Advancing the State of AV-Vulnerable Road User Interaction: Challenges and Opportunities

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Abstract

While great strides have been taken in advancing the field of Human-Robot Interaction (HRI), challenges abound in understanding and improving how Autonomous Vehicles (AVs) will interact with and within society. Through this paper, the authors attempt to paint the picture of challenges unique to the study and advancement of interfaces between AVs and vulnerable road users (VRUs). In turn, these gaps in research highlight the opportunities for academia, industry, and public policy to collaborate and advance the state of the art of AV-VRU interaction, and the need for a dedicated forum for sharing insights across these various sectors.

Introduction

Automated and autonomous vehicles (AVs) are predicted to be prevalent on highway, city, and suburban streets in the near future (Tabone et al. 2021a). Indeed, AVs bring much promise of safe, accessible, and abundant transportation and delivery of goods to urban and disabled populations (Anderson et al. 2014) (Claypool, Bin-Nun, and Gerlach 2017). As AVs become integrated into society, a number of issues have been postulated and researched, such as building trust and confidence, communication between humans and AV, ethical questions about decision-making and responsibility, and meeting the disparate needs and preferences of users. Some of these issues might seem to resonate with classic Human-Robot Interaction problems, by considering the robot as the autonomous vehicle, and the human as the VRU (a passenger, pedestrian, cyclist, another human driver, or even a first responder depending upon the scenario and context). With respect to the passenger in particular, we agree that significant preexisting research on HRI for digital agents, such as virtual voice assistants and avatars, can be applied, and is incorporated by ongoing User Interface and User Experience efforts in this space. However, in the current work, we focus on the less well-trodden subdomain of interactions that reach beyond the vehicle's interior. For the remainder of this paper, we refer to this subdomain as **AV-VRU** interaction. The interaction between AVs and VRUs brings up new and unique challenges as AVs are designed primarily for transportation and typically interact with users through displays and controls, as compared to social robots intended to provide companionship, entertainment, or education. In addition to this, AVs are subject to different regulations and standards and, as such, issues of safety are under closer scrutiny here than within the larger field of social robots. Finally, the diversity of types of road users and their individual behaviors, attitudes, and expectations, as well as their varying levels of awareness and understanding of autonomous vehicle technology adds another layer of complexity to the interaction between AVs and external road users.

The focus of this paper is to bring the HRI community's attention to the unique research, challenges, and advancements of AV-VRU interaction, and the need for a new, fundamentally interdisciplinary framework for global collaboration.

Prior and Current Work

In this section, the authors provide a wide overview of AV and VRU interfaces in literature, research programs, and novel concepts. Prior to and in parallel with this work, many studies have focused on understanding human-to-human road communication patterns and models in Europe, and North America (Rothenbucher et al. 2016) (Mizuno et al. 2018) (Wilde 1976).

In extending this type of research to include AVs, some studies have attempted to evaluate the relative effectiveness of different AV intent communication modes including light displays, exaggerated sounds, and dynamic vehicle motions (Schmitt et al. 2022) (Jenness et al. 2021) (Song et al. 2018). For example, Song et al. (2018) used interviews, field studies, and assessments of eHMI designs to suggest how a combination of eHMIs and vehicle behaviors helped people to know if the vehicle is autonomous and that it recognized their presence. Schmitt et al. (2022) further showed how expressive behaviors (like gradually stopping and stopping farther away from pedestrians) can help decision-making for pedestrians and increase safety, confidence, and intention understanding. Mahadevan, Somanath, and Sharlin (2018) considers the effectiveness and likeability of auditory cues for signaling information to pedestrians.

Other studies have delved deeper into the visual media, studying the pragmatic effectiveness of specific technologies such as LED light strips and digital screens that produce patterns on the windshield and elsewhere on the exterior of the vehicle (Clamann, Aubert, and Cummings 2017) (Kaup et al. 2019) (Block et al. 2023). Habibovic et al. (2018) found that the use of an external interface significantly increased the likelihood of a positive experience and improved perceived safety in pedestrian encounters with AVs. Clamann, Aubert, and Cummings (2017)'s work comparing the effectiveness of various methods of presenting vehicle-to-pedestrian street crossing information suggested that although pedestrians rely on traditional vehicle behaviors over information on an external display they believe additional displays are needed on autonomous vehicles.

Considering that at present, expressive behaviors and external interfaces are the primary ways AVs rely on for interaction with road users, novel product design concepts have been developed and studied with various levels of academic and industrial support. These include car with eyes (JaguarLandRover 2018) (Chang et al. 2022), crosswalk projecting headlights (Mercedes-Benz 2016), a smiling car (Semcon 2016), vehicle mounted visual displays (Patent US009196164) (AUVSI 2019), textual displays (Nissan 2015), and augmented reality (AR) interfaces (Dalipi et al. 2020) (Tabone et al. 2021b).

In addition to these largely product development-oriented efforts, the formal research programs that focus on AV and VRU interfaces and effectiveness generally come from Europe and include InterACT (Kanellopoulos 2020) and SHAPE-IT (Bärgman 2019) effortss, supported by the EU's Horizon research and innovation funding program. Kanellopoulos (2020) focuses on a broad range of projects such as assessing AV intentions, controlling AV behavior, and establishing evaluation methods for studying road user interactions with AVs. Bärgman (2019) funds academic research and innovation in collaboration with industry partners, with quite an emphasis on understanding behaviors and interactions of VRUs, such as by investigating their cognitive processes, trust, and acceptance.

The relative scarcity of collaborative, rigorous research efforts is probably indicative of the technical and financial difficulties and idiosyncrasies of applying HRI perspectives directly to AV-VRU interaction. The dependence on new expressive behaviors and external displays for AVs rather than embodiment, lifelike behaviors, and human-like communication for social robots seems to be one of the most significant factors.

In this burgeoning space, here have been several exciting developments in eHMI interfaces, other modes of communication, and early indications of efficacy. However, many research gaps and challenges remain, as we attempt to highlight in the following section.

Challenges and Current Status

There are many underlying challenges when considering interfaces between AVs and other road users. While some challenges are similar to broader HRI research, there are multiple aspects of the autonomous vehicle that require a new perspective within the HRI field. These include aspects such as the heavily constrained physical form of the AV, the data and research methods available, and the AV's unique place in current and future society.

Since AVs have evolved from traditional vehicles, and are intended to integrate into human society alongside these vehicles, they are often impacted by widely held notions based on human-driven vehicles. There is a special expectation placed on AVs that they somehow both demonstrate their technical advancements and simultaneously support human behaviors and expectations that are based on their human-driven predecessors. Physically, this means that their appearance should not deviate too far from current vehicular norms. Similarly, the visual and behavior designs of AVs are beholden to many of the legal regulations which were developed for human-driven vehicles. These considerations, among others, are largely distinct from the challenges faced by those researching interaction with a humanoid robot, which involves far fewer legal constraints, and fewer preconceived expectations about their design and behavior.

Current challenges in the space can be broadly categorized into three major groups. The first group pertains to the lack of mature data and insights that characterizes the nascent field of AV-VRU interaction. Given the complexity of the scenarios involved, this calls for a need for deep insight into the availability of existing data and the type of data desired from new research. The second set of challenges arises from the breadth of the problem space (the AV's environment once deployed) and the diversity of the many agents within. Solutions that cater to one segment of the population are not guaranteed to work for others, and solutions that are robust to the diversity of humans that the vehicle may need to interact with are necessary. Furthermore, such solutions must be designed while conforming to regulations, and their ethical implications must be carefully considered. The third group of challenges pertains to the vastness of the solution-space. Designers and engineers building solutions face a complex problem space, and potential solutions pose a multitude of open questions. Tough design decisions must be made when crafting solutions, such as determining the appropriate amount of information to be conveyed to vulnerable road users (VRUs) and the modality of the interface used to convey this information.

Research Challenges

Testing and Data Collection Unlike HRI research, which is most often conducted in lab settings or field sites of a controlled nature, to understand how an AV performs with road users in the complex, dynamic environment of the streets, ideal testing should involve or closely approximate real-world conditions (Tabone et al. 2022). Significant safety concerns must be taken into account with respect to other vehicles, and external agents. Additionally, testing can be difficult and expensive, and may not be feasible in certain locations. In order to capture the breadth of environmental possibilities, collecting and analyzing extremely large amounts of data is essential. To limited success, some groups have attempted to mitigate this concern by using a combination of real-world data and data gained through simulated methods, such as the Robot Operating System (ROS) (Prédhumeau et al. 2022) and virtual reality (Merat et al. 2019) (Schneider and Bengler 2020) (Grush 2021). However, it can be difficult to obtain data that is representative of the distribution of complex, dynamic environments in which AV-VRU interaction takes place. Finally, teasing out causal relationships requires understanding how human perception can vary depending on environmental factors, culture, age, and previous experience.

Naturalistic Dataset Availability While some research indicates the benefits of AV driving behavior that mimics or exaggerates that of human drivers, only recently have researchers begun to examine, clarify, and quantify these behaviors. And while such studies would naturally benefit from naturalistic data sets, very few exist. Those that do exist (Caesar et al. 2020) (Sun et al. 2020) (Wilson et al. 2021) (H. Caesar 2021) (Liao, Xie, and Geiger 2021) were developed mainly by AV companies for advancing state-of-the-art perception and motion planning approaches, so are poorly annotated for finding relevant sets of various human to human engagement scenarios.

Cross-Discipline Insights As with most HRI use cases, findings from multiple disciplines are needed to characterize the gaps, propose solutions, and assess efficacy. These may include elements of robotics, computer science, engineering, psychology, sociology, transportation planning, and design. However, AV-VRU interaction especially stands to benefit from the additional perspectives of ethnographic and sociological studies such as Vinkhuyzen and Cefkin (2016), human factors (Schaudt, Russell, and Owens 2019), user experience, and public policy.

While engineers and computer scientists work on developing the technology and algorithms that allow AVs to perceive and understand their environment, cognitive psychologists, human factors experts, and user researchers study how people interact with AVs, and how the design of AVs and their communication systems can influence the behavior of pedestrians, drivers, and other road users. Further, sociologists and transportation planners could help study the broader social and economic impacts of AVs, and policy makers work on creating regulations and guidelines that will ensure the safe and efficient deployment of AVs on public roads. The authors believe that the study of AV-VRU interaction lies right at the intersection point of each of these seemingly disparate disciplines, and calls for academia, industry and policy to come together to share insights and support each others' future work.

Environmental Diversity

Acceptance and Cultural Differences Another significant challenge facing AV-VRU interaction researchers is the difference in cultural norms and driving practices that exist between many areas of the world (Özkan et al. 2006). For example, road user acceptance of vehicles with an empty or nonexistent driver seat is unclear. To pedestrians and other road users, how significant a factor is the appearance of a driver behind the driver's seat? Indeed, acceptance at local and regional governance levels is an open question as well (Wessling 2021) (Cornwell 2022) (Parliament 2019). A potential solution in one culture may not work well in another. Socio-cultural differences can affect the acceptance of AVs and result in varying levels of technology trust, which can affect perceptions of risk associated with sharing roads with them (Rasouli and Tsotsos 2019) (Hulse, Xie, and Galea 2018). Some external users may be more concerned about the data collected by autonomous vehicles as being used for surveillance or targeted advertising (Liu, Nikitas, and Parkinson 2020).

In some cultures, the autonomous vehicle is seen as a new form of transportation that must obey traffic rules where pedestrians have the right of way (Gupta, Vasardani, and Winter 2018). As such, autonomous vehicles would need to be programmed to be cautious when interacting with pedestrians, and may stop or slow down more frequently to allow pedestrians to cross the street or walk through intersections. However, in a culture where an AV is seen as a tool to improve traffic flow and reduce congestion, AVs would have to prioritize being more assertive and less cautious to preserve the flow of traffic (Straub and Schaefer 2019).

Special Needs Populations Even if an interface with one modality is found to be effective, the ideal solution should be designed for accessibility, to accommodate diverse populations such as those with visual and auditory impairments (Kassens-Noor et al. 2021). While such interfaces have been developed successfully for laptop and mobile device use cases (and are being studied for AV interiors), there are few studies (Brinkley et al. 2020; Hong et al. 2008; Fink, Holz, and Giudice 2021) involving AV-VRU interaction at, for example, noisy, busy intersections (Asha et al. 2021).

Complex Interaction Scenarios Much of the current HRI literature is focused on one-to-one interaction between a robot and an individual or a small group of users. Applying this perspective would mean modeling and researching relations of one AV to one external road user (Schmitt et al. 2022) (Block et al. 2023). However, it is unclear if and how much pedestrian behavior may change when exposed to more realistic urban scenarios involving multiple vehicles and or VRUs simultaneously. In addition to pedestrians, and cyclists, the population of VRUs includes wheelchair and mobility scooter users, people with visual and auditory imupariments, first responders (Lee et al. 2023b), small animals, traffic controllers, people with strollers, and many more. Additionally, every interaction scenario with an autonomous vehicle will involve interaction between the vehicle, its occupants, VRUs, any teleoperators involved, and other users of similar vehicles. This presents AV-VRU researchers with a complex, multifaceted universe of scenarios which involve 'robot + user within the robot + user outside the robot + virtual robot operators + other robots' interaction.

Design Considerations

Unique Form Factor While it is reasonable to suggest that advances in interfaces between AVs and external road users fall within the realm of HRI research, it is probably also fair to say that it is an atypical branch. Much of HRI research targets robots with more anthropomorphic form factors. This field of study is filled with its own impressive feats and daunting challenges(Nelson, Saunders, and Playter 2019) (Suguitan and Hoffman 2019). A key distinction here is that in the AV case, the robot lacks a torso and limbs. Rather, it must build upon the road vehicle platform, which offers very few degrees of freedom, beyond the turning of its wheels or perhaps its side view mirrors. Thus, much of the existing work on movement (Hoffman and Ju 2014), legibility (Dragan, Lee, and Srinivasa 2013), exaggeration (Gielniak and Thomaz 2012), biomimicry (Oudshoorn et al. 2021), etc., must be re-interpreted or re-imagined for a different form factor. In order to account for this gap, many ongoing research projects in the area of AV-VRU interaction include varying combinations of communicative motion behaviors or explicit visual displays. At present, the efficacy of an external human-machine interface (eHMI) is unclear, and some parties are wary of the potential for eHMIs to cause unwarranted distraction. Similarly, early inquiries have been conducted into the use of expressive sound as a communication channel for AVs (Schmitt et al. 2022), though this specific subfield is in its relative infancy. Perhaps a naturalistic driving behavior will be sufficient, but a framework for naturalistic autonomous driving (e.g., definitions, data, and metrics) is still far from being established (de Winter and Dodou 2022) (Dey et al. 2020) (Song et al. 2018).

Information to Communicate In addition to acceptance of the mere presence of an AV, there is a question of what specific information to communicate with external observers. What information is necessary, and what is superfluous, distracting, or dangerous? Examples of research on this question include the following:

- Autonomous Mode on or off (SingaporeLTA 2019)
- Vehicle stopped/parked (Lee et al. 2023b)
- Vehicle about to move (Habibovic et al. 2018)
- Vehicle about to stop (Schmitt et al. 2022)
- Vehicle about to change lanes (Lee et al. 2023a)
- Vehicle in failure mode (Lee et al. 2023b)

However, this particular question requires consideration of the potential consequences of revealing various pieces of information about the AV's state. For instance, is the disclosure that the AV is in a failure mode likely to result in tampering? Is the disclosure that the AV is holding passengers more likely to result in their potential harassment (Moore et al. 2020)? Alternatively, researchers must also explore the impact of omitting these pieces of information, and whether this causes untenable levels of ambiguity in instances of AV-VRU interaction.

Ethics Researching interfaces for AV-VRU interaction raises ethical concerns about how autonomous vehicles should be programmed to make decisions in situations where there is a risk of harm to pedestrians. Ensuring that the vehicles' interfaces are intuitive is not only a matter of aesthetics and preference. It also carries safety implications, as an intended message from the AV may be incorrectly interpreted by its human receiver or vice versa, and lead to mutually unexpected behaviors.

Additionally, the prospect of AVs on public roads presents an ethical challenge around data privacy and transparency (Mulder and Vellinga 2021). It is correctly assumed by many members of the public that AVs collect immense amounts of (potentially identifiable) data about their surroundings (Bloom and Emery 2022). Thus, the job of an AV-VRU interaction reseacher should also include gaining the trust of the public by embedding some level data transparency in interface designs, and by striving to minimize the privacy encroachment that may result from these interfaces.

Looking Forward

Having addressed the multitude of challenges facing this new area of research, and the current status of work being conducted in this area, the authors also consider constructive next steps for this emerging field. Many disparate industries and research efforts are gaining valuable insights into specific subsets of this challenge, and it is the intention of the authors to encourage interdisciplinary collaboration and discussion of these insights. We envision a near future in which this important topic brings together experts from many different domains, both academic and industrial, from technical to sociological backgrounds. We also recognize some current trends in this direction, which are already demonstrating the immense value of a wide-net approach to this work. This section highlights the main discussion forums that are "moving the conversation forward" in either highlighting AV and external road user interface research or discussing standards or regulations.

Conferences

The following is a non-exhaustive list of conferences that cover AV, eHMI, and VRU studies.

- **Transportation Research Board.** The TRB traditionally has a workshop dedicated to the topic of "Perspectives on Automated Driving Systems Communication to Existing Road Users" which is sponsored by several standing committees (Bao and Domeyer 2023). This is an annual event that generally caters to transportation infrastructure and policy professionals in the United States at the city, county, state, and federal levels.
- **Automated Road Transport Symposium** ARTS is actually a part of the TRB conference family and focuses on "opportunities and challenges associated with automating road transportation". This is an annual event with a broad swath of attendees from the AV industry, government, and research. This conference will typically have a workshop focused on AV and external road user issues.
- **ICRA and IROS IEEE Robotics and Automation Society Conference.** Both the IEEE Robotics and Automation Society and the IEEE Intelligent Robotics and Systems conferences typically have a paper presentation session on "Intent and Gesture Recognition". As one may expect from the title, this session is quite broad covering

a broad spectrum of robot form factors as well as perception techniques. Both ICRA and IROS are annual events with an attendee base of professional academic robotics researchers.

- **Human Robot Interaction** The ACM/IEEE International Conference on Human-Robot Interaction also does not have workshops or sessions dedicated to AV robots but will include the topic in sessions dedicated more generally to sensing human, understanding human intent, or communicating with humans. HRI is an annual event generally catering to academic HRI researchers.
- **Automotive User Interface** The ACM AutoUI conference has traditionally focused on vehicle interior interfaces with driver and passenger. Recently this conference has added a session dedicated to external HMI research papers that mainly focus on AVs. This is an annual conference with an attendee base of both academic and automotive industry researchers.

Public Policy

There are a couple of known AV external interface public policy initiatives. The United Nations Economic Commission for Europe (UNECE) has a Working Party for Autonomous and Connected Vehicles (GRAV) that is actively seeking input and recommendations for external Human Machine Interfaces for autonomous vehicles (Mehler 2021) (Shutko and Bray 2018).

Additionally, the Singapore Land Transport Authority requires AVs exhibit lighting for identification of Auto Mode status (SingaporeLTA 2019).

Standards

A few teams are actively developing standards for AV communication with external road users. The SAE Automated Driving System Lamps Task Force has released J3134-201905, Automated Driving System Marker Lamp Recommended Practice (SAE J3134-201905), and continues to review opportunities for improvements. The ISO Transport Information and Control Systems Working Group (also known as "ISO/TC 22 SC39 WG 8") has developed the standard ISO/TR 23049:2018, "Road Vehicles – Ergonomic aspects of external visual communication from automated vehicles to other road users", and continues to review opportunities for the next version (ISO/TR 23049:2018). Project ISO 4448 Ground Based Automated Mobility is developing a standard for sidewalk delivery and service robots (Grush 2021). European organizations such as the European Telecommunications Standards Institute have also put forth standards such as "ETSI TR 102 638 on Intelligent Transport Systems' (ETSI 2009).

Expert Discussion Forums

One forum dedicated for thought leaders specifically to review, discuss, propose updates and advancements to external AV interfaces is the MassRobotics Socially Aware Automated Mobility (SAAM) consortium (Shingu 2022). The SAAM meets quarterly. No others are known at this time.

Research Programs

Supporting the Interaction of Humans and Automated Vehicles: Preparing for the Environment of Tomorrow (SHAPE-IT) is a European Union funded research project aimed at "safe, acceptable, and desirable integration of user-centered and transparent automated vehicles into urban traffic environment"(Bärgman 2019). It funds fifteen PhD research projects and invites industry supervision.

Considering the various forums where AV and external road user interfaces are addressed, there does not appear to be a centralized forum. Rather there are many forums involving a subset of experts needed to address the challenges. Each forum looks at the challenge through the resulting facets. Almost all are infrequent, occurring annually.

Discussion

Overview

AV-pedestrian interactions have taken HRI from the lab and field sites to more dynamic, ever-changing open environments, such as streets, vehicular roads, sidewalks, and public spaces.

While the 'social' robot is obviously designed for interactions that are beneficial to its users, AV-pedestrian interactions have to overcome the historical conflict of pedestrian and vehicles and intentionally design interactions to convey that the autonomous vehicle does not harm pedestrians, cyclists or other road users. In addition, HRI often involves interactions between humans and robots that carry out or emulate human behaviors, such as teleoperated robots or robots that are programmed to respond to human gestures or commands. However, interactions between autonomous vehicles and pedestrians, so far, are perceived as a vehicle making decisions on its own based on sensor data and pre-programmed rules. HRI also typically involves direct physical or visual interactions between the human and the robot, while AV and pedestrian interaction is based on the perception and understanding of the environment, the vehicle's prediction of the pedestrian's behavior, and importantly the pedestrian's understanding of the vehicle's intentions. Additionally, this research domain goes beyond interactions with a single human or small groups of humans that are often trained or familiar with the robot's behavior, and involves interactions with large and diverse groups of pedestrians with different ages, cultures, and abilities, who may have different expectations of the autonomous vehicle's behavior.

In summary, researching AV-VRU interaction is a challenging task that requires a multidisciplinary approach to address the complexity of the system, safety concerns, ethical implications, cultural differences, data collection, human behavior, and regulatory compliance. Some of these challenges may be more effectively tackled by industry, academia, or policy makers individually, while others will require a collaborative effort among all stakeholders, as presented below.

Opportunities

In reflecting upon the challenges and gaps above, several opportunities are proposed for academic research, industry, and public policy collaborations.

Academic Community The authors envision several opportunities for the academic community.

- **eHMI** As described within "Multi-modality" above, several eHMI research areas are within early stages.
  - **Auditory Signals** A significant research opportunity exists within the potential for sound to enrich AV-VRU interaction. While this is a developing area within the broader HRI field (Zhang and Fitter 2023) (Robinson, Bown, and Velonaki 2022), application to AV external interfaces is in earlier research stages. Opportunities exist to adapt HRI sound taxonomies for AV use cases (e.g., "about to accelerate", "courtesy", etc.) and develop an open source library of promising sounds.
  - **Visual Displays** While a larger body of AV visual display research exists, the best solutions to date are not intuitive but rather learned. The authors propose a potential for cross-pollination with the broader HRI body of knowledge.
  - **Expressive Behaviors** Current research indicates that vehicle dynamics are perhaps the most promising intuitive medium for AV intention communication (Jenness et al. 2021) (Schmitt et al. 2022). The authors propose that research opportunities exist to understand the key vehicle motion parameters and connect with AV use case taxonomy. Additionally, the authors propose opportunities for reinterpretation of existing HRI robot motion literature for the AV form factor.
  - **Multi-modal Techniques** Another significant research gap exists in identifying an optimal mix of the above modalities for VRU use cases, especially for the blind and deaf community.
- **Standards** Key research questions in front of the standards community are highlighted above within "Regulations and Standards". The authors propose studies that leverage data from diverse community groups to highlight areas of confusion and quantify potential benefits of producing standardized, uniform behaviors across the AV industry.

Industry As described within "Challenges and Current Status", many existing datasets would benefit a VRU interaction lens, but as of today most are best suited for perception and motion planning studies. The authors recommend efforts within industry to open source datasets that enable this type of research. Such datasets would include a wide variety of indexed external agents. Complex scenarios involving these agents would be consistently labeled, and easily searchable.

The authors note that providing large, open source datasets requires significant resources and as such is not an exercise taken lightly. As a first step, we recommend the research community leverage existing open source datasets tailored for perception system research (Caesar et al. 2020) (Sun et al. 2020). Although not ideal for VRU studies, brute-force search approaches should yield enough scenarios of interest to demonstrate the benefit of this approach and hopefully inspire further open source efforts.

Academia and Industry While this and prior work envision a number of AV-VRU interaction use cases, the authors propose the need for a use case classification taxonomy. Such a taxonomy would help clarify and structure studies developing interface solutions. This work should align with, but not mirror, the proposed eHMI classification taxonomy (Dey et al. 2020). To clarify, the eHMI taxonomy helps classify solutions, while the use case taxonomy would classify the need and interaction scenarios.

Public Policy The authors envision several opportunities for public policy makers.

- **Engage** The authors encourage public policy makers to engage with community groups on the issue of AV benefits and challenges for communities. Recognize the benefit of AVs that integrate well within society. Identify key areas in society that would benefit from clear understanding of AV interactions.
- **Promote Research** The authors encourage public policy makers to initiate and coordinate research programs targeting the challenges outlined in this work. While the EU has strong examples of this (Kanellopoulos 2020) (Bärgman 2019), other regions are not as explicit about their investment in this area. As highlighted above, solutions for one culture or geographic area may not extrapolate well.
- **Advance Policy** The authors encourage public policy makers to take a measured approach to new policy development. Leverage new research for policy proposals. Seek and incorporate input from community groups, but also cademia and industry.

Cross-sector Collaboration Considering the different stakeholders involved and the lack of community engagement in AV-pedestrian interaction research and design, there is a need for a dedicated consortium, track or a venue for bringing interdisciplinary experts together for collaborations, research updates, panel discussions, and idea exchanges. Ideally, such a consortium would engage frequently given the forecasted rate of AV adoption and potential to benefit society. A key challenge and opportunity is to bring the needed cross-discipline perspectives together in one venue. AV-VRU interaction research could benefit greatly from sites of collaboration, active dialogue, and problem-solving around broader interaction specific to social, cultural, and physical contexts of specific communities while informing the broader understanding of interactions between AV and pedestrians.

While both industry and academia are interested in conducting AV-VRU interaction research and development activities to advance the state of the art in autonomous vehicle technology, they may have different perspectives and priorities. For example, the goal of industry-led research with its practical and market-driven approach and limited timeframes may be to develop a working prototype and prioritize aspects of safety and reliability. On the other hand, academic research may be more interested in scientific rigor, long-term impact and answering fundamental theoretical questions. However, their overlapping interests in evaluation and testing involve learning about stakeholder perspectives, running simulations, test tracks, and real-world prototype deployment on public roads. Additionally, both can and are significant for contributing to the development of standards and regulations for AV technology and require working with government agencies and other stakeholders to develop guidelines and best practices for the safe and ethical deployment of autonomous vehicles.

Conclusion

The interaction between AVs and VRUs is one that will benefit from more collaborative research from a diverse set of disciplines. As we are awe-inspired by the technologies that allow us to continue to roll out driverless vehicles in our streets, we are also reminded of their current lack of social awareness. In order for AVs to realize their true potential and support safety and comfort in personal mobility, it is essential for them to provide communities with a sense of trust and ease.

The AV-external user challenges are similar to and yet distinct from traditional HRI challenges or the broader AV user challenges. We call for attention from the HRI community towards the need for a focused track or consortium to assess different approaches for design and evaluation within this problem space. Further, we emphasize the importance of accounting for different interaction modalities, human behaviors, and contexts (cultural and situational) of the interactions. Work advanced by industry experts, public policy officials, research programs and conferences will be crucial to the path forward in this field.

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