The Road Ahead: Advancing Interactions between Autonomous Vehicles, Pedestrians, and Other Road Users

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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.**

I. Introduction

Automated and autonomous vehicles (AVs) are predicted to be prevalent on highway, city, and suburban streets in the near future [1]. Indeed, AVs bring much promise of safe, accessible, and abundant transportation and delivery of goods to urban and disabled populations [2] [3]. 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.

II. 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 [4] [5] [6].

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 external Human-Machine Interface (eHMI), exaggerated sound, and dynamic vehicle motion [7] [8] [9]. For example, Bengler 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 [9]. Schmitt 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 [7]. [10] 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 [11] [12] [13]. Habibovic et al. found that the use

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of an external interface significantly increased the likelihood of a positive experience and improved perceived safety in pedestrian encounters with AVs[14]. Cumming'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 [11]. These include car with eyes [15] [16], crosswalk projecting headlights [17], a smiling car [18], vehicle mounted visual displays (Patent US009196164) [19], textual displays [20], and augmented reality (AR) interfaces [21] [22].

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 [23] and SHAPE-IT [24] efforts, supported by the EU's Horizon research and innovation funding program. Interact 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 [23]. Shape-It 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 [24].

Although there have been several exciting developments in this immense effort, the relative scarcity of collaborative, rigorous research efforts is probably indicative of the novel technical and financial difficulties of applying HRI perspectives directly to AV-VRU interaction. Many research gaps and challenges remain, as we attempt to highlight in the following section.

III. 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 demonstrate their technical advancements and simultaneously support human behaviors and expectations. Physically, this means that their appearance should not deviate too far from current vehicular norms. Similarly, the designs of AVs are beholden to many of the legal regulations which were developed for human-driven vehicles. These considerations are largely distinct from the challenges faced by those researching interaction with a humanoid robot, which involves far fewer legal constraints, and fewer pre-conceived expectations about their design and behavior.

Current challenges in the space can be broadly categorized into three major groups. The first group of challenges (expanded in subsection A below) pertains to the difficulty of conducting rigorous research in this area, with widespread peer and expert support. This difficulty stems from a lack of mature data and consolidated insights, which characterizes the nascent field of AV-VRU interaction. Given the complexity of the scenarios involved, this calls for a need for collaborative insight into the availability of existing data and the type of data desired from new research. The second set of challenges (subsection B below) arises from the breadth of the application domain (the many environments in which an AV may be 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 yet solutions that are robust to the diversity of humans that the vehicle may need to interact with are necessary for the successful worldwide integration of AVs. The third group of challenges (subsection C) pertains to the boundlessness of the design/solution space itself. Designers and engineers building HRI-focused autonomous vehicles face a vast, and largely unexplored landscape of novel approaches to this emerging design gap. Nuanced 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. The conciseness, specificity, and legibility of these techniques also carry significant ethical weight, due to the potential consequences of unnecessary distraction or miscommunication.

A. Research Challenges

1) 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 [25]. 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) [26] and virtual reality [27] [28] [29]. 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. This challenge is particularly relevant for those working in industry, as it makes it much more difficult for commercial user researchers to produce findings that satisfy scientific standards of validity, reproducibility, and generalizability.

2) Naturalistic Dataset Availability: Given the difficulties described above in producing sufficient experimental data, an emphasis must also be placed on the availability and use of naturalistic, observational data from real environments. For instance, 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 human behaviors. And while such studies would naturally benefit from naturalistic data sets, very few exist. Those that do exist [30] [31] [32] [33] [34] were developed mainly by AV companies for advancing state-of-the-art perception and motion planning approaches, and so are poorly annotated for finding relevant sets of various human to human engagement scenarios. These datasets were also developed to address specific company needs, and therefore have lower widespread utility to other organizations. We propose that this is a challenge well-suited for an academia-based response. Academic research, such as in the fields of ethnography, urban planning, and science and technology studies, regularly applies techniques for conducting scrupulous naturalistic observation, as well as more longitudinal studies. In addition, an academic focus on accurately describing trends, rather than producing actionable recommendations, makes such datasets likely to be more widely useful across various facets of the AV industry.

3) 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 inclusion of perspectives from ethnographic and sociological studies such as [35], human factors [36], 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.

B. Environmental Diversity

1) 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 [37]. 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 [38] [39] [40]. 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 [41] [42]. Some external users may be more concerned about the data collected by autonomous vehicles as being used for surveillance or targeted advertising [43].

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 [44]. 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 [45]. For academics, this challenge centers on providing localized expertise and reliable characterizations of specific cultural contexts. Those working in industry, on the other hand, must assume the responsibility of internalizing and synthesizing a wide variety of such contributions and incorporating these findings into their design solutions.

2) 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 [46]. 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 [47], [48], [49] involving AV-VRU interaction at, for example, noisy, busy intersections [50]. Similarly to the previous subsection, the focal point of this challenge is for industry to seek out and absorb information from various subfields of disability studies, and to reflect the recommendations of these subfields in their product designs and design processes.

3) 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 [7] [13]. 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 impairments, first responders [51], 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 that involve 'robot + user within the robot + user outside the robot + virtual robot operators + other robots' interaction.

C. Design Considerations

1) Unique Form Factor: A key distinction in the physical design of HRI-competent AVs is that 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 [52], legibility [53], exaggeration [54], biomimicry [55], etc., must be re-interpreted or re-imagined for a different form factor. This new field of study is filled with its own impressive feats and daunting challenges[56] [57], though there are extremely few consensuses or established frameworks. 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 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 [7], 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 [58] [59] [9]. Widespread agreement and consistency on the question of modalities will require a collaboration between academia and industry, in which academics are provided the resources to conduct research that is not as tightly bound to the financial and commercial implications of recommending one approach over another.

2) 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?

Exploration into this question includes research on displaying whether the vehicle is in Autonomous Mode or not [60], whether it is stopped/parked [51], about to move [14], about to stop [7], about to change lanes [61], or whether it is in some particular failure mode [51].

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 [62]? 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.

3) 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 [63]. It is correctly assumed by many members of the public that AVs collect immense amounts of (potentially identifiable) data about their surroundings [64]. Thus, the job of an AV-VRU interaction researcher should also include gaining the trust of the public by embedding some level of data transparency in interface designs, and by striving to minimize the privacy encroachment that may result from these interfaces. Due to concerns around safety, liability, and responsibility to users and customers, we believe that this challenge should be of the utmost consideration for industry, the group that will face the vast majority of repercussions for missteps in this domain.

IV. Recent Developments

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.

1) Conferences: The following is a non-exhaustive overview of the current conferences that cover aspects of AV-VRU interaction research. Transportation industry conferences include **Transportation Research Board (TRB)** and its spinoff conference, **Automated Road Transport Symposium (ARTS)**. These conferences feature workshops such as "Perspectives on Automated Driving Systems Communications to Existing Road Users", though human-driven systems remain their primary focus.

Robotics industry conferences include the more technologically-oriented **ICRA**, **RO-MAN**, and **IROS** conferences (which often hold workshops on relevant topics such as intent and gesture recognition), as well as **Human-Robot Interaction (HRI)**, a conference with a more human-facing and social-theory based focus. **AutoUI**, a conference dedicated specifically to vehicle interface technology and design, occupies the middle ground between these robotics and transportation categories.

In addition, a growing number of social science conferences and journals, such as **Ethnographic Praxis in Industry Conference (EPIC)** and **Current Sociology** are beginning to publish research on the human impact of the widespread deployment of autonomous vehicles.

2) 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 [65] [66].

Additionally, the Singapore Land Transport Authority requires AVs to exhibit lighting for identification of Auto Mode status [60].

3) 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 [67], 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 [68]. Project ISO 4448 Ground Based Automated Mobility is developing a standard for sidewalk delivery and service robots [29]. European organizations such as the European Telecommunications Standards Institute have also put forth standards such as "ETSI TR 102 638 on Intelligent Transport Systems' [69].

4) Expert Discussion Forums: One forum dedicated for thought leaders specifically to review, discuss, and propose updates and advancements to external AV interfaces is the MassRobotics Socially Aware Automated Mobility (SAAM) consortium [70]. The SAAM meets quarterly. No others are known at this time.

5) 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"[24]. 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.

V. Discussion

A. 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 pedestrians 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.

B. Opportunities

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

1) Academic Community: The authors envision several opportunities for the academic community. These opportunities have been designated as such because we believe that they benefit from a more unbiased perspective. We also suggest that the open-ended nature of the current phase of research questions is more well-suited to academic inquiry.

- **eHMI - 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 [71] [72], 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.
- **eHMI - Visual Displays** While a larger body of AV visual display research exists, the literature indicates that 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 [8] [7]. The authors propose that research opportunities exist to understand the key vehicle motion parameters and connect them 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. Similarly, increased access to the sorts of datasets that would produce these standards can also lead to the adoption of widely agreed-upon benchmarks of performance in VRU-interaction tasks such as intersection and traffic navigation and intent signalling.

2) Industry: The authors also envision several opportunities for the commercial AV industry. These opportunities have been designated as such because the authors believe that they benefit from resources that are typically more prevalent or available in industry, such as high volumes of data, and the financial backing to realize and ”productize” promising research findings. As described within “Challenges and Current Status”, many existing datasets would benefit from 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 [30] [31]. 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.

In addition to this specific opportunity, the authors suggest more generally that a significant opportunity exists for industry to seek out and ingest the extremely useful, well-founded research being produced by specific academic disciplines with which they may not be traditionally familiar. While we also suggest the creation of additional forums for effective knowledge transfer, we emphasize that many smaller repositories of such knowledge are already being developed. These represent a potent opportunity for designers to build on verified hypotheses regarding social expectations and acceptance of autonomous vehicles.

3) 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 [59]. To clarify, the eHMI taxonomy helps classify solutions, while the authors’ proposed use case taxonomy would classify the need and interaction scenarios.

4) Public Policy: The authors envision several opportunities for public policy makers.
- **Engage** The authors encourage public policy makers to engage with community groups [73] 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 [23] [24], 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.

5) 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.

VI. 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.

References

[1] W. Tabone, J. de Winter, C. Ackermann, J. Bärgman, M. Baumann, S. Deb, C. Emmenegger, A. Habibovic, M. Hagenzieker, P. Hancock, R. Happee, J. Krems, J. D. Lee, M. Martens, N. Merat, D. Norman, T. B. Sheridan, and N. A. Stanton, "Vulnerable road users and the coming wave of automated vehicles: Expert perspectives," *Transportation Research Interdisciplinary Perspectives*, 2021.

[2] J. M. Anderson, N. Kalra, K. D. Stanley, P. Sorensen, C. Samaras, and O. A. Oluwatola, *The Promise and Perils of Autonomous Vehicle Technology*. RAND Corporation, 2014, pp. 9–40.

[3] H. Claypool, A. Bin-Nun, and J. Gerlach. (2017) Self-driving cars: The impact on people with diabilities. https://rudermanfoundation.org/wp-content/uploads/2017/08/Self-Driving-Cars-The-Impact-on-People-with-Disabilities_FINAL.pdf.

[4] D. Rothenbucher, J. Li, D. Sirkin, B. Mok, and W. Ju, "Ghost driver: A field study investigating the interaction between pedestrians and driverless vehicles," in *2016 25th IEEE Intrl. Symp. on Robot and Human Interactive Communication (RO-MAN)*.

[5] N. Mizuno, A. Yoshizawa, A. Hayashi, and T. Kawashima, "Estimation of drivers ' awareness of pedestrians," in *2018 IEEE 17th International Conference on Cognitive Informatics Cognitive Computing (ICCI*CC)*, 2018, pp. 381–386.

[6] G. J. S. Wilde, "Social interaction patterns in driver behavior: An introductory review," *Human Factors: The Journal of Human Factors and Ergonomics Society*, vol. 18, pp. 477 – 492, 1976.

[7] P. Schmitt, N. Britten, J. Jeong, A. C. K. Clark, S. S. Kothawade, E. C. Grigore, A. Khaw, C. Konopka, L. Pham, K. Ryan, C. Schmitt, and E. Frazzoli, "Can Cars Gesture? A Case for Expressive Behavior Within Autonomous Vehicle and Pedestrian Interactions," in *IEEE Robotics And Automation Letters, VOL. 7, NO. 2, APRIL 2022*.

[8] J. W. Jenness, A. K. Benedick, J. Singer, S. Yahoodik, E. Petraglia, J. Jaffe, J. M. Sullivan, and A. K. Pradhan, "Automated Driving Systems' Communication of Intent With Shared Road Users," National Highway Transportation Safety Administration, Technical Report DOT HS 813 148, 2021. [Online]. Available: https://rosap.ntl.bts.gov/view/dot/58325

[9] Y. E. Song, C. Lehsing, T. Fuest, and K. Bengler, "eHMIs and their effect on the interaction between pedestrians and automated vehicles," in *Intelligent Human Systems Integration*, 2018.

[10] K. Mahadevan, S. Somanath, and E. Sharlin, "Communicating awareness and intent in autonomous vehicle-pedestrian interaction," in *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, ser. CHI '18, 2018, p. 1–12.

[11] M. Clamann, M. Aubert, and M. Cummings, "Evaluation of vehicle-to-pedestrian communication displays for autonomous vehicles." Transportation Research Board 96th Annual Meeting, 2017.

[12] M. Kaup, J.-H. Willrodt, A. Schieben, and M. Wilbrink, "Final design and HMI solutions for the interaction of AVs with user on-board and other traffic participants ready for final implementation," EU's Horizon 2020 Program, Grant Agreement 723395," Technical Report, 2019.

[13] A. Block, A. Pandya, S. H. Lee, and P. Schmitt, "I see you! design factors for supporting pedestrian-av interaction at crosswalks," in *HRI 2023: Proceedings of the 2023 ACM/IEEE International Conference on Human-Robot Interaction*. IEEE Press, 2023.

[14] A. Habibovic, V. Lundgren, J. Andersson, M. Klingegård, T. Lagström, A. Sirkka, J. Fagerlönn, C. Edgren, R. Fredriksson, S. Krupenia, D. Saluäär, and P. Larsson, "Communicating intent of automated vehicles to pedestrians," *Frontiers in Psychology*, 2018.

[15] JaguarLandRover. (2018) Jaguar land rover's virtual eyes look at trust in self-friving cars. https://media.jaguarlandrover.com/news/2018/08/jaguar-land-rovers-virtual-eyes-look-trust-self-driving-cars.

[16] C.-M. Chang, K. Toda, X. Gui, S. H. Seo, and T. Igarashi, "Can eyes on a car reduce traffic accidents?" in *Proceedings of the 14th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, 2022.

[17] Mercedes-Benz. (2016) Revolution in headlamp technology: Mercedes shines in hd quality: Digital light. https://group-media.mercedes-benz.com/marsMediaSite/ko/en/14872032.

[18] Semcon. (2016) Self driving car that sees you. https://semcon.com/smilingcar/.

[19] AUVSI. (2019) Drive.ai uses external communication panels to talk to the public. https://www.auvsi.org/industry-news/driveai-uses-external-communication-panels-talk-public.

[20] Nissan. (2015) Nissan ids concept: Nissan's vision for the future of autonomous driving. https://global.nissannews.com/en/releases/release-3fa9beacb4b8c4dcd864768b4800bd67-151028-01-e.

[21] A. F. Dalipi, D. Liu, X. Guo, Y. Chen, and C. Mousas, "Vr-pavib: The virtual reality pedestrian-autonomous vehicle interaction benchmark," in *12th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, 2020, pp. 38–41.

[22] W. Tabone, Y. M. Lee, N. Merat, R. Happee, and J. de Winter, "Towards future pedestrian-vehicle interactions: Introducing theoretically-supported AR prototypes," in *13th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, 2021.

[23] P. Kanellopoulos, "Proceedings of the interACT Final Event," European Union's Horizon 2020 Research and Innovation Programme, Grant Agreement No 723395," Technical Report. [Online]. Available: https://www.interact-roadautomation.eu

[24] J. Bärgman. (2019) Shape-it: Supporting the interaction of humans and automated vehicles: Preparing for the environment of tomorrow. https://www.shape-it.eu/about/.

[25] W. Tabone, R. Happee, J. Garcia de Pedro, Y. M. Lee, M. Lupetti, N. Merat, and J. de Winter, "Augmented reality interfaces for pedestrian-vehicle interactions: An online study," 11 2022.

[26] M. Prédhumeau, L. Mancheva, J. Dugdale, and A. Spalanzani, "Agent-based modeling for predicting pedestrian trajectories around an autonomous vehicle," *J. Artif. Int. Res.*, 2022.

[27] N. Merat, Y. M. Lee, G. Markkula, J. Uttley, F. Camara, C. Fox, A. Dietrich, F. Weber, and A. Schieben, "How do we study pedestrian interaction with automated vehicles? preliminary findings from the european interact project," in *Automated Vehicles Symposium*. Springer, 2019, pp. 21–33.

[28] S. Schneider and K. Bengler, "Virtually the same? analysing pedestrian behaviour by means of virtual reality," *Transportation Research Part F: Traffic Psychology and Behaviour*, 2020.

[29] B. Grush, "Making room for robots: A draft iso technical standard for ground-based automated mobility: Loading and unloading at the kerbside and footway," 08 2021.

[30] H. Caesar, V. Bankiti, A. H. Lang, S. Vora, V. E. Liong, Q. Xu, A. Krishnan, Y. Pan, G. Baldan, and O. Beijbom, "nuScenes: A multimodal dataset for autonomous driving," in *CVPR*, 2020.

[31] P. Sun, H. Kretzschmar, X. Dotiwalla, A. Chouard, V. Patnaik, P. Tsui, J. Guo, Y. Zhou, Y. Chai, B. Caine, V. Vasudevan, W. Han, J. Ngiam, H. Zhao, A. Timofeev, S. Ettinger, M. Krivokon, A. Gao, A. Joshi, Y. Zhang, J. Shlens, Z. Chen, and D. Anguelov, "Scalability in perception for autonomous driving: Waymo open dataset," in *Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition (CVPR)*, June 2020.

[32] B. Wilson, W. Qi, T. Agarwal, J. Lambert, J. Singh, S. Khandelwal, B. Pan, R. Kumar, A. Hartnett, J. Kaesemodel Pontes, D. Ramanan, P. Carr, and J. Hays, "Argoverse 2: Next generation datasets for self-driving perception and forecasting," in *Proceedings of NeurIPS Track on Datasets and Benchmarks*, 2021.

[33] H. Caesar et al., "nuPlan: A closed-loop ML-based planning benchmark for autonomous vehicles," *CoRR*, vol. abs/2106.11810, 2021.

[34] Y. Liao, J. Xie, and A. Geiger, "KITTI-360: A novel dataset and benchmarks for urban scene understanding in 2d and 3d," *arXiv preprint arXiv:2109.13410*, 2021.

[35] E. Vinkhuyzen and M. Cefkin, "Developing socially acceptable autonomous vehicles," *Ethnographic Praxis in Industry Conference Proceedings*, vol. 2016, no. 1, 2016.

[36] W. A. Schaudt, S. Russell, and J. M. Owens, "The role of human factors in the design of automated vehicle external communication," in *Road Vehicle Automation 6*, G. Meyer and S. Beiker, Eds., 2019.

[37] T. Özkan, T. Lajunen, J. E. Chliaoutakis, D. Parker, and H. Summala, "Cross-cultural differences in driving behaviours: A comparison of six countries," *Transportation research part F: traffic psychology and behaviour*, vol. 9, no. 3, pp. 227–242, 2006.

[38] B. Wessling. (2021) Toronto city council votes to ban sidewalk robots. https://www.therobotreport.com/toronto-city-council-votes-to-ban-sidewalk-robots/.

[39] P. Cornwell. (2022) "Amazon robots scooting along sidewalks". https://www.seattletimes.com/seattle-news/eastside/for-now-kirkland-says-no-to-small-amazon-robots-scooting-along-streets-and-sidewalks/.

[40] "Regulation EU 2019/2144 of the european parliament and of the council of 27 november 2019 on type-approval requirements for motor vehicles and their trailers," Official Journal of the EU L325, Dec 2019.

[41] A. Rasouli and J. K. Tsotsos, "Autonomous vehicles that interact with pedestrians: A survey of theory and practice," *IEEE transactions on intelligent transportation systems*, vol. 21, no. 3, pp. 900–918, 2019.

[42] L. M. Hulse, H. Xie, and E. R. Galea, "Perceptions of autonomous vehicles: Relationships with road users, risk, gender and age," *Safety science*, 2018.

[43] N. Liu, A. Nikitas, and S. Parkinson, "Exploring expert perceptions about the cyber security and privacy of connected and autonomous vehicles: A thematic analysis approach," *Transportation research part F: traffic psychology and behaviour*, 2020.

[44] S. Gupta, M. Vasardani, and S. Winter, "Negotiation between vehicles and pedestrians for the right of way at intersections," *IEEE Transactions on ITS*, no. 3, 2018.

[45] E. R. Straub and K. E. Schaefer, "It takes two to tango: Automated vehicles and human beings do the dance of driving–four social considerations for policy," *Transportation research part A: policy and practice*, 2019.

[46] E. Kassens-Noor, M. Cai, Z. Kotval-Karamchandani, and T. Decaminada, "Autonomous vehicles and mobility for people with special needs," *Transportation research part A: policy and practice*, 2021.

[47] J. Brinkley, E. W. Huff Jr, B. Posadas, J. Woodward, S. B. Daily, and J. E. Gilbert, "Exploring the needs, preferences, and concerns of persons with visual impairments regarding autonomous vehicles," *ACM Transactions on Accessible Computing*, 2020.

[48] D. Hong, S. Kimmel, R. Boehling, N. Camoriano, W. Cardwell, G. Jannaman, A. Purcell, D. Ross, and E. Russel, "Development of a semi-autonomous vehicle operable by the visually-impaired," in *2008 IEEE International Conference on Multisensor Fusion and Integration for Intelligent Systems*. IEEE, 2008, pp. 539–544.

[49] P. D. Fink, J. A. Holz, and N. A. Giudice, "Fully autonomous vehicles for people with visual impairment: Policy, accessibility, and future directions," *ACM Transactions on Accessible Computing*, 2021.

[50] A. Z. Asha, C. Smith, G. Freeman, S. Crump, S. Somanath, L. Oehlberg, and E. Sharlin, "Co-designing interactions between pedestrians in wheelchairs and autonomous vehicles," in *Designing Interactive Systems Conference 2021*, 2021, pp. 339–351.

[51] S. H. Lee, V. Patil, N. Britten, A. Block, A. Pandya, M. Jung, and P. Schmitt, "Safe to approach: Insights on autonomous vehicle interaction protocols with first responders," in *HRI 2023: Proceedings of the 2023 ACM/IEEE International Conference on Human-Robot Interaction*. IEEE Press, 2023.

[52] G. Hoffman and W. Ju, "Designing robots with movement in mind," *Journal of Human-Robot Interaction*, vol. 3, no. 1, p. 89, Mar. 2014.

[53] A. D. Dragan, K. C. Lee, and S. S. Srinivasa, "Legibility and predictability of robot motion," in *2013 8th ACM/IEEE International Conference on Human-Robot Interaction (HRI)*, 2013.

[54] M. J. Gielniak and A. L. Thomaz, "Enhancing interaction through exaggerated motion synthesis," in *Proceedings of the 7th Annual ACM/IEEE International Conference on HRI*, 2012.

[55] M. Oudshoorn, J. de Winter, P. Bazilinskyy, and D. Dodou, "Bio-inspired intent communication for automated vehicles," *Transportation Research Part F: Traffic Psychology and Behaviour*, 2021.

[56] G. Nelson, A. Saunders, and R. Playter, *The PETMAN and Atlas Robots at Boston Dynamics*, 01 2019, pp. 169–186.

[57] M. Suguitan and G. Hoffman, "Blossom: A handcrafted open-source robot," *J. Hum.-Robot Interact.*, vol. 8, no. 1, 2019.

[58] J. de Winter and D. Dodou, "External human–machine interfaces: Gimmick or necessity?" *Transportation Research Interdisciplinary Perspectives*, 2022. [Online]. Available: https://www.sciencedirect.com

[59] D. Dey, A. Habibovic, A. Löcken, P. Wintersberger, B. Pfleging, A. Riener, M. Martens, and J. Terken, "Taming the eHMI jungle: A classification taxonomy to guide, compare, and assess the design principles of automated vehicles' external human-machine interfaces," *Transportation Research Interdisciplinary Perspectives*, 2020.

[60] SingaporeLTA. (2019) Autonomous vehicles: Identifying avs and trials on roads. https://www.lta.gov.sg/content/ltagov/en/industry_innovations/ technologies/autonomous_vehicles.html.

[61] S. H. Lee, N. Britten, A. Block, A. Pandya, M. Jung, and P. Schmitt, "Coming in! : Communicating lane change intent in autonomous vehicles," in *Proceedings of the 2023 ACM/IEEE Intrl. Conf. on HRI*.

[62] D. Moore, R. Currano, M. Shanks, and D. Sirkin, "Defense against the dark cars: Design principles for griefing of autonomous vehicles," in *Proceedings of the 2020 ACM/IEEE Intrl. Conf. on HRI*.

[63] T. Mulder and N. E. Vellinga, "Exploring data protection challenges of automated driving," *Computer Law Security Review*, 2021.

[64] C. Bloom and J. Emery, "Privacy expectations for human-autonomous vehicle interactions," in *2022 31st IEEE International Conference on Robot and Human Interactive Communication (RO-MAN)*, 2022.

[65] B. Mehler, "Considerations regarding introduction of optical, audible signals intended to signal the status & intent of automated vehicle systems," https://unece.org/sites/default/files/2021-11/ECE-TRANS-WP1-2021-Presentation-21e.pdf, UNECE, 2021.

[66] J. Shutko and T. Bray, "Evaluation of AV external communication in the wild," https://wiki.unece.org/download/attachments/75531441/AVSR-02-23e.pdf?api=v2, UNECE, 2018.

[67] "Automated driving system marker lamp j3134-201905," Society of Automotive Engineers," Standard, 2019.

[68] "Road vehicles — ergonomic aspects of external visual communication from automated vehicles to other road users," https://www.iso.org/standard/74397.html, ISO, Standard, 2018.

[69] ETSI, "Tr 102 638 intelligent transport systems; vehicular communications," Jun 2009. [Online]. Available: https://www.etsi.org/standards

[70] S. Shingu, "Socially aware autonomous mobility lightning talks," https://www.massrobotics.org/socially-aware-autonomous-mobility-lightning-talks/, May 2023.

[71] B. J. Zhang and N. T. Fitter, "Nonverbal sound in human-robot interaction: A systematic review," *Transactions on HRI*, 2023.

[72] F. A. Robinson, O. Bown, and M. Velonaki, "Designing sound for social robots: Candidate design principles," *International Journal of Social Robotics*, 2022.

[73] S. Joshi, "Towards Community-Robot Interactions," in *Proceedings of the 17th European Conference on Computer-Supported Cooperative Work: The International Venue on Practice-centred Computing and the Design of Cooperation Technologies*, 2019.

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