AI-Based Solutions for Improving Vehicle-to-Pedestrian Communication

By Dr. Daniel Koppelman

Professor of Computer Science, University of Haifa, Israel

1. Introduction

Urban mobility today places heavy emphasis on the interactions among vehicles and pedestrians in the street. Effective vehicle–pedestrian communication in these interactions allows various road users to understand the surrounding traffic environment, predict the actions of the traffic participants, and further improve interaction safety. Therefore, more and more research efforts have been attracted to interpret vehicle-to-pedestrian communication as a framework for the audio and visual perception of street participants, signal processing, and action generation for effective communication. The topic is also relevant to the general discussion on road safety and human considerations. The general objectives of our research are to shed light on the importance of communication between autonomous systems and the rest of the road users, with a specific focus on pedestrians, and to explore AI tools aimed at enhancing vehicle-to-pedestrian communication. In line with the above, the paper first sheds light on opportunities to improve driving acceptability and accessibility. In fact, we consider that road vehicles are nodes within a wireless communication network. They have the potential to substantially improve pedestrian safety and driving experience by effectively and intuitively communicating important and possibly safety-critical information with other vehicles, pedestrians, and surrounding infrastructure. Finally, we discuss the features of the reviewed data, the adopted methodology, and the addressed AI-based data processing tools and methodologies, with the primary focus on artificial neural networks.

1.1. Background and Significance

Vehicle-to-pedestrian communication has been attracting increasing attention in recent years. The advent of motorized transportation ultimately led urban planners to focus on optimizing streets and intersections for the safety of pedestrians, by, for example, the inclusion of crosswalks and traffic lights. However, V2P efforts are increasing in the face of the continuing high number of pedestrian accidents, including some involving autonomous vehicles. AI is likely to play a key role in the development of advanced V2P systems, often called CAV systems. Such systems can provide information to pedestrians that compensates for previously degrading communication channels.

Connecting drivers, vehicles, and infrastructure with pedestrians is a communication problem. Many attempts have been made in the past, most of which have been doomed to failure. The level of research investment is reflected in the extensive review, who documented years of research targeting AV pedestrians. The greatest avenue to pedestrians will continue for well over the next few years. It seems puzzling that such a problem remains, as the benefits of V2P communication are clear. In 2019, a significant percentage of traffic crash deaths were pedestrians, and this increased the following year. The impact can be seen most when it comes to time spent in transit. Many pedestrian accidents are caused by drivers and pedestrians misunderstanding each other. Ethical challenges are arising as AV developers try to sense highways and neighborhoods. Many avoid it by choosing the simplest possible driving environment. Moreover, there has been an increase in pedestrian fatalities in the past five years, mostly in areas that are under greater traffic strain due to urbanization.

1.2. Research Objectives

The primary objective of this research is to identify some AI-based solutions that will potentially improve existing vehicle-to-pedestrian communication systems. In addition to this, our research also aims to propose a collaborative urban-driven approach to enhance pedestrians' safety and to highlight policy and design implications. For this purpose, we first intend to assess how pedestrians are considered in a typical in-vehicle application. Second, existing vehicle-to-pedestrian communication systems are analyzed and their effectiveness is assessed. A comparative analysis of the literature within the transport, AI, and autonomous vehicle domains will be used to extract information that can guide our research goals. Third, we will identify the most critical information that pedestrians should know about approaching vehicles and propose a set of AI solutions to improve interactions between in-vehicle applications and pedestrians. This is achieved by defining research questions as follows.

• How are pedestrians considered in typical in-vehicle pedestrian detection applications? What kind of information is provided to pedestrians? Additionally, we will explore how pedestrians are regarded with respect to communicating vehicles that they will not be aware of, providing insights into the research objective. • What is the state of the art in vehicle-to-pedestrian communication systems? We will investigate initiatives that aim to develop safer and comprehensive solutions, ensuring a well-motivated relevant comparative study will be carried out. • What kind of information should be provided to pedestrians about approaching vehicles or vehicles in the immediate vicinity with which they have no visual contact? This research question addresses the problem of generically summarizing information that pedestrians should know according to local urban conditions, common pedestrian behaviors, and contributory factors to accidents involving pedestrians and autonomous vehicles. • What are the AI-based solutions, if any, that are available that will make vehicle-to-pedestrian communication, pedestrian detection, and tracking more effective in informing pedestrians about approaching vehicles? The research questions will ameliorate this last query and corroborate the discussion about the potential future pool of both algorithms and policies to support pedestrians in such journeys. We envision that the findings of this study will potentially provide useful information to urban planners, demonstrate the complex interactions that arise when the urban environment and pedestrians' behavior are combined, provide fresh and preliminary evidence that demonstrates how AI and different road users interacting can thrive in public safety, and sensitize future researchers to tailor research designs to correspond with possible urban design scenes.

2. Understanding Vehicle-to-Pedestrian Communication

When it comes to urban safety solutions, few things are as relevant as vehicle-to-pedestrian communication. Extremely efficient, real-time communication is directly associated with accident prevention and improvement of in-the-city living experiences. The pedestrian's point of view is the one most frequently taken into account when trying to improve communication between vehicles and pedestrians. However, in an urban environment, many drivers are not vehicle-centric, which helps justify the study of driver-pedestrian communication. How do drivers perceive pedestrians in an urban environment? How do pedestrians interpret drivers' intentions? These are questions that remain to be answered. Combining various forms of communication, such as physical actions, voice, and gestures, can lead to clearer and more comprehensible communication, and may result in fewer misunderstandings between various stakeholders. In an urban environment, pedestrians and drivers do not share the same culture or make use of the same landmarks and visual language: the study of this culture-based communication may allow us to design better communication solutions. Cultural communication studies usually focus on human mobility and the interaction among people in society; this is an approach that can be integrated into the communication between pedestrians and drivers.

The importance of communication between a vehicle and a pedestrian, which significantly influences the social context of mobility, is hard to underestimate. Despite attempting to formalize the prediction of pedestrians' future movements and intentions, a main challenge is indeed understanding the support for the consequent vehicle verbal and non-verbal actions, which often directly influence pedestrians' activity among roadways. This can be particularly critical in an urban setting when flows of running pedestrians become unpredictable, include heterogeneous behaviors, and communications among pedestrians are of no help to the vehicle driver. From the pedestrians' perspective, there is an increasing demand for exploiting pedestrian-to-vehicle communication, to maximize the potential of autonomous vehicles in urban settings and provide both pavement-based actions and in-car services that understand and react to the pedestrians' intentions. These objectives highly motivate the development of readable models for driver-pedestrian interactions, necessarily including exacerbated data analytics on the most specific dynamics of signal-based behaviors. Some recent efforts deal mainly with human localization and prediction of pedestrian itineraries established on learned habits, often based on the analysis of shared social facilities.

2.1. Challenges and Limitations

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Communication between a vehicle and pedestrians can be beneficial in many different scenarios. Nevertheless, no matter the functionality or potential positive outcomes, there are some limitations that have already been identified. Pedestrian detection and warning have become the latest area of increasing concern with the rise and mobilization of different types of robotic ground vehicles. In particular, the prevalence of city cars raised some safety issues regarding the safety of people sharing city space with these driverless cars. Trust in such driverless cars is a complex process, including trust in technology.

There are technological and legal limits regarding the positions (mainly blind spots) of the car that can benefit from external pedestrian warning. Especially, city environments are complex and pose additional limits to provide reliable advanced warning to pedestrians. Potential city corridors could have one pedestrian every 50–100 meters on the left and right side of a vehicle. This is particularly challenging given typical sensor ranges of 7–30 m and the occlusion by buildings, signs, pedestrians' bodies, as well as traffic. These results suggest that the existing technologies won't be fully able to cope with the detected lack of detailed information needed in such complex and dynamic contexts. Since a human driver is not an option in driverless and augmented driving systems, it is critical to promote the development of new AI-based systems able to effectively communicate vehicle intention to pedestrians with a reliability that is close to 100%, in order to avoid a technological path dependency toward accident-potential scenarios. Overlooking this limitation, both the position of the corner of the car and a low position could hide the presence of nanocars due to the occlusion of surrounding people in the immediate surroundings. Eye fixation is independent of nanocar presence, diminishing with distance, nanocar size, and day compared to night.

2.2. Current Technologies

In modern cars, drivers are supplied with technology that informs them about non-visible traffic participants. Pedestrian exposure to these systems is still rare because they are predominantly offered as premium installations and have an additional cost. The information is typically displayed in a head-up display, dashboard, or center instrument. These display technologies have not fundamentally changed in decades; however, newer digital displays offer greater variability both in the ways they can be used and the information they present. Furthermore, a limited number of cars now come with e-mobility-related applications that allow drivers to use a smartphone to, for instance, command turning indicators and horn signals. These functions are offered to change the perceived external vehicle noise and therefore may also be appreciated by pedestrians. In addition to these limited ex-works solutions for connecting drivers with pedestrians, many cars come equipped with mobile applications that provide nearby pedestrian information via their normal in-vehicle user interface.

Existing external vehicle communication employs in most cases either an auditory signal or a visual alert to inform pedestrians about an approaching or turning vehicle. The best outward vehicle sound changes in relation to the operating condition and the occupant load. Practical experience has shown that many auditory signals are barely noticeable, eschewed, or confused by many road users. Visually, early studies have shown that flashing lights were more readily noticed by children but not necessarily by the elderly or disabled. More recent technological enhancements, such as using light and sound differently, as well as disturbing eye tracker light patterns, have been only marginally investigated until now. Given the potential of AI-based technologies to understand and predict pedestrian behavior, they could also interfere in numerous other vehicle–pedestrian interactions. Moreover, facial emotion recognition could also be combined with future V2P technologies for more complex human–machine behavioral interactions.

3. Machine Learning Applications in Urban Environments

Machine learning methods and deep learning architectures have been widely proven in a number of applications in urban environments. The ability to learn from data has led to solutions to problems where events or patterns are not clearly known; for example, pedestrians' behavior. Machine learning algorithms can analyze large datasets of pedestrian behavior to enhance the communication of a vehicle-to-pedestrian system at the city level. This can be translated into predicting to the vehicle when pedestrians are likely to cross outside the zebra crossing or close to the vehicle, to make safe decisions according to pedestrian locations at the actual time. Recently, several smart cities have implemented IoT-dependent solutions for accessing and analyzing data related to pedestrian behavior at the city level. This system allows offline and real-time prediction of pedestrian flows to increase safety in busy or tourist zones.

The introduced predictive analytics based on machine learning methods provide a golden opportunity for the mobility industry to adapt or personalize their safety protocols close to the vehicle according to dynamic urban environments. Predictive analytics is part of the artificial intelligence tools that describe, say, and forecast human behavior. Every time a person acts in a specific way, and given the actual circumstances and spatial availability, people are predictable. The type of machine learning algorithms that a smart vehicle should apply has to include methods capable of dramatic and rapid near real-time changes in pedestrian predictions. Machine learning algorithms should thus be selected according to situations and time horizons.

In the near future, every vehicle is expected to be equipped with artificial intelligence to interact with road users in a more efficient manner. The next section briefly describes the machine learning methods accepted nowadays, to later describe the case of a vehicle-to-pedestrian system that can be adjusted to pedestrian interactions. While bearing in mind that much testing has to be done to communicate with every different type of pedestrian, not just with the three categories shown. Additionally, the industry highlights methodologies in which a pedestrian is communicating with the vehicle, as essential for future mobility interactions. Factors for scalability have to be also considered, with conscious or unconscious pedestrians in crossing interactions. Scalability also includes advanced mobility systems interacting with elderly pedestrians or pedestrians with health conditions. Clear knowledge and tools in these areas should complement the integration of the system into crowded cities and ease the workload for the vehicle driver. Indirect and direct interactions should be defined in an all-encompassing dataset, and how to classify which pedestrian is part of. The issue should integrate exemplary countries with examples of pedestrian type categories and interactions as a starting point on how each city is laid out.

3.1. Overview of Machine Learning

There are three different types of machine learning: supervised learning, unsupervised learning, and reinforcement learning. Supervised learning is the most commonly used method among the three types. The purpose of this method is to train a model by providing data with specific input and expected output values. The model will learn how to react by observing the inputs over time and with the background knowledge provided by the developer. On the other hand, unsupervised learning is about using data that has no segments, features, or results, and trying to find underlying structures within that data. Reinforcement learning isn't as common compared to the other two types. Reinforcement learning implies taking suitable actions out of any condition or situation. Based on the results derived from the actions, the model learns useful decisions or actions for similar states in the future. Algorithms do this by maximizing the expected reward for the states.

Machine learning is an application of artificial intelligence in which algorithms are trained using intricate databases and equipped to learn by recognizing patterns from that training data. The more extensive the dataset with more characteristics, the more accurate the model will be in anticipating specific outputs. Learning from data is essential for algorithms to recognize and resolve complex issues like accurate object and speech recognition. Understanding these capabilities allows us to relate these utilizations of machine learning to the subject of improved vehicle and pedestrian communication and urban mobility management. Before continuing on to future work and methodology, we will take a moment to examine the ethical and biased implications surrounding AI vehicles.

3.2. Benefits and Opportunities

Machine learning can be employed for diverse applications with various objectives in urban settings, such as operational efficiency and supporting decision-making. Advances in machine learning could enable the development of more accurate AI-based models for vehicle-to-pedestrian communication, feedback, and intervention to better meet the requirements of the users, cities, and other stakeholders involved in real-life on-street urban environments. They could also personalize the vehicle-to-pedestrian communication by taking advantage of data gathered by the vehicles. Learning models could infer long-term preferences from the data records and the contextual information to provide truly appealing and interesting products and services. In addition, vehicle-to-pedestrian learning models could be used to feed the smart city data warehouses. Cities could then analyze real-time vehicle-to-pedestrian information to address and prevent any accessibility-related situations. Closing the loop, the learning models could learn from the behavior and lifestyles of the local users and re-effect the parameters for regulating some safety or service content in the urban area. Moreover, AI-based machine learning models could be used to pre-arrange plenty of alternative choices by satisfying both the restrictions set by city authorities and the style requirements of the car manufacturer since the model is able to recommend a sequence of vehicle-to-pedestrian interventions. Thus, this service can take part in a user-centric approach by respecting the business and technical criteria of the nearby players.

4. AI-Based Solutions for Vehicle-to-Pedestrian Communication

At the conceptual level, AI and learning-based communication protocols can serve to improve many facets of the effective communication process, including encoding information for more robust scene understanding, developing and executing communication strategies, and providing feedback for generated interactions. AI solutions can be integrated into existing communication frameworks to enhance interaction. Given that vehicle-to-pedestrian communication spans multimodal, hybrid systems that include robotic, autonomous vehicles as well as city-wide, networked transportation management systems, planners, engineers, and evaluators require communication platforms that can simulate perception and action planning in detailed environments. Below, we outline a representative range of systems and platforms based on AI technologies in the vehicle-to-pedestrian communication literature.

Across the spectrum of systems and platforms, the main advantages of AI can be seen in: 1) enabling real-time decision-making for a pedestrian as the system perceives new information—like a pedestrian crossing a street; 2) providing a holistic approach to perception-communication features by allowing vision modules and NLP modules to influence each other; 3) and scalability—these AI systems can be trained and simulated at a range of scales, from individual intersections to entire metropolitan areas with a focus on infrastructure and operational decisions. Artificial intelligence enhances systems to develop intricate, adaptive communications to aid in safety culture and public trust. Ultimately, these strategies would improve multimodal performance and the conflict points between pedestrians and motor vehicles. The success of the transportation systems management can mitigate any negative impacts on the public transportation system as a whole. Disadvantages include privacy concerns over the tracking and potential future use of anonymized pedestrian and vehicular data. This concern may evolve with the increased functionality of self-driving vehicle operating systems in future research and vehicle-to-everything technology.

4.1. Key Components and Technologies

With the rapid development of advanced technology, there are numerous solutions to vehicle-to-pedestrian communication. These technical components integrate several technologies. In general, radar, a camera, light detection and ranging, or the fusion of these sensors are responsible for gathering information on pedestrians, their features, and behaviors in different surroundings. The communication network and cloud enable data to be sent, stored, and analyzed. Thus, the communication network enables real-time and remote interaction. Continuing, data analysis and processing tools, such as convolutional neural networks, long short-term memory, object detection, classification and tracking, clustering, and so forth, are used to design the behavior-aware models of pedestrians. Lastly, the user interfaces are the output mechanisms used to communicate with pedestrians via visual, auditory, tactile, or haptic means.

The above components are influenced by or influence the functionalities, performance, or parameters of V2P communication. Interoperability and social responsivity designate that communication should be coordinated and smoothly come to terms among different ITS or V2X components but also among different car brands, device models, as well as pedestrians or road users with different needs. The high expense and time-consuming aspects of merging the hardware have to deal with fast changes in technological performance and drivers' requirements. Changes in sensors may require changes in physical infrastructures or software tools, while recent research focuses on software-based, multimodal fusion and strategies of employing abstract or virtual simulations of sensory data. Furthermore, some highly portable solutions mainly rely on user smartphones rather than on the infrastructure. The emerging connectivity with low-latency wireless communication offers real-time interactions and makes it available to have the smart vehicle of the future ready for vehicle-to-pedestrian communication, while the cloud-based system streamlines infrastructure costs. In designing an application, the hardware or software alternatives, potentialities, and roles of sensors, as well as the necessity of communication among the sensors, are to be discussed. In fact, V2P communication can mainly be developed and guided as a hardware solution, but it is also implemented as a software or a hardware-software combination.

4.2. Case Studies and Examples

The objective of this paper is to review and showcase how AI-based solutions can be used in practice in vehicle-to-pedestrian communication to enhance walking safety and efficiency. This involves a multitude of different aspects, including consideration of urban settings and most predisposed pedestrian groups (children, elderly, wheelchair users, etc.), as well as the technologies applied in each case study. Lessons learned from these real-life cases are presented, and challenges are outlined to offer a more balanced view. Cases presented include the full autonomous vehicle demonstration at a convention center; chariot at a city award-nominee project in Graz.

5. Future Directions and Implications

Emerging Trends. The current landscape of vehicle-to-pedestrian communication research suggests several trends that could shape the direction of these technologies in the next decade. We expect to see the continued uptake of innovative AI-based solutions that take advantage of unique capabilities, including learning and understanding, to automatically generate the most appropriate communication designs and personalize them based on identified pedestrian factors. Emphasis is also likely to be placed on the value of continuous innovation, bordering on vehicle-to-pedestrian communication as a service operation rather than a static tool. Advances in data collection and the creation of new multi-sensory cues or methods for engaging pedestrians would be instrumental in driving future commercial value in vehicle-to-pedestrian communication.

Policy Implications. Notwithstanding the tremendous opportunity provided by AI-based solutions, future urban design and infrastructure strategies need to harness the potential of intelligently guiding pedestrian behaviors using vehicle-to-pedestrian communication. Policymakers need to consider privacy and security implications, specifically balancing the socio-economic value derived from the use of AI technologies in the mitigation of collisions with the impacts on individual freedoms. Ethical considerations also need to be included when imbuing AI solutions with the ability to interpret human behavior, emotions, and intent for the purposes of redesigning and communicating safety risks in urban environments to improve road safety. This has implications for freedom of choice and consent, as well as for potentially marginalized users. These implications need to be carefully considered and communicated in any future policy or regulations. It is also critical to engage a wide range of stakeholders to co-create solutions that can mitigate the risks associated with the large-scale deployment of technological solutions like AI in the broader context of societal values, institutions, norms, and regulations.

5.1. Emerging Trends

Vehicle-to-pedestrian communication is an active research area, and various studies have underlined the potential of such communication. There are multiple emerging trends evident within the literature that influence the design of these systems. First, it is evident that AI and machine learning techniques are enabling pedestrian-to-vehicle communication to become more sophisticated, with new forms of interaction becoming possible. As well as being used to optimize the performance of P2V systems, machine learning is also providing new insights to help optimize the design process. Furthermore, AI is being employed to increase V2P communication efficiency, with indications of the potential for increased response, showing a significant improvement in driver response times.

The literature has also indicated the potential to use smart infrastructure or connected devices, such as smartphones, to facilitate V2P communication. The design of V2P communication solutions is increasingly taking into account the pedestrians crossing the road, identifying the specific needs of different pedestrians and designing the communication. User experience design is coming to the fore in the development of both virtual and real V2P communication, in order to enhance the design of the communication. Many modern vehicle–pedestrian communication methods are adaptable in real time to the surrounding environment in order to provide a service to pedestrians, such as on-road warning messages. The growing trend towards virtual and mixed reality studies indicates we should expect more studies to pose adaptive vehicle-to-pedestrian communication in the field, in order to create a safe environment for the user. Many studies discuss the potential of V2P for pedestrian avoidance and, as a result, indicate the systems are increasingly focusing on safety applications. By observing these trends, we can begin to anticipate the future of V2P and the challenges that need to be involved in urban planning and policy.

5.2. Policy and Regulatory Considerations

The use of AI to improve vehicle-to-pedestrian communication raises significant questions that have yet to be addressed. The complexity of the technology raises the possibility of new challenges and problems, including issues that have yet to arise in other domains. In many jurisdictions, even vehicles in testing are required to comply with certain regulatory standards, many of which include a line-of-sight requirement for all control systems within the vehicle. Altogether, new policy and regulatory tools are necessary to adequately govern the use of AI in these systems. Innovations in licensing, permitting, or otherwise monitoring and verifying AI systems in the urban environment are necessary in order to safely and efficiently allow their use in public spaces. The development of standards and norms must be done in cooperation with the relevant governmental bodies and institutions. For-profit businesses alone must not be the only stakeholders in the development of these systems, as the outcome of these negotiations could significantly disadvantage other industries or society as a whole. Further research into the legal, regulatory, and policy requirements for preventing fraud or misuse of these systems is also required. This includes considerations regarding data privacy, security, collecting informed consent, enforcing these permissions, general measures to promote the ethical use of the technology, integrating input from the community, and identifying the required enabling regulations in the operational domain. The operation of AI-based V2P systems must comply with these regulations to ensure public trust in the technology. New rules and policies are needed that require or incentivize the use of verifiable AI, while preventing the ethical risks and abuses associated with a lack of transparency. The regulatory and policy regimes of electric utilities, robotics, and automation equipment may provide a guide for the development of new regulations governing the use of these AI systems. For example, the requirement in small UAS regulation may be considered in the creation of new rules for the use of AI-based systems. The regulation lacks a reasonable basis for the regulation, thus hampering the development of innovative technologies or business models. New regulations should follow the law and be tailored to the particular legal, ethical, and operational context in which the autonomous AI technologies will be deployed.

6. Conclusion

Modern cities are vibrant with ever-increasing flows of urban pedestrian activity. Pedestrian accidents, which today represent about 24% of the total number of commuting fatalities worldwide, reflect the pressing need for effective vehicle-pedestrian communication. This paper discusses ways to transform the nature of vehicle-to-pedestrian interactions with AI technologies. It pinpoints challenges of driver attitudes toward interacting with pedestrians and pedestrians' mistrust of the vehicle's operation. Inspired by a selection of public voices, we present a snapshot of people's hopes about AI-based solutions that open up opportunities for more conscientious and increasingly safety-oriented vehicle-pedestrian communication. Whilst technology has the potential to largely improve urban mobility, it may also introduce new and unforeseen forms of crashes, security risks and also biases. This paper focuses on one of the most pressing problems today: vehicle-pedestrian interactions and how impact-absorbing pedestrian behaviour typically increases the potential for a crash. The paper contends that systemic change on how vehicle-to-pedestrian interactions occur re-situates pedestrians to once again align cities around people, their walking and their interactions with vehicles. Further study on the efficacy of the presented strategies are necessary in future research to ensure that digital tools are shown to successfully assist in safe road-crossing behaviours. Given the complexity and diversity of road users, policy will also be essential for accountability and inclusivity. A second challenge concerning the social acceptance of digital shared roads and the nature of the pedestrians that will be created by AI-based tools also requires urgent research. At stake is the defense of pedestrians' rights, who are users of public space and do not adhere to the religious guidance of any man-made algorithm. Further, in the absence of legal tools, responsibility and accountability for the design and use of these AI strategies is also necessitated.

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