Roberts, 2020). The full questionnaire is included in Table A1 in the appendix.

The interviews were conducted online via Zoom and transcribed using Microsoft's Teams transcription software. To minimize subjectivity in the research process and ensure consistency across all interviews, we developed a standardized interview protocol in Qualtrics. At the start of each interview, participants received a link to the questionnaire via Zoom's chat function. They were then instructed to either read the questions aloud or, if they preferred, review them silently. This method was specifically designed to minimize subjectivity in the interviewer-interviewee interaction, particularly the influence of the interviewer's tone or question phrasing, as certain words carry weight and can shape how participants interpret the question (Harrell & Bradley, 2009). Allowing participants to view the questions directly aimed to reduce the risk of embarrassment or frustration that might arise from misinterpreting or not understanding the questions (Harrell & Bradley, 2009).

Participants could view the questions directly on their screens and navigate through the questionnaire independently, such as skipping or advancing to the next question. The interviewer primarily focused on listening, allowing participants to share their stories freely. Additionally, if participants appeared to need help understanding a question, the interviewer provided support. Researcher intervention was kept minimal since the questions were standardized and designed to build upon one another. The same procedure was adopted in Nordhoff (2024).

2.3. Data analysis

The interview transcripts were analyzed in several steps.

In the first step, we conducted a content analysis to manually identify themes within the dataset. These themes represented the general topics participants discussed in response to the interview questions. Themes were identified by searching the text for keywords and patterns. The process involved examining repetitions, similarities, and differences in key words and phrases. Both main themes and sub-themes were derived from the dataset, with the sub-themes offering more nuanced insights into the main themes. Each sub-theme was carefully defined to ensure it could be effectively measured in future studies (Glaser, Strauss, & Strutzel, 1968). This part of the analysis was conducted in Atlas.ti (Version 22.0.2).

The development of the sub-themes followed an iterative and emergent process, with researchers refining them at various stages of the analysis and aligning them with insights from the literature (e.g., European et al., 2021; Torfs & Meesmann, 2019).

Second, we used the large language model (LLM) GPT-3.5 of ChatGPT as second coder as in Nordhoff (2024). We used ChatGPT because its performance in analzing qualitative data was comparable to the performance of human coders and it was considered useful for generating descriptive responses (Chew et al., 2023; Morgan et al., 2023). This aligns with the development of our coding scheme that provides a descriptive representation of the interview data. To support the development of themes, GPT-3.5 was provided with the raw interview transcripts without any personally identifiable information. The following prompt was used: *"We conducted interviews with road users interacting with driverless automated vehicles on public roads in selected U.S. cities. The comments below are from these participants. Based on the comments, what common themes do you observe in the data? Provide a summary of the themes along with labels and definitions."* The results generated by GPT-3.5 were compared to our own coding scheme, leading to the integration of critical aspects identified by GPT-3.5 that we had not initially recognized, enhancing the richness and comprehensiveness of the coding scheme. In line with practical guidelines for conducting qualitative research (McDonald et al., 2019), we did not calculate interrater reliability agreement as we did not use an existing codebook nor did we want to provide an interpretative but descriptive representation of the data. Instead, we ensured reliability by continuous meetings between the authors of this study to discuss and refine the codes and identify and resolve disagreements until consensus was reached, a practice that is commonly applied in the context of conducting qualitative research (see McDonald et al., 2019).

Third, to ensure each sub-theme was adequately represented, we selected up to three illustrative concise, representative, and sufficiently aligned quotes (Lingard, 2019). Three quotes were selected because we wanted to provide a detailed and rich representation of the data and ensure that the stories of participants are adequately reflected. The quotes may reflect multiple references to a sub-theme made by the same participant at different stages of the interview. We adjusted quotes whenever necessary, correcting typos or punctuation errors, and reducing the length, to better document the meaning of each sub-theme. We did not change any quotes beyond these small edits.

Fourth, the frequency of each sub-theme was counted. Each mention of a sub-theme by a participant was assigned a frequency of 1, with multiple mentions by the same participant counted as a single occurrence. Sub-themes mentioned by fewer than five participants were grouped under the category ‘Other’ within each main theme.

Finally, we calculated Spearman rank-order correlations between the sub-themes to identify significant associations. To represent the sub-themes, we created dummy variables with a value of 1 if the sub-theme was present, and 0 if it was absent. A detailed correlation matrix is provided in Table A2 in the appendix. This part of the analysis was carried out using R.

2.4. Participants

Information about participants’ socio-demographic profile and travel behavior is provided in Table 1.

3. Results

The results of the content analysis revealed road user-, vehicle-, and road environment-related themes, as shown in Table 2. Within each main theme, the sub-themes are listed in descending order of frequency, from most to least common. Additionally, we identified several miscellaneous themes that could not be categorized under the road user-, vehicle-, or road environment-related themes.

We also analyzed the number of participants who believed that the AV had a steering wheel and whether they thought there was a driver inside the vehicle, as shown in Figs. 1a and 1b. Approximately 8 out of 10 participants believed the AV had a steering wheel, as depicted in Fig. 1a, while more than half indicated that there was no driver behind the steering wheel of the AV.

Table 1
Information about participants’ socio-demographic profile and travel behavior.

Variable	Response categories (relative and absolute frequencies)							*n*
Gender	Male 53 % (27)	Female 45 % (21)	Other 2 % (1)					49
Year of birth	2000–2005 19 % (8)	1990–1994 23 % (10)	1984–1989 14 % (6)	1970–1978 19 % (8)	1960–1969 12 % (5)	1952–1959 9 % (4)	1943–1946 5 % (2)	43
Education level	None of those 9 % (4)	Trade / technical / vocational training 9 % (4)	University degree 82 % (37)					45
Number of adults in household	0 36 % (16)	1 44 % (20)	2 2 % (9)	≥ 3 or more				45
Number of children under 18 years	0 78 % (35)	1 9 % (4)	2 9 % (4)	≥ 3 or more 4 % (2)				45
Type of residence location	Urban environment (i.e., urban city / town center with dense housing) 70 % (32)		Suburban area (surrounding a city or town center) 30 % (14)					46
Availability of car for your use	No or hardly ever 16 % (7)	Yes, sometime 11 % (5)	Yes, nearly always 73 % (33)					45
Number of years of driving experience	Less than one year 2 % (1)	1–2 years 4 % (2)	2–10 years 11 % (5)	More than 10 years 78 % (35)	I don’t have a driver’s license 4 % (2)			45
Annual mileage in the last 12 months (in km)	Less than 2,000 26 % (11)	2,000–4,999 19 % (8)	5,000–9,999 23 % (10)	10,000–14,999 14 % (6)	15,000–19,999 7 % (3)	20,000–50,000 12 % (5)		43
Frequency of interaction with AVs								
	Never	Less than once a month	Less than once a week but at least once a month	At least once a week but not every day	Every day			
As pedestrian	0 % (1)	9 % (3)	18 % (6)	41 % (14)	35 % (12)			34
As cyclist	32 % (10)	10 % (3)	13 % (4)	42 % (13)	3 % (1)			31
Motorcyclist	93 % (25)	4 % (1)	0 %	4 % (1)	0 %			27
Car driver	3 % (1)	9 % (3)	9 % (3)	50 % (17)	29 % (10)			34
Frequency of travel mode use								
	Less often or never	At least monthly	1–2 days / week	3–4 days / week	(Nearly) Every day			
Car	15 % (8)	5 % (3)	16 % (9)	11 % (6)	33 % (18)			55
Public transport	17 % (8)	30 % (14)	26 % (12)	20 % (9)	7 % (3)			46
Active travel modes (i.e., walking (more than 0.50 km per trip), cycling)	7 % (3)	5 % (2)	18 % (8)	27 % (12)	43 % (19)			44

Note: The differences in “*n*” can be attributed to two factors: (a) participants providing inaccurate or outdated information on their User Interviews Inc. profile, or (b) participants being unwilling to share personal information during the interview.

Table 2
Results of content analysis (i.e., # = number of main theme, main theme, sub-theme, description, *n* = number of participants mentioning sub-theme).

#	Main theme	Sub-theme 1	Sub-theme 2	Description	*n*
Research question 1: How do road users respond to AVs in traffic?					
1	Behavioral responses	Being more cautious		Being more cautious, hesitant, and defensive around AV	19
		Letting AV pass		Waiting, and letting AV pass before moving	17
		Monitoring / checking AV		Waving and gawking at AV, which draw the attention of road users and bystanders, who often stopped to watch them pass, taking pictures and/or recording videos	16
				Attentive AV operator observed monitoring the vehicle's operation while also engaging in non-driving activities, such as taking notes, conversing with passengers, or working on a laptop	12
				Non-attentive human operator of Tesla's partially automated driving system observed misusing the technology, such as placing weights on the steering wheel, working, or sleeping	8
		Increasing distance to AV		Decelerating to increase the longitudinal or lateral distance to AV	15
		Resisting AV		Expressing opposing views (e.g., criticizing on social media), avoiding interaction with AV (e.g., changing travel direction), and protesting or attacking AV	14
		Overtaking AV		Increasing speed to overtake AV from behind	10
		Taking advantage of AV		Cutting AV off, slowing it down, taking the right of way, or crossing the road recklessly or intentionally stepping in front of AV	10
		Being more aware / attentive		Being more aware and attentive around AV	8
2		Explicit communication		Road user making eye contact with human driver	31
				Road user using hand signals and / or body / head movements in interaction with human driver	20
				Road user making eye contact with AV	9
				Road user using hand signals and / or body / head movements in interaction with AV	7
				Road user using turn indicator, flashlight, or hazard light to communicate with AV	5
				Road user using horn in interaction with AV	5
		Implicit communication		Road user responding to vehicle movements (i.e., maintaining speed, decelerating, or stopping)	17
3	Curiosity	Curiosity		Exposure to AVs in traffic, sparking interest and fascination with their presence on public roads, raising awareness of the information gap, and creating a desire to close that gap by acquiring more knowledge about AVs	14
Research question 2: Which factors affect road users' responses to AVs in traffic?					
Road-user related factors					
4	Knowledge, familiarity	Knowledge		Lack of or limited knowledge about how to communicate with AV (e.g., understanding AV's ability to recognize)	26
		Familiarity		Exposure to AV's operation daily lives, as participants live in areas where AVs are common and observe them regularly on the road, leading to increased familiarity and adaptation to AVs	24
5	Vulnerability	Vulnerability		Lack of protection of VRU against speed and mass of other traffic, increasing their risk of injury and involvement in road traffic casualties	21
6	Personality	Perceived lack of control		Inability of road user to intervene, control, or influence the AVs' operation due to its driverless nature and lack of communication with road users	12
7	Cognition	Perception of benefits		Safety improvements (i.e., reduced frequency and severity of road fatalities and injuries) due to decreased human error, cautious AV behavior, adherence to speed limits, respectful driving habits, and prioritization of pedestrian safety	32
				Ability to engage in non-driving related tasks (e.g., using the AV while impaired by alcohol or drugs, using a phone, relaxing, or singing)	5
		Perception of risks		Concerns about the overall safety of the technology, including potential failures or malfunctions, and its ability to operate safely in various complex road and weather conditions	30
				Traffic flow and congestion concerns due to AVs' conservative driving style and unpredictable behavior, which can slow traffic down and lead to longer travel times as AVs may choose longer routes	11

(*continued on next page*)

Table 2 (*continued*)

#	Main theme	Sub-theme 1	Sub-theme 2	Description	*n*
				Legal liability concerns regarding financial compensation for AV users in cases of improper AV behavior or accidents caused by the vehicle	6
				Negative economic impact due to the automation replacing human labor, particularly in industries like taxi services and trucking	5
				AVs not aligning with local driving norms and culture, leading to conflicts with human drivers' expectations	5
		Trust	Distrust	Distrust in the current state of AV technology, including doubts about AV's ability to recognize and respond to road user and perform maneuvers safely	19
			Trust	Trust in AV's ability to recognize and respond to road user, perform maneuvers safely, and ensure safe interactions	19
		Comfort		Feeling of comfort when interacting with AV	7
8	Affect	Perceived safety	Feeling unsafe	Feeling unsafe or less safe compared to interactions with human-controlled vehicles	25
				Feelings of stress, nervousness, fear, anxiety, or surprise during AV interactions	10
			Feeling safe	Feeling safe or safer using and sharing the road with AV's compared to human-controlled cars, as expressed through feelings of safety, lack of worry, or reduced fear of accidents, particularly for VRUs	20
				No perceived unsafe interaction with AV experienced by road user	22
		Frustration and road rage	Increase	Increased frustration and anger of road user in certain situations (e.g., when AV gets stuck or hesitates at intersections), manifesting as emotional, physiological (e.g., nausea), and behavioral responses (e.g., giving the finger, yelling, waving hand at other drivers, using horn), especially related to route choices and response times in traffic	17
			Decrease	Decrease in frustration and anger due to AV not responding to emotional responses from road user, such as when the horn is used in interactions with AVs	10
Vehicle-related factors					
9	Appearance	Recognizability	Clear	Clear recognizability of AVs through their appearance and distinctive features compared to conventional vehicles, including: sensor suite ($n = 50$), driverless operation ($n = 34$), operation by hands-free supervisors ($n = 5$), vehicle branding ($n = 23$), consistency in car brands, models, and colors ($n = 22$), and electric vehicle sound ($n = 6$)	140
			Unclear	Unclear recognizability of AVs, causing road user to confuse them with other ridesharing or mapping vehicle	7
10	Performance	Reliability		Consistent and reliable AV performance in similar conditions across different instances	20
		Predictability	Unpredictability	Uncertainty about the AV's next move or intended maneuvers	18
			Predictability	Accuracy of AV's behavior, with vehicle adhering to traffic rules, operating smoothly, and meeting road user's expectations	10
11	Driving style	Conservative		AV exhibiting cautious, hesitant, defensive, and rule-abiding driving style (e.g., making complete stops, staying in the right lane, not overtaking other vehicles), which is seen as a safety benefit but can also frustrate human drivers	32
		Human-like / natural	Human-like/ natural	AV exhibiting human-like or natural driving style (i.e., behavior aligning with road users' expectations), leading road user to treat them as conventional, human-controlled vehicle	23
			Unhuman-like/ unnatural	AV exhibiting unhuman-like or unnatural driving style, characterized by hesitant and slower behavior, getting too close to road user, maintaining pace without slowing down, failing to respond appropriately to road user, and stopping in unexpected ways	11
12	Behavior	AV being stuck		AV stopping or getting stuck, failing to navigate around objects, blocking traffic, including emergency responders	27
		AV passing road user		AV passing road user	23
		AV stopping for road user		AV stopping to allow road user to pass or move	21
		AV keeping pace, (almost) running into road user		AV maintaining speed and causing near misses or collisions with road user, leading to evasive maneuvers by road user	8

(*continued on next page*)

Table 2 (*continued*)

#	Main theme	Sub-theme 1	Sub-theme 2	Description	*n*
		AV stopping suddenly		AV stopping abruptly and then resuming movement shortly after	7
13	Communication capabilities	Current	Communication from AV to road user	AV using turn signals, headlights, or hazard lights	33
				Lack of clear, proactive, and intuitive communication from AV, causing uncertainty about its ability to understand and respond to human forms of communication, such as eye contact, hand signals, body language, or honks	25
			Detection by AV	Uncertainty among road user about whether they are acknowledged, recognized, or detected by the AV	20
			Auditory eHMIs	Support for hearing AV approaching via vehicle noise or sound	27
				Opposition to auditory signals due to their noise pollution and potential cognitive overload for road user	11
14		Imagined	Visual eHMIs	Support for digital displays or screens showing symbols, icons (e.g., hand wave), or text messages	37
				Support for lights or light strips	18
				Support for labeling AV as "automated" due to the unclear recognizability of AV and the lack of transparency regarding their next maneuvers	6
				Support for human machine interfaces (HMI) on road user	6
			Cooperative, pro-social capabilities	Information about the cooperative and pro-social capabilities of AV, such as responding to explicit human communication and giving instructions about future trajectories (e.g., "You should cross now," "Walk," "Go ahead," or "It's your turn")	36
			Intentions	Providing information about AV's actions and intentions, such as turning or stopping, to enhance clarity and predictability for road users	32
			Perception of road user in environment	Providing information about the AV's perception and detection of road user, ensuring transparency and increasing road user confidence in the AV's awareness and decision-making	30
			Easy, intuitive to understand, and efficient	Importance of displaying messages that are easy to understand, intuitive, and noticeable in real-time situations, to avoid road user distraction or confusion	27
			Status/ capabilities	Providing information about AV's status and capabilities, such as labeling the AV with information like 'student driver'	24
			Vehicle driving mode	Providing clear information about current driving mode of AV (manual or automated) to address confusion regarding control, especially related to Tesla's partially automated driving system, where it's unclear whether the driver or automation is in control	10
			Decision-making process	Communicating the AV's decision-making process to enhance understanding and transparency of its behavior, helping to build trust and reduce uncertainty	8
15	Evaluation of eHMIs	Perceived benefits	Promoting perceived safety	Replacing human communication cues with alternative signals (e.g., digital displays, auditory signals) to enhance the perceived safety of road users interacting with AV	25
			Usefulness	General usefulness of eHMIs	23
			Unnecessary	Receiving explicit information from AV is considered unnecessary given AV's conservative and seemingly safe(r) driving style	16
			Temporary feature for trust building	Temporary feature to build trust among road user in AV, becoming redundant with sufficient development of trust in and maturity of technology	8
		Additional communication requirements	Easy, intuitive to understand, and efficient	Importance of displaying messages that are easy to understand, intuitive, and noticeable in real-time situations, to avoid distracting or confusing road users	27
			Like human drivers	Preference for AV to communicate like human drivers given the unnecessity of additional forms of communication beyond traditional methods	19
			Accessibility	Preference for using visual and auditory eHMIs that meet the needs of visually and hearing-impaired road users	11
			Universal applicability	Preference to design information on eHMI that can be understood by people speaking different languages	8
Road environment-related factors					
16	Situational eHMI acceptance	Situational eHMI acceptance		Crosswalks	17
				Stop signs / stop lights	16
				Intersections / curves	9
17	Media / marketing, word of mouth (WOM)	Media reports, word-of-mouth (WOM)		Media reports or stories covering fatal accidents involving AVs, primarily related to Tesla's partially automated driving system	28

(*continued on next page*)

Table 2 (*continued*)

#	Main theme	Sub-theme 1	Sub-theme 2	Description	*n*
18	Road user education	Better road user education		Need for better education about the technology, its benefits, and how to interact with AV, as well as how to understand their behavior and signals to overcome mistrust and resistance and encourage acceptance and adoption	5

The subsequent sections will provide a descriptive presentation of the results, supported by quotes.

3.1. How do road users respond to AVs in traffic?

This theme reflects road users' behavioral responses to AVs in traffic. The most common behaviors were being more cautious, hesitant, and defensive around AVs, followed by allowing AVs to pass and monitoring or checking the AV's actions.

> *„Once I was walking across the street, and a self-driving car with no human driver in it, truly self-driving car, was coming up towards me, and it was night time. It was dark. I stopped and waited. I don't want to get hit by a car."* (P003)
> *„I'm very cautious and leery. I feel like I'm not going to be spotted in a crosswalk or on a sidewalk or while the car is making a turn."* (P013)
> *„If there is an autonomous vehicle around, I probably won't cross in front of it. I'll wait for it to go versus crossing."* (P022)

Waving and staring at the AV were the most common types of 'monitoring/checking AV behavior' observed or performed by participants.

> *„I always wave at the cars, wave at the cameras when I see them. That's very different than when I interact with humans."* (P004)
> *"It was more of a social media experience. I did get quite a lot of reactions from other drivers. I've seen people filming the car. People eating at a restaurant or outdoors, or crossing the street. People like to take a picture or film."* (P005)

The safety operators of the AVs were generally focused on monitoring the vehicle's operation, engaging in tasks such as taking notes, chatting with passengers, or working on a laptop.

> *„They're not paying attention. They're often on a cell phone or on a laptop, or talking to a person in the passenger seat. It doesn't seem they're very attentive to what's happening around them."* (P002)
> *"You'll see the Waymo cars where there's one in the driver seat writing things down. So that's how you know it's automated."* (P021)
> *„I've found them to not actually do much. They're almost very unexpressive human drivers. I haven't seen any hand gestures or eye contact from the safety drivers in San Francisco."* (P030)

Our data also revealed instances of inattentive human operators of Tesla's SAE Level 2 partially automated driving system, including cases where operators were sleeping while the automation was engaged or placing weights on the steering wheel to enable hands-free driving.

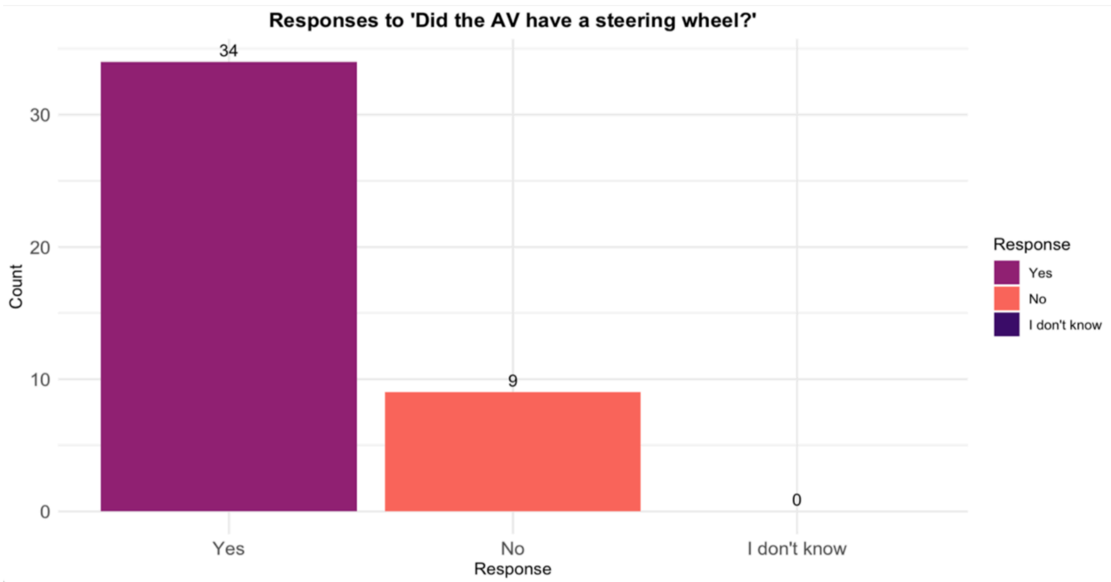

Fig. 1a. 'Did the AV have a steering wheel?', with response options 'Yes', 'No' and 'I don't know'.

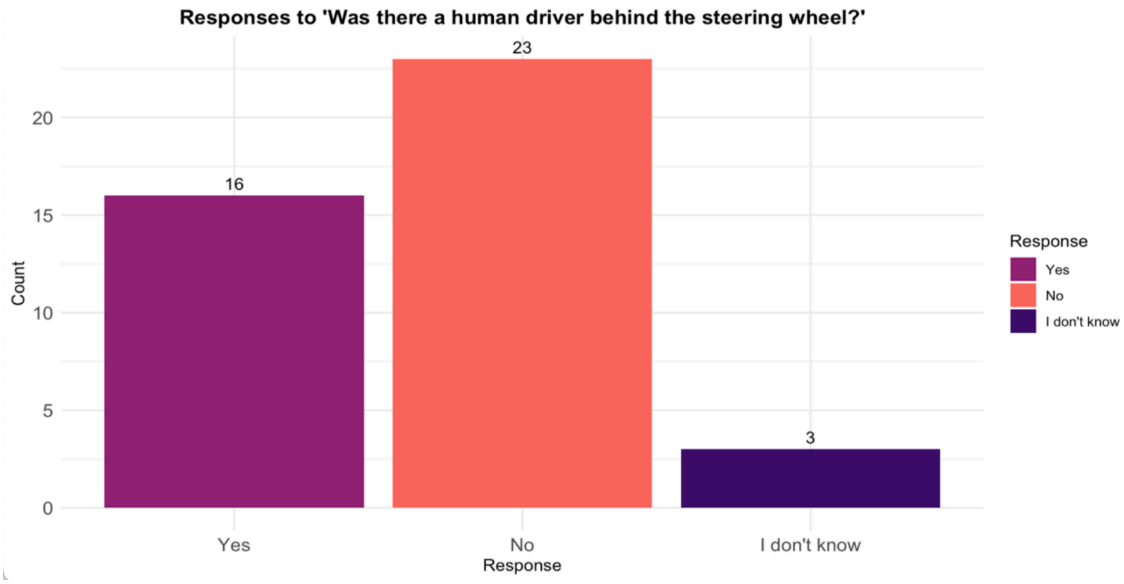

Fig. 1b. 'Was there a human driver behind the steering wheel?', with response options 'Yes', 'No' and 'I don't know'.

> *„I've seen Teslas with one person completely hands-free, not looking at anything. I've seen someone completely sleeping in their Tesla while the Tesla is still driving up and down the road. I've seen that a couple of times."* (P014)
> *„Somebody bought one of the first Tesla's, and I asked him 'So, you don't have to drive the car, right?', and he's like, 'No', and*
> *I'm like 'Isn't that weird?, and he's like, 'I love it'.*
> *[Interviewer] 'And your friend said that he doesn't need to drive the Tesla anymore?'*
> *'More or less, sits in it and gets work done on the way to work.'* (P048)
> *„The guy with this Tesla has a little clip on his steering wheel so he doesn't have to interact with the car, which is probably unsafe, but it's something that people do, probably super illegal."* (P050)

The sub-theme 'taking advantage of AV' encompasses various road user behaviors, such as intentionally stepping onto the curb or decelerating in front of the AV, causing it to slow down or stop. Other reported behaviors include cutting off AVs to perform merging maneuvers and crossing the road in front of them.

> *„It is very easy to cut them off. They will stop. If you need to merge, you're like ‚Oh, there's a robot car, I can definitely merge in front of that robot car', or if you're a pedestrian and you're like ‚They're going to stop for me because they see you, they see you coming.'"* (P016)
> *„It has gotten really fun to play with them. If you try to bluff them, you can make them stop or clinch. You'd see one coming along and you wait until the last second and step off the curve. That's enough to stop them. The human drivers are going to dominate them."* (P025)
> *„I remember having fun with these self-driving cars. I would be in the bicycle lane, and these Cruise cars would never pass me. I would purposefully go very, very slow to see what would happen, and the car would go slow, slow, slow, slow and come to a complete stop."* (P050)

This theme captures the communication behaviors of road users interacting with both conventional vehicles and AVs, utilizing both implicit and explicit forms of communication. Participants most commonly engaged in making eye contact with human drivers, as well as using hand signals and body/head movements when interacting with AVs. They also made eye contact with AV operators.

> *„Other people will try and make eye contact and wave at the car even though there's not really anybody to make eye contact with. The human behavior there is still in play."* (P006)
> *„Strangely enough, I'm looking to make eye contact with a human being, as you would do in a regular situation to make sure they've seeing you. It's probably the way I'm programmed. That would be for me a huge reassurance."* (P013)
> *„There has been a handful of times where I would make eye contact or do a hand gesture to whoever's in the AV, and they'll wave me through and hold back the AV."* (P027)

Others reported using implicit vehicle dynamics, such as the vehicle's speed, deceleration, and stopping behavior, to guide their interactions with the AV.

> *„I don't think it really communicates with you unless it's creeping or scooping ahead. It does communicate to traffic by moving ahead slightly."* (P007)
> *„If I could see it slowing down, then I'd be more likely to go in front of it."* (P043)

„If you're within range of it, and it thinks it's gonna hit you, it brakes itself, and so in that way it communicates that it sees me." (P049)

The presence of AVs on public roads sparked participants' curiosity, driving them to seek more information and learn about these vehicles.

„Curiosity is the first part of my interaction with the AV." (P029)
„I've been in awe and watching and intrigued. It generates conversation with people. We always say 'Look, that's one of those cars', 'Ohh, I'm starting to see more of those' and we'll ask each other. 'How do you see those? Do you want one? Do you think you would drive one? Would you feel safe in one?' I, my friends, people I'm with, are interested. It is intriguing, and I might do it someday." (P031)
"I'll look inside the car to see if there's a human behind the wheel, it's pure personal curiosity.
I'm curious to know if it's a fully autonomous test drive or there's a human behind the wheel." (P033)

3.2. Which factors affect road users' responses to AVs in traffic?

3.2.1. Road user-related factors

Our study also identified several road-user related factors that influence road users' responses to AVs in traffic. These include knowledge and familiarity. Participants lacked understanding of how to communicate with AVs, particularly regarding the AV's ability to recognize and respond to explicit signals.

„I don't feel there's any way to communicate with them.
As a car driver you would be communicating with the turn signal or with brake lights, but it's unclear to me if that's something that those cars are picking up. That goes beyond my scope of knowledge." (P013)
„It doesn't know how to talk back. I would not know what a honk or horn does to autonomous vehicles. Does that awaken some technology up or not?" (P020)
„They have that bubble on top, whatever that's called, that helps them navigate. I'm not even sure what it's used for." (P044)

Another sub-theme is 'familiarity', which captures participants' exposure to AVs in traffic given that they live in areas in which AVs operate, leading to familiarization with AVs.

„Where I live in San Francisco, they're driving fast and forth under my windows, driving around, waiting for me in the crosswalk all the time." (P004)
„I'm starting to get used to it the more I experience it. At first, it was a little unsettling." (P023)

The lack of protection or vulnerability of road users emerged as another sub-theme.

„I have been hit twice by drivers in San Francisco. They weren't looking, and that have been scary. I have been told by other people that I'm crazy for riding a bike." (P008)
„I'm always subjected to so much danger. I wish there were more autonomous vehicles. I am excited for the day when I don't have to trust that a human being isn't going to crash into me. A bicyclist visibility is always gonna be lower than the ability of a human to see a bicyclist." (P009)

The sub-theme 'perceived lack of control' encompasses the inability to control or intervene in the vehicle's operation due to its driverless nature, as well as the lack of communication with road users.

"My vehicle was trying to merge into a very busy area during rush hour and it was stopping and starting and it was jolting, and it was frustrating because I can do nothing." (P016)
„It's weird seeing a 2000 lb vehicle driving at you and knowing ‚Ohh, the machine is determining how I will live. Will I be hit and have my life completely altered?' It's a big change to experience." (P035)
„With the human, I could have made eye contact. Could have yelled at them, dinged my bell, and something would have happened, but with this robot car I couldn't. It never stopped. I felt really powerless because I couldn't communicate with it. It didn't do anything. There's really a powerless feeling. I can't do anything. There's nothing I can do." (P046)

The perception of benefits associated with AVs in traffic primarily focused on safety, particularly the reduction of human error and the cautious, conservative driving behavior of AVs, which adhere to speed limits and prioritize the safety of vulnerable road users. However, participants also expressed concerns about the overall safety of the technology, citing the potential for failures or difficulties in operating safely under more complex conditions. The second-most reported benefit was the ability to engage in secondary activities as a passenger in an AV.

„I am a singer. I took it to an audition. I was able to warm up my voice without needing to talk to an Uber driver and be like 'I'm so sorry. I'm going to make some annoying sounds.' I can sing and it's really lovely to have my own space." (P016)
„It's a comfier, more luxurious experience. I also have started meditating in the vehicles and that has exponentially increased my happiness. To close my eyes and not drive and interact with other humans, it really has greatly improved my quality of life." (P016)

Trust and distrust were other cognitive factors we identified. Participants expressed trust in the AV's ability to recognize and respond to them appropriately, ensuring safe interactions.

„If I walk in front of one, if I'm crossing the street, I don't have to worry about it." (P006)

„I trust, I know, they see me. I work with kids, and I would say ‚It has 100 eyes, and it never blinks, and it sees everything because it does have human-like vision, but in 360-degrees plus all those other tools'." (P007)
„I have so much experience as a passenger, I know they are going to stop for sure, and I'm safe." (P016)

Some participants expressed distrust in the AV's ability to perceive and respond to them properly, leading to uncertainty about how to navigate the situation safely.

„With a self-driving car and there's no one there, you have to trust that technology will stop it, whereas with the human, you have to trust them to stop it, but you can make eye contact, and you know that the person's gonna stop and it's nothing to worry about." (P010)
„I don't really trust that it sees me. I make eye contact with the driver to make sure that they see me. I can't tell if it can see me or understand my behaviors." (P022)
„I felt less safe because I couldn't communicate with it or I couldn't trust it, or I wasn't acknowledged." (P030)

Affective factors include perceived comfort, safety, frustration, and road rage experienced during interactions with AVs. While some participants felt safe interacting with AVs, others reported feeling unsafe around them.

„Some intersections near where I live are very difficult and dangerous for pedestrians, but I know that if I encountered an autonomous vehicle, I wouldn't worry. I 100 % feel safe. I've never not felt safe." (P007)
„The interaction is that of nervousness because you don't know whether it's gonna stop, especially when you see one without a human in it. It's like. 'Hey, I wanna make sure that you see me.'" (P003)
„I got more stressed. If someone's in there, it's fine. If there's not a person in there, and the AV is coming, I rather wait until the AV goes away." (P036)

This sub-theme also encompassed the impact of using and interacting with AVs on road users' frustration and anger. Participants noted both an increase and decrease in frustration and anger in automated traffic, based on their observations and expectations.

„I've had a number of times people get angry with the Waymo." (P007)
„As a car driver, I'm very much annoyed if I'm stuck behind this car because they drive very slowly, sometimes under the speed limit even, and I always go 5 miles over, which is OK here." (P015)
„It didn't stop, it kept slowly going and I find that really frustrating as a cyclist because I don't want a car to be moving into me, even if it's slow." (P042)

A decrease in frustration and anger was linked to the AV's lack of response to road users' emotional reactions, such as using the horn.

„It's tough to get angry with it because there's nothing to get angry at. It diffuses that ‚What a crazy person', or ‚What a terrible person'. Classic road rage. This feeling of wanting to be angry at something. There's nothing there to be angry at, and so you're not angry at all." (P008)
„It doesn't give you the finger. You don't have to worry about road rage with them." (P019)
„In terms of interacting differently, I have yelled at human car drivers who have cut me off or not come to a full stop at a stop sign when I'm crossing the street. I have even given the finger to some of them. I no longer engage in road rage." (P042)

3.2.2. Vehicle-related factors

This main theme summarizes the vehicle-related factors identified in the study, focusing on the vehicle's appearance, performance, driving style, and behavior.

The theme of 'appearance' relates to participants' ability to accurately identify an AV. However, for a smaller group of participants, AVs were not easily recognizable, as they could be confused with other mapping or ridesharing vehicles.

„If there was something that made it clear that it is an AV, that would be helpful. It is possible to confuse a self-driving car with a mapping car because their cars also have sensors on them." (P003)
„These cars have extra sensors. The sensors were strapped onto an ordinary vehicle. It's real obvious that it was a special vehicle. Now they don't look like somebody strapped a giant insect onto a car." (P025)

The performance of the AV was characterized by its reliability and predictability. Reliability was linked to the AV's consistent and reliable performance, as experienced by road users over time.

„I know it won't hit, that's for sure. It's gonna behave the same all the time. When you're crossing a street and it's coming towards you, it's gonna slow down because it always slows down the same way." (P008)
„When I'm crossing the street and an automated vehicle is approaching. I know they're gonna stop. I've been in them a million times, and they stop even when you don't want them to stop." (P016)
„I'm not really concerned about crossing the road with an automated vehicle anymore. It's been from time and time again that they stop and they're safe. I don't have any issue." (P047)

Predictability was associated with accurate behavior, with the AV following the traffic rules better compared to human drivers.

„An AV would probably be more trustworthy. They would always signal or always do the thing that they're going to do. A human might change their mind middle of the way through." (P009)

„They're going so slow, being so predictable in their movement. If you are so predictable and you're slower than traffic, then that builds the trust that yes, they're going to turn or stop at the stop sign." (P052)

Unpredictability was associated with the uncertainty about the next and intended vehicle maneuvers.

„One of the giant unknowns is that we don't know what they are doing. They will slow down in places that a human driver wouldn't slow down and they will stop in places that human drivers wouldn't stop." (P003)
„This one is an unpredictable entity, makes me much more cautious." (P022)
„They seem to be safe, but you never know if one might go rogue or not." (P037)

The driving style of the AVs was represented by its conservative and human-like driving style. Participants referred to the cautious, slow, and traffic law-abiding behavior of the AV, giving road users right of way.

„They always seemed very cautious and a very respectful road user. They go exactly the speed limit, I never get to drive next to them for very long because they're always the slowest road user." (P006)
„They drive much more conservatively where humans drive usually a little more aggressively. The AVs follow all the rules, slow to accelerate, smooth braking, complete stops where a stop is required." (P017)
„They are more cautious. If you are behind him, there's no driver. You will see brake lights applied more often than maybe a normal a driver would apply it, so they're very careful." (P020)

AVs were treated as regular, human-controlled cars, indicating that the AV behavior mimicked the behavior of human drivers.

„When I'm on the road, it seems like another car." (P026)
„It felt a lot like driving next to a real human who is trying to make a lane change. It felt very similar to my experience with the human-controlled car." (P030)
„I'm so used to it by now that it's like a regular driver. I don't care one way or another. I don't even think about it, another car on the road. I don't necessarily differentiate in automated versus a person." (P047)

To other participants, the behavior of the AV was unhuman-like or robotic.

„They didn't drive like a human driver. They drive like a robot drives. They drive weird where I'll define weird as too slow or they'll stop in places where it doesn't really make sense to stop." (P003)
„As a cyclist, I was waiting at the light and the car stopped and I thought it was odd that it got that close, maybe 2 feet from me, waiting at the light for the light to turn green, where usually it's more 5 feet." (P041
„They're going so slow and being so predictable in their movement. If you are so predictable and you're slower than the regular traffic, then that kind of builds the trust." (P052)

We identified several behaviors of AVs when interacting with road users. AVs were observed to become stuck, confused, and unable to navigate around obstacles, often blocking traffic, including hindering the passage of emergency responders.

„My Waymo was moving through a crosswalk. There was a disruption in traffic ahead. Through an entire light cycle, we remained in this crosswalk. Some people are like ‚Oh my gosh, what are you doing?'" (P007)
„They sit there not knowing what to do, like scratching-their-head kind-of-thing. You don't know what it's doing." (P019)
"I was recently at an intersection. The AV stopped in the middle of the intersection and was waiting for this other car to take a left, but it couldn't take a left, and so it was another build up." (P022)

The least common behavior observed was the AV maintaining pace and (almost) colliding with road users, resulting in near misses and accidents.

„A Tesla self-driving vehicle hit me in the middle of the freeway, rear-ended me, and pushed me into the center divider, and he was still asleep when the accident occurred. I was like 'OK, this guy sound asleep. The chair was reclined.' The police took all the video and pictures and he still had to be woken up by the police officer. He woke up like 'I don't even know.' They ended up shattering his window, and getting him more involved. I saw glass all over the floor." (P024)
„I was jogging about a month ago. It's about 11:00o'clock. A car was turning from one of the main streets to a site street, and I was crossing that street, but it didn't slow down or pause." (P047)

The theme 'communication capability' captures responses pertaining to AV's current and imagined communication capabilities. Current communication capabilities include responses capturing AVs using turn signals, headlights or hazard lights. Participants indicated that AVs currently lack the capability to interact cooperatively with other road users in a pro-social manner. They do not respond to explicit forms of human communication, which creates uncertainty about whether AVs can recognize and react to such cues. Participants also expressed uncertainty about whether they were being detected by the AVs. There is a need for AVs to provide clear instructions regarding potential future trajectories.

„We can't honk. They don't respond to honking. They're doing their own thing. They're not very collaborative. If everybody's going slow, they're still going the same speed. If everyone's going fast, they're still going the same speed. If they're in this fast lane, they're still going the same speed on the fast lane. It's all about them. They're very self-centered, very self-centered." (P019)
„If Waymo was able to use their screens to give a hand wave, a digital hand wave, and say ‚Go ahead. Cross the street.'" (P006)

This theme also encompasses the evaluation of auditory eHMIs. Hearing the vehicle via sound received the highest support given that sound can be easily detected by vulnerable road users. However, auditory signals may also contribute to noise pollution, potentially leading to cognitive overload for vulnerable road users.

„I do like to hear our car. You get surprised because you don't hear them, and then all of a sudden they are there, and you get startled. I would want for the car to have sound." (P044)
„It would be visual. Sound is too difficult on the road. I find it hard to hear things while I'm in a car. As a bicyclist, there's so many sounds and things going on. It's so loud on the street that I would feel some visual signal would be best." (P008)

Imagined communication capabilities include visual eHMIs were digital displays or screens displaying icons / symbols or text messages, followed by lights or light strips.

„Most people are very used to the blinker, turn signals and brake lights." (P013)
„It's good to have that screen: ‚OK, I'm gonna be turning left or right turn, or I'm going straight or I'm picking up at this address, or not this address, but I'm gonna be stopping in 2 houses'." (P027)

The sub-theme 'type of requested information' refers to the information participants preferred to receive from AVs. This includes details about the cooperative, pro-social capabilities of AVs, their response to explicit forms of communication, and instructions about future trajectories. Participants also emphasized the importance of human communication forms, such as eye contact and gestures, for facilitating efficient traffic negotiations and ensuring (perceived) safety. AVs should provide information about their ability to detect road users, reassuring them that they are correctly recognized. Additionally, information should be offered about the vehicle's driving mode and decision-making process.

„You don't really know what the machine is doing or thinking. There's no way for the AV to communicate to other drivers in the roadway what it's about to do." (P001)
„My biggest fear as a motorcyclist is for a vehicle to pull out in front of me because it doesn't detect me. They can't communicate that they've seen me. I want some reassurance that the vehicle can see me." (P001)
„The biggest factor is eye contact. It's the ability to know that the vehicle has recognized my existence as a human driver." (P028)

The sub-theme 'evaluation of eHMIs' as imagined communication abilities of AVs highlights participants' need for clear and intuitive messages in their interactions with AVs. Information displayed on visual eHMIs should be easy to understand, efficient, and prioritize safety while avoiding distraction and confusion among road users. Additionally, AVs should mimic human communication behaviors, resembling conventional human-controlled vehicles, to facilitate road users' adjustment, supporting acceptance and the transition to a future with AVs. The implementation of visual eHMIs may become more effective as the deployment of AVs in transportation increases.

„Cars want to be trusted and the best way to do that is to be a car. Emulate what other users are doing and not stand out too much. That is important to adoption. Now it's probably better to pretend that we are a normal car." (P008)
„How would AVs behave towards you in a perfect world? They behave exactly like a human driver." (P036)

Participants also highlighted the benefits of eHMIs, noting that they can enhance traffic safety by replacing traditional human communication cues, such as eye contact and hand gestures.

„That would make me feel much safer. I am all the time making eye contact with drivers to feel safe.
That's a really important factor of road safety and communication between drivers, it's really lacking right now." (P001)
„You can make eye contact with the driver, either gesturing that they're seeing you, but the robot doesn't have that. Replacing that kind of communication would probably be an important step in making things safer." (P004)
„Having an eHMI would at least add to that feeling of safety." (P027)

Some participants felt that visual eHMIs were not necessary, given the conservative driving style of AVs, reducing the need for communication beyond the traditional forms used with human-controlled vehicles.

„AV drivers have been so conscientious and defensive that I never needed to rely on eye contact or hand gestures. I've never seen an AV try to turn right in front of me. I've never felt at a stop sign that I couldn't turn in front of it, and I've never been afraid that it might cut me off. I've never had to really interact with the driver of an autonomous vehicle." (P009)
„When I know that a person is in the car, I do rely on making eye contact or I will provide a hand up to indicate I am crossing the street. Because I have so much experience as a passenger in these automated vehicles, I don't do that for the automated vehicles when I see them approaching because I know they are going to stop for sure, and I'm safe." (P021)
„There hasn't been a need. There's never been a reason to communicate with them." (P023)

Additionally, visual eHMIs could play a key role in building trust in the technology, although over time, as trust in and the maturity of the technology increase, they may eventually become unnecessary.

„I think an AV would only need it [eHMI] because people distrust AVs. You attack this problem by solving the root of the issue, which is people distrusting or not understanding AVs." (P007)
„That would be important, but seems a little overkill if you get used to these enough. You're like 'Oh, it's not gonna hit me. You feel safe and so there's no need for it to communicate that to you." (P008)

3.2.3. Road environment-related factors

This sub-theme captures factors in the road environment that influence road users' behavior in automated traffic. The main theme 'road environment' addresses the situational acceptability of visual eHMIs—specifically, the scenarios in which participants would prefer to rely on information provided by these systems. The most common situations favored by participants were crosswalks, stop signs/stop lights, and intersections/curves.

The sub-theme 'media reports and personal stories' examines the influence of media coverage and personal accounts of fatal accidents involving AVs, particularly those related to Tesla's partially automated driving system.

> „*We've had some serious accidents in California with Tesla. That's always floating around in the back of my mind. There was an incident half a mile away from my home, and there was a fatality.*" (P013)
> „*There was a Tesla and it was driving and it suddenly stopped and there was a crash behind it and a bunch of cars crashed in the back. When I hear that, it makes me a little nervous about being around a Tesla in case it makes some sort of error.*" (P023)
> „*Most of the people are skeptical because they haven't had the greatest press. They're saying 'Oh, yeah, the Teslas, a lot of them have already been killed in them. They've had many accidents.*" (P041)

The sub-theme 'road user education' addresses the need for increased education to help road users better understand the functionality of AVs and the appropriate ways to communicate with them.

> „*We need something to communicate to all the users. Maybe the DMV,*[1] *and the road safety authorities should educate everyone saying that ‚OK, if an AV is coming around, it's completely safe to cross the road or to drive around'. That level of educational enlightenment has not started yet.*" (P029)
> „*We know what a siren means, right?*
> *Unless there's gonna be the DMV's or our motor vehicle organizations, gonna be OK, this means this, a light might mean X', unless there's that kind of a standards organization for the development, then you're gonna have everyone doing something different, which is not gonna work for mass consumption right now.*" (P042)

Next, we calculated Spearman rank-order correlations between our sub-themes to identify significant associations. Several significant associations were found, as detailed in Table A2 in the appendix. Please note that Table A2 includes only significant associations. We will discuss the results in the following section.

4. Discussion

This study explored road users' real-world interactions with AVs in natural traffic conditions to understand how and why they respond to AVs. Unlike previous studies, which have primarily focused on interactions between pedestrians, drivers, and AVs text, our research explores a broader range of road users' perspectives. Additionally, we examined how eHMIs can support road users in their interactions with AVs.

4.1. Pertaining to how road users respond to AVs in traffic?

Our study identified several behaviors how road users respond to AVs in traffic. The most common behavior was increased caution around AVs, such as yielding and allowing AVs to pass before proceeding, which supports findings from previous research (Li et al., 2024a). Additionally, road users took advantage of AVs by cutting them off, slowing them down, or recklessly crossing in front of them, which aligns with previous research on more aggressive and reckless behavior towards AVs (Alozi & Hussein, 2023, 2024). We also observed significant negative associations between taking advantage of AVs and increasing the distance to AVs, which is plausible and suggests that these behaviors are less likely to occur together.

AV safety operators were typically attentive in monitoring the AV's operation, which contributed to the perception that AVs are safe and predictable. This indicates that AV safety operators may play a crucial role in the early stages of AV deployment. Furthermore, participants who noted that AV safety operators were attentive were less likely to report instances of AVs getting stuck, possibly because the safety operators could intervene in such situations. We could not identify additional studies exploring how the behavior of AV safety operators influenced other road users.

Other participants reported instances of inattentive drivers or human operators of Tesla's partially automated driving system, including one case where a driver was observed sleeping in the AV and subsequently rear-ended one of our participants. This finding aligns with previous research (Smyth et al., 2021). Previous studies examining the impact of Tesla's automated driving system on other road users have primarily focused on the behavior of the drivers themselves (Nordhoff et al., 2023).

The most common external communication cue between road users and human drivers was eye contact. Some participants also reported making eye contact with AVs, even in cases where no operator was present, or when the AV was observed maintaining pace, almost causing a collision. A recent study supports the prevalence of bi-directional gazing—where both drivers and pedestrians look at each other—in naturalistic settings, particularly during interactions between pedestrians and human drivers (Pipkorn et al., 2024). Participants also relied on implicit forms of communication in their interactions with AVs, such as the vehicle's speed and dynamics (e.

[1] Department of Motor Vehicles.

g., deceleration and stopping), which supports previous research (Chang et al., 2024). Additionally, participants who expressed curiosity about AVs were more likely to engage in behaviors such as waving or gawking at them.

4.2. Which factors affect road users' responses to AVs in traffic?

4.2.1. Road user-related factors

Additionally, participants who were familiar with AVs, likely due to living in areas where AVs operate, were more likely to report instances of AVs stopping suddenly. These participants also tended to perceive AVs as more reliable. In Rahman et al. (2023), participants who were more familiar with the technology behind AVs and had more experience sharing the road with them were more likely to feel safe around AVs.

Not being able to communicate with AVs contributed to a perceived lack of control and feeling of powerlessness, supporting research with cyclists who expressed a feeling of helplessness in making drivers aware of them in interactions with AVs (Parnell et al., 2024). The positive association between perceived lack of control and taking advantage of AVs suggests that a perceived lack of control may provoke aggressive or impatient behaviors from road users.

We found significant positive associations between distrust and behaviors such as being more cautious around AVs, allowing the AV to pass, and increasing the distance to the AV. Conversely, trust was positively associated with taking advantage of the AV in line with Alozi & Hussein (2023). Tran et al. (2024) and Zhao et al. (2024) have shown that participants engaged in riskier behaviors due to the misconception that AVs would always stop or slow down for them. In our study, distrust was also associated with road users relying on hand signals or eye contact to communicate with human drivers. This suggests that participants who typically use traditional, explicit forms of communication with human drivers may be more likely to report distrust in AVs.

Consistent with existing research (Nordhoff et al., 2021; Pyrialakou et al., 2020), feeling safe was associated with perceiving AVs as safe and with having trust in AVs, reducing the likelihood of resisting AVs. We were unable to identify other studies that explored this specific relationship. In our study, feeling unsafe was associated with increasing the distance to the AV, as well as with feelings of frustration or anger. Participants who reported feeling stressed or nervous were more likely to perceive AVs as unsafe and to distrust them, often waving or gawking at the vehicles. This behavior may reflect an attempt to communicate with the AV and seek additional reassurance. Additionally, feelings of stress or nervousness were linked to instances where the AVs stopped suddenly, likely because such behavior is perceived as unexpected and unpredictable. Pyrialakou et al. (2020) have shown that observing an AV performing a dangerous or unsafe maneuver is associated with feeling unsafe around AVs.

Participants in our study expressed frustration and anger due to the AV's conservative driving style, which included operating at lower speeds, adhering strictly to traffic laws, not following the social norms of driving, and naturally adjusting to the flow of traffic. Additionally, we found that frustration and road rage were negatively associated with both traffic safety and flow efficiency. Frustration during manual driving can impair traffic safety (Bosch et al., 2023). Frustration and anger was also linked to the AV being stuck in traffic, encouraging road users to pass and take advantage of the situation. Anger can potentially increase the likelihood of aggressive or violent behavior (Bowen et al., 2016). At the same time, our study has shown that frustration or anger may decrease because AVs do not respond to road users' emotional reactions (e.g., gestures, yelling, using the horn). The impact of AVs on road users' anger is underexplored, primarily due to the challenges of studying the influence of AVs on emotions in a naturalistic setting.

Behaving more cautiously around AVs and instances of AVs being stuck in traffic were both negatively associated with traffic flow efficiency. Additionally, we found positive associations between liability concerns and behaviors such as increasing the distance to the AV and being more attentive around AVs. Previous studies have shown that individuals who are more concerned about potential attacks from hackers or other parties, and who hold stricter attitudes toward AV regulations, tend to feel less safe around AVs (Pyrialakou et al., 2020; Rahman et al., 2023).

4.2.2. Vehicle-related factors

The unpredictability of the AV was associated with increased caution around AVs, as well as perceptions of AV technology as unsafe or risky. It was also linked to distrust, feelings of stress or nervousness, frustration and anger, and the AV's behavior of being stuck in traffic. Vehicle reliability was positively associated with taking advantage of AVs and was strongly linked to trust, supporting a well-established relationship in the literature (see Mishra, 1996; Rempel et al., 1985).

Our findings support the characterization of AVs as cautious, conservative, and law-abiding agents (Alozi & Hussein, 2024; Ma & Zhang, 2024; Millard-Ball, 2018; Li et al., 2024b; Rahmani et al., 2024). The conservative driving style of AVs may enhance traffic safety but could have a negative impact on flow efficiency (Li et al., 2024b; Rahmani et al., 2024) and road users' well-being, due to the potential increase in frustration or road rage. AVs were observed to behave in ways that seemed unnatural or unhuman, making its actions difficult for road users to predict, which aligns with previous research (Alozi & Hussein, 2023, 2024; Ma & Zhang, 2024; Rahmani et al., 2024). The unnatural or unhuman driving style of the AV may increase road users' tendency to seek communication with the vehicle through eye contact. This may reflect the habitual nature of eye contact in navigating interactions in traffic, particularly in safety–critical situations. On the other hand, other participants treated AVs as conventional human-controlled cars, given that the AVs behaved similarly to human drivers, aligning with previous studies (Holländer et al., 2019; Ma & Zhang, 2024; Tran et al., 2024). Participants who perceived the AV's behavior as natural or human-like were less likely to increase the distance to the vehicle. This is plausible, suggesting that human-like behavior in AVs may result in fewer behavioral changes among road users.

Additionally, the absence of communication from the AV to road users was linked to distrust in the AV and low perceived safety, which in turn increased the likelihood that road users would allow the AV to pass. In the study of Tran et al. (2024) participants reported a lack of trust in the AV and low perceived safety when there was no clear communication from the AV indicating that they had been detected. Furthermore, we have shown that participants who believed that AVs lacked the ability to communicate with road users were more likely to engage in eye contact with human drivers. Similarly, the AV behavior of “stopping for road users” was associated with distrust, possibly due to its unexpected and confusing nature for road users. Functional vehicle incompetence was identified as a key reason for distrusting AVs (Lee et al., 2016).

Among all interfaces, auditory interfaces received the strongest support, aligning with research that has shown cyclists prefer auditory signals over visual or vibrotactile ones. This preference may result from the perception that auditory signals are more urgent and are more commonly associated with warnings (see Erdei, Steinmann, and Hagemeister, 2020). At the same time, participants expressed concerns about the effectiveness of auditory interfaces in automated traffic, mentioning the potential for increased noise pollution and higher cognitive or mental workload in line with Berge et al. (2023). Participants unintentionally stepped onto the road in front of AVs because they did not hear the vehicles approaching, potentially creating additional safety risks for vulnerable road users (Parnell et al., 2024). Drivers of electric vehicles were involved in a higher frequency of accidents compared to drivers of internal combustion engine vehicles (McDonnell et al., 2024). Cocron & Krems (2013), however, found that critical noise-related incidents between electric vehicles and other road users were rare, and concerns about noise diminished with increased experience. Visual eHMIs could complement auditory signals, addressing the needs of both visually and hearing-impaired road users. Future research should explore the impact of sound on road user behavior, identifying the types of sounds that reduce the likelihood of unsafe behaviors. Interestingly, participants who reported behaving more cautiously around AVs were less likely to support auditory eHMIs and preferred receiving information from AVs via light signals. An open research question remains whether auditory signals from AVs can be effectively detected by vulnerable road users in noisy, busy environments (Hasan & Hasan, 2022).

We also explored the role of eHMIs in facilitating road users’ interactions and communication with driverless AVs. Some participants considered visual eHMIs unnecessary, as AVs drive more conservatively and safer than human drivers, effectively replacing explicit human communication cues. On the other hand, others highlighted that eHMIs could enhance perceived safety and promote trust, consistent with findings from previous research (De Clercq, Dietrich, Núñez Velasco, De Winter, & Happee, 2019; Habibovic et al., 2018). Participants who exhibited more cautious behavior around AVs (e.g., being more attentive, allowing AVs to pass, or making eye contact with human drivers), those who distrusted AVs or felt stressed or nervous preferred eHMIs (i.e., visual displays, lights) that signal to road users that they are seen or detected, particularly at crosswalks or stop signs. Previous research supports the importance of road users being detected by AVs (Parnell et al., 2024; Tran et al., 2024). Communicating to road users that they are seen or detected by AVs can promote trust in the technology and alleviate concerns about liability, as indicated by the positive associations between these sub-themes. Participants who typically use hand signals to communicate with human drivers and those who are vulnerable road users preferred information that is easy and intuitive to understand.

We also found significant associations between different behavioral responses and the perceived usefulness of eHMIs. Participants who reported behaviors such as waving at or gawking at AVs, as well as those who resisted and passed AVs, were less likely to consider eHMIs useful. It is plausible that these participants had already adapted their behavior to AVs in ways that allowed them to cope with them on the road, reducing the need for additional communication cues. The perception of eHMIs as useful was also linked to visual eHMIs that communicated the AV’s intentions to road users. Furthermore, participants who made eye contact with the AV safety operators or engaged in traditional human communication (e.g., waving or gawking) were less likely to consider eHMIs as necessary. This implies that for some participants, traditional forms of communication may be sufficient, and eHMIs could be deemed redundant. However, participants who observed the AV keeping pace, almost leading to a collision, were more likely to perceive eHMIs as useful, especially in safety–critical situations. Additionally, our findings suggest that vehicle reliability and labeling a vehicle as automated can reduce the perceived need for eHMIs.

4.2.3. Road environment-related factors

Participants who were curious about AVs were less likely to prefer eHMIs at stop signs, possibly because they had already adjusted their behavior in ways that made communication beyond traditional human cues unnecessary. Our findings suggest that eHMIs can help build trust, at least temporarily, especially for those who feel unsafe or experience stress or nervousness around AVs, particularly at crosswalks, stop signs, or when the AV is stuck or stopping suddenly. This suggests that eHMIs can facilitate safer and more effective interactions between road users in these situations. Madigan et al. (2023) have highlighted the importance of eHMIs in situations where there is uncertainty about right-of-way between AVs and road users. Additionally, factors such as vehicle unpredictability, unrecognizability, the AV passing road users, and the AV’s lack of cooperative abilities were positively associated with the preference for eHMIs at stop signs or crosswalks. Conversely, participants who used implicit vehicle communication cues, such as the speed and dynamics of the vehicle, and those who reported that AVs used headlights or turn indicators, were more likely to view eHMIs as useful—particularly at crosswalks. This suggests that traditional vehicle cues may not be sufficient for these participants.

Our study detected a significant positive association between media reports and fatal incidents involving Tesla’s automated driving system, which contributed to the perception of automated driving as unsafe or risky. This is plausible, as fatal accidents involving Teslas have been widely covered in the media (Penmetsa et al., 2023). In contrast, in Pyrialakou et al. (2020) participants who reported to follow news about AVs regularly perceived sharing the road near an AV as safer. Given that awareness of Google’s (Waymo’s) AV was associated with a higher perceived safety when driving near AVs, it is plausible that perceptions of safety may vary across different vehicle brands (see Rahmani et al., 2024). This suggests that perceptions of AV technology—likely shaped by media coverage or word of mouth—can influence road users’ behavior.

Road user education may reduce the need for visual eHMIs to communicate the intentions of AVs to road users, as evidenced by the negative association between these sub-themes. The relationship between eHMIs and road user education is little understood. Zhao et al. (2024) found that, in the presence of an eHMI, the number of participants crossing in front of AVs decreased significantly after they received formal education. However, the same study also observed that even after participants were educated about the meaning of the eHMI, they were more likely to cross in front of the AV when the eHMI was present compared to when it was absent.

4.3. Conclusions

In this study we have offered a comprehensive and detailed view on the different behaviors that may occur following the deployment of AVs on public roads. These behaviors can have important implications for traffic safety, efficiency and road users' well-being. We have also shown that sharing the roads with AVs may not only induce changes in road users' behavior, but also cognition and affect. Promoting road users' trust in AVs and reducing distrust may be effective in reducing the occurence of behaviors that negatively affect traffic safety and flow efficiency and possibly introduce new, unintended risks for road users. However, too much trust is also not desirable given that road users may take advantage of AVs when trust exceeds the capabilities of AVs (Tran et al., 2024).

Moreover, given that feeling safe around AVs was negatively associated with resisting AVs, promoting road users' perceived safety around AVs may be effective in reducing resistance towards AVs. Exposure to AVs in traffic triggered the interest and curiosity in AVs. More trials with AVs on public roads may thus promote the interest and curiosity of road users, and their acceptance and use of AVs. Additionally, we found that participants generally expressed familiarity of sharing the road with AVs and responded to them in traffic, treating them as any other car. Therefore, the need for eHMIs as explicit forms of communication and their effectiveness of promoting safer, more efficient, and comfortable interactions needs to be further investigated. In Carlowitz et al. (2023) participants did not use the eHMI to inform their crossing decisions. Gesture-based eHMIs may improve the cooperative and pro-social capabilities of AVs (Chang et al., 2024).

The clear recognizability of AVs in terms of its sensor suite, driverless operation and vehicle branding can make AVs a target of attacks from bystanders and road users. Future research should investigate the prevalence of this phenomenon, analysing human behavior, motives and characteristics of attackers (Khalid Khan, Shiwakoti, & Stasinopoulos, 2022). Successful attacks can cause severe traffic chaos, undermining the attractiveness of AVs and acceptance (Chang et al., 2024; Khan, Shiwakoti, Stasinopoulos, & Warren, 2023; Maeng, Kim, & Cho, 2021; Nikitas et al., 2022). AV designers and manufacturers should develop effective mitigation strategies, and actively inform, educate, and engage the public in the design and deployment of AVs. This will ensure that AVs meet the needs of a diverse group of road users.

Given the significant negative associations between road user education and visual eHMIs (displays) communicating the intentions of the AV to road users, road user education may reduce the need for these types of eHMIs, or conversely, visual eHMIs may reduce the need for road user education. We encourage future research to explore this relationship further. However, given that participants expressed a lack of knowledge regarding how to communicate with AVs, road user education remains essential, as it may help mitigate unintended behavioral effects. We posit that a comprehensive approach that relies on diverse communication channels (e.g., engagement with non-governmental organizations, mass media, social marketing) becomes necessary (see Zhao et al., 2024).

4.4. Limitations and future research

First, our participants did not have direct experience with visual eHMIs, as AVs equipped with such systems were not available during the data collection for this study.

Second, the data in this study reflect participants' subjective perceptions, and we were unable to objectively verify how closely these perceptions align with their actual experiences.

Third, our small binary convenience sample overrepresented highly-educated individuals, meaning the results may not be representative of the more broader and diverse population. Further research is needed with more gender-, age-, ethnicity/race- and education-balanced samples that reflect the varied road user groups that these populations represent, taking into account cross-cultural and national differences in perceptions and behaviors.

Fourth, we used ChatGPT as second coder for the data analysis. The performance of ChatGPT varies across domains, and depends on the unambiguity and clarity of the prompts (Zhang et al., 2023). We recommend future research to evaluate ChatGPT's performance in transportation science, making adjustments and assessing its accuracy based on specific prompts (Zhang et al., 2023), and comparing it with the judgements of human coders.

Fifth, we did not operationalize or provide evidence for when theoretical saturation was reached (i.e., at which interview). Future qualitative research should define an initial sample to be interviewed in the first round of analysis and establish a stopping criterion based on the expected number of interviews that no longer generate new insights or ideas. Researchers could also provide frequency graphs to support their assessment that saturation has been achieved (Vasileiou et al., 2018).

Sixth, it was beyond the scope of this study to provide a comprehensive analysis of the differences in perceptions and behaviors across the road user groups we recruited. We recommend that future research conducts a detailed analysis of how internal (e.g., passengers, drivers) and external road users (e.g., VRUs, car drivers) differ in terms of key cognitive and affective constructs, as well as their interaction and communication behaviors.

CRediT authorship contribution statement

S. Nordhoff: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **M. Hagenzieker:** Writing – review & editing, Supervision, Conceptualization. **Y.M. Lee:** Writing – review & editing, Conceptualization. **M. Wilbrink:** Writing – review & editing, Conceptualization. **N. Merat:** Writing – review & editing, Funding acquisition, Conceptualization. **M. Oehl:** Writing – review & editing, Conceptualization.

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Appendix A

Table A1
Interview instructions and questions.

Instruction / question	Question
Introduction	Dear participant, welcome to the interview, in which we would like to explore your experiences regarding your interactions with an automated vehicle (AV). During the interview, we want to understand your general experiences with the AV in that interaction, and the benefits and risks associated with interacting with the AV in comparison to human-controlled cars. We will specifically explore the role of so-called eHMIs (external Human Machine Interfaces). An eHMI is defined as communication device located on the outside of the vehicle that can communicate to surrounding road users. An example is an electronic display on the front of the car. We define an automated vehicle as SAE Level 4 automated vehicle that controls the lateral and longitudinal part of the driving task normally without the need of the human user to intervene in the vehicle's operations. Still, a human may be present in the driving seat as user of the automated vehicle. Please remember that you are the expert in this study. There is no wrong answer. Your unique experience with the AV matters, and we are excited to learn from this experience and get inspired by you! Let's start!
Informed consent	Who is responsible for the research project? Delft University of Technology (TU Delft) is the institution responsible for the project. We will collect the following data: An audio tape and video recording of the interview will be made. Note that you can switch off your camera. In this case, only an audio recording will be made. General demographic information you provide us by filling in the questionnaire as well as your opinions pertaining to the relevance of communication and interaction between automated vehicles and vulnerable road users. Note that you are free to leave parts of the questionnaire not answered if you do not wish to answer certain questions. Participation is voluntary Participation in the project is voluntary. If you chose to participate, you can withdraw your consent at any time without giving a reason. All information about you will then be made anonymous. There will be no negative consequences for you if you chose not to participate or later decide to withdraw. Your personal privacy – how we will store and use your personal data We will only use your personal data for the purpose(s) specified in this information letter. We will process your personal data confidentially and in accordance with data protection legislation (the General Data Protection Regulation and Personal Data Act). During the course of this project, all data will be stored on local servers maintained and automatically backed up by TU Delft ICT. Only team members will have access to the designated server, limited to project leader and supervisors. The audio files from the interviews will be transcribed and then deleted within the end of the project (no later than 31.06.2025). Any personal data from the transcripts will be anonymized and no personal information will be recognizable in publications. Your rights Access the personal data that is being processed about you. Request that your personal data is deleted. Request that incorrect personal data about you is corrected/rectified. Receive a copy of your personal data (data portability), and Send a complaint to the Data Protection Officer or the Faculty Data Steward. Where can I find out more? If you have questions about the project, or want to exercise your rights, contact: TU Delft via Sina Nordhoff (s.nordhoff@tudelft.nl). Informed consent I hereby declare that I have been informed in a clear manner about the nature and method of the research. I agree, fully and voluntarily, to participate in this research study. With this, I retain the right to withdraw my consent, without having to give a reason for doing so. If my research results are used in scientific publications or are made public in another way, this will be done such a way that my anonymity is completely safeguarded

(*continued on next page*)

Table A1 (*continued*)

Instruction / question	Question
	My personal data will not be passed on to third parties without my express permission. I have received and understood the information about the project and have been given the opportunity to ask questions. I give consent: I give consent for my personal data to be processed until the end date of the project, approx. 31.06.2025. Please write down your name, provide your signature and the date and location.
Type of road user (Q1)	Please select which of the following response options describe your experience with AVs best. I am passenger user of self-driving cars. I live in an area in which self-driving cars are tested and share the road with them mainly as pedestrian. I live in an area in which self-driving cars are tested and share the road with them mainly as cyclist. I live in an area in which self-driving cars are tested and share the road with them mainly as motorcyclist. I live in an area in which self-driving cars are tested and share the road with them mainly as car driver. I live in an area in which self-driving cars are tested and share the road with them mainly as other type of road user:___________ I live in an area in which self-driving cars are tested and share the road with them mainly as driver of emergency vehicle (e.g., police, firefigther).
Q2	Please describe the AV that you interacted with, e.g., how it looked / the key features that it had.
Q3	Do you know from which company the AV was? If yes, please write the name of the company in the field below.
Q4	How did you know that it was an AV, and not a conventional human-controlled car? (1 = Yes, 2 = No, 3 = I am not sure)
Q5	Did the AV have a steering wheel? (1 = Yes, 2 = No, 3 = I am not sure)
Q6	Was there a human driver behind the steering wheel? (1 = Yes, 2 = No, 3 = I am not sure)
Q7	Could you describe a typical interaction that you had with the AV and your general experience with it, and the benefits and risks in comparison to the interaction with a human-controlled car.
Q8	Did you interact and communicate differently with the AV in comparison to how you commonly interact with a human-controlled vehicle? If so, please describe the difference and explain why it may exist.
Q9	What / which factors did impact how you interacted and communicated with the AV? Please explain.
Q10	Did the AV communicate with you, if so, how? Please explain.
Q11	Did the AV communicate to you that it has seen you? If so, how? Please explain.
Q12	How did / do you communicate with the AV? Please explain.
Q13	What kind of information would you need from the AV in addition to the information that the AV communicated to you? Please explain.
Q14	Now, with the next section we would like to specifically explore the role of eHMIs. To recap: eHMIs are external communication devices located on the outside of the AV to communicate to surrounding road users.
Q15	In your interaction with the AV, did you notice that an eHMI was located on the outside of the AV, and if so, how did it look / which features did it have? Please explain.
Q16	Did the information displayed on the eHMI affect your interaction with the AV? If so, how? If not, why not? Please explain.
Q17	Did you rely on eye contact or hand gestures of the driver / operator of the AV? Why / why not? Please explain.
Q18	In which situations in which you interact/ed with the AV did you rely on the information displayed on the eHMI in your interaction with the AV? Please explain.
Q19	Did the AV with whom you interacted on public roads communicated with multiple external road users, if so, how? If not, do you think that AVs should be able to communicate to multiple external road users at the same time? Why / why not? Please explain.
Q20	If the AV did not use an eHMI, what do you think about eHMIs as external communication devices located on the outside of the vehicle to communicate to you as external road user? Please explain.
Q21	Do you think eHMIs are needed, relevant? If so, why, why not? Please explain.
Q22	In which traffic situations would you rely on eHMIs in your interaction with the AV? Please explain.
Q23	Can you think of an interaction with the AV in which you did not feel safe. Please explain why you considered this interaction as unsafe, and how you interacted and communicated with the AV in that situation.
Q24	Now I would like that you think of your perfect interaction and communication with an AV (it does not have to be realistic). Some of the questions below may help you to organize your thoughts … How would AVs behave towards you in a perfect world? Why? How would you like to communicate with the AV? Why? How should the AV communicate to you? Why? Which characteristics would this type of communication (medium) have? Why? Which information should be displayed / should not be displayed? Why?
Q25	There is currently a large number of eHMIs (> 70) proposed by industry and academy. What do you think: Shall we develop more, stop developing eHMIs, or do something else? Please explain.
Q26	What do you think about the standardization of eHMI design? Please explain.
Personal information	With the final questions, we would like to collect some personal information.
Q27	Where do you currently live?
Q28	What year were you born?
Q29	What is your gender?
Q30	What is your profession?
Q31	What is the highest level of education that you have completed (including ongoing education or studying at the moment)?
Q32	Please indicate how often you interacted with the AV.
Q33	How many adults live in your household?
Q34	How many children under 18 years of age live in your household?
Q35	What kind of environment do you live in?
Q36	How many years of driving experience do you have?
Q37	Do you have a car available for your use?
Q38	Approximately how many miles did you typically drive in the last 12 months as a driver?
Q39	On average, how often do you drive a car?
Q40	On average, how often do you use public transport?
Q41	On average, how often do you use active travel modes (walking more than 500 m and cycling)?

(*continued on next page*)

Table A1 (*continued*)

Instruction / question	Question
	Thank you so very much for your time and effort that makes this research study possible. If you have any additional comments, remarks, or questions, feel free to share them here. For further inquiries, you could also contact Sina Nordhoff at s.nordhoff@tudelft.nl.

Note: The responses to the questions Q25-Q26 were not analysed.

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.trf.2025.01.024.

Data availability

Data is made available upon request.

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