Communication and Intention between Autonomous Vehicles and Vulnerable Road Users: A Systematic Review

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As the role of drivers becomes less active, autonomous vehicle technology will need to fill in the gap concerning the communication between vehicles and pedestrians moving in shared spaces. This article presents a systematic review of all research conducted in regard to external vehicle to pedestrian communication systems in autonomous vehicles. Identified research was categorized by method, interaction setting, communication method, message content and dependent variables. Important themes are addressed in the discussion which provides guidance for future research.

INTRODUCTION

Advancement in autonomous vehicle (AV) technologies bring new challenges to complex and busy urban environments, where vehicles and pedestrians are expected to move in shared spaces. Currently, pedestrians gain knowledge about a vehicles intention from a variety of different means. Pedestrians learn of a vehicles intent from formal communication methods such as turn signals, brake lights and driving behaviors like deceleration (Clamann, Aubert, & Cummings, 2017), as well as informal communication. Driver-pedestrian informal communication occurs in the form of body language, eye contact, nods and hand signals (Rasouli, Kotseruba, & Tsotsos, 2017). Interactions between pedestrians and vehicles occur in a variety of different settings and in many different contexts. Vehicle-pedestrian communication is especially critical at crosswalks, parking lots, and unmarked street crossings where formal regulations are ambiguous (Ackermann, Beggiato, Schubert, & Krems, 2019).

Encounters with AVs, on the other hand, are different than encounters with manually driven vehicles because there is no human operator to provide cues to negotiate an interaction (Habibovic et al., 2018). When pedestrians encounter an autonomous vehicle with passengers that do not provide acknowledgment or communication, they may experience feelings of stress or unsafety (Habibovic et al., 2018). Furthermore, pedestrians may take longer to cross or become hesitant, which could lead to traffic inefficiency or risky vehicle-pedestrian interactions (Habibovic et al., 2018). Without major infrastructural changes to roadways, intersections and sidewalks, autonomous vehicles will require methods of communication to negotiate interactions with pedestrians, cyclists and manually driven vehicles traveling in shared spaces.

GOALS

Research in the area of autonomous vehicle communication with pedestrians has been largely unexplored (Lagström & Lundgren, n.d.-a). The goal of this paper is to identify the methods, designs and practices of AV-pedestrian interactions that are being used in academic research and summarize common themes in the current body of knowledge.

METHOD

A systematic review of research conducted in the area of autonomous vehicle-pedestrian communication was conducted using the following databases: Academic Search Complete, ACM Digital Library, Engineering Village, IEEE Xplore, Science Direct, and Scopus. The key words "*autonomous vehicle*" and "*pedestrian safety*" were cross-referenced with the terms "*communication*" and "*intention*", as well as relevant synonyms. Resulting articles were cataloged and screened for duplicates using an excel spreadsheet. Relevant articles were selected by first filtering by title, then by abstract and finally by conducting a full-text review. Articles were selected based on the following inclusion and exclusion criteria:

Inclusion Criteria: Articles included must have (1) Involved an empirical study of autonomous vehicle interaction with pedestrians. (2) Use an interface that communicates with pedestrians in some form. (3) Use quantitative or qualitative metrics to evaluate pedestrian interaction in terms of trust, comfort, safety or ability to discern communicated intention.

Exclusion Criteria: Articles were excluded if they (1) Did not involve an empirical study of autonomous vehicle interaction with pedestrians. (2) Did not use an interface to communicate with pedestrians. (3) Did not assess participants subjective feelings of AV encounter.

RESULTS

The database search resulted in 165 unique entries. An additional 19 articles were found via initial literature review and investigation of references, totaling 184 unique entries. 156 entries were filtered out by reviewing title and abstract leaving 28 articles. After a full text review of 28 articles, 19 matched the predetermined inclusion and exclusion criteria and are featured in this systematic review.

The selected research articles were coded and categorized on five different criteria. (1) Research Method, (2) Interaction Setting, (3) Communication Modality, (4) Message Content, (5) Dependent Variables. The studies investigated may or may not have involved one or more of any of the previously stated criteria. In instances where this occurred, each of the relevant criteria was accounted for, resulting in some articles being referenced more than once.

Research Methods: All selected articles investigated vehicle-to-pedestrian (V2P) communication systems (Hussein, García, Armingol, & Olaverri-Monreal, 2016) with pedestrians. Four different research methods were identified. Of the 19 accepted research articles, 74% were conducted in either virtual reality or real world settings. Only 26% were conducted using video or surveys. It should be noted that some of the articles conducted design research, such as focus groups in addition to V2P communication research. Design research is not the focus of the current systematic review and these methods were not reported here.

Table 1: Research Methods

Research Methods	N
Virtual Reality	7
Real World	7
Video	3
Survey	2

Interaction Setting: The interaction setting refers to the setting in which the vehicle-pedestrian interaction occurred. Four types of interaction settings were identified. A total of 22 interaction settings were tested across 19 research articles. Zebra crosswalks were most prevalent, appearing in 68% of articles, followed by unmarked/unprotected crossings, parking lots and other/unspecified interactions.

Table 2: Interaction Setting

Interaction Setting	N
Zebra Crosswalk	13
Unmarked/Unprotected Crossing	4
Parking Lot	3
Other/Unspecified	2

Communication Modality: All V2P communication system used one or more communication modalities to deliver a message to pedestrians. Across all studies, three communication modalities were used. Nearly all communication systems (94%) used visual means to communicate with pedestrians. 32% of research investigated auditory modalities. Haptic communication methods were only investigated by 2 articles.

Table 3: Communication Modalities

Communication Modality	N
Visual	18
Auditory	6
Haptic	2

Message Content: Message content refers to what information is actually conveyed to the pedestrian. There were four different types of messages communicated across multiple modalities. Most articles investigated multiple content types.

Vehicle intention, where the vehicle informs pedestrians of what it will do next (ex. slowing down or stopping) was the most common message communicated, occurring in 79% of research. Pedestrian advice, where the vehicle informs pedestrians what they should do (ex. "you may cross" or "don't cross") was the second most prevalent message conveyed occurring in 58% of research. Pedestrian acknowledgment and vehicle mode were used 32% of research and 16% of research respectively.

Table 4: Message Content

Message Content	N
Vehicle Intention	15
Pedestrian Advice	11
Pedestrian Acknowledgment	6
Vehicle Mode	3

Dependent Variables: Interactions between pedestrians and V2P communication systems were measured by a variety of different means. Researchers most often measured either pedestrians perceived comfort / safety or signal intention understanding. Each were used as dependent variable measurements in 42% of research. The remaining measurements were each used in 15% or less of research.

Table 5: Dependent Variables

Dependent Variables	N
Perceived Safety and Comfort	8
Signal Intention Understanding	8
Trust in Autonomous Vehicles	3
Subjective Rating	3
Decision to Cross Time/ Time Taken to Cross	3
Safe to Cross Duration	2
Participant Behavior/Hesitation	2

DISCUSSION

Across the selected articles, researchers created and tested different vehicle to pedestrian communication systems. V2P designs tended to consist of some combination of LED light strips, LED monitor displays, projectors or speakers applied to either the windshield, body, or grill of the vehicle.

Seven research articles strictly focused on determining if a given V2P design was better or worse than another. Of the twelve articles that answered whether or not the V2P system was necessary compared to an autonomous vehicle without a V2P system, nine researchers found that V2P systems improved pedestrian crossing in terms of crossing time, trust or feelings of safety. Three articles determined that, while V2P systems helped some pedestrians, there are other more important factors for pedestrian crossings and that V2P systems may not be needed. The following section discuss commonalities and points of interest across research.

Research Methods

Of the four research methods identified, real world and virtual reality were the most common. Real world research generally tested fewer V2P designs than other research methods with only one out of seven testing more than one design. Furthermore, only three out of seven real world studies involved cars. Other vehicles included, golf carts, pods and segways. No real world vehicle in the selected research was autonomously controlled and all experiments involved some form of deception to convince participants that they were experiencing an autonomous vehicle. Vehicles were actually controlled via remote control or some variation of a wizard of oz driver.

Virtual reality was generally less restrictive because it allowed for more V2P designs to be tested. The majority of virtual reality studies tested more than two types of V2P communication systems. While it was found that "participants will respond to traffic in a simulator as they would in the real world"(Deb, Strawderman, & Carruth, 2018) and simulations were regarded as "realistic and immersive" (de Clercq, Dietrich, Núñez Velasco, de Winter, & Happee, 2019), virtual reality simulations are not without their limitations. Participants can become nauseous from prolonged interaction and must be monitored and allowed to take breaks (de Clercq et al., 2019; Hudson, Deb, Carruth, McGinley, & Frey, 2019; Nguyen, Holländer, Hoggenmueller, Parker, & Tomitsch, 2019).

Interaction Setting

Zebra crosswalks have been primarily investigated by current research. Zebra crosswalks are designated crossing locations characterized by white striped lines and where vehicles are obliged to stop for pedestrians. Unmarked/unprotected crossings and parking lots by contrast are much more ambiguous and require more communication between vehicles and pedestrians to negotiate interactions (de Clercq et al., 2019; Habibovic et al., 2018). Only seven articles researched unmarked/unprotected crossings and parking lots, and only two articles compared a given V2P communication system to more than one interaction setting. Due to the limited research in more complex interaction settings, it is difficult to say whether the current methods of V2P communication will be effective for all traffics situations.

Implicit vs Explicit communication

Researchers tended to disagree in regard to whether or not information should be presented implicitly or explicitly. In one design study, the most important characteristics of a V2P communication systems to a research focus group was found to be intuitive comprehensibility, recognizability and unambiguousness. (Ackermann et al., 2019). Pedestrians are able to make crossing decisions faster and are able to more accurately predict a vehicles intention with explicit messages (Burns, Oliveira, Thomas, Iyer, & Birrell, 2019). Conversely, explicit information is also subject to language and cultural barriers, making it difficult to create explicit messages that can be easily understood in all potential pedestrian encounters. Due to limitations in AV technology and complexity of vehicle pedestrian interactions, several researchers have noted that it may never be safe for an AV to give explicit instructions to pedestrians (Clamann et al., 2017; Habibovic et al., 2018; Lagström & Lundgren, n.d.-a). This is because the scenarios that pedestrians encounter AVs are likely to include other vehicles, pedestrians, cyclists or moving objects. The potential for dangerous conditions outside an AV's awareness or control is beyond the scope of what an autonomous vehicle can safely predict.

Implicit messages, on the other hand, can communicate information to pedestrians without using any particular language, making it easier to create a standardized communication method that could work in all countries and cultures. Implicit communication has been shown to necessitate some degree of learning and therefore is problematic when attempting to introduce autonomous vehicles into the market (Ackermann et al., 2019; de Clercq et al., 2019; Habibovic et al., 2018; Lagström & Lundgren, n.d.-a; Matthews, Chowdhary, & Kieson, 2017). A learning curve could increase pedestrian risk and reduce overall trust in autonomous cars.

Communication Modalities

Visual communication modalities were the most common and diverse. Visual information is the primary means of perception for most pedestrians however, it has been noted that these types of communication are not ideal for pedestrians who are "color blind, visually impaired or.. distracted" (Ackermann et al., 2019; Mahadevan, Somanath, & Sharlin, 2018). Text displays (ex. "you may cross") were found to be the least ambiguous form of communication (Chang, Toda, Igarashi, Miyata, & Kobayashi, 2018). Concerns about Text displays are that they can be difficult to read, especially under certain weather conditions and are subject to language barriers (Ackermann et al., 2019).

Other forms of visual communication included light displays and anthropomorphic features such as face, smile, eyes and hands. Light displays were among the most commonly tested, but in many cases required a learning period to be fully understood (Habibovic et al., 2018; Lagström & Lundgren, n.d.-b; Nguyen et al., 2019).

Auditory modalities took the form of explicit messages in either a human or synthetic voice and implicit messages like music, tones or beeps. Auditory information is typically good for grabbing distracted pedestrians attention and is important for visually impaired (Deb et al., 2018). Some researchers noted concern that auditory messages may be drowned out by other sounds or become unrecognizable when many vehicles are present at once (Mahadevan et al., 2018). Some participants expressed confusion of the meaning of certain tones and beeps and became hesitant, misinterpreting them as some form of alarm (Deb et al., 2018; Hudson et al., 2019).

Two articles investigated haptic feedback by means of engaging with pedestrian cell phones. This type of feedback lacks any localization cues and may not be noticeable among other notifications received through this device (Hussein et al., 2016; Mahadevan et al., 2018). Each article reached a different conclusion and more research is necessary to determine if this would be an effective means of communicating with pedestrians.

Message Content

Message content can take one of four forms: vehicle mode (autonomous or manually driven), acknowledgment of pedestrian, intention of vehicle, or advice to pedestrian.

Mode: Several studies found that it is important to communicate the vehicles mode to pedestrians (Chang et al., 2018; Charisi, Habibovic, Andersson, Li, & Evers, 2017; Habibovic et al., 2018; Hudson et al., 2019).When AVs are fairly new, pedestrians will have to interact with several different types of vehicles, full AVs, semi-autonomous vehicles, and manually driven cars. As demonstrated by the passenger in the driver seat phenomenon, a situation in which pedestrians become uncertain when encountering a vehicle with an obviously distracted person sitting in the traditional driver seat (Habibovic et al., 2018; Hudson et al., 2019; Lagström & Lundgren, n.d.-b). The pedestrian can be hesitant because traditional crossing behavior dictates that they make some sort of contact with the person in the driver seat to be sure that they have been noticed. Pedestrians do not experience the same hesitation in instances where there is nobody in the traditional driver seat or when the passengers in the vehicle is attentive (Hudson et al., 2019). Lagström et al (2015), hypothesized that communicating that the vehicle was in autonomous mode would allow pedestrians to quickly disregard the passenger in the driver seat phenomenon and reduce hesitation.

Acknowledgement: Acknowledgement can take many forms but always involves a pedestrian receiving feedback that a vehicle is aware of their presence. Perhaps the most notable form of acknowledgment that has been tested is the "eyes on the car", a study which seeks to demonstrate that AV communication with pedestrians can take the form of physical eyes on the body of a vehicle that act much like human eyes making eye contact and acknowledging pedestrians (Chang, Toda, Sakamoto, & Igarashi, 2017). Chang et al (2017), found that they were able to reduce crossing decision times by .287 seconds and resulted in higher feelings of safety. Other forms of acknowledgement are faces, smiles, hands, sounds and lights. Anthropomorphic forms of communication were also found to be among the most ambiguous (Deb et al., 2018; Mahadevan et al., 2018)

Intention: Vehicle intention was the most widely study content type. This included informing pedestrians that the vehicle is slowing down, stopping, not stopping, turning, waiting, starting, etc. Intention was found to reduce crossing decision times and increase pedestrian reported safety and comfort (Chang et al., 2017).

Advice: Advice was widely researched and found to be the least ambiguous form of communication. Advice could take the form of text scrolling across a vehicle's grill or a projected crosswalk on the road in front of a vehicle inviting pedestrians to cross. All advice suffers from the same limitations as explicit communication in terms of what can be safely communicate to a pedestrian.

Color

There was contention among researchers in regard to appropriate colors to use in the V2P communication systems. Several researchers chose to avoid red, yellow green and blue on the grounds that they already used in other traffic communication systems such as stoplights and emergency vehicles (Habibovic et al., 2018). For researchers that did use these colors, red and yellow were found to be perceived as the most urgent and was often used to indicate that a vehicle was not stopping (Fridman et al., 2017; Li, Dikmen, Hussein, Wang, & Burns, 2018). Green on the other hand was often used to indicate that it was safe for a pedestrian to cross because it does not have the same warning effect (Ackermann et al., 2019; Nguyen et al., 2019).

Some participants noted confusion with certain colors which are traditionally used in traffic lights. They did not understand if the message that was being displayed was an "instruction or express(ed) the vehicles intentions" (Nguyen et al., 2019). This makes sense because when a pedestrian approaches an intersection and checks the light, if it is green it means that traffic is not stopping and the pedestrian should not cross.

Trust

The more exposure a pedestrians have with an AV, the more they trust it. (Matthews et al., 2017) This suggests that trust in AVs will develop as pedestrians gain more experience interacting with them. The need for V2P communication systems may become less prevalent as autonomous vehicles become more common. Furthermore, it was found that even when pedestrians encountered V2P communication systems that fail to function properly and give incorrect information, pedestrians trust was reestablished rapidly (Holländer, Wintersberger, & Butz, 2019).

Time and hesitation

Measuring time and hesitation were important variables in determining the effectiveness and necessity of V2P communication systems. Hesitation and longer crossing decisions could lead to inefficient road ways and increased pedestrian risk (Habibovic et al., 2018). Time was measured in several different ways: response time to make a crossing decision, time it takes a pedestrian to cross (hurrying, slowly crossing) and the amount of time during an interaction that a pedestrian would feel safe crossing. In most research, crossing time was found to be improved when a V2P communication system was used. However, in several studies, vehicle behavior and gap distance were found to effect crossing time and hesitation the most (Clamann et al., 2017; Fridman et al., 2017; Mahadevan et al., 2018; Nguyen et al., 2019).

LIMITATIONS

One of the major limitations in researching V2P communication devices and autonomous vehicles is the fact that AVs operating in this capacity currently do not exist (Habibovic et al., 2018). Because of this, it is impossible to predict or create a scenario that encompasses the complexity of what actual pedestrian-autonomous vehicle interactions would look like.

Furthermore, current research has, for the most part, only investigated one-on-one pedestrian-AV interactions. More research is necessary to address the complex multi-party situations that drivers and pedestrians encounter every day, especially in densely populated urban environments.

Finally, this review represents only research that was discovered via the stated method and only from the listed data bases. There may be other research conducted in this area that was not discovered in this systematic review and that the author is unaware of.

CONCLUSION

While research has demonstrated that V2P systems can provide value to pedestrians in terms of feelings of safety, trust and crossing decision time, it has also demonstrated that vehicle communication to pedestrians may not be the most important factor. Gap distance and driving behavior still play an important role for pedestrian crossing decisions.

In terms of what needs to be communicated to pedestrians, so far there is no best answer. Communication of mode, acknowledgement, intention and advice have all been shown to aid in pedestrian-AV interactions. Explicit and implicit forms of communication have both been shown to be beneficial.

This systematic review has identified common themes in V2P research as well as highlighted areas of contention among researchers. Future research in this field should focus on: (1) Comparing the four message content types (mode, acknowledgement, intention and explicit directions), (2) investigate combinations of explicit and implicit communications messages across multiple communication modalities and (3) research more complex vehicle-pedestrian interactions, especially those that involve multiple vehicles and pedestrians.

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