Exploring Road Traffic Interactions Between Highly Automated Vehicles and Vulnerable Road Users

Victor Fabricius
Abstract

Understandings of road traffic interactions are largely based on human-human interactions. However, the development of vehicles controlled by highly automated driving systems (ADS) would introduce a radically novel type of road user. This compilation thesis explores encounters between these “autonomous vehicles” (AVs) and human vulnerable road users (VRUs) such as pedestrians and cyclists. The included publications are connected to three research questions. First, empirical studies are reviewed to highlight existing interactive behaviors and communication cues. This is followed by a methodological question of how to investigate AV-VRU interactions. Finally, VRUs’ experiences from initial experiments on AV crossing encounters are presented.

While road user trajectories and kinematic behaviors are viewed as primary mechanisms to facilitate traffic interactions, they might also be influenced by cues such as appearances, gestures, eye-gaze, and external human-machine interfaces (eHMI). Using the Wizard-of-Oz approach, we are able to explore VRU encounters with a seemingly highly automated vehicle. Compared to meeting an attentive driver, AV encounters resulted in a reported lower willingness to cross, lower perceived safety, and less calm emotional state, indicating that the absence of driver-centric cues could lead to interaction issues and impede acceptance of AVs. To further explore this, we included light-based eHMI to signal the driving mode and intent of the vehicle (e.g., intent to yield). Future research should continue to investigate how AVs may co-exist with human road users focusing on aspects such as behavioral adaptations, research methodologies, and the role of various eHMI.
List of Publications

This compilation licentiate thesis includes the following papers.


**Additional Publications**

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### Abbreviations

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<tr>
<th>Acronym</th>
<th>Full Form</th>
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<tbody>
<tr>
<td>ADS</td>
<td>Automated Driving System</td>
</tr>
<tr>
<td>AI</td>
<td>Artificial Intelligence</td>
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<td>AV</td>
<td>Autonomous Vehicle</td>
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<td>HMI</td>
<td>Human-Machine Interface</td>
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<td>HCI</td>
<td>Human-Computer Interaction</td>
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<tr>
<td>VRU</td>
<td>Vulnerable Road User</td>
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1 Introduction

1.1 Motivation

New transportation technologies have historically impacted our use, perception, and design of road space. Whether this was the bicycle, tram, motorcar or today’s e-scooters, a new set of rules and societal norms have emerged following each transition, and this in turn has affected how road users are expected to behave within the traffic environment. Existing understandings of road traffic interactions are largely based on human-human interactions and common categories of road users are set by their characteristics, such as, form factor, weight, and relative risk exposure (e.g., personal vehicle, heavy goods vehicle, vulnerable road user etc.). The development of vehicles controlled by highly automated driving systems (ADS) - i.e., autonomous vehicles (AVs) able to take over the complete driving task - would introduce a radically novel type of road user, extending the traffic landscape beyond the primarily human-human interactions that characterize it today. While there are strong business motifs for this development, potential societal benefits include increased traffic safety and a more efficient use of time and other resources. There are multiple scenarios where AVs could operate, including within 1) completely segregated networks, 2) semi-segregated highway/urban networks, and 3) shared road spaces (Parkin et al., 2018). While the first scenario could include occasional AV-human interactions (e.g., within a terminal area), it is the public contexts that highlights the need for co-existence between AVs and human road users. This includes vulnerable road users (VRUs), such as pedestrians and cyclists, who will become incidental users (Inbar & Tractinsky, 2009) of these systems as they encounter them in the traffic environment. As such, AVs must excel when it comes to technical capabilities and reliability, as well as in terms of social interaction and sharing the road with human road users. The research included in this compilation thesis is motivated by the need to explore AV-VRU interaction scenarios as AVs begin their journey towards technological acceptance (Davies, 1989) and adoption (Rogers, 1962).
1.2 Delimitations and Research Questions

The previous section points to an emerging research agenda of advancing understanding and guiding the development of how AVs and human road users co-exist and interact. Within this broader scope, the studies summarized in this thesis focuses on the perspective of vulnerable road users (VRUs) in the context of shared public road space. In addition, the research targets AVs controlled by highly automated driving systems capable of (conditionally) taking over the complete driving task (i.e., Level 4-5 on the driving automation taxonomy, SAE, 2021). The scope of the included publications is here summarized with the following research questions:

1. What interactive behaviors and communication cues can be identified in existing studies on road traffic interactions?
2. How can we study interactions involving highly automated driving systems (i.e., AVs) and VRUs?
3. What are VRUs’ experiences of encounters with AVs?

Research question 1 aims at highlighting existing interaction patterns, behaviors, and mechanisms that are used to facilitate traffic encounters and interactions. From this foundation of current practices, research question 2 raises the need for new insights with a methodological focus on how to practically investigate AV-VRU interaction scenarios. Finally, research question 3 addresses the results from these empirical studies.

1.3 Disposition

The remainder of this thesis is organized in the following way. First, a background section provides a brief theoretical account of interaction research, the notion of road traffic interaction (including some of its related concepts and proposed definitions) as well as theory related to AV-VRU communication. This is followed by a methods section explaining the adopted research approach, and summaries of the included papers. Finally, there is a section for discussion and suggestions for future work and a list of conclusions based on the three research questions.
2 Theoretical Background

2.1 Interaction Research Paradigms

While there is no consensus on what existing theoretical perspective is best suited for AV-VRU traffic interaction, the field of human-computer interaction (HCI) has a long tradition of studying people’s interactions with computational systems. The evolution of research within HCI is often described by three paradigms. These paradigms, or waves, have been summarized in the following way (Duarte & Baranauskas, 2016): The first wave focuses on human factors (favouring concrete problems and simple performance metrics). Interaction is perceived as a form of “man-machine coupling” that is improvable by solving ergonomics issues and decreasing interaction disruptions. The second wave is strongly connected to cognitive science and what happens in the human mind in terms of information processing. Interaction is perceived as a metaphor for “mind and computer as coupled information processors”. The concept of context also begins to come into focus. The third wave brings forth previously underrecognized and marginalized topics such as culture and values, along with a view of the active and influencing role of the researcher. Interaction is seen as a form of meaning creation where both artifact and its context exert mutual influence and subject to multiple interpretations. Duarte & Baranauskas (2016) state that although these three waves follow a chronological order, the emergence and acceptance of a newer wave does not in fact replace the existing ones. Even though there are significantly different views on how to conduct research between researchers positioned in different waves, it is important to observe that these waves seem to co-exist in the same scientific community.

Recent advances in artificial intelligence (AI) have been highlighted as argument for the need of a fourth wave in HCI research. One suggestion is a post-interaction computing paradigm driven by a transfer of value from interaction to data, and by the argument that the computing impacting human-computer relations is no longer happening only in, or within, the interaction itself, but also without and outside that interaction (Comber et al. 2019). Another suggestion is entanglement HCI (Frauenberger, 2019), which is based on the premise that humans and their things are inseparable
and that we need to elevate the role of the non-human from a passive backdrop to active contributors. Additionally, it has been suggested that the “black box”-nature of AI (i.e., with limited possibility of explaining outcomes by looking “under the hood”) necessitates a study of observable *machine behavior* (Rahwan et al., 2019). The authors conclusions include: 1) Studying machine behavior does not imply that AI algorithms necessarily have independent agency nor bear moral responsibility for their actions. 2) It is just as critical to understand how machine behavior varies with altered environmental inputs as it is to understand how biological agent behaviors varies depending on the environments in which they exist. 3) Machines exhibit behaviors that are fundamentally different from animals and humans, so we must avoid excessive anthropomorphism and zoomorphism.

### 2.2 Framing Road Traffic Interaction

The more general term *encounter* has been suggested for indicating the situation when road users have the possibility to accommodate one another, but do not have to because only one or neither has to adjust their behavior. The term *interaction* is then suggested for indicating when at least two road users adjust their behaviors in ways that could be interpreted as intending to accommodate one another (Domeyer et al., 2020a).

Markkula et al. (2020) seeks to align the traditionally scattered field of traffic interaction studies, identifying the following main theoretical perspectives: (1) traffic conflict and safety, (2) game theory, (3) sociology, and (4) communication and linguistics. Connected to these perspectives, researchers have studied interactions with different research interests, including investigating road users’ collision avoidance, order of access, coordination, reciprocity, and communication. Aiming to provide a cross-theoretical definition, the authors first specify the following two terms:

- **Space-sharing conflict**: An observable situation from which it can be reasonably inferred that two or more road users intend to occupy the same region of space at the same time in the near future.
- **Interactive behavior**: Road user behavior that can be interpreted as being influenced by a space-sharing conflict.

Based on this, they subsequently define *traffic interaction* as:

- A situation where the behavior of at least two road users can be interpreted as being influenced by a space-sharing conflict between the road users.
While it is important to align the field of traffic interaction studies around common definitions, research within HCI provides testament that the term interaction is broadly used and hard to define (Hornbæk et al., 2019; Hornbæk and Oulasvirta, 2017). This suggests that there should be room for additional perspectives such as extending the scope beyond conflicts and including indirect interactions between road users.

### 2.2.1 Interactive Scenarios in Road Traffic

Markkula et al. (2020) state that there are a limited number of ways two road users can approach an interaction space, and that these situations can be generalized into five prototypical space-sharing scenarios, including obstructed paths, merging paths, crossing paths, and unconstrained and constrained head-on paths (see Figure 1). When more than two road users are involved, multiple prototypes can apply simultaneously. Other researchers have proposed more extensive taxonomies of scenes, situations, and scenarios that include additional attributes and value facets (Ulbrich et al., 2015; Fuest et al., 2017).

![Figure 1. Five prototypical space-sharing scenarios based on Markkula et al. (2020).](Image)

### 2.2.2 Road User Behavior and Communication

Domeyer et al. (2020a) adapted the transactional model of communication explaining how communication is situated within interactional-, relational-, and societal layers relying on common ground (Clark & Brennan, 1991) between interactants to be successful (see Figure 2). Verbal and non-verbal communication, behavioral cues, context, and noise are examples of aspects composing and affecting a message, and each communicator acts and reacts depending on their background, prior experiences, attitudes, and cultural beliefs. Domeyer et al. (2020a) further suggest that it is the degree of interdependence between road users that will affect the need for communication and interactive behaviors. In earlier research (Johnson et al., 2014), interdependence has been defined as the set of complementary relationships that
two or more parties rely on to manage required (hard) or opportunistic (soft) dependencies in joint activity. Here, the term joint activity is a generalization of Herbert Clark’s (1996) work on joint action and describes situations when what one party does depends on what another party does (and vice-versa) over a sustained sequence of actions.

![Diagram of transactional model of communication](image)

*Figure 2. Transactional model of communication (Barnlund, 1970) adapted by Domeyer et al. (2020a).*

Still, getting around in traffic is often a straightforward activity consisting of *perceiving* and *moving* as the two fundamental tasks. Markkula et al. (2020) suggest three types of behavioral effects in relation to these tasks ("achieving", "signaling", "requesting"), resulting in actions that impact traffic situations in up to six ways (see Figure 3). On top of this, they identify a seventh (purely socially motivated) category of effect/impact where road users signal appreciation to each other. In terms of communication, road users’ interactive behaviors have also been classified into the following two main categories (ISO, in progress):

- **Implicit communication**: Behavior that can be interpreted as serving the purpose of conveying information to another road user, but also as serving some other purpose (e.g., locomotion).
- **Explicit communication**: Behavior that can be interpreted as serving the exclusive purpose of conveying information to another road user.
Indeed, the mechanisms through which road users communicate are diverse and include both explicit cues (such as hand gestures and turning indicators), and more implicit cues, commonly conveyed *via* road users’ kinematic behavior. The range of available channels for nonverbal communication typically includes body movements and gestures, managing space and territory, touch, tone, and appearance (Knapp et al., 2013), however, there are also other channels and mechanisms for sharing information such as verbal communication, text, signs, and symbols. Ultimately, universal questions of communication are concerned with accuracy, meaning, and effect (Shannon, 1948).

2.2.3 Factors Influencing Traffic Interactions

Road user behavior is influenced by elements such as infrastructure, traffic rules, and cultural expectations (Renner & Johansson, 2006) and can include actions that are more strategic in nature (aligning with a game-theoretic perspective) or that arise in less calculated ways. Based on pedestrian negotiation and decision-making in crossing scenarios, Rasouli & Tzotsos (2019) synthesized a figure showing 38 influential factors including pedestrian-centric factors (e.g., age, attention, past experiences etc.), and environmental factors (e.g., traffic characteristics, weather conditions, crossing infrastructure etc.). Similarly, Madigan et al. (2019) concluded that the level and criticality of interactions between vehicles and VRUs is influenced by three broad factors, environmental/situational characteristics, road user characteristics, and vehicle characteristics.
2.3 Vehicle-VRU Communication

The research topic of vehicle-VRU interaction and communication has grown substantially since the initiation of the studies summarized in this thesis. Lee et al. (2021) found that explicit driver communication strategies (e.g., use of eye contact, gestures, horn, and flashing headlights) are rare and VRUs reported using more vehicle-based, than driver-based, information to make crossing decisions. Dey & Terken (2017) concluded that the intent of the vehicle will be inferred from a momentary glance at the movement and body language of the oncoming vehicle, and VRUs will only resort to explicit communication when the expected behavior of the vehicle has been violated. Lee et al. (2021) suggested that explicit communication is more prominent when road users need to negotiate priority at lower speeds, during dead-lock scenarios, and encounters at short distances. In addition to investigating current interaction practices, AV-VRU research has focused on adding eHMI s to convey information from the AV to surrounding road users, envisioning how such (standardized) solutions could facilitate safe, efficient, and satisfactory future AV-VRU interactions (e.g., Tabone et al., 2021; Faas et al., 2020; Dey et al., 2020; Colley & Rukzio, 2020).
3 Research Approach

3.1 Research Within a Socio-Technical System

The AV-VRU domain can be viewed as a socio-technical system consisting of various actors (i.e., road users) in a context including physical- and digital infrastructure, transportation technologies, practices, rules, and norms. For the research and development of socio-technical systems, Woods & Christoffersen (2002) distinguish between efforts of advancing technology, developing problem-centered solutions, and advancing domain understanding and guiding change. They illustrate these perspectives as three cycles that should interlock to create the best opportunity for innovation and to promote proactive development where technology and solutions are grounded in what is needed and useful (see Figure 4). While this synchronization is challenging (i.e., the cycles run on different time scales, with specific goals and focus, and across organizational boundaries), failing to connect these perspectives may result in technological development based on short term trends, trial and error, perceived needs, and a research community tasked with documenting classic problems and well-known mistakes. In Figure 5, the three included research questions are positioned in a domain-specific adaptation of the research cycle of advancing understanding and guiding change. The following sections include further motivation of the included research activities.
Figure 4. “The Engine of innovation” as conceptualized by Woods & Christoffersen (2002).

Figure 5. Positioning of the included research questions within the research cycle. The text in the original model has been adapted for the AV-VRU traffic interaction domain.
3.2 Highlighting Existing Patterns

Webster and Watson (2002) state how a review of prior, relevant literature is an essential feature of any academic project, creating a firm foundation for advancing knowledge. It facilitates theory development, closes areas with an overlap, and uncovers areas where research is needed. In this thesis, Paper A includes a theoretical background for framing the notion of road traffic interaction, and a systematic literature review of a sub-set of traffic interaction studies. This is aimed at providing insights on road user interactive behaviors, practices, and abstracted patterns based on existing empirical studies.

3.3 Prototypes as Tools for Discovery

Investigating interactions with incomplete technology is clearly a challenge. One approach to inform systems under development is by so-called Wizard-of-Oz studies with a person “behind the curtain” simulating the system or interface (Dahlbäck et al., 1993). The empirical work summarized in this thesis comprise one of the first examples of using this approach to simulate the experience of interacting with an AV. It provides a probing technique and tool for discovery for starting to understand how these vehicles are to be perceived in the public traffic context, and a research platform to pose hypotheses about what could be useful when designing for appropriate AV-VRU interaction.

3.4 Road User Studies

Empirical studies related to road traffic interaction can be described as either controlled (e.g., repeatable studies on test sites or in simulators), semi-controlled (e.g., studies based on pre-determined scenarios or routes), or naturalistic (e.g., naturalistic driving/riding studies with instrumented vehicles). In general, controlled studies are often used to compare baseline conditions to other experimental conditions, while naturalistic studies enable investigations of behaviors and phenomena under real-life conditions. The road user studies included in this thesis follow a controlled experiment approach exploring envisioned future systems and AV-VRU scenarios. Data collection is largely based on self-reported measures using rating scales, stated preferences, and semi-structured interviews.
4 Summary of Papers

4.1 Paper A

This paper contains an extensive theoretical background (in line with what is included in this thesis) before reporting on a systematic literature review of a sub-set of existing empirical traffic interaction studies. Using the definitions and concepts presented in the theoretical background, we conducted a qualitative analysis of the selected studies to extract reports of road users’ interactive behaviors and communication cues. Table 1 shows an excerpt of the results, listing reported behaviors and cues followed by their motivation/effect, communication channel/mechanism, type of cue, and reference. In line with general traffic interaction literature, there are more frequent reports of interactive behaviors and (implicit) communication cues based on road user trajectories and dynamic behavior (i.e., nonverbal communication via movement and gestures (kinesics), space/position (proxemics), and timing (chronemics)). However, there are also examples of communication cues based on additional nonverbal categories including road user appearance and eye-gaze, existing interfaces (e.g., turning indicators), and new types of eHMI. Interactive behaviors and communication cues from road users can be viewed as vehicle-centric and driver/VRU-centric, as well as spontaneous (i.e., provided on a nonvoluntary basis), symbolic (i.e., provided deliberately to communicate), or pseudo-spontaneous (seemingly spontaneous but with a concealed intentionality). We conclude that the reviewed studies indicate that encounters and interactions are largely facilitated by implicit communication derived from road users’ movement-achieving and perception-achieving behaviors. In addition, explicit communication including eHMI, could be used for such things as appreciation-signaling, movement-signaling/requesting, or perception-signaling/requesting. The general appearance and attributes of interacting road users (e.g., appearance of VRU, light vs. heavy vehicle) can affect both objective outcomes and subjective experiences of encounters and interactions. In addition, AVs might need to compensate for the loss of driver-centric cues (e.g., eye-gaze, gestures).
Table 1. Examples of reported interactive road user behaviors/communication cues from crossing paths scenarios, including their motivation/effect, communication channel/mechanisms, type of cue, and references.

<table>
<thead>
<tr>
<th>Road user behavior/communication cue</th>
<th>Motivation/effect</th>
<th>Communication channel/mechanism</th>
<th>Type of communication cue</th>
<th>Reference(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle characteristics (large/heavy vehicle)</td>
<td>Sets expectations and may affect road users’ behavior such as gap acceptance</td>
<td>Appearance</td>
<td>More implicit cue</td>
<td>(Petzoldt, 2016)</td>
</tr>
<tr>
<td>Driver stopping farther from the stop line when a cyclist is present</td>
<td>Driver seeking overview and greater safety margin to VRUs</td>
<td>Proxemics</td>
<td>More implicit cue</td>
<td>(Pokorny and Pitera, 2019; Kircher and Ahlström, 2020)</td>
</tr>
<tr>
<td>Driver/cyclist glances towards other road users</td>
<td>Monitor the environment (i.e., perception-achieving behavior). Signal/request for movement or perception</td>
<td>Ocullesics, Kinesics</td>
<td>More implicit cue</td>
<td>(Kircher and Ahlström, 2020; Kircher et al., 2020; Richter and Sachs, 2017; Schindler and Bianchi Piccinini 2021)</td>
</tr>
<tr>
<td>Driver considerably reducing speed when encountering a VRU</td>
<td>Movement achieving/signaling/requesting</td>
<td>Kinesics</td>
<td>More implicit cue</td>
<td>(Schindler and Bianchi Piccinini 2021)</td>
</tr>
<tr>
<td>Cyclist waving arm</td>
<td>Thank driver after negotiation</td>
<td>Kinesics</td>
<td>More explicit cue</td>
<td>(Pokorny and Pitera, 2019)</td>
</tr>
<tr>
<td>Driver using turning indicators</td>
<td>Movement signaling</td>
<td>Human-machine interface</td>
<td>More explicit cue</td>
<td>(Thorslund and Lindström, 2020)</td>
</tr>
</tbody>
</table>
4.2 Paper B

Paper B presents the results of a controlled VRU experiment (n = 13) and complementing questionnaire study (n = 50) investigating the effect of a range of driver-centric cues on pedestrians’ willingness to cross and perceived safety during crossing encounters with a personal vehicle. Using the Wizard-of-Oz methodology to operate the vehicle, we were able to present different “driver” behaviors and vehicle conditions including 1) giving/not giving eye-contact, 2) using a phone, 3) reading a newspaper, 4) sleeping, and 5) empty driver’s seat (see Figure 6). Meeting an attentive driver resulted in a more frequent willingness to cross, more content/calm emotional state and higher perceived safety. Expectedly, the condition with the empty driver’s seat was a highly surprising and unfamiliar event functioning as a mediating experience when discussing a possible future with AVs.

Figure 6. Wizard-of-Oz vehicle set-up and experiment conditions included in paper B.
4.3 Paper C

This paper summarizes two additional vehicle-VRU experiments where pedestrians experienced crossing paths scenarios, at a zebra crossing (n = 9) and in a parking garage (n = 24). The participants were informed that they would be interacting with an experimental vehicle and were briefed on the Wizard-of-Oz set-up after the session. This approach was also used to control an added light-based eHMI prototype which included the signals/messages “AV mode”, “intent to yield”, “waiting/idle”, and “about to start driving” (see Figure 7). In the two studies, participants experienced experiment conditions based on 1) manual driving (i.e., an attentive driver), 2) AV driving (e.g., “driver” reading newspaper), and 3) AV driving + eHMI signals. In addition, the behavior of the vehicle was alternated between standing still, approaching, and passing by. In general, the pedestrians reported lower perceived safety when they encountered the AV without an eHMI, compared to manual driving and the AV with an active interface. This provides initial indication that the eHMI could contribute to a positive experience in terms of perceived safety in AV-VRU encounters – and might be of importance for AV acceptance and adoption. With the introduction of ADS functions and a transfer of control from the driver to the vehicle, VRUs cannot rely on driver-centric cues for information. The explored eHMI is an example of a minimalistic way of showing that the vehicle is in AV mode and what it intends to do next. Due to safety concerns, the interface will not advice pedestrians when to cross the road using messages such as “safe to cross” or “please go ahead”.

Figure 7. The AV-VRU crossing scenarios and research prototypes (vehicle + eHMI) included in paper C.
5 Discussion

5.1 Contributions and Method

With reference to the generic research cycle illustrated in Figure 5, the broader purpose of this research is to contribute to advancing understanding and guiding change in the emerging field of AV-VRU traffic interactions. The included studies and related research questions reflect a need for taking an exploratory approach for the initial cycle of this agenda, drawing inspiration from multiple theoretical sources and findings pragmatic ways to investigate envisioned AV-VRU futures. Here, research question 1 aims at highlighting existing patterns (largely based on human-human interactions) contributing to the understanding of established behaviors and practices as a foundation for AV-VRU studies. Following this, our subsequent studies leave the more passive role of observation and analysis, instead seeking new insights based on pragmatic approaches and including elements of design to explore possible futures. Figure 5 illustrate this need by highlighting that fields of practice (i.e., domains) are continuously evolving – forcing us to pose hypotheses about what might be useful and construct prototypes as tools for discovery. However, Woods & Christoffersen (2002) also state that there tends to be a plurality of (typically underspecified) envisioned futures, and that related predictions might be ungrounded and overconfident. For AV-VRU interaction, this suggests that we need to be careful when drawing conclusions and defining possible needs, problems, and solutions too early and too strictly. For example, VRUs’ experiences and attitudes might change substantially in relation to AVs - where adaptation and building of trust could result in a drastically different baseline for AV-VRU acceptance and experience. During the research activities summarized in this thesis, we have tried to align views and assumptions of the (AV) future by closely collaborating with developers and stakeholders.

Zamfirescu-Pereira et al. (2021) state how exploratory prototyping techniques are critical for devising new technology forms, actions, and behaviors, and for eliciting human responses to designed interactive features. We have made use of the Wizard-of-Oz methodology for creating safe, low-cost, and practical research prototypes. However, while this is a well-
established approach, it is not without methodological concerns. Firstly, there is the consideration that interactions with the simulated system or interface will be based on the capabilities of the human in control. While this is what enables rapid prototyping and flexibility, the operator’s abilities might not reflect the behavior of the envisioned autonomous system. According to Fraser & Gilbert (1991), to conduct a valid Wizard-of-Oz simulation the following requirements must be met: 1) It must be possible to simulate the future system, given human limitations; 2) It must be possible to specify the future system’s behavior; 3) It must be possible to make the simulation convincing. In our exploratory studies, we have constrained these requirements by conducting controlled experiments based on rather simple crossing scenarios. However, as we see a need for investigating more complex scenarios with multiple road users, the possibility of specifying the future system’s behavior will surely be more limited. In addition, there are clear ethical considerations when simulating/faking the actions of a system and interface by having a human “behind the curtain”. In our case, we created the perception of an experimental AV with implemented eHMI to signal system states and intentions. While this has become a widely adopted method used in both naturalistic studies (e.g., Rothenbücher et al., 2016) and controlled experiments (e.g., Faas et al., 2020), individual research activities must always include thorough risk assessments and be conducted in line with good research ethics. Importantly, this includes a debriefing session, explaining what you have done and why, and furthermore that the collected data will be deleted immediately if the participant so wish (Dahlbäck et al., 1993).

When it comes to data collection and analysis of the included empirical studies, results are based on small samples and predominately limited to subjective measures. However, we believe that these initial insights are highly relevant when seeking to “design the right thing” in relation to AV-VRU interaction, and that more extensive studies and measures such as extensive usability testing will follow to inform in “designing the thing right” (Buxton, 2010; Zimmerman et al., 2007). Sharing these explorations with the larger research and development community will hopefully spark additional research interest, improve community dynamics, and plant relevant design seeds. Indeed, since our initial studies were conducted the AV-VRU community has grown substantially, continually adding findings based on different types of data such as more detailed subjective measures (i.e., perceived safety reported over time (de Clercq et al., 2019)) and observational data (e.g., crossing onset (Faas et al., 2020)).
5.2 Future Work

The introduction of AVs has proved more challenging than manufacturers and developers initially hoped. Still, systems are continuously being tested and improved, and as we see more public trials and deployments, researchers will have an important role in investigating how AVs manage to co-exist with traditional road users and what novel phenomena and potential problems might emerge. Additionally, the research cycle should include proactive approaches, collaborating with developers and various stakeholders to gather insights on envisioned futures and contributing to designing the right things. This could be based on finding solutions to indicated interaction problems, as well as on the design opportunities that may arise based on AVs as a new technology. For example, our studies have indicated that communicating driving mode could be a solution for avoiding a potential problem of mode confusion, but also that signalling AV intent may provide added value enabled by the prospect of a consistent and precise ADS. Future studies should continue to explore AV-VRU scenarios and the role of eHMI to support interactions, gradually adding perspectives (e.g., are we designing the thing right) including usability and inclusive design.
6 Conclusions

This section presents conclusions connected to the three research questions.

- What interactive behaviors and communication cues can be identified in existing studies on road traffic interactions?

Moderated by various environmental- and situational factors, road user trajectories and kinematic behaviors (i.e., kinesics, proxemics, and chronemics nonverbal behavior) are primary mechanisms to facilitate traffic encounters and interactions. However, traffic encounters and interactions may also be influenced by additional explicit and implicit cues such as appearance, eye-gaze, gestures, and eHMI. Interactive behaviors and communication cues from road users can be viewed as vehicle-centric and driver/VRU-centric, as well as spontaneous (i.e., provided on a nonvoluntary basis), symbolic (i.e., provided deliberately to communicate), or pseudo-spontaneous (seemingly spontaneous but with a concealed intentionality). Ultimately, road users interactive behaviors and communication cues are included in the 38 factors (Rasouli & Tsotsos, 2019) which might influence VRU crossing decisions.

- How can we study interactions involving highly automated driving systems (i.e., AVs) and VRUs?

Highly automated driving systems are meant to take over the complete dynamic driving task, and AVs controlled by such systems would constitute a radically novel type of road user. While it is an open question how to best study interactions with these AI-enabled systems, it might require diverse theoretical approaches and methodologies including established and new perspective from the field of HCI. In shared mixed traffic environments, VRUs are incidental users of AVs demanding safe, efficient, and satisfactory interactions for technological acceptance. The Wizard-of-Oz prototyping approach can effectively be used for probing VRUs’ experiences of AVs and evaluating eHMI concepts.
- What are VRUs’ experiences of encounters with AVs?

In crossing scenarios, meeting an attentive driver resulted in VRUs’ reporting a higher willingness to cross, more content/calm emotional state and higher perceived safety. Most VRUs stated they would not start crossing before the AV stopped completely and perceived safety was significantly higher in encounters with an approaching manual vehicle (Mdn = 5) compared with encounters with a seemingly AV (Mdn = 3). VRUs highlighted how they pay attention to vehicle behavior, but also that contact with the driver is important. Experiencing an empty driver’s seat was surprising and unsettling, and the presence of a “disconnected driver” could be a misleading cue if the person is no longer representing the behavior of the vehicle. In addition to current vehicle signals (e.g., turning indicators, brake lights), acceptance of AVs might benefit from providing additional explicit information using eHMI. Initially, we have proposed communicating driving mode/status and intent of the ego-vehicle (e.g., intent to yield).
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8 References


