Editorial to the Special Issue on Road User Interactions in the Age of Vehicle Automation

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1. Introduction

In the last decade, the introduction of vehicle automation, also termed Automated Driving Systems (SAE J3016) or automated vehicles (AVs), has motivated novel approaches to exploring safe interactions among road users. A unique focus that has emerged is how AVs will integrate with existing traffic that includes a variety of road users. This special issue of TRF (SI; papers denoted with *) punctuates a decade of research on the interaction of other road users and AVs and brings together 15 articles from across the globe exploring a wide range of road user interactions—including those between drivers, cyclists, pedestrians, and automated vehicles (Figure 1).

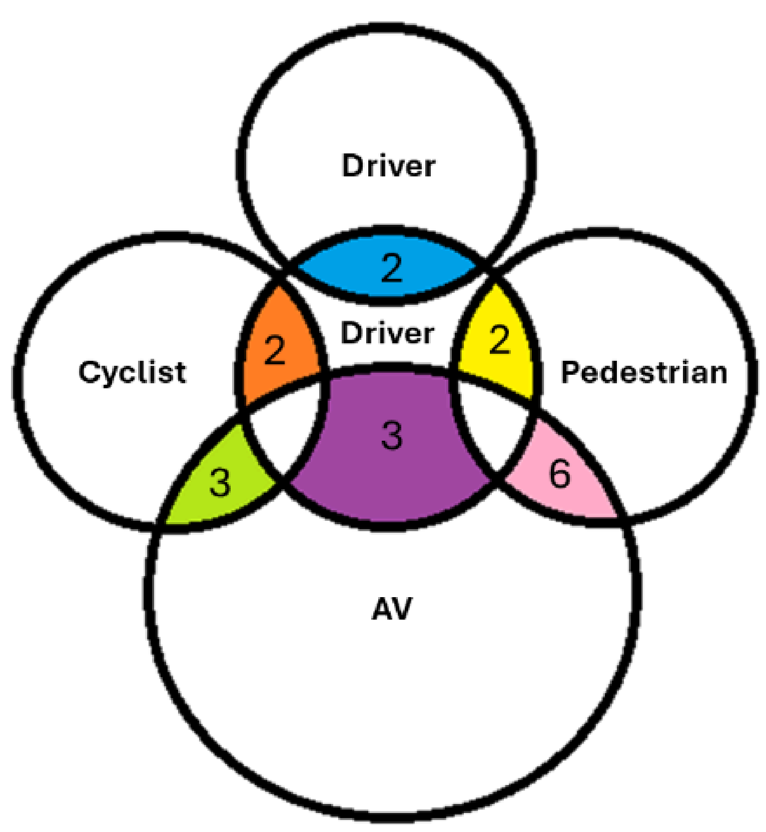

Figure 1. Interactions included in the SI articles.

We use three overarching themes to synthesize the articles: current mechanisms used in road user communication, or the fundamental aspects of kinematic cues, explicit signals, and their combination (section 2); integration of AVs into traffic, or how their presence reshapes the communication between road users (section 3); and context dependency of road user communication, or how interactions differ based on the traffic scenario or individual differences (section 4). The contributions employ diverse methodologies, including four naturalistic studies, three Wizard-of-Oz studies, four head-mounted display experiments, and four driving simulator studies. The papers span a broad set of use cases and scenarios, with several also addressing individual differences. Notably, many articles examine multiple interaction types and apply more than one method, reflecting the complexity and richness of this research domain (Table 1). Finally, we highlight how these articles are connected to trends in vehicle-road user communication and traffic psychology and behaviour in general.

Table 1. Range of articles included in the SI. Abbreviation under 'Type of Other Road User (ORU)': Driver-Driver (D-D); Cyclist-Driver (C-D); Pedestrian-Driver (P-D); Pedestrian-Automated Vehicle (P-AV); Driver-Automated Vehicle (D-AV); Cyclist-Automated Vehicle (C-AV)

No.	Citation	Type of ORU	Methods	Use Cases and Scenarios	Countries	Themes
1	Felbel et al (2025)	D-D	Naturalistic data	Motorway	Germany	2.1,4.1
2	Mohammadi et al. (2025)	C-D	Naturalistic data	Unsignalised intersection	Sweden	2.1
3	Pipkorn et al. (2025)	P-D	Naturalistic data	Protected (traffic light/stop sign), Designated (zebra), Undesignated	USA	2.2, 4.1
4	Theisen et al. (2025)	P-AV	Head Mounted Display	Undesignated crossing	Germany	2.2
5	Yang et al. (2024)	P-D	Distributed Simulator (pedestrian&driving sim)	Designated (zebra), Undesignated (non-zebra)	UK	2.2, 4.1
6	Harkin et al. (2025)	C-AV&P-AV	Wizard of Oz with an onsite questionnaire	Signalised intersection with turning AV	Germany	3.1, 4.2
7	Mohammad et al. (2024)	D-AV	Driving simulators (Reversed Wizard of Oz)	Rural road (overtaking)	Netherlands	3.1, 3.3
8	Berge et al. (2025)	C-AV	Wizard of Oz; Eye Tracking; Interview	Unsignalised Y intersection	Netherlands	3.1
9	Brill et al. (2024)	C-AV&P-AV	Questionnaire with Images	Shared space	UK&Australi a	3.2, 4.2
10	Lau et al. (2024)	P-AV	Head Mounted Display	Shared space	Germany	3.2
11	Gwak et al. (2025)	D-AV	Driving simulator	Motorway (merging)	Japan	3.2
12	Pan&Shi (2025)	D-AV	Driving simulator	Motorway (overtaking)	China	3.3, 4.2
13	Zhang&Theisen (2024)	C-D&D-D	Naturalistic data	Unsignalised intersection	Germany	4.1
14	Hubner et al. (2024)	P-AV	Head Mounted Display, Eye Tracking, Questionnaire	Undesignated crossing	Germany	4.1

15	Tran&Parker (2024)	P-AV	Head Mounted Display, Interview	Undesignated crossing	Australia	4.1

2. Current Mechanisms Used in Road User Communication

This section focuses on how current communication unfolds among road users. A key finding from prior research is that road users primarily rely on kinematics, or movement cues, to determine whether to yield (Domeyer et al., 2022). In this SI, Felbel et al. (2025)* and Mohammadi et al. (2025)* highlight how explicit and implicit signals are used in different scenarios. Meanwhile, Pipkorn et al. (2025)*, Theisen et al. (2025)*, and Yang et al. (2024)* investigated how interactions unfold over time.

2.1 Use of Explicit and Implicit Signals

In a verbal diary study about lane changes, Felbel et al. (2025)* found that 42% of communication relies on implicit cues (e.g., longitudinal and lateral movement), 45% were about context (e.g., vehicle spacing and traffic environment), and only 13% were about explicit cues (e.g., indicators), demonstrating the how signals are used as communication cues for drivers on the motorway. The authors concluded that the qualitative interpretation of drivers offers insights into how automated driving styles (e.g., lateral offset before using the indicator or changing lanes) could emulate human-like behaviour, helping to make AVs more intuitive and predictable for road users. Similarly, in a game-theoretic model of drivers and cyclists, Mohammadi et al. (2025)* showed that, while drivers relied on kinematic cues, other behaviours such as glances towards the vehicle and pedalling informed driver yielding behaviour. In addition, professional drivers were less likely to yield, suggesting an effect of experience (discussed further in Section 4).

2.2 How Road Users' Behaviour Evolves Over Time

Pipkorn et al. (2025)*, Theisen et al. (2025)*, and Yang et al. (2024)* focused on how road users' behaviours evolve over time during interactions. One salient finding from this research is that the interactions change from early kinematic cues to incorporating more frequent explicit cues as the road users get closer to one another. Pipkorn et al. (2025)* used Hidden Markov models to show patterns in movement, gaze, and waving behaviour between drivers and pedestrians. Sixty percent of the encounters included bidirectional communication where drivers and pedestrians exchanged cues. This was usually at the beginning of the encounter. The bidirectional communication evolved into unidirectional communication later in the interaction where only the driver or pedestrian were sending signals. Theisen et al. (2025)* also investigated the evolution of signals—using an omnidirectional treadmill, which allows continuous walking in virtual reality. They found that the prominent indicator of pedestrians' crossing intention at the beginning of the interaction is characterized by head movements, where latter parts of the interaction are related to pedestrian walking speed. Finally, in a distributed simulation study, Yang et al. (2024)* examined the reciprocal behaviour of drivers and pedestrians at zebra and non-zebra crossings. They found that drivers' decisions were bimodal, occurring early or late, during interactions with pedestrians. Drivers who braked *soft and early* or *hard and late* produced more intentional crossing behaviour than other combinations of timing and magnitude. In addition, drivers moved laterally away from pedestrians when they were not yielding or towards them when they were yielding. These studies reveal new findings about the behaviours of road users over time, which may be useful for determining whether and when to deploy interventions to reduce conflicts.

3. Integration of AVs into Existing Traffic Settings

This section investigates how road user behaviour is influenced by the communication cues provided by AVs when they are introduced into existing traffic settings. Examples include studies how road user behaviour changes after they identify an AV and how the AV's kinematics or the use of novel eHMIs influences road user behaviour. In this SI, Mohammad et al. (2024)*, Harkin et al. (2025)*, and Berge et al. (2025)* explore how human-like behaviour can ease the introduction of AVs into existing traffic settings. In addition, Brill et al. (2024)*, Lau et al. (2024)*, and Gwak et al. (2025)* investigate whether eHMIs can aid in their introduction. Finally, Mohammad et al. (2024)* and Pan and Shi (2025)* use vehicle kinematics as a communication mechanism to further integration goals.

3.1 Introducing AVs into Traffic

One of the first questions posed by the introduction of AVs is whether other road users behave differently towards these vehicles compared to manually-driven vehicles (MVs). Using a range of Wizard-of-Oz (WoZ) techniques, Mohammad et al. (2024)*, Harkin et al. (2025)*, and Berge et al. (2025)* found that integrating human-like behaviour into AVs reduces the tendency of road users to behave differently. In WoZ studies, a vehicle is operated by a hidden driver, simulating the appearance of a "driverless" vehicle for participants (Rothenbücher et al., 2015); the opposite of this—reverse WoZ—is a related approach where participants believe they are interacting with another human, while the system is, in fact, pre-programmed. Using WoZ, Harkin et al. (2025)* examined pedestrian and cyclist behaviour at a signalised turning intersection and found that interactions with apparent AVs were associated with shorter crossing initiation times and more frequent head turns towards the vehicle—both during and after crossing—compared to MVs. Despite these behavioural differences, road users did not report reduced feelings of safety, although only 18.7% correctly identified the vehicle as an AV. The authors concluded that when AVs behave in expected ways, their impact on behaviour and perception is minimal, though not absent. In another WoZ-type study, Mohammad et al. (2024)* used the reverse WoZ and presented the same vehicle kinematics for both AVs and MVs in driving simulators and found no differences in driver behaviour in an overtaking scenario. As described in Mohammad et al. (2024)*, studies that primed participants about AVs tended to find differences in road users' behaviour towards AVs, whereas those that did not often observed no distinction in how road users behave towards AVs and MVs. This insight is echoed by Berge et al. (2025)*, whose WoZ study found that 30% of cyclists noticed the absence of a driver, but the percentage rose to 98% when prompted by the experimenters. This is similar to the findings by Harkin et al. (2025)*, who found that cyclists felt safe during interactions with apparent AVs.

3.2 Response to eHMI

A subset of studies in this SI addresses eHMI implementation for AVs. The most commonly evaluated eHMI signal is one that communicates "yielding". Although eHMIs can lead to earlier decision-making (Madigan et al., 2023) and improved subjective experiences (Habibovic et al., 2018), their need and implementation remain a subject of debate (de Winter & Dodou, 2022). Concerns include over-reliance by road users and the potential for conflicting signals from multiple sources (Holländer et al., 2019).

In this SI, Brill et al. (2024)* used an online image-based questionnaire and found that eHMIs increased pedestrians' willingness to cross and feelings of security and relaxation. For cyclists, however, eHMIs improved only perceived security, with no effect on willingness to cross or relaxation, suggesting the need for targeted interventions based on user type. Similarly, Lau et al. (2024)* focused on subjective attitudes as well as crossing intention using a head-mounted display study. They compared a static eHMI which communicates AV status, a dynamic eHMI which communicates AV status and yielding, and no eHMI, on large and small AVs that were either yielding or not on crossing intention. Dynamic eHMIs led to the earliest crossing initiation and the highest trust, perceived safety, and pleasantness regardless of vehicle size. However, when dynamic eHMIs were paired with non-yielding AVs, about 10% of participants (3/31) crossed unsafely compared to none when no eHMI or static eHMI was presented with non-yielding AVs, indicating potential risks when incongruent behaviour was presented.

Moving beyond a comparison of presence versus absence, Gwak et al. (2025)* investigated the timing of eHMI that communicates AV status on automated platooning trucks. Their simulator study showed that eHMI presented at the start of a merge reduced ease of avoiding the merging truck and increased risky behaviours (e.g., abrupt lane changes, yielding, higher jerk values). In contrast, eHMI presented 300 m ahead from the beginning point of merging lane instead of at the beginning point, further improved ease of avoidance without compromising safety, highlighting the critical role of timing for eHMI to avoid unintended consequences.

These studies show the challenges in determining the benefits of eHMI, as their potential benefits and risks are highly context-dependent.

3.3 Response to AV kinematics

In addition to eHMIs, two studies in this SI explore the use of vehicle behaviour (i.e., kinematic cues) as signals that may be used by AVs to communicate intent. Pan and Shi (2025)* and Mohammad et al. (2024)* used driving simulators to examine AVs' driving style and kinematics manipulation on drivers' behaviour in overtaking scenarios. First, Pan and Shi (2025)* showed that the driving styles of the preceding and opposing AVs (i.e., other lane) affected subjective ratings of the drivers. In addition, more aggressive AV driving styles led to longer following distances and positioned closer to the edge of the road. They concluded that aligning the AV behaviour with human expectations can enhance acceptance and safety. However, Mohammad et al. (2024)* incorporated brief deceleration "nudges" to signal intention but did not find an effect on gap acceptance or response times, perhaps due to limitations in humans' ability to perceive these nudges in the simulated environment. However, they found that there were individual differences in these responses. Mohammad et al. (2024)* demonstrate the power of cognitive models in deciphering driver responses to AVs.

4. Context Dependency of Road User Communication

This section focuses on how interactions change based on the use cases and traffic scenarios, and are influenced by individual differences. We encourage readers to reflect on the role of context in shaping each study's conclusions, and to consider the caution when generalising findings across different scenarios and with different populations. In this SI, papers highlight how context continuously evolves and affects communication (Felbel et al., 2025)[*], the role of infrastructure (Pipkorn et al., 2025; Yang et al., 2024)[*], regional traffic rules (Zhang&Theisen, 2025)[*], and multi-agent interactions (Hübner et al., 2025; Tran&Parker, 2025)[*]. In addition, other studies explore individual differences related to region and demographic factors (Brill et al., 2024; Harkin et al., 2025; Pan & Shi, 2025)[*].

4.1 Use Cases and Scenarios

One topic that is highlighted by Felbel et al. (2025)* is how context is a dynamically changing element of driving. They found that the importance of implicit and explicit cues in lane change behaviours is different across contexts—including in overtaking, slow traffic, ambiguous behaviour of other vehicles, and entrance and exit ramps. This highlights the need to identify key elements of scenarios that influence behaviour.

Pipkorn et al. (2025)* and Yang et al. (2024)* both investigated how infrastructure (e.g., zebra crossing) affects patterns of behaviour. Pipkorn et al. (2025)* found that zebra crossings and stop signs had the lowest rate of bidirectional interaction while moving, suggesting that the infrastructure mediates the communication requirements. Yang et al. (2024)* found higher deceleration and closer lateral and longitudinal proximities for zebra crossings compared to unsignalized crossings. These studies suggest that the communication afforded by infrastructure shapes road user interactions.

Zhang and Theisen (2025)* took an interesting approach for understanding implicit communication by examining drivers' and cyclists' adherence to the "priority-to-the-right" rule in Germany using naturalistic data. They found that, while cyclists are more likely to disregard the rule, all road users are more likely to relinquish priority if they are turning right, arriving later, and encountering an opposing road user who is close to the centre of the road, showing that regional rules may influence emergent norms in traffic interactions.

Tran and Parker (2025)* and Hübner et al. (2025)* focused on multi-agent scenarios and their challenges. Hübner et al. (2025)* found effects of group crossing in a virtual reality study, resulting in participants crossing earlier and more confidently. Tran and Parker (2025)* focused more on the methodology of virtual reality experiments and conclude that feelings related to the social aspects of interactions are important factors for influencing realism of the experience. Overall, the effects of group dynamics remain challenging to study, and an important aspect of aiding AVs in their decision-making.

4.2 Individual Differences

AVs will interact with diverse road users, making AV-human interactions complex. Subjective experiences such as comfort, perceived safety, and willingness to cross can vary considerably across these groups.

In this SI, Brill et al. (2024)*, using images in an online questionnaire, found that males, younger individuals, regular cyclists, and Australian (compared to the UK) participants reported more positive feelings when interacting with AVs compared to their respective counter groups. Harkin et al. (2025)* report that older pedestrians perceived greater safety when interacting with AVs in a WoZ study. Their observational data also showed that younger participants and males looked back at vehicles more frequently while crossing, possibly reflecting heightened interest in technology or different risk perception. In addition, Pan and Shi (2025)* found that female drivers have lower dynamic trust and higher perceived risk, despite their lower objective risk than male drivers. These studies demonstrate the complexity of subjective and objective measures with respect to demographic factors.

While findings on demographic influences remain mixed, this may be due to the predominance of exploratory rather than theory-driven approaches, limiting our understanding of the mechanisms behind these differences. Nonetheless, diversity in research remains an important aspect of building AVs that are widely used, not only including demographic diversity but also diversity of human capabilities and limitations.

5. Discussion

The articles included in this SI highlight several key themes relevant to future research on AV-other road user interactions. These include: (1) primacy of vehicle movement, (2) the effect of temporal aspects on how interactions evolve, (3) the challenges of evaluating communication, (4) context-dependency in interactions, and (5) the importance of diverse populations. They also showcase a variety of methods and analysis techniques.

In addition to the findings from the articles contained within this SI, we provide our perspective on where AV-road user interaction research stands after a decade of work. This is briefly outlined below.

5.1 From Understanding Road User Communication to Designing Human-like AV Behaviour

To design effective AV behaviour, it is essential to translate our understanding of current mechanisms used in road user communication into data-driven AV integration strategies. By grounding design in how humans naturally interact and communicate with each other on the road, we are better positioned for developing AVs that will be accepted and understood by human road users. These may be through development of human-like kinematic behaviours (e.g., driving styles, time-varying dynamics) or explicit signals (e.g., eHMIs), while also considering known capabilities and limitations in human perception, decision-making, and response. Finding the appropriate way to emulate humans can be challenging because normative behaviours often diverge from optimal behaviours, and behavioural noise may in fact serve as a mechanism to aid coordination.

Key future directions for a general understanding of road user behaviour are (a) using the knowledge about the current interaction context to define challenging scenarios for testing interventions, and (b) characterising the extent to which human-like behaviours are needed based on the individual, social, and local norms.

5.2 The Role of eHMI: Nuance, Timing, and Context

Current research challenges the assumption that additional explicit cues, such as an eHMI, will reduce ambiguity and help resolve road user interactions. This assumption has oversimplified the complexity of real-world encounters, leading to contrived scenarios that overlook side effects that might introduce risk. Effective communication depends not only on the presence of signals, but also on *when* they are presented, *how* they are interpreted by one or many road users, and the potential for *unintended consequences*. The need for eHMIs, therefore, remains unclear without clear metrics to evaluate them.

To this end, ISO/TR 23049:2018 and ISO/PAS 23735:2025 were careful in providing principles and guidance for eHMI and noted that, if used, they should: (1) be coordinated with the vehicle's motion and not in contradiction, (2) not provide advice to road users since it is not possible to account for every context, and (3) limit the number of messages to as few as possible (i.e., three or less). Importantly, these ISO documents make no determination about whether eHMIs are needed, only how to constrain them to be appropriately used.

Key future directions for designing suitable interactions by AVs include: (a) identifying specific use cases to investigate how AVs should be designed, through in-depth understanding of current mechanisms used in road user communication, (b) moving beyond simple comparisons of eHMI versus no eHMI toward a more theoretical approach that includes perceptual needs as well as top-down and bottom-up processing of information, and (c) exploring the temporal aspects of interactions and how eHMIs interact with kinematic behaviours.

5.3 Evaluating AV Communication Design

Finally, if this research area intends to influence design, it must seek data-driven performance criteria and associated design recommendations. Too often, traffic psychology and behavioural research focuses on simple comparisons of interface options, without strong theoretical support. To achieve this, we need clear criteria and thresholds with appropriate behavioural references, such as models of *normative and/or safe* road users.

6. Conclusions

This SI provides an inflection point as we consider where AV-other road user research began and where it needs to go. With an increased deployment of AVs on our roads and the prospect of a true mixed traffic environment becoming a reality, it is important that this research progresses towards a better understanding of appropriate design options for guiding the AV's behaviour and means of communication, during its interactions with a range of other road users. We hope that this SI renews interest and leads to an expansion of this valuable work.

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