# Communicating Awareness and Intent in Autonomous Vehicle-Pedestrian Interaction

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## ABSTRACT

Drivers use nonverbal cues such as vehicle speed, eye gaze, and hand gestures to communicate awareness and intent to pedestrians. Conversely, in autonomous vehicles, drivers can be distracted or absent, leaving pedestrians to infer awareness and intent from the vehicle alone. In this paper, we investigate the usefulness of interfaces (beyond vehicle movement) that explicitly communicate awareness and intent of autonomous vehicles to pedestrians, focusing on crosswalk scenarios. We conducted a preliminary study to gain insight on designing interfaces that communicate autonomous vehicle awareness and intent to pedestrians. Based on study outcomes, we developed four prototype interfaces and deployed them in studies involving a Segway and a car. We found interfaces communicating vehicle awareness and intent: (1) can help pedestrians attempting to cross; (2) are not limited to the vehicle and can exist in the environment; and (3) should use a combination of modalities such as visual, auditory, and physical.

### ACM Classification Keywords

H.5.m. Information Interfaces and Presentation (e.g. HCI): Miscellaneous; I.2.9 [Robotics]: Autonomous vehicles.

### Author Keywords

Autonomous vehicle-pedestrian interaction; perceived awareness and intent in autonomous vehicles

## INTRODUCTION

Research in the domain of autonomous vehicles is at the cusp of transformation from academic exploration to commercial products. Google [1] and Uber [2] have been testing their vehicles on public roads for several years, accruing millions of miles of safe operation. The benefits of autonomous vehicles are well-stated: they offer the potential to save valuable time normally spent driving, provide a dramatically safer passenger experience, and are accessible to people who cannot drive [2]. However, surveys of the public perception of autonomous vehicles have revealed both positivity and concerns about safety, legal liability, and interactions with pedestrians and cyclists, among others [11, 28]. While much of the research emphasis thus far is on the technological challenges associated with autonomous driving (such as motion planning, localization, perception, and control), a relatively less explored domain is autonomous vehicle-pedestrian interaction [22].

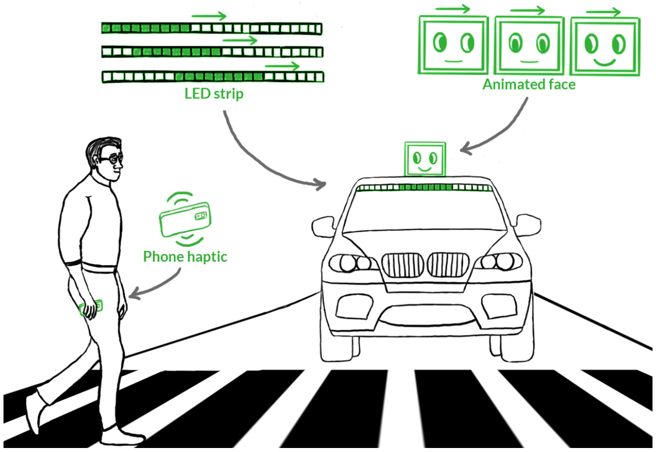

**Figure 1: Potential interface for communicating awareness and intent to pedestrians (interface elements in green).**

Vehicle-pedestrian interactions are diverse and complex [8]. Limiting the scope to crosswalks and to pedestrian crossing decisions, vehicles can provide pedestrians with ample information on their awareness and intent using movement patterns, including speed, acceleration, and stopping distance [24]. In addition, in traditional vehicle-pedestrian interactions, pedestrians receive nonverbal cues from the driver to ensure safe interactions. Informal communication channels from the driver including facial expression, eye gaze and contact, gestures and body movement, and possibly voice and tone of speech, can reassure the pedestrian about the driver's awareness and the imminent vehicle's actions [9, 10, 14, 23, 27, 29].

We think that in the short term, the challenge of vehicle-pedestrian interactions is going to become complex: with the introduction of varying levels of autonomy in vehicles [2], pedestrians would be interacting with manually-driven vehicles, semi-autonomous vehicles, and fully autonomous vehicles. While manually-driven vehicles are expected to continue providing driver cues, fully autonomous vehicles will not provide them (given that they will not have a driver), and semi-autonomous vehicles may allow the driver to become

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[1] https://goo.gl/iM1wB1 [2] https://goo.gl/nQHzCa

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distracted, also resulting in the lack of driver-provided cues. Recent work suggested, on one hand, that perhaps autonomous vehicles will not need driver-provided cues and will be able to communicate with the majority of pedestrians using physical movement alone [25]. On the other hand, recent findings have also shown that the loss of driver cues may decrease the pedestrian's confidence [16] and trust [17].

In response to this overarching challenge, our work focuses on the design of interfaces for explicitly communicating awareness and intent of fully autonomous vehicles to pedestrians (as shown in Figure 1). In the context of autonomous vehicle-pedestrian interactions, we define the *communication of awareness* as the vehicle's ability to acknowledge the pedestrian's presence and the *communication of intent* as the vehicle's ability to communicate its next action to the pedestrian (such as about to stop or not stop for the pedestrian).

We explored the role of interfaces in explicitly communicating the awareness and intent of an autonomous vehicle to a pedestrian via a two-phase study. In a design study (phase I of our evaluation), we gathered interface design ideas through a series of sketching sessions and determined an overall design space for autonomous vehicle-pedestrian interfaces. Within this design space, we identified four categories of interfaces: (i) interfaces that reside on the vehicle, (ii) interfaces that reside on the vehicle and street infrastructure, (iii) interfaces that reside on the vehicle and the pedestrian, and (iv) interfaces that reside in conjunction with the vehicle, street infrastructure, and the pedestrian. Based on the design study, we developed prototype interfaces for each of the four categories, deploying them on a Segway and on a car. In phase II of our evaluation, we tested the four interfaces we designed, with pedestrians in two studies, using the Segway and the car prototypes. Overall, our findings highlight that interfaces that explicitly communicate the vehicle's awareness and intent can be more useful to pedestrians in making crossing decisions than just perceiving the vehicle's movement and signals.

We suggest that interfaces like those we propose in this paper can address autonomous vehicles' missing informal communication channels, while retaining existing vehicle cues such as their movement. Based on our studies, we think that in autonomous vehicle-pedestrian interactions, pedestrians will still need reassuring feedback that the vehicle has sensed them and will stop before they cross a street. Our goal is also to draw attention to the non-trivial nature of the autonomous vehicle-pedestrian interaction challenge, especially given the short-term complexity expected with emerging and varying levels of vehicle autonomy. This view seems to be reflected in recent industry demonstrations from Nissan [3], Mercedes [4], and Ford [5], who demoed the possibility of incorporating pedestrian-focused interfaces in autonomous vehicles, though without sharing the background or studies that pointed at this outcome.

In the remainder of the paper, we discuss the design study findings, and then describe the design and implementation of the four interfaces that emerged from it. Then, we describe and discuss the results of the two studies we conducted after deploying our interfaces on a Segway and a car. Finally, based on our findings, we discuss our views on autonomous vehicles communicating awareness and intent, and on the design of future autonomous vehicle-pedestrian interfaces.

## RELATED LITERATURE

There are two distinct focuses of research into autonomous vehicle interactions. The major emphasis of related work is on the interaction between the autonomous vehicle and the person inside the vehicle, which we call the *driver-centred approach* (such as [1, 19, 21, 34]). The *pedestrian-centred approach*, which focuses on the interaction of the vehicle and the pedestrian, is less explored, and is the focus of our work.

Research in traditional vehicle-pedestrian interactions has shown that pedestrians rely on many nonverbal cues from the driver and the vehicle. They can be classified as driver cues (such as eye contact) and vehicle cues (such as speed or stopping distance) [9, 23, 27, 29].

Rothenbucher et al. [25] suggest that for autonomous vehicles, specialized interfaces for communicating the missing driver cues may not be needed for the majority of pedestrians. They found that most pedestrians managed to make crossing decisions based on vehicle cues alone through their study where pedestrians were faced with a Wizard-of-Oz autonomous vehicle. Risto et al. [24] further add that while interfaces for autonomous vehicle-pedestrian interactions might be promising, their ability to scale in the presence of many vehicles and pedestrians as in the real world is challenging. They found that human drivers and pedestrians communicate via the medium of vehicle movement, and suggested that interface designers should take this mechanism under consideration.

In contrast, Lagström and Lundgren [15, 16] placed an LED strip on the windshield of a car (which communicated intent to pedestrians) and found it effective in helping pedestrians make crossing decisions. They argue that vehicle movement alone is not enough to compensate for the loss of driver cues in autonomous vehicles and suggest the creation of specialized interfaces for communicating with pedestrians. However, more recently, a field study which tested interfaces for such interactions showed mixed results. Clamann et al. [4] designed and mounted a display on a vehicle, which communicated intent cues in two ways: (i) through the road symbols "cross" or "don't cross", and (ii) an information display showing the speed of the vehicle. Their study revealed that gap distance and crossing strategies that pedestrians had developed over time influenced crossing decisions more than the display.

From these discussions, it is evident that the role of interfaces for autonomous vehicle-pedestrian interactions is still unclear. Based on prior work showing that pedestrians are used to receiving both vehicle and driver cues when making crossing decisions, we hypothesize that, at least initially, when autonomous vehicles are first introduced, the explicit communication of cues beyond vehicle movement could be necessary.

Our view that interfaces can help communicate an autonomous vehicle's awareness and intent to pedestrians is shared by some industry designs and demonstrations. In 2015, Google patented the idea of pedestrian notifications, where the vehicle

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[3] https://goo.gl/IXLOQE

[4] https://goo.gl/2wvL61

[5] https://goo.gl/1FUPWa

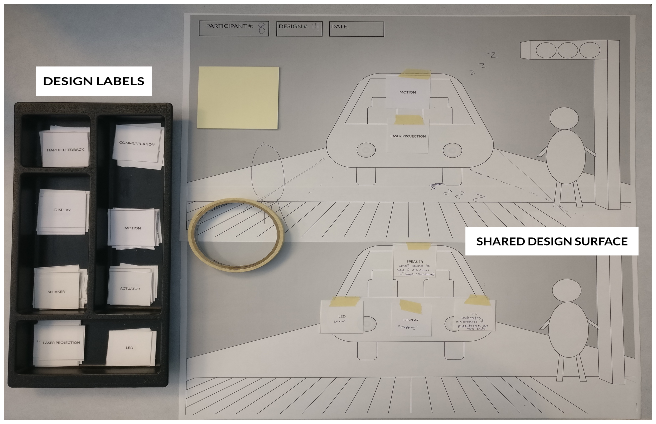


Figure 2: PICTIVE setup showing designs from Participant 8.

assesses a pedestrian's intentions and responds by explicitly communicating intent cues, awareness cues, or both [32]. Car manufacturers like Mercedes[3] and Nissan[4] have also proposed their visions for autonomous vehicle interfaces. The Mercedes F105 concept uses laser projection and an LED display. The laser projection alerts pedestrians of the car's awareness, and communicates that the car will stop to let them cross, while the LED display provides the current state of the car. Nissan's IDS concept leverages visual cues in two ways: an LED indicator strip on both sides of the car provides information about the car's awareness of pedestrians, and a text display on top of the vehicle provides information about the car's intent.

Overall, many industry concepts and a few research groups have proposed interfaces that can help pedestrians in their decision-making process when interacting with autonomous vehicles. We contribute to this growing body of work through a systematic exploration of the role of interfaces for communicating autonomous vehicle awareness and intent to pedestrians. We first explore how pedestrians perceive the creation of interfaces for autonomous vehicle-pedestrian interactions. Then, we design, develop, and evaluate prototype interfaces to assess the importance of these interfaces in autonomous vehicle-pedestrian interactions.

## PHASE I: DESIGN STUDY

We conducted a preliminary design study with a twofold goal: to learn if people perceive interfaces that explicitly communicate an autonomous vehicle's awareness and intent to be important, and to gain insight about designing such interfaces.

### Participants

We recruited 12 participants for the study (7 male and 5 female). Due to a protocol revision and a refusal to provide consent by one participant, we discarded data of two participants. The remaining 10 participants were in the age range of 23-47. They varied in experience from senior-year undergraduate students to postdoctoral researchers, and had previous experience with designing user interfaces. They were provided a remuneration of $20 for their participation.

### Study Procedure

To conduct the study, we chose a participatory design method called PICTIVE [20]. In this method, participants reflect on interface design by sketching or altering an existing researcher created sketch. We used PICTIVE, as through the act of putting down ideas on paper and inspecting them, end-users (potential pedestrians) have early exposure to, and provide input about the target implementation technology. To apply PICTIVE, we created sketches showing a traditional pedestrian-vehicle crossing scenario at a controlled intersection from two views (front and side). This was our *shared design surface*, which all participants used to create their designs. To facilitate participants' creation of interfaces, we made eight labels depicting common design cues. We used cues that prior work has proposed for autonomous vehicle communication interfaces (such as LED and laser projection) and introduced some additional cues. Our eight labels were haptic feedback, communication methods such as WiFi and Bluetooth, display, motion, speaker, actuator, laser projection, and LED. We provided office stationary (pens, sticky notes, and tape) so participants could place their labels on the design sheet and annotate them. Figure 2 shows the study setup.

#### *Sketch Phase*

In this phase, we gave participants thirty minutes to create three unique interface designs which communicated the awareness and intent of an autonomous vehicle to pedestrians trying to cross a street. We allowed participants to use any of the labels present or define their own. Participants placed labels on the design surface as per the real-world location of the cue (such as placing the LED label on the windshield of the car). We allowed participants to use any part of the design surface, including the vehicle, the pedestrian, the crosswalk, or the traffic signal to house their interface elements. Each of the three designs could be iterative and build on their earlier designs. We also encouraged participants to describe their thought process through a think-aloud protocol [12].

#### *Interview Phase*

After the sketch phase, we presented participants with eight diverse scenarios where the vehicle had to communicate its awareness and intent. Some example scenarios included (1) the vehicle cannot stop due to bad road conditions, (2) the vehicle spots a jaywalker and will stop, and (3) the vehicle reverses at a parking lot. We asked participants to rank their designs as a best, fair, or worst fit in handling each scenario, and propose any changes that could improve their interfaces.

### Data Sources and Analysis

From each study session, we collected participant-created designs, and a video recording. We transcribed the interviews and qualitatively assessed the transcripts and designs created by participants to identify common threads [3, 18]. Two researchers independently coded two participants' designs and transcripts and discussed their results to ensure consistency in the qualitative analysis. A few examples of the codes we created were "use of visual cues to communicate awareness", "communication between car and embedded technology on human or infrastructure", and "use of new or upcoming technology". We also counted how many designs incorporated the communication of awareness cues only, intent cues only, and both awareness and intent cues. To evaluate the designs that we collected from participants, we leveraged the *generic design thinking* approach suggested by Wiberg et al. [35], and identified a higher-level category of cues that were present in all our participants' designs.

### Findings from the Design Study

From 34 unique designs that 10 participants created, all featured cues that communicated the vehicle's intent to pedestrians. Twenty-two designs featured cues that communicated both the vehicle's awareness and intent to pedestrians. This indicated to us that awareness and intent were both important but hinted that intent was considered slightly more important.

For communicating awareness, the use of an LCD display featured the most (in 9 designs), and for communicating intent, LED lights featured the most (in 14 designs). However, participants also included other elements to accommodate pedestrians who suffer from visual impairments, such as haptic feedback and audio messages. Almost all participants borrowed from cues that people are already familiar with (*"I don't want to add more to the pedestrian or driver workload so using things they are already familiar with is better to train them" [P3]*). Following a similar approach, some participants incorporated human-like cues in their designs. Ten designs featured the use of such cues with examples including hand gestures, eye gaze, and verbal messages.

Table 1 shows our proposed design space for designing interfaces for autonomous vehicle-pedestrian interactions. We found three major modalities for cues across the 34 designs: visual, auditory, and physical, which are listed in the first column. The *visual* modality primarily leverages visual cues like color, patterns, and text, which pedestrians can perceive. The *auditory* modality aims to provide audio feedback through sounds and verbal messages. The *physical* modality also leverages visual cues but provides additional feedback through actuation, such as an actuated hand and haptic through phone vibration. The second column shows examples of participant-used visual, auditory, and physical cues from the design study. Following the *generic design thinking* approach [35], we also found that all designs could belong to one of four categories based on where participants placed their interfaces. The four categories were (1) vehicle-only, (2) vehicle and street infrastructure, (3) vehicle and pedestrian, and (4) mixed. These are listed in columns 3-6 of Table 1, and are described below.

Vehicle-Only: These interfaces involve placing cues on the vehicle such as an LED strip or a display. Thus, the responsibility of communicating with the pedestrian rests on the vehicle.

Vehicle and Street Infrastructure: These interfaces involve the placement of cues on both the vehicle and street infrastructure, including but not limited to, traffic lights, laser projection on the street, and the road on which the vehicle traverses. This design category splits the responsibility of communicating cues between the vehicle and street infrastructure.

Vehicle and Pedestrian: These interfaces incorporate cues on the vehicle and on the pedestrian. An example of such an interface is the use of haptic through a phone, where the pedestrian gets direct feedback about the vehicle's next action.

Mix of Car, Infrastructure, and Pedestrian: Interfaces in this category leverage a combination of cues of the previous three categories. Cues in this interface lie on the vehicle, street infrastructure, and the pedestrian.

| Cue Category | Participant's Implementation of Cue | Vehicle-Only | Vehicle & Street | Vehicle & Pedestrian | Mixed |
|---|---|---|---|---|---|
| Visual | Display with road signs/symbols | | | | |
| | Display with text | | | | |
| | Embodiment of human face/eyes on display | | | 🟩 | |
| | LED strip on car | 🟩 | | | |
| | Projecting lines on street | | | | |
| | Projecting car speed | | | | |
| | Google Glass on pedestrian | | | | |
| | Traffic lights | | 🟩 | | 🟩 |
| Auditory | Human-like voices | 🟩 | 🟩 | | |
| | Nonverbal sounds | | | | |
| | Car sounds | | | | |
| | Bracelet w/ speaker on pedestrian | | | | |
| | Pedestrian's phone playing message/sound | | | | 🟩 |
| Physical | Car lowering/rising | | | | |
| | Actuated hand | | | | 🟩 |
| | Movement/motion of car | 🟩 | 🟩 | 🟩 | 🟩 |
| | Haptic feedback on bracelet | | | | |
| | Haptic feedback of pedestrian's phone | | | 🟩 | |
| | Haptic feedback on traffic light | | | | |

**Table 1: Our proposed design space. Boxes in green indicate the elements we used to create the four prototypes.**

## INTERFACES: DESIGN AND IMPLEMENTATION

To investigate the usefulness of interfaces communicating autonomous vehicle awareness and intent to pedestrians, we developed simple proof-of-concept prototypes. It is beyond the scope of this paper to implement interfaces that occupy all combinations of cues presented in our design space (Table 1). However, as a starting point, we implemented 4 proof-of-concept interfaces based on our design space. The idea of demonstrating a design space using a smaller subset of instances is a valid methodology discussed by Wiberg et al. [35].

In each interface prototype, we selected cues based on two criteria: 1) we included popular interface elements as suggested by participants in the design study, and 2) we incorporated all modalities (visual, auditory, and physical) and all cue locations (vehicle, street, and pedestrian) to encapsulate our design space. The boxes highlighted in green in columns 3-6 of Table 1 show the cues we used in each interface.

In all our interfaces, we incorporated both awareness and intent cues. In addition to specific visual, auditory, and physical cues, all our interfaces included vehicle movement. Similar to [24], we treat vehicle movement in a simple manner wherein the vehicle follows social behaviors that drivers typically exhibit in their interactions with pedestrians (such as a vehicle stopping short of a crosswalk).

We later deployed our interfaces on a Segway and a car as part of two studies we conducted indoors and outdoors respectively. Between the two studies, we implemented minor revisions for the interfaces. This was done to accommodate participant suggestions and to address study-setting changes between indoors and outdoors. We highlight these changes along with our description of each interface below.

### Prototype 1: Vehicle-Only

Prototype 1 (Figure 3A) incorporated a visual cue and an auditory cue. We used an LED strip and a speaker to represent

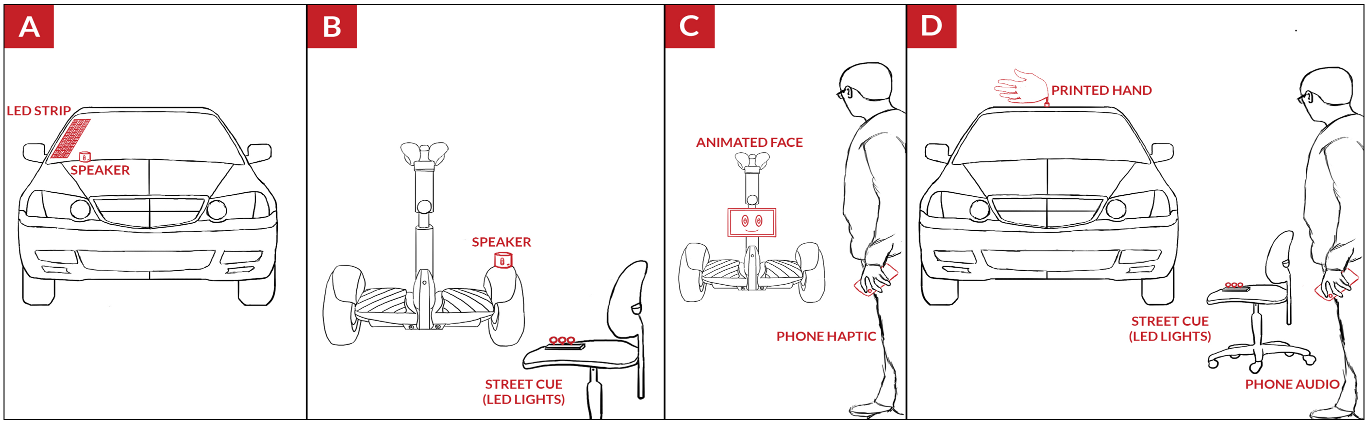


**Figure 3: Interfaces implemented in the Segway and car study: A - Vehicle-Only, B - Vehicle and Street Infrastructure, C - Vehicle and Pedestrian, D - Mixed. Participants saw all interfaces A-D in the Segway and car studies.**

the visual and auditory cues respectively. The LED strip was mounted on the vehicle and exhibited four states. Solid red lights indicated that the pedestrian shouldn't cross as the vehicle would not stop. Blinking blue lights meant that the vehicle was aware of the pedestrian. We chose blue as an alternate color to the three established colors that are commonly used in traffic lights. Green lights moving from left to right indicated to the pedestrian that the vehicle had fully halted and that it was safe to cross. Purple lights moving from right to left meant that the vehicle would start soon. For the car study, we eliminated the animations and used solid lights to make the strip more visible in outdoor settings. We also replaced the purple lights with yellow lights because some participants in the Segway study felt yellow better represented the state of "be cautious". The LED lights were controlled by an Arduino.

The speaker was also mounted on the vehicle and played the messages "about to stop" and "about to start" indicating to the pedestrian that the vehicle would stop and start soon. In the car study, we shortened the messages to "stopping" and "start" which repeated four times, because participants in the Segway study found that the audio messages were too long. In this interface, the visual cue could communicate awareness through the blue light and intent through the other three colors. The auditory cue communicated intent through voice.

### Prototype 2: Vehicle and Street Infrastructure

This prototype featured the use of two modalities of cues; auditory and visual (Figure 3B). The auditory cue was in the form of a speaker mounted on the vehicle. The speaker played the message "I can see you" and "you can cross now" indicating the pedestrian was seen and could cross. In the car study, we shortened the messages to "I see you and "cross" so that it would communicate its state to participants quickly.

A street cue in the form of three LED's represented the visual cue, and was placed on top of a chair near the participant in both studies. It was operated by an Arduino. Red meant it was not safe to cross, green meant it was safe to cross, and white meant it was about become unsafe to cross. In the car study, we replaced the white light with yellow because participants preferred traditional traffic light colors. In this interface, the auditory cue communicated awareness and intent (a message for each respectively) and the visual cue communicated intent through various colors.

### Prototype 3: Vehicle and Pedestrian

This prototype featured a physical cue and a visual cue (Figure 3C). A display mounted to the front of the vehicle represented the visual cue. The display incorporated an animated face with eyes. Initially, the eyes were centred, then oscillated sideways, and finally, followed the direction of the participant.

The physical cue was embedded in an Android phone. The phone was held by the participant and vibrated to indicate that it was safe to cross. In this interface, the visual cue communicated awareness through the animated face, and the physical cue communicated intent through haptic feedback.

### Prototype 4: Mixed

The mixed design featured a combination of cues on the vehicle, street infrastructure, and the pedestrian (Figure 3D). A visual cue in the form of three LED's (street cue), a physical cue using a printed hand mounted to the vehicle, and an auditory cue through an Android phone on the participant were all present in this design. The street cue functioned in the same manner described in Prototype 2. An Android phone controlled by a researcher played the message "I can see you" indicating that the pedestrian had been seen. Finally, a printed hand attached to a Servo motor could imitate the waving of a hand by rotating left to right three times. The hand gesture indicated to the pedestrian that it was safe to cross. The hand was controlled by a timed program on an Arduino. In this interface, the visual and physical cues communicated intent, while the auditory cue communicated awareness.

## PHASE II - VEHICLE-PEDESTRIAN STUDIES

We conducted two studies, using a Segway and a car, to test our interfaces in a street crossing scenario. The goal of conducting these studies was to demonstrate our interfaces to participants and elicit their feedback about the broader role of interfaces for communicating intent and awareness in autonomous vehicle-pedestrian interactions. In this section, we describe our methodology for both studies.

### Testing Platforms - Segway and Car

We decided to perform our tests on two platforms, a Segway and a car. The Segway study was part of an evolutionary study approach, and provided two unique advantages: 1) we could have participants cross in front of it, which was not allowed by our ethics board in the car study, and 2) it could appear fully autonomous when being operated remotely, whereas the car study always had two researchers on board. However, because the Segway is a small vehicle, we feared its harmless profile could introduce confound in our study. In addition, since the Segway is not a "street legal" vehicle, we had to perform the study indoors. To counterbalance this, we also opted to test interfaces on a car in outdoor conditions.

### Participants

For the Segway study, we recruited 10 participants (3 male and 7 female) in the age range of 18 to 65. For the car study, we also recruited 10 participants (5 male and 5 female) but in the age range of 18 to 55. The participants came from a wide range of disciplines, including actuarial science, psychology, engineering, mathematics, accounting, and computer science. Participants were recruited using posters placed around our university campus, social media ads and word of mouth. They received $20 in remuneration for their participation.

### Study Tasks

We included five tasks for the participant in both the Segway study and the car study. All participants in both studies experienced all the interfaces A-D as seen in Figure 3. The first task was always the baseline task, where the participant interacted with just the vehicle without an interface, receiving information via the vehicle's movement. This task helped us establish a baseline to compare with the interface tasks. We tested this task in the Segway study by teleoperation, and in the car study by telling the participant that two researchers would be on board the vehicle to collect data (but were not in control of the vehicle).

In the remaining four tasks, we evaluated the four interfaces one at a time (as shown in Figure 3) by randomizing the order in which they appeared to the participant to avoid learning effects. Here, participants received information via our interfaces as well as through the vehicle's movement. In each task, which lasted ten minutes, there were two trials. In each trial, the participant had to decide if they would cross or not. We randomized the order of the vehicle stopping and not stopping trials in both studies. As such, participants responded to the vehicle's actions. While participants crossed the corridor in the Segway study, for safety reasons, participants only verbally expressed their crossing decisions in the car study.

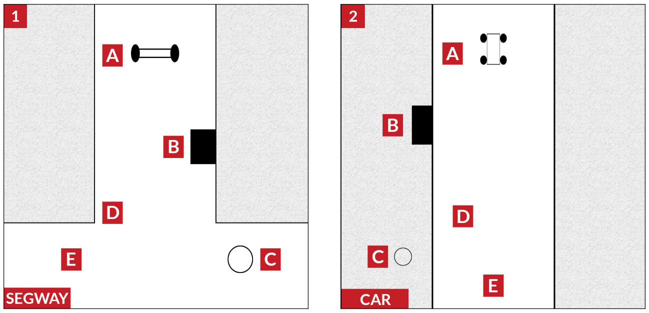
### Study Procedure

For both our studies, we used the Wizard-of-Oz technique [5], because neither the Segway nor the car had fully autonomous capabilities. Per this technique, the researcher controlled the vehicle and its different interface cues. As an example, in prototype 1 (vehicle-only), the researcher would first play the audio message, "about to stop", and then stop the vehicle.

Figure 4a shows the setup of the Segway study, which we conducted in an empty corridor of a building. We mounted a camera to a tripod and placed it in front of the corridor to capture both the Segway and the participant. The Segway was operated at 5 km/h in every trial. In all tasks, we teleoperated the Segway using the official Ninebot mobile application with the aid of video feed from a camera mounted on the Segway. We asked the participant to stand at point C before each trial. The Segway always started from point A, and when it reached point B, the researcher utter the phrase "Go" indicating to the pedestrian that they could proceed forward. Once the pedestrian arrived at the corridor, they could observe the Segway and make one of two decisions: cross or stay. We asked the participant to say "I'm crossing" if crossing and walk over the other side of the corridor, arriving at point E. Otherwise, they uttered "I'm not crossing" and stood in the same spot. In the trials where the Segway would stop, it would be at point D. At the end of each trial, we asked the participant to head back to point C and the Segway would be back at point A.

Figure 4b shows the setup of the car study. We conducted the study in a closed off section of a parking lot. We placed one camera to capture the pedestrian and the vehicle, and placed another camera across from the participant to capture their crossing reactions. The vehicle always had two researchers on board, one of whom controlled the vehicle at all times, and the other who controlled the interfaces. The vehicle was driven at 10 km/h. We informed the participant that both researchers were only on board to collect data. The vehicle would start at point A as shown in Figure 4b. In each trial, the participant started by facing away from the vehicle by standing at point C. Once they heard the vehicle horn at point B, we asked them to turn, face the vehicle, observe what it was doing, and make a decision. If the car stopped, it was at point D. At the end of each trial, whether the vehicle stopped or not, it would be at point E. If the participant decided that they wanted to cross, we asked them to raise their hand and show a *thumbs up* gesture. Otherwise, they stood in the same spot without gesturing.

In each study session, participants completed a pre-study questionnaire, collecting demographic information. Before each trial, we briefed the participant of the task we were testing. We also informed them the vehicle may or may not stop and that this was randomized. We introduced each interface as a single entity via a description sheet, which we gave them to refer to during the trials. Participants then evaluated each interface as a single unit. We also informed participants that the interfaces merely provided suggestions but the final crossing decision rested on them. At the end of each task, participants filled out a mid-study questionnaire including two five-point Likert scale questions about their confidence in the vehicle's awareness and intent, and two open ended questions that asked them to mention the most and least effective part of the interface respectively. At the end of the study, participants completed another set of four five-point Likert scale questions comparing the interfaces to the baseline task (no interface), and one Likert question comparing the importance of awareness and intent. Finally, participants also took part in a semi-structured interview through which we gathered overall feedback on the perceived strengths and weaknesses of each interface, the effectiveness of individual modalities, and reflections on their real-world applications.



**(a) A: Segway start position, B: Researcher says "Go", C: Participant start position, D: Segway stop position, E: Pedestrian end position when crossing.**

**(b) A: Car start position, B: Car "honks", C: Participant position, D: Car stop position, E: Car end position.**

**Figure 4: Experimental setup of the Segway and car studies.**

| | Baseline | | Vehicle Only | | Vehicle Infrastructure | | Vehicle Pedestrian | | Mixed | |
|---|---|---|---|---|---|---|---|---|---|---|
| | *C* | *DC* | *C* | *DC* | *C* | *DC* | *C* | *DC* | *C* | *DC* |
| *Segway* | 1 | 3 | 0 | 0 | 1 | 2 | 0 | 0 | 0 | 1 |
| *Car* | 2 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |

**Table 2: Incorrect crossing decisions made by participants out of 10 in each study for each task. C - did not cross when could cross, DC - crossed when could not cross.**

## Data Sources and Analysis

In Phase II, we collected data responses to a pre-study questionnaire, mid-study questionnaires between tasks, a post-study questionnaire, and a video recording of the entire experiment including the interview. We also maintained a count of crossing decisions (correct or incorrect) that participants made in each scenario and trial. We transcribed and coded each interview to identify the kinds of considerations that affected a participant's evaluation of an interface. A few examples of the codes we chose were "human-like vs machine-like cues", "binary vs many states", and "cues from the vehicle vs third party". We quantitatively analyzed the Likert scale questions to test significance. In the remainder of the study, we refer to the participants of the Segway study as SP, and the participants of the car study as CP.

## Findings from the Segway and Car Studies

### *Importance of Awareness and Intent*

In Phase II, for both the Segway study and the car study, all participants found communicating awareness and intent cues to be important. However, we found that communicating intent was more important than communicating awareness. In the Segway study, 6 out of 10 participants chose intent to be more important than awareness. In the car study, 7 out of 10 participants chose intent to be more important than awareness. From our interviews, we found that while communicating awareness was important to pedestrians, awareness alone did not provide complete reassurance of the vehicle's imminent action. One participant said, *"I don't think it's [awareness] the most important, because once you know the driver sees you, you have these expectations that they would slow down but you never know" [SP6].*

| Question | Platform | Comparison | df | t | p |
|---|---|---|---|---|---|
| *Awareness* | *Segway* | Base (M = 3.3, SD = 0.68) vs VO (M = 4.2, SD = 1.07) | 17 | 2.11 | 0.046 |
| | | Base (M = 3.3, SD = 0.68) vs VS (M = 4.1, SD = 0.77) | 18 | 2.10 | 0.049 |
| | | Base (M = 3.3, SD = 0.68) vs Mix (M = 4.2, SD = 1.07) | 17 | 2.11 | 0.046 |
| *Intent* | *Segway* | Base (M = 3.1, SD = 0.77) vs VO (M = 4.2, SD = 0.40) | 16 | 2.12 | 0.005 |
| | *Car* | Base (M = 2.8, SD = 1.29) vs VO (M = 4, SD = 0.67) | 16 | 2.12 | 0.015 |
| | | Base (M = 2.8, SD = 1.29) vs VS (M = 3.9, SD = 1.21) | 16 | 2.10 | 0.041 |
| | | Base (M = 2.8, SD = 1.29) vs Mix (M = 3.9, SD = 1.21) | 18 | 2.10 | 0.041 |

**Table 3: Significance testing of pedestrian confidence in vehicle awareness and intent between baseline and interface cases through the t-test** ($\alpha = 0.05$)**. VO - Vehicle-Only, VS - Vehicle-Street Infrastructure.**

Despite the differences in the importance of awareness and intent, one participant raised an important point. SP8 said, *"[autonomous vehicles] being a new thing to the pedestrian, significant cues are required in the beginning. Maybe after some time, when it becomes familiar, not much is required."* Based on this, one could consider the interface to be like "training wheels" through which pedestrians can learn to interact with autonomous vehicles. Over time, interactions with autonomous vehicles may become second nature, so at that point, interfaces may not be necessary. However, their importance when these vehicles are introduced cannot be understated.

### *Importance of Interfaces*

In this paper, we proposed the use of interfaces for communicating autonomous vehicle awareness and intent to pedestrians. Overall, we found that participants preferred receiving cues from an interface and vehicle movement over communication via the vehicle alone.

Comparing Between Interfaces: In terms of effectiveness of an interface in helping make a crossing decision, we saw a difference in opinions for the most effective interface - in the Segway study, 6 out of 10 participants chose the mixed interface (prototype 4) as the most effective interface, and in the car study, 5 out of 10 participants chose the vehicle and street infrastructure interface (prototype 2) as the most effective interface. For the position of least effective interface, we had consensus - in both studies, a majority (5 out of 10 in the Segway study, and 6 out of 10 in the car study) of the participants found the vehicle and pedestrian interface (prototype 3) to be the least effective. Further, Table 2 shows the number of instances where participants made incorrect decisions in each scenario, suggesting that with interfaces, participants were less error-prone.

Comparing the Baseline Cases and the Interfaces: When we asked participants to compare the effectiveness of the interfaces with the baseline task (where vehicle movement was the only communication cue), on average, they rated all interfaces higher than the vehicle alone across both studies on the Likert scale. We also found significance when comparing participants' awareness and intent confidence between the baseline and interface tasks using the t-test as Table 3 shows.

## DISCUSSION

Our findings suggest that participants preferred to receive explicit information about the vehicle's awareness and intent via interfaces as opposed to only receiving information from the vehicle's movement. In this section, we discuss high-level themes which stem from our findings and reflect on how future interfaces for autonomous vehicle-pedestrian interactions could be designed.

## Revisiting our Design Space

Our design space (as shown in Table 1) follows two categories: (a) modalities of cues, and (b) interface location. In the following section, we revisit our findings in the context of the proposed design space, solidifying its validity and proposing implications for future design.

### *Modalities of Cues*

We observed that three modalities of cues can be important for creating interfaces that explicitly communicate an autonomous vehicle's awareness and intent to a pedestrian (see Table 1). However, each modality has specific trade-offs which designers should consider when making new interfaces.

Visual cues: In our Segway and car studies, we found that the LED strip was often ranked higher compared to other auditory and physical cues. In the Segway study, 6 out of 10 participants ranked it as the best cue for awareness, and for intent, 7 out of 10 participants ranked it as the best cue. This is not surprising as visual cues are the primary means of perception for most pedestrians. For example, currently pedestrians receive visual information from vehicle movement, traffic signals, pedestrian crossing signals, and vehicle turn signals when they attempt to cross. In contrast, we often heard participants comment about the disadvantage of visual cues for those who might be color blind, visually impaired, or for distracted pedestrians (a problem also discussed by [31]). Based on this, while familiarity with visual cues might be a reason to consider them as the primary modality of communication in the interfaces, designers should consider diverse pedestrians and constantly evolving personal technology usage patterns, and include alternative modalities when needed.

Auditory cues: In the car study, we found that several participants (6 out of 10) liked audio feedback from the vehicle for awareness communication. One participant explicitly mentioned that a voice message saying "cross" felt like a command that provided clear instructions to them (*"when the speaker said I see you and cross, it was like a direct acknowledgement that the vehicle wants me to do this" [SP2]*). However, on the downside, several participants mentioned that in the real world, auditory cues could be difficult to process by pedestrians. For example, in situations where multiple unsynchronized autonomous vehicles might try to communicate with pedestrians using audio messages, the result may be cacophony rather than useful information for the pedestrian. Based on our results, and considering the traditional usage of auditory cues in places such as on an emergency vehicle, we think auditory cues could be included in interface designs, but perhaps reserved to be used to provide clear commands to the pedestrian during an emergency, or when a group of autonomous vehicles synchronize an auditory message to pedestrians.

Physical cues: These cues expand the physical movement of the car and add physical expressions which may be less common in vehicle-pedestrian interactions in some cultures. If well designed, we think there is value in integrating these types of physical cues in interfaces for autonomous vehicles. From the Segway study, we found that half our participants liked the actuated hand because it was clearly visible and straightforward to interpret. In contrast, phone vibration was typically not preferred. This was because the communication was subtle and sometimes, pedestrians were not confident whether the phone had vibrated. In addition, participants mentioned that in real-world scenarios, vibration communicated through a phone could be confused with other phone functionality (such as receiving a text message). Based on this, we suggest that if physical cues are to be used, they should be clearly sensed, and be easy to interpret.

### *Interface Location*

We found that interfaces can be positioned on the vehicle, on street infrastructure, on the pedestrian, or on a combination of the three. When placing cues on other entities than the car, the reliability of the information received is an important consideration for pedestrians when they make crossing decisions. We noticed a distinct split of opinions when we asked participants about the reliability of cues originating directly from the vehicle as opposed to cues that communicated information through a third party like cues on the pedestrian. This was especially evident in the case of the audio message, "I can see you", which played through a speaker mounted on the vehicle versus when an audio message played through a phone held by the participant. In the car study, 4 out of 10 participants told us that they preferred hearing the audio message from the vehicle or the "source". A possible explanation is that people trust the audio message coming from the vehicle because they feel it is tied to the vehicle's operation as opposed to an audio message which is sent to and received through a "second-hand" source. Still, 5 out of 10 participants told us that they preferred the phone audio message because they felt it was more practical in the real world (since relative to a hand-held phone, sounds projecting from a speaker on the car could be more affected by background noise, distance, and multiple cars playing the same message).

This pattern implies a shift in the way we think of communication between the vehicle and a pedestrian. Interface elements can rely on mobile technology, and do not necessarily have to be placed only on static infrastructure (such as traffic lights), or on the vehicle to be perceived as effective and perceived reliable by pedestrians. Moreover, interfaces should capture some of the direct ad-hoc communication between a driver and a pedestrian (eye gaze, hand gestures, and vehicle speed) and deploy them using the vehicle or externalize them dynamically to the pedestrian via existing mobile interfaces.

## How Many Cues are Too Many?

Management-related work on the phenomenon of receiving too much information, or *information overload* [7], indicates that the decision-making performance of an individual improves with respect to the amount of information received up to a certain point. After this "threshold", an individual's performance rapidly declines. Our findings suggest that additional information supported pedestrian crossing decisions, but also that information overload may become a factor when pedestrians are provided with too many cues.

We noticed these trends with the mixed interface which included three explicit cues. While participants selected the mixed interface in the Segway study as most effective, it was not the most effective interface in the car study. One explanation that could account for the mixed interface's popularity in the Segway study is the presence of multiple cues, allowing participants that missed one of the three cues to compensate for it by using the others (*"Because there are many cues to tell you when it's safe and when it can see you. There are many tools to increase your safety and boost your confidence" [SP7]*). At the same time, the mixed interface's lack of popularity in the car study was attributed by several participants to the presence of too many cues (*"I had to wait for all of them [the cues] to give me a go-ahead. First the light, then the phone, and then the hand. I think it takes a lot of time and could be confusing to many people" [CP9]*).

Seeking the threshold separating helpful additional cues and information overload from perceiving too many cues can be elusive. Once we begin considering a wider net of pedestrians, especially vulnerable road users such as elderly pedestrians, this challenge becomes acute. A study assessing the effect of age on crossing [6] found that declines in certain perceptual and cognitive abilities caused older pedestrians to overestimate some bad crossing opportunities while missing good crossing opportunities. Overly complicated interfaces would not be very effective for these types of pedestrians and additional cues may become disadvantageous.

However, since older pedestrians have trouble perceiving a vehicle's speed correctly, especially at higher speeds [6], providing additional cues beyond the autonomous vehicle's movement could be crucial. Our findings do not point to a specific threshold but rather emphasize the possibility of information overload for some pedestrians as additional cues are provided.

### The Complexity of Presented Cues

Cues that exhibited only a few states and clearly communicated with the pedestrian were generally more popular among participants in both studies than cues with multiple states or that were ambiguous to interpret. One example of a simple cue from our prototypes is the actuated hand (Figure 3D), which 5 out of 10 participants cited as the best intent cue in the Segway study. Although the phone vibration was not a popular cue due to its impracticality as a cue in the real-world, it was also a simple cue with two states. One participant said, *"Because it's immediate (phone vibration). You don't have to process four different colors. It's a yes or no, vibrating or not" [CP3].*

In contrast, the LED strip and the animated face had multiple states which participants sometimes found difficult to interpret. The LED strip could show four clear states yet one participant felt it was too complex, especially in real time crossing scenarios. CP3 said, *"Because those LED's - there were too many colors so I had to look at the sheet [interface description] and decide. In reality, I cannot bring a sheet"*. The animated face was the worst performing cue in both studies. CP6 said, *"The reason I don't like eye contact as much as hand gestures is because eye contact is kind of ambiguous. I don't know if you see me or someone next to me or if you're actually making eye contact. A gesture is very explicit when driving"*. One participant suggested an improvement to the current animated face using a fixed number of states (*"It has to be logical, like one, two, and three. Only three positions or states" [CP9]*).

Our finding that autonomous vehicle interfaces need to provide stable and clear cues to pedestrians is not surprising, and is aligned with the basic HCI principle of clear and continuous feedback [13]. Based on this, we suggest that designers should include clear-to-interpret cues, with distinct and stable states.

### Responsibility Distribution

In a traditional driver and pedestrian crossing scenario, the driver and the pedestrian share some responsibility for ensuring that the interaction takes place smoothly. Drivers are expected to observe the pedestrian and make a rational decision, as per the rules of the road; this implies, for example, that they should yield to pedestrians at an intersection. Pedestrians are also expected to observe the vehicle before crossing, even if they have the right of way, given the asymmetrical relationship between their fragile body and the momentum of a heavy, fast vehicle. However, our findings indicate that the current distribution of shared responsibility may be changing in the case of autonomous vehicles.

In the no interface task of the car study, 2 out of 10 participants mentioned that they felt an added responsibility for making the crossing decision (*"Normally it's 50-50, but with autonomous vehicles, it's more on the pedestrian. I mean, I cannot speak to the autonomous car, since there is no driver inside. Otherwise, I could wave my hand or something" [CP5]*).

In contrast, 5 out of 10 participants felt interfaces reduced their responsibility in making crossing decisions. CP10 said *"I think if the car gives me all the cues that I should cross, and I follow it, and there's something wrong, it's the full responsibility of the car. They reduce my responsibility to zero because I was induced into taking an action based on what I saw"*.

These two patterns do not necessarily contradict each other: they suggest that autonomous vehicle interfaces can help pedestrians make crossing decisions, but also that pedestrians will become much more reliant on them. This expected over-reliance on autonomous vehicle cues shifts the responsibility burden onto designers, who would need to carefully design interfaces and perform thorough evaluation to ensure that only the correct information is transmitted.

### Anthropomorphism

While prototyping, we borrowed heavily from the current interaction of drivers and pedestrians. For example, we included eye gaze in the animated face as part of the car and pedestrian interface (prototype 3), human voice for our speaker messages, and hand gestures in the mixed interface (prototype 4). As discussed previously, the animated face implemented in the vehicle and pedestrian interface was not received very well in either study. However, the actuated hand performed well in both studies, with participants citing its familiarity and explicit communication of intent as reasons for its effectiveness. Similarly, audio cues were especially popular in the car study. One participant said, *"the confidence when I heard a familiar voice like a human was increased" [CP10].*

While we observed positivity towards some human-like cues being used in autonomous vehicle-pedestrian interactions, we are still unsure about its overall effect as some human-like cues (such as eye gaze) can be difficult to interpret. We expect that relying on anthropomorphic cues may become a thing of the past as pedestrians interact more with fully autonomous vehicles, and less with human drivers.

### The Significance of Motion Cues

In traditional interactions between vehicles and pedestrians, the vehicle's movement plays a fundamental role in influencing the pedestrian's crossing decision. Pedestrians rely on vehicle speed and distance to judge both the awareness and the intent of the driver [27, 30, 33]. A study conducted by Risto et al. [24] found that vehicle and pedestrian behavior are purposely communicative. They argue that when the socially acceptable behaviors of slowing early and stopping short are not followed, pedestrians experience discomfort in crossing. Our findings indicate that vehicle movement patterns will continue to be a significant cue in autonomous vehicle and pedestrian interaction, even in the presence of interfaces. In our studies, participants experienced both the *slowing early* and *stopping short* behaviors (when intending to stop, the vehicle slowed down early, and always stopped at a considerable distance away from the designated crosswalk). In the no interface conditions, a majority of participants (9 out of 10) pointed to vehicle speed and stopping distance as reasons for their confidence in the vehicle's awareness and intent. One participant in the Segway study argued that speed was the most crucial cue, even in the presence of interfaces. This was reflected in their crossing behavior, where in some trials with interfaces, they crossed before some or all of the cues had been communicated (*"If the vehicle was too far away, you wouldn't see the driver, but if it was close, then I'd base my decision on the eye gaze and hand gestures. But mainly it's the speed and how close it is" [SP7]*). Designers should consider autonomous vehicle movement patterns as a key layer of interaction with pedestrians, providing baseline information that should be reinforced by other explicit communication cues.

### Limitations

Our work demonstrated that explicitly communicating information about autonomous vehicle awareness to pedestrians can help them in making crossing decisions.

However, we looked at only a small (but meaningful) slice of the wider autonomous vehicle-pedestrian interaction space, focusing on crosswalk scenarios. We conducted controlled studies using Wizard-of-Oz, had a small sample size, and tested our prototypes in a specific context, limiting the realism and generalizability of our work. An important caveat is that our studies and discussion are rooted in current vehicle-pedestrian interaction patterns observed in a North American context. We posit that differences in road culture will affect many future design considerations. For example, while our participants reflected of respectful hand gestures, or polite audio messages, in more aggressive driving cultures, pedestrians will expect drivers to honk and flash their lights at them. Autonomous vehicle interfaces in such driving cultures may be forced to imitate some of these behaviors simply to hold their ground, though they can also be used to slowly facilitate change in driving culture and safer interaction with pedestrians.

Despite these limitations, our prototypes and studies provide a strong indication that people prefer to receive information from autonomous vehicle interfaces that explicitly communicate with them, rather than through vehicle movement alone.

## CONCLUSIONS AND FUTURE WORK

We proposed the use of interfaces for explicitly communicating vehicle awareness and intent to pedestrians. As part of our exploration, we conducted a design study to gain insight on designing interfaces for autonomous vehicle-pedestrian interactions. We implemented the design study findings by creating four prototypes and deploying them on a Segway and a car, and conducting two user studies to assess their usefulness in helping pedestrians make crossing decisions. We found that interfaces which communicate awareness and intent can be helpful to pedestrians attempting to cross a street. In summary, our work makes three contributions: (i) showing that autonomous vehicle interfaces that explicitly communicate vehicle awareness and intent can be helpful to pedestrians in making crossing decisions, (ii) identifying a preliminary design space that can aid future designers build interfaces that explicitly communicate awareness and intent, and (iii) presenting (in the Discussion Section) considerations for designing future interfaces that can help pedestrians interact with autonomous vehicles.

We plan to expand our work and prototypes to testing with an actual autonomous vehicle, and to deployment on pedestrian's mobile and wearable devices. We are also interested in testing our work with multiple vehicles and pedestrians where we predict that scalability will become a critical challenge. By revisiting our design space in different scaling conditions such as one-to-one, one-to-many, and many-to-many instances of vehicles and pedestrians, we can refine our findings to reflect scalability. Our work has focused on the pedestrian-centered approach to handling the autonomous vehicle-pedestrian interaction, but there are also challenges in the driver-centered approach, such as maintaining driver situational awareness, which need to be addressed. Further, we can learn from research being conducted in vehicle-to-vehicle communication. For example, Sadigh et al. [26] propose using an autonomous vehicle's actions to communicate awareness and intent to drivers of manually-driven vehicles.

The near future will force pedestrians to expand their view of vehicles, a future where they will not expect the driver (if there is one) to provide them with familiar cues. Other variables impacting future design of vehicle-pedestrian interfaces are expected to emerge from new policies governing the introduction of autonomous vehicles (such as the US Department of Transportation's recent framework [6]). While still preliminary, our work outlines a future path forward where the interaction flow to the pedestrian is shifting from the driver to the autonomous vehicle, and possibly drifting from static infrastructure (such as crosswalks and traffic lights) to vehicle interfaces and to the pedestrian's mobile appliances. Our findings suggest that expecting pedestrians to rely on cues provided by movement alone will be an oversight, and that future interfaces for autonomous vehicle-pedestrian communication are an acute challenge for the interaction design community.

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[6] https://goo.gl/DHcYR8

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